Spatial Tools for Guiding Forest Restoration and Fuel Reduction Efforts

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Abstract

The Forest Ecosystem Restoration Analysis (ForestERA) Project provides a framework for assessing the impacts of ponderosa pine restoration and fuel-reduction treatments at landscape and regional scales. We are developing spatial tools in the ArcGIS environment for prioritizing forest treatments and analyzing their cumulative effects on wildlife distributions, fire threat, and other parameters relevant to fire and forest ecology. These capabilities allow managers to address planning challenges at the scale of several thousand to several hundreds of thousands of hectares, providing an expanded planning context beyond the scale of individual management units. This paper discusses work to date on the project.

Introduction

ForestERA models are predictive tools that link field and remotely-sensed data in a landscape model that permits comparison of the impacts of alternative forest treatment strategies on fire hazard and wildlife. They are constructed so that stakeholders can create their own hypothetical scenarios and explore the potential outcomes of alternative management strategies.

At all stages of our work, from planning to implementation, the ForestERA project has been informed and guided by a diverse group of collaborators and a science advisory committee. At the start of our project in the fall of 2001, in order to guide our project planning, we held meetings, sent out questionnaires and conducted personal interviews with representatives from local, state, and federal agencies, academic and other institutions, and environmental groups. In the fall of 2002, we held a series of open houses to update them on progress and elicit more feedback. In addition, we use e-mail announcements and our web page to keep stakeholders informed of our activities. To move our products from research to implementation this fall and winter (2003/04), we will distribute our spatial data and tools and hold user-training workshops and other forums, which will also assist us with fine-tuning our products.

Study area description

Many forests in the western US are dense and historic fire suppression efforts have contributed to excessive ground and ladder fuel accumulations that increase the likelihood of catastrophic fire (Cooper 1960, Harrington and Sackett 1990, Swetnam 1990, Covington and Moore 1994, Allen et al. 2002). More recent fire control efforts have caused wildland fire frequency and intensity levels to exceed those encountered during the early part of the 20th century (Agee 1993).

The ForestERA project is focused on ponderosa pine forests in northern Arizona and western New Mexico (Figure 1) including several patches north and south of the Grand Canyon and a largely contiguous belt extending from the San Francisco volcanic field to the southeast along the Mogollon Rim into New Mexico. The forests grade to mixed conifer and spruce-fir at higher elevations and to pinyon-juniper at lower elevations. Other fairly common tree species include quaking aspen and Gambel's oak.

Over the past 1,000 years, ponderosa pine forests in this region occurred in relatively open stands interspersed with grasslands (Cooper 1960). The herbaceous understory carried frequent, low intensity fires along the forest floor, with stand replacing crown fires occurring infrequently (Covington and Moore 1994, Korb and Springer 2003). Beginning in the late 1800s, the introduction of domestic livestock, combined with active fire suppression, dramatically altered the historical regime. This, combined with wholesale logging of the older, bigger trees, resulted in today's dense forests of small trees that are more prone to stand-replacing crown fires. Changes in forest structure, composition, and function have been well-documented, and the native biota, adapted to open stands and frequent fire, has suffered.

Elevations throughout the project study site range from approximately 6,000 feet to 12,633 feet on Humphrey's Peak, the highest elevation in Arizona. Precipitation ranges from 17 to over 30 inches at the highest elevations, with approximately 65 percent of the precipitation falling as snow (USDA NRCS). Recreation is an important land use in this area, which contains five national forests (Kaibab, Coconino, Apache-Sitgreaves, Tonto and Gila) and many Wilderness and other specially designated areas. Cattle grazing is also common across the area. Commercial timber cutting used to be dominant, however since the early 90s, the listing of the Mexican spotted owl and other endangered species has drastically curtailed timber cutting. Major towns and cities include Williams, Parks, Flagstaff, Heber, Alpine, and Pinetop.

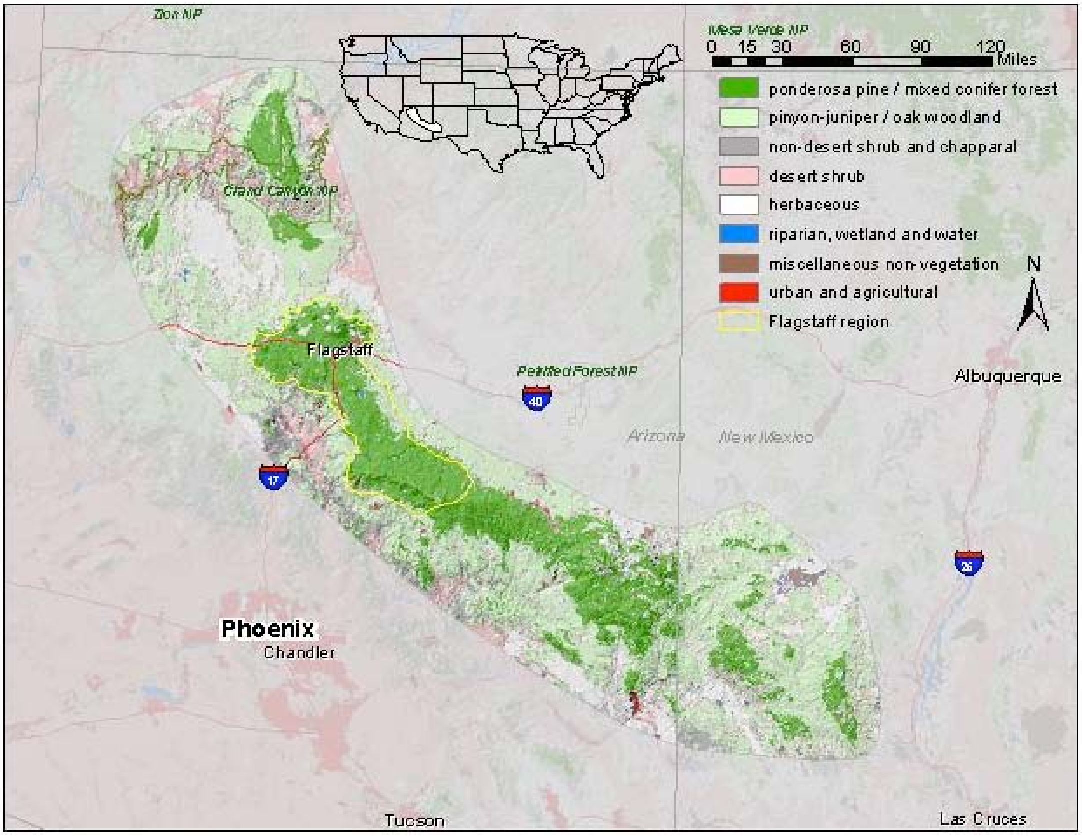


Figure 1. The project will focus on selected ponderosa habitat within the boundaries of this region. Current modeling efforts have focused on the Greater Flagstaff region (two million acres) outlined in yellow, however we are planning to expand the total area modeled southeast along the Mogollon Rim into New Mexico and north into the Kaibab Plateau.

Methods

Multi-Criteria Decision Analysis Framework

In this paper we demonstrate the integration of the following ForestERA models in the context of a multi-criteria decision making framework (Figure 2): 1) vegetation models of overstory tree composition, basal area, stem density, canopy cover, and ground fuels, 2) fire models of crown fire hazard and fire risk, 3) forest treatments models of predicted vegetation structure, 4) wildlife models of predicted habitat quality and population density, and 5) watershed models of post-fire erosion and deposition potential.

Our vegetation composition and structure models form the backbone of the majority of our modeling efforts. Along with other important predictor variables, such as wildlife habitat requirements and invasive plant growth curves, spatial layers of predicted vegetation are fed into fire behavior, wildlife, forest treatment, and invasive plant models. These, in turn, are used to develop spatial data for user-chosen decision criteria in a decision-making framework. This framework is designed to allow users to explore various forest treatment designs and to estimate their impacts (i.e., cumulative effects) on a suite of variables, which include various indices of wildlife response and changes in fire hazard.

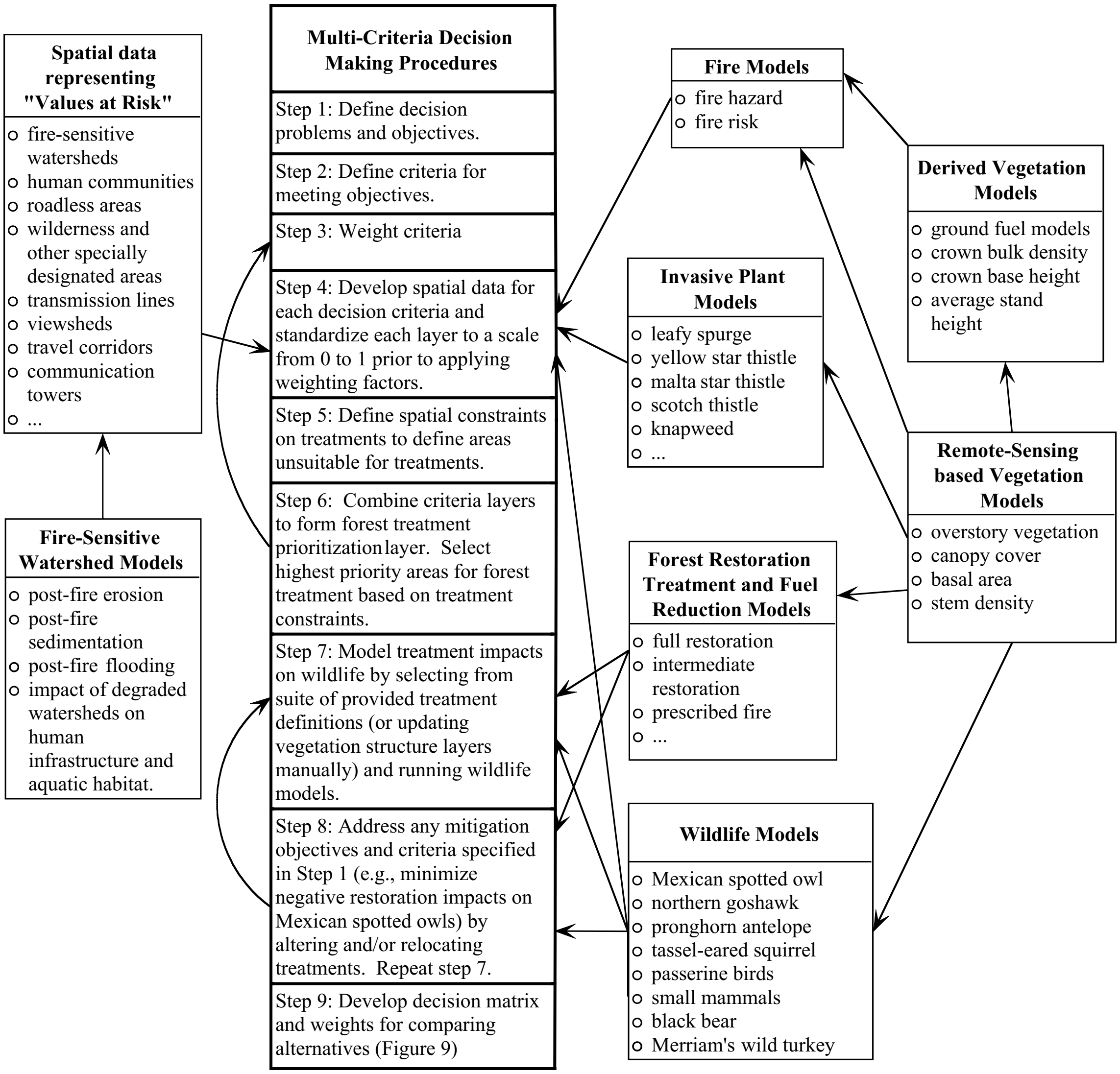


Figure 2. Flowchart depicting interplay between ForestERA model components and multi-criteria decision-making process.

ForestERA ArcGIS Extension

ForestERA tools are being developed with Visual Basic and ArcObjects for use on the ArcGIS platform. The ForestERA extension adds a tool bar to ArcMap with a series of buttons (Figure 25). When clicked, the buttons open interfaces (e.g., see Figure 26) that allow the user to work his way through the multi-criteria decision making process described in this paper. Additional functions specifically developed for charactering the size and type of treatment are coded in dynamic link libraries (DLLs) and added to the tool bar. A documentation feature allows the user ready access to detailed information for using each extension component. In addition, we are developing tools that will allow users to run our wildlife, fire behavior, invasive plant and forest treatment models independently.

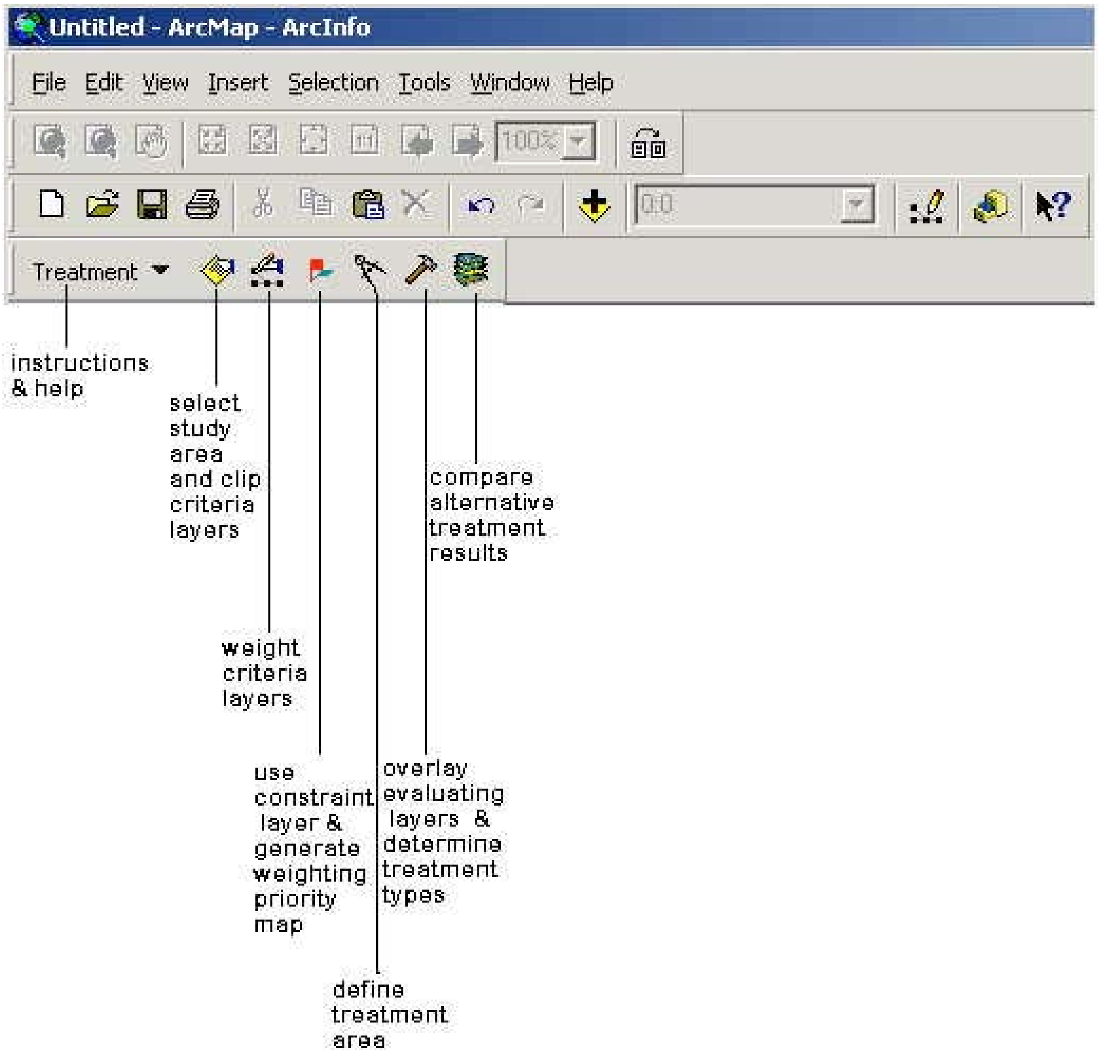


Figure 25. Draft version of ForestERA Multi-Criteria Decision Making menu bar

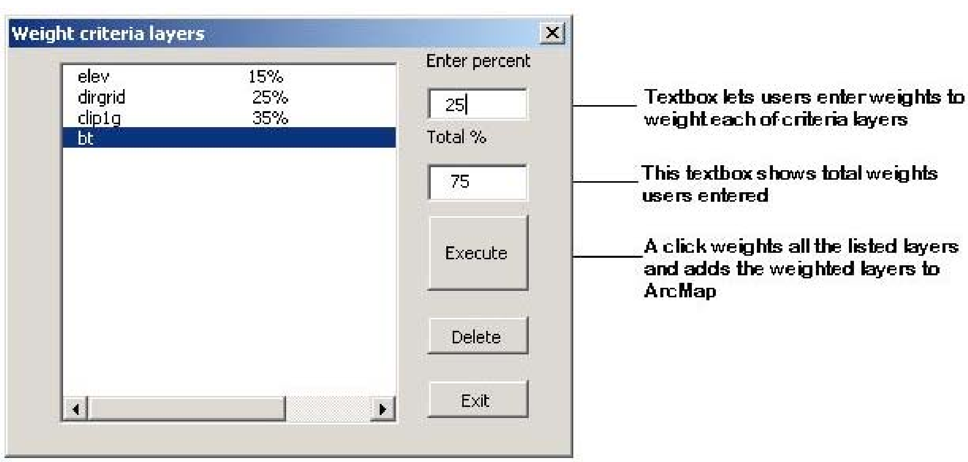


Figure 26. Draft interface for associating weighting factors with data layers

Vegetation Mapping

Our predicted vegetation composition and structure layers are the primary inputs to our wildlife, fire, and restoration treatments models and our stakeholders have expressed great interest in their development, including for applications outside of restoration planning. To date, we have generated maps of dominant species (Figure 3), basal area (Figure 4), tree density (Figure 5), and canopy cover (Figure 6) over a focal area (yellow outline in Figure 1) approximately half the size of our (four million acre) study area.

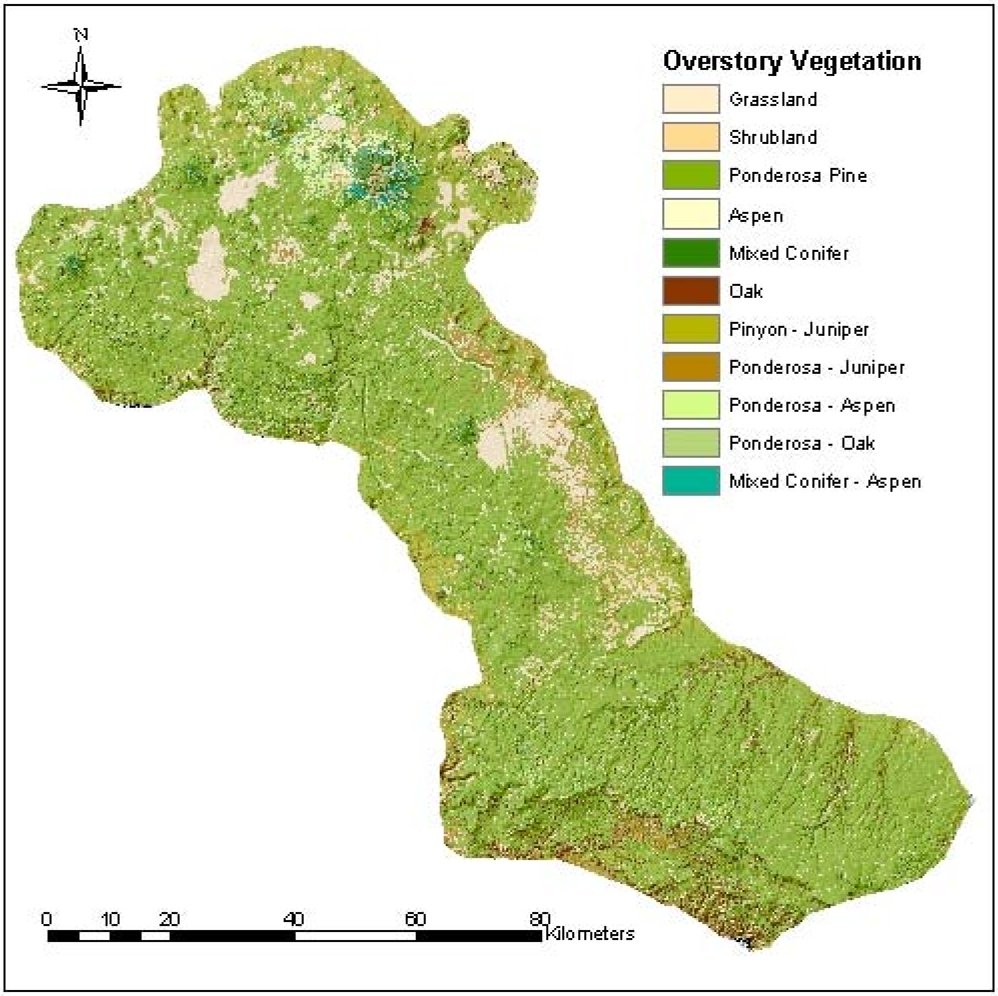


Figure 3. Map of predicted dominant species

Although we considered the use of a broad range of remote-sensing imagery to accomplish this work, due to many factors, including the large extent of our study area and the costs of various options, we chose multi-temporal images from the Landsat 7 satellite's enhanced thematic mapper (ETM), digital orthophotoquadrangles (DOQs) and ENVISAT C-band radar data for this task. To offer the capability of creating higher resolution vegetation models, for possible application within treatment areas identified as priorities with our landscape-scale vegetation models and tools, we have developed a crown-delineation methodology for use with high-resolution multi-spectral imagery. Preliminary tests of the methodology using QuickBird imagery (0.7 m panchromatic; 2.4

m multispectral resolution) show it to be a promising option for estimating crown size and counting individual stems (Figures 7 and 8).

The vegetation composition, basal area, and stem density layers each have a minimum mapping unit (MMU) of one hectare and were created using Classification and Regression Tree (CART) methods that relate vegetation plot data to over twenty data layers derived from and including multi-temporal Landsat 7 ETM, digital elevation models (DEMs), and solar radiation estimates. We will test the added usefulness of advanced synthetic aperture radar (ASAR) data in developing our final products. The canopy cover layer (0.1 ha MMU) was developed directly from DOQs by applying a fractal concentration value-area method, which differentiates tree crown, shadowed, and non-forested areas. Based on preliminary accuracy assessments comparing predicted forest structure values to an external dataset, 90% of the values in any one hectare area for basal area are within 9 m^2/ha of their true value, 204 trees/ha are within their true value for stem density, and 13% are within their true value for canopy cover. A ten-fold cross-validation of the vegetation composition layer resulted in an overall accuracy of 87%. We are in the process of conducting a formal accuracy assessment for all layers to be completed in summer/fall of 2003.

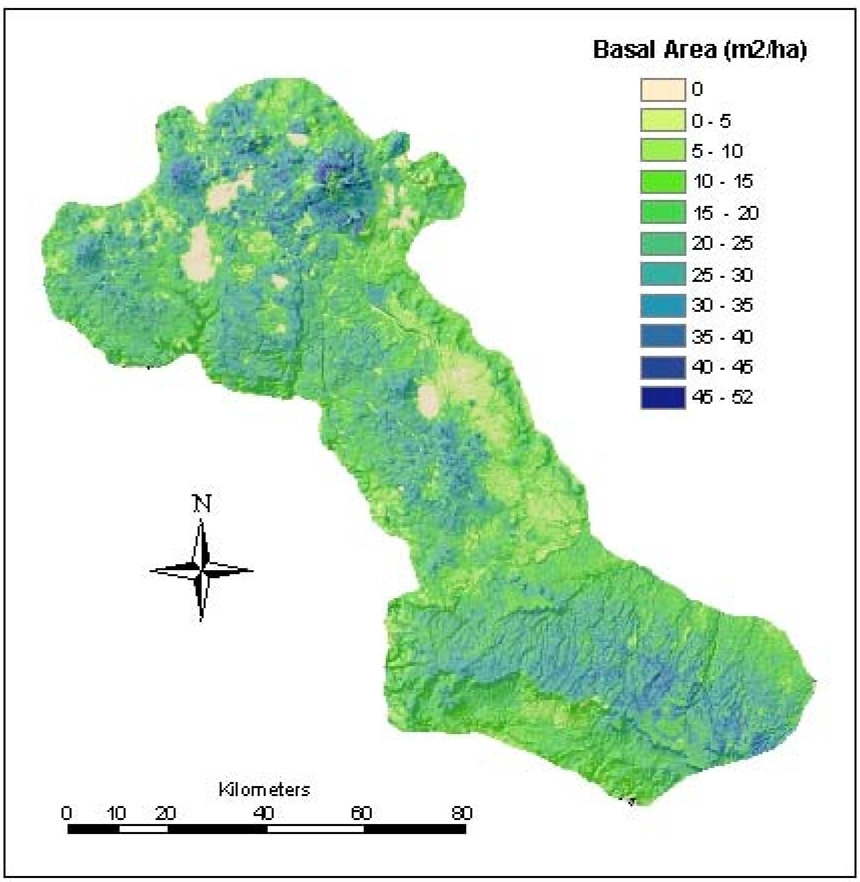


Figure 4. Map of predicted basal area

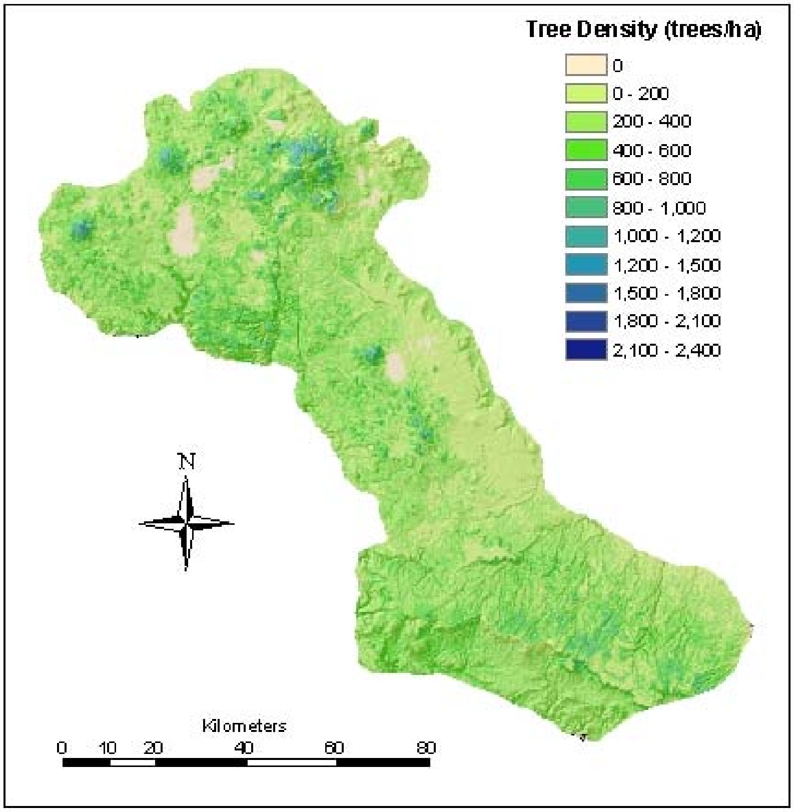


Figure 5. Map of predicted stem density

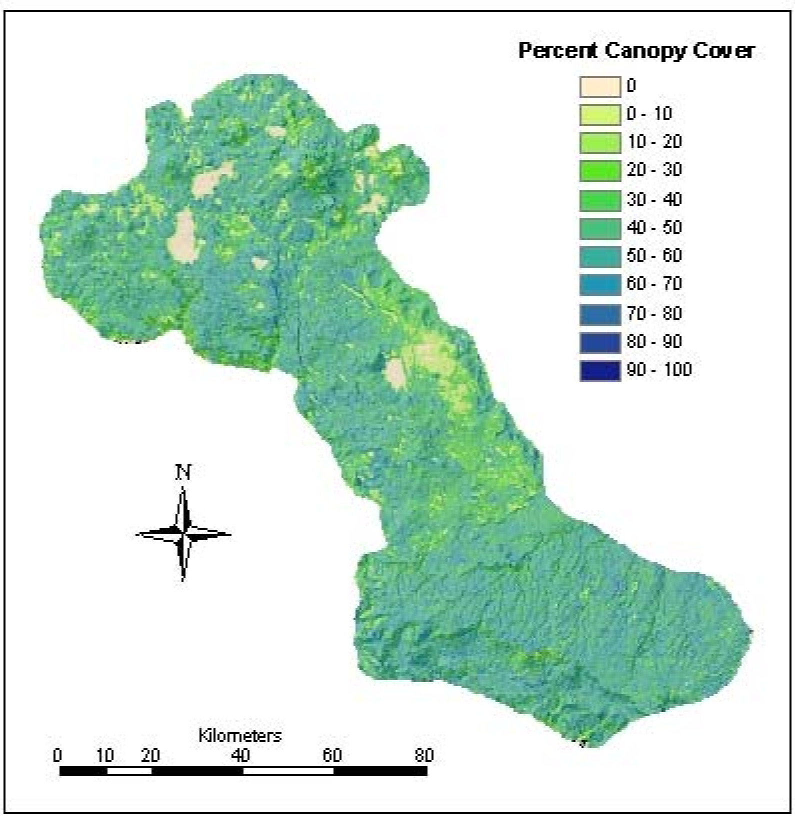


Figure 6. Map of predicted canopy cover

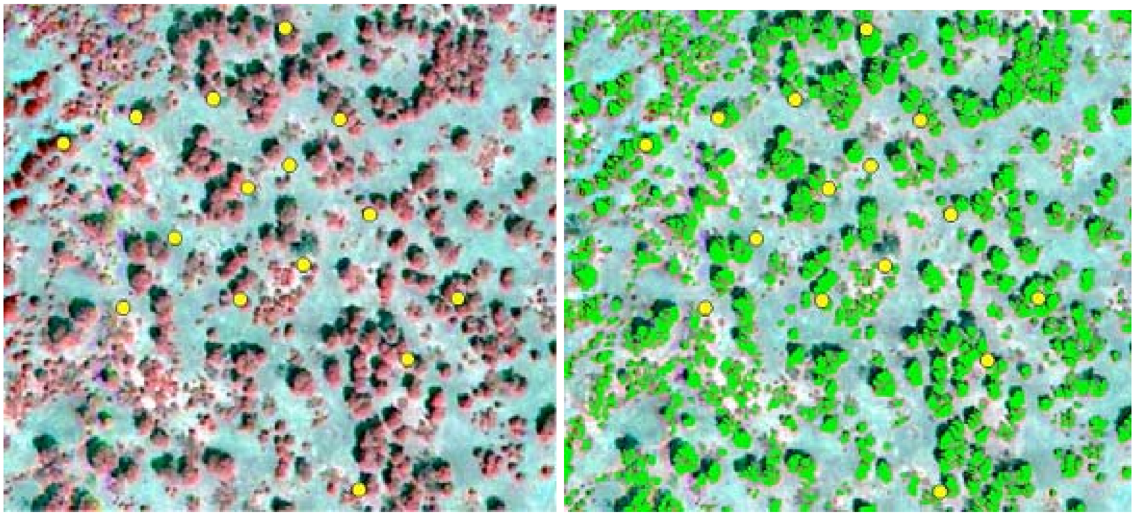


Figure 7. Multispectral Quickbird image (on left) with 15 ground plot locations (yellow circles). Quickbird image with tree crowns delineated (on right; Gambel's oak and ponderosa pine crowns in green).

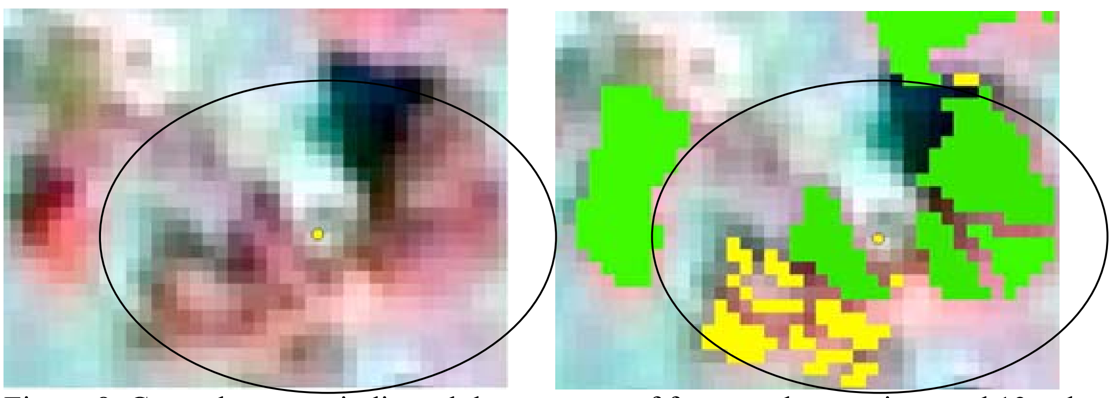


Figure 8. Ground surveys indicated the presence of four ponderosa pines and 13 oaks within the black oval (on left). The algorithms we developed to delineate tree crowns and calculate stem density found four ponderosa pines (green) and 12 oaks (yellow) (shown at right).

Fire-Sensitive Watershed Analysis

Given the potential damage to forest soil and hydrological systems from intense wildfire and subsequent negative impacts on human and natural communities, we are developing spatial data layers for use in designing forest treatments to mitigate these impacts. If it was known with greater certainty which areas or watersheds were more "sensitive" to intense wildfire, forest treatments could be strategically placed across the landscape to reduce the likelihood of fire damaging these areas. Our project stakeholders rated the development of a scientifically rigorous coverage of fire-sensitive watersheds as highly important to landscape-scale forest restoration analysis.

Damage to soil and hydrological processes caused by high-intensity crown fire can be categorized into immediate damage to soils caused by extreme heat, subsequent increased erosion on-site, and increased erosion, sedimentation, and flooding down slope. We are developing models of the potential for soil erosion, sedimentation, and possibly flooding, following intense crown fire. The modeling objectives can be broken down into two steps. First, where would we expect the greatest runoff and soil erosion leading to sedimentation, degraded water quality, and flooding regardless of whether there is a value at risk down slope? Secondly, what is the potential for post-fire damage to aquatic communities or human infrastructure (e.g., sediment deposition in reservoirs, degraded water quality, flooding of populated areas)?

The goal of the watershed analysis is to create a spatial data layer describing the potential for soil erosion, flooding, and degradation of surface water following high-intensity crown fire. This layer can be used in conjunction with spatial data on human infrastructure and aquatic communities to define critical fire-sensitive areas. The critical fire-sensitive area layer can then be used by itself, in any number of geographic information system (GIS) analyses, or in ForestERA's multi-criteria analysis tool. As described in this paper, it could be combined with proximity to urban areas, high fire hazard, and high fire risk areas in a GIS overlay analysis to select areas in most need of forest restoration treatments. As a placeholder for our final fire-sensitive watershed layer, we are using a map (dark blue areas, Figure 19, map 3) that we developed for this purpose during a brief consultation with a senior hydrologist in USGS's Water Resources Division (Hart, pers. comm. 2002).

Fire Modeling

We are using the FlamMap (Finney, in press; Figure 9) fire behavior program to create fire "hazard" maps. This program is a simplified version of the widely-used FARSITE program. The major difference is that FlamMap does not track fire behavior over time, but instead produces outputs that assume the entire landscape is burning and presents fire behavior under a fixed set of weather conditions. Unlike other fire modeling programs, which are largely designed to predict the behavior of a moving fire (e.g., FARSITE), or fire effects such as smoke production and fuel consumption (e.g., FOFEM), FlamMap is designed to allow assessment and comparison of potential fire behavior across an entire landscape. In addition, like FARSITE, but unlike NEXXUS and some other fire behavior programs, FlamMap is spatially explicit and can be run using ascii grids created in ArcInfo. Thus, FlamMap can relatively quickly and easily create maps of fire behavior across large landscapes.

At present, FlamMap does not provide any accounting for the potential spread of fire across the landscape. In order to incorporate fire spread in our current analyses we currently use a spatial layer representing areas upwind of values at risk, although we are exploring other options. In 2004, FlamMap will likely be available with a fire-spread capability (Finney, pers. comm. 2003). This will allow the strategic placement of treatments designed to slow the movement (i.e., minimize the travel time) of fire across the landscape. A potential update of ForestERA tools would be to incorporate this new feature once it is available.

Spatial data required by FlamMap include elevation, slope, aspect, average stand height (m), crown base height (m), crown bulk density (kg/m^3), and canopy cover (%). For elevation, we use a mosaic of USGS 30m digital elevation models (DEMs). Slope and aspect are derived from the DEM mosaic using GIS software. As described earlier, we generate a canopy cover layer directly from DOQs. We use allometric equations to calculate crown bulk density from our predicted vegetation maps of stem density and basal area. We are using crown base height and canopy height layers derived from USDA Forest Service stand data. All layers are resampled to 90m grid for use in

FlamMap. Fuel models are based on predicted dominant vegetation using the Anderson fuel model classification system (Anderson 1982).

FlamMap also requires wind data and fuel moisture content (%) as inputs. We use 30 mph winds from the southwest in our models. These values are representative of the prevailing wind direction and the strongest sustained winds in this region during the fire season. The fuel moisture content contains estimates of 1h, 10h, and 100h fuels for each fuel model. We have chosen to use 97th percentile dry fuel moistures. Foliar moisture content is set at 85%, which is extremely low and representative of drought conditions. Fuel moisture conditions and weather conditions are taken from actual measurements of these conditions over the last 20 years, and should be highly accurate.

The fire “hazard” layer is based on two outputs from FlamMap: crowning behavior and heat per unit area. Under a given set of weather conditions, some percentage of the forest will carry crown fire and these areas are used for analysis (we include both active and passive crown fire areas). Because ground fires can occur nearly anywhere, and because these are not necessarily undesirable (for example, ground fires are necessary to maintain “restored” forests), we ignore these areas in our analyses. The heat per unit area output is used to scale the threat posed by crown fire. Areas of higher heat output indicate more intense fire activity and also correspond tightly to areas that can carry crown fire under lower wind speeds.

Our fire "risk" maps are based on fire ignitions and can optionally include their relationship to the frequency of large fires (>10 ha) on the landscape (Figure 10). For fire risk modeling we have obtained a dataset of all reported ignitions between 1986 and 2000 in our study area. Only fires from the peak fire season (May-August) are used in the analysis. Approximately 70% of the ignitions and large fires in our study area occur during these months. The resolution of these data allows for analysis at a minimum of 1 km^2. We have smoothed the layer by a weighted averaging method using all of the 1 km^2 blocks in a 9 km^2 area. Fire ignition densities are reported as number of fire ignitions/km^2. When combined, the "fire hazard" and "fire risk" maps predict the locations on the landscape most in need of treatment. We believe that our fire hazard and risk predictions are sufficiently accurate to assist in efforts to decide where and when to apply restoration treatments across the landscape.

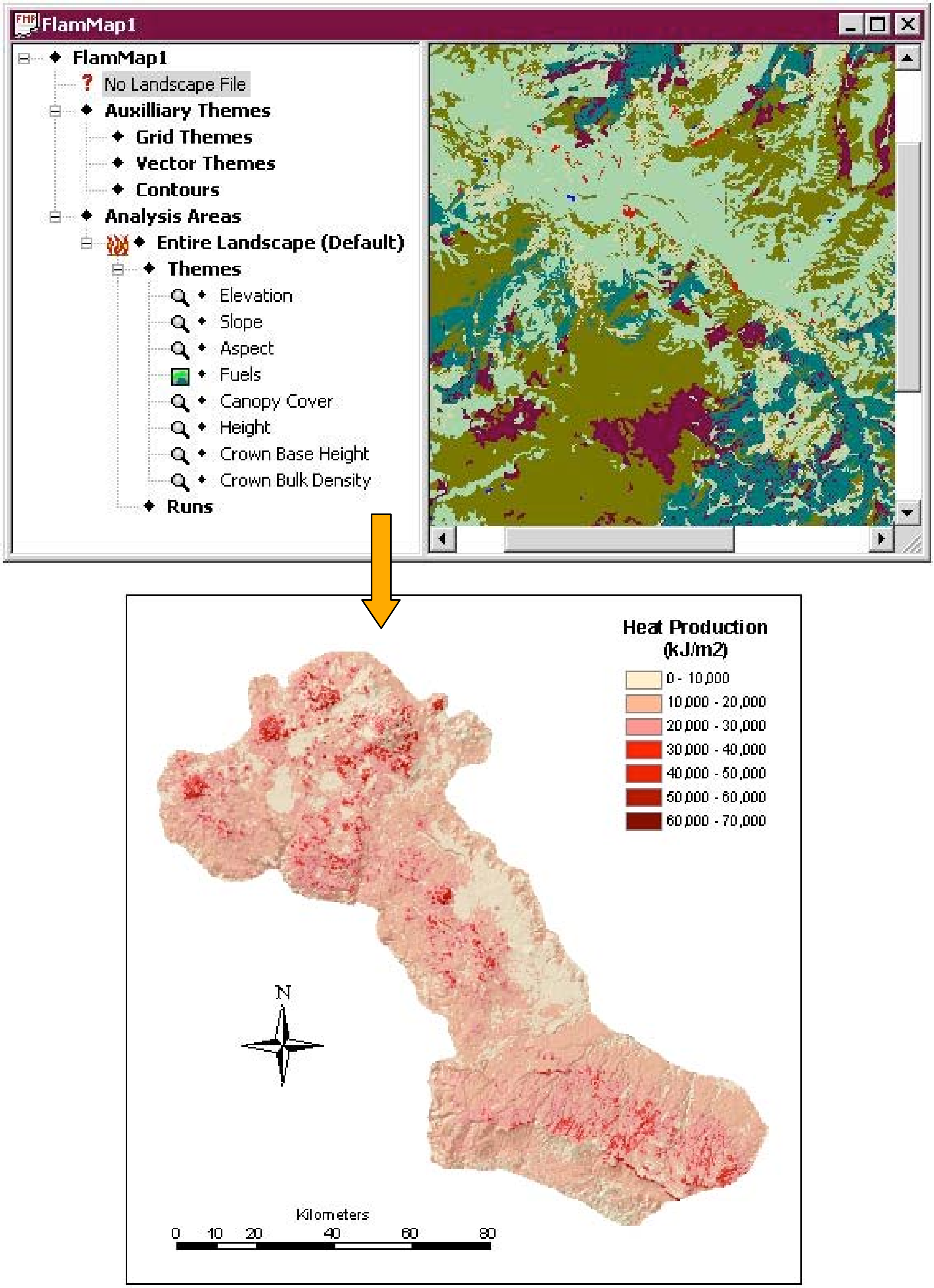


Figure 9. FlamMap model (landscape analysis interface of FlamMap shown above) used to estimate fire hazard in terms of heat output (below).

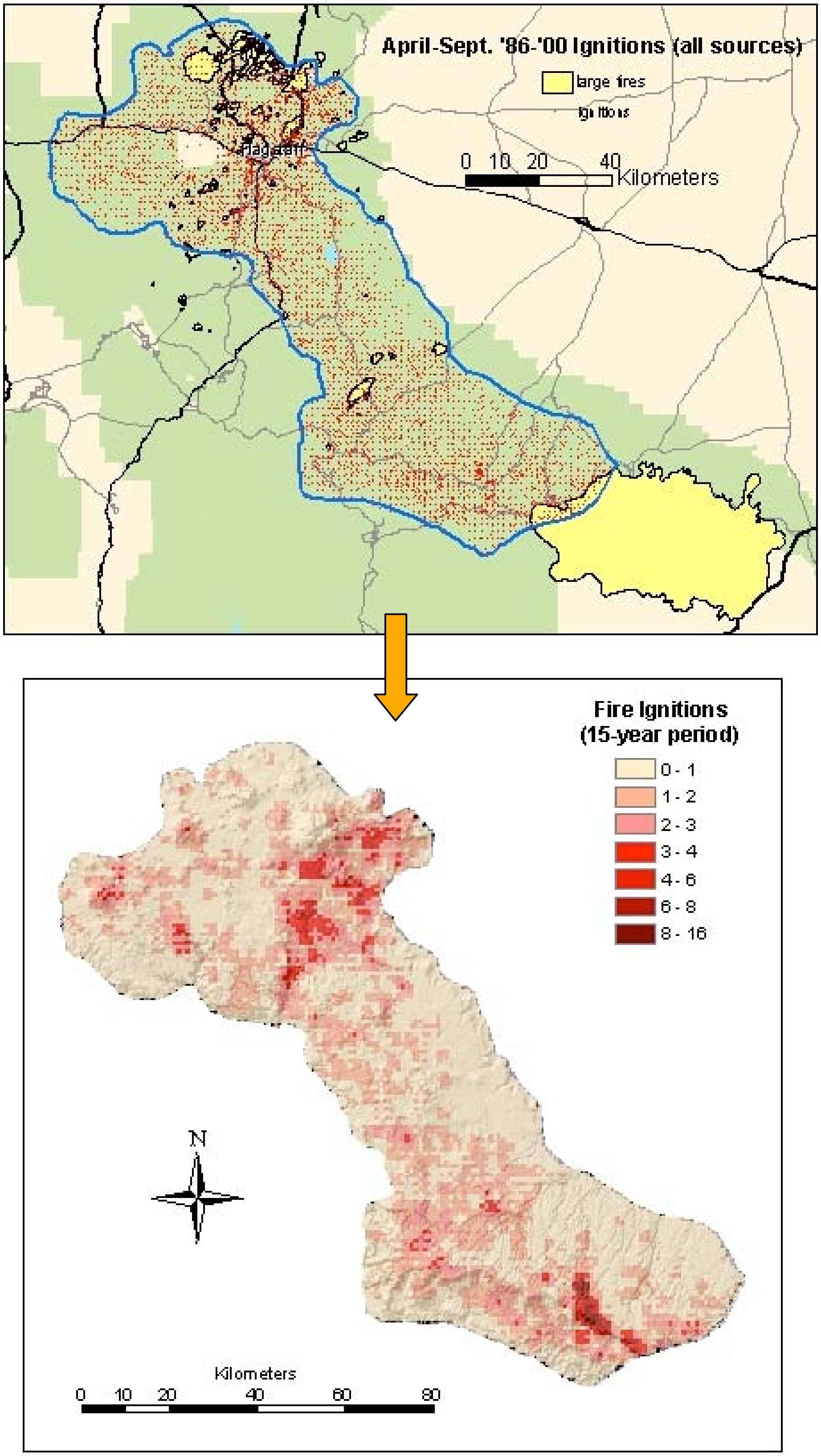


Figure 10. Fire ignitions data (top; large fire perimeters shown in yellow) were used to create fire ignitions density layer, ignitions/15yr/km^2 (bottom).

Wildlife and Invasive Plant Modeling

The primary goal of our wildlife modeling effort is to provide managers with GIS data layers that predict suitable wildlife habitat. Using considerable input from stakeholders we have created a list of locally important species or taxonomic groups for which models will be created. Species chosen were primarily those representative of ponderosa pine and its associated habitats across the study region. The list includes a variety of species that are representatives of various functional or taxonomic groups, and that respond to landscape-level habitat patterns at different scales. In addition, the inclusion of species that are considered forest "management indicators" or "sensitive" was important, as these species are those most likely to be taken into account by managers when making decisions about forest management practices. Finally, the amount of empirical data available on a species or group was taken into consideration when choosing both the taxa to be modeled and the modeling procedure to be used.

After considerable review, we decided on three different modeling procedures: CART, regression techniques, and rule-based models developed from the literature and expert opinion. Classification trees were chosen as our primary modeling procedure for estimating **passerine bird** (e.g., western wood-pewee, Figure 11) and **small mammal** presence or absence. A total of 8-12 passerine birds and 3-5 small mammal species will be chosen as representatives of these taxa based on the quality of the models. Because CART models require large amounts of data, sufficient data were available only for these two taxonomic groups. However, considering these data requirements, CART has previously proven to be an excellent tool for modeling wildlife habitat across heterogeneous landscapes (De'ath and Fabricius 2000). We are using regression techniques, particularly Generalized Linear Models (Hilbe 1994), to predict **tassel-eared squirrel** density (Figure 12) and recruitment, as moderate amounts of empirical data are available (Dodd et al. 1998; Dodd, unpublished). Because of a lack of field studies that overlap both spatially and temporally with our project area, we have chosen to build the remainder of our models using decision rules created through a literature review and in consultation with experts. Considerable published literature exists on the habitat requirements for these species, including **Mexican spotted owl** (Figure 13; Kaufman 1995), **Merriam's wild turkey** (Mollohan et al. 1995)**, northern goshawk** (Reynolds et al. 1992), **pronghorn antelope** (Figure 14; Ockenfels et al. 1994), and **black bear** (LeCount and Yarchin 1990). Local and regional experts for these species are involved in working groups to help create and assess the models.

Since **invasive plant** species are, generally, weeds with broad habitat requirements, we are not modeling invasive species habitat, but are instead creating a tool to allow managers to determine from where and how quickly invasive species could invade an area prioritized for treatment. To develop these models, we are working with USDA Forest Service personnel who have collected data on the distribution and spread rates of approximately a dozen species of invasive plants.

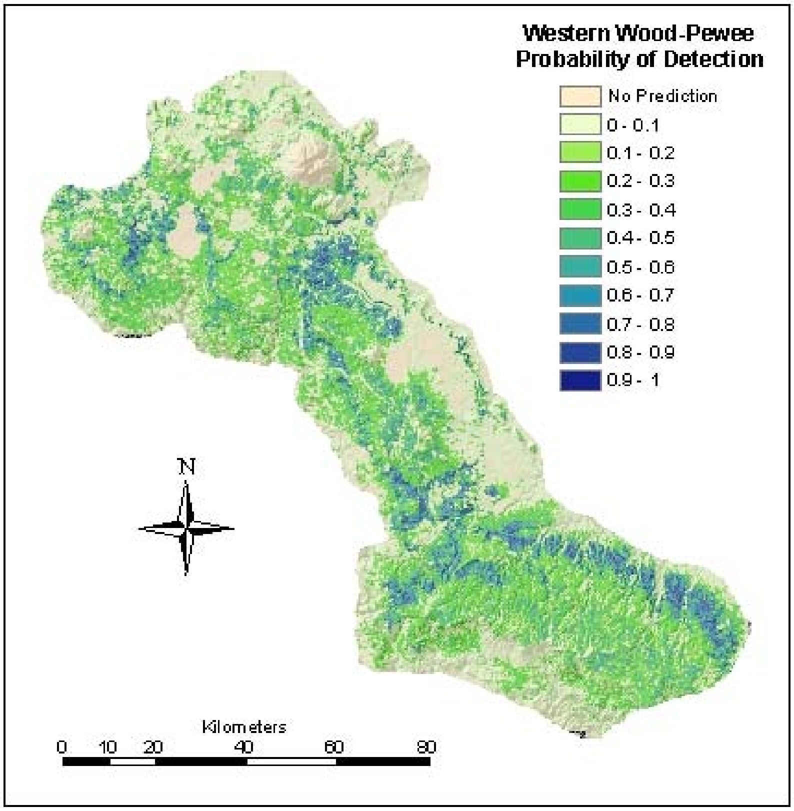


Figure 11. Predicted western wood-pewee probability of presence

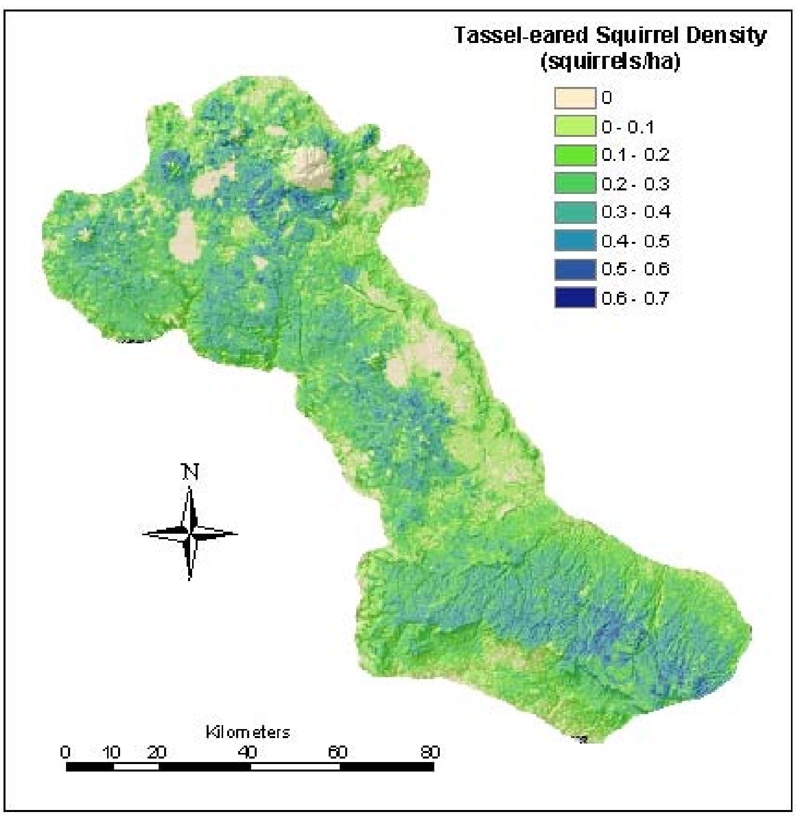


Figure 12. Predicted tassel-eared squirrel density

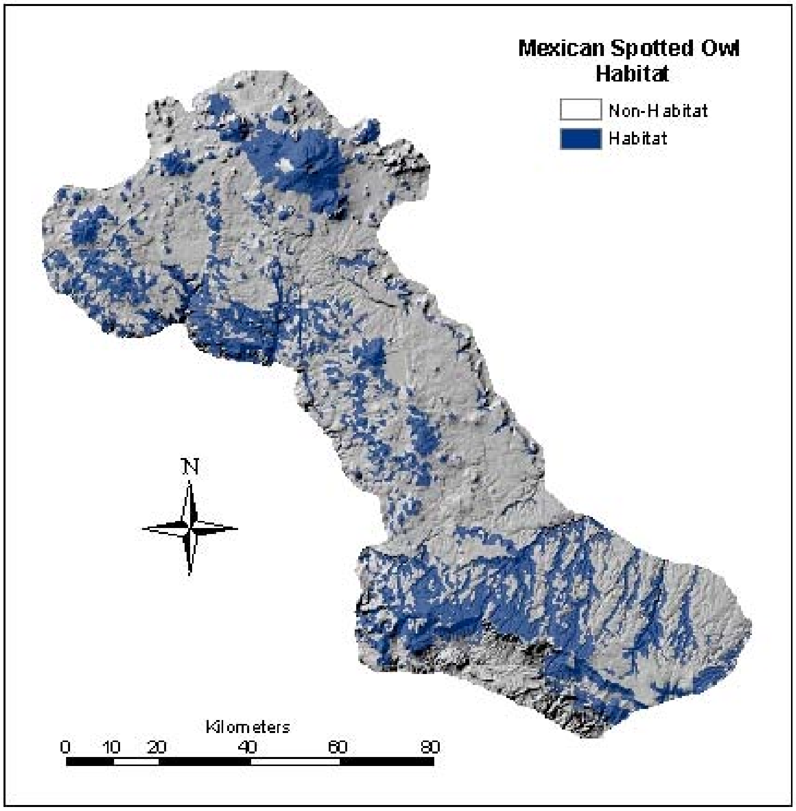


Figure 13. Predicted Mexican spotted owl habitat

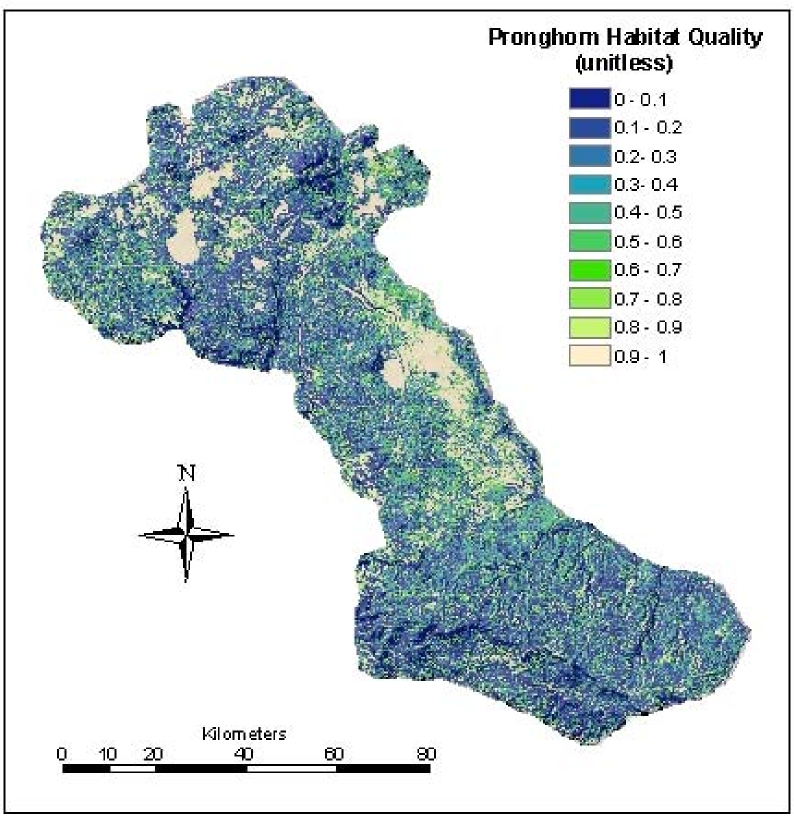


Figure 14. Predicted pronghorn antelope habitat quality

Forest Treatment Modeling

We are developing a set of procedures for estimating and predicting changes to forest structure following various forest management activities, such as, fuels and restoration treatments (e.g., thinning plus prescribed burning) and prescribed fire. These procedures will be encoded in a spatial tool that will allow users to model changes in forest structure (e.g., canopy cover, stem density, basal area) following various treatment alternatives (Figure 15). Currently, we are compiling data from published and unpublished sources and developing a database that will allow us to characterize a broad spectrum of practical treatment alternatives (e.g., "intermediate" restoration, "full" restoration, and prescribed-burn only) for ponderosa pine dominated forests. For example, the assumptions of our intermediate and full restoration alternatives presently borrow from experimental studies conducted on ponderosa pine stands in Arizona (Fulé et al., 2001a; Fulé et al., 2001b; Fulé et al, 2002; Waltz et al., in review), Colorado (Lynch et al., 2000), and Montana (Scott, 1998). In addition to the application of empirical data from field studies designed to quantify post-treatment structure, the use of ordination and other multivariate techniques, and the incorporation of expert knowledge will also be integral to the modeling of treatment alternatives.

Challenges involved in this effort include the scarcity of empirical data, the need to consider multiple structural variables simultaneously, dependence of post-treatment structure on initial conditions, and traversing the gap between plot-level and landscape-scale analyses. We are attempting, however, to reconcile these challenges through collaborative efforts with many scientists and stakeholders. In cooperation with the USDA Forest Service Rocky Mountain Research Station, we are assessing the effects of prescribed fire on four large stands of ponderosa pine dominated forest in the Southwest. Since prescribed fire may be the most ecologically and economically reasonable treatment option in areas that have high fire threat, we are incorporating measures of pre- and post-treatment structure into our models of prescribed fire as a landscape-level treatment alternative.

Because the effects of fuels and restoration treatments on various ecosystem attributes are not well understood (Tiedemann et al. 2000, Wagner et al. 2000), managers will require improved information before recommending and implementing forest treatments on the landscape. By presenting a range of treatment options, the ForestERA project will better allow managers to produce predictive models of forest fuels and restoration treatments that may be overlaid with taxonomic distributions, inhabited areas, and other spatial data.

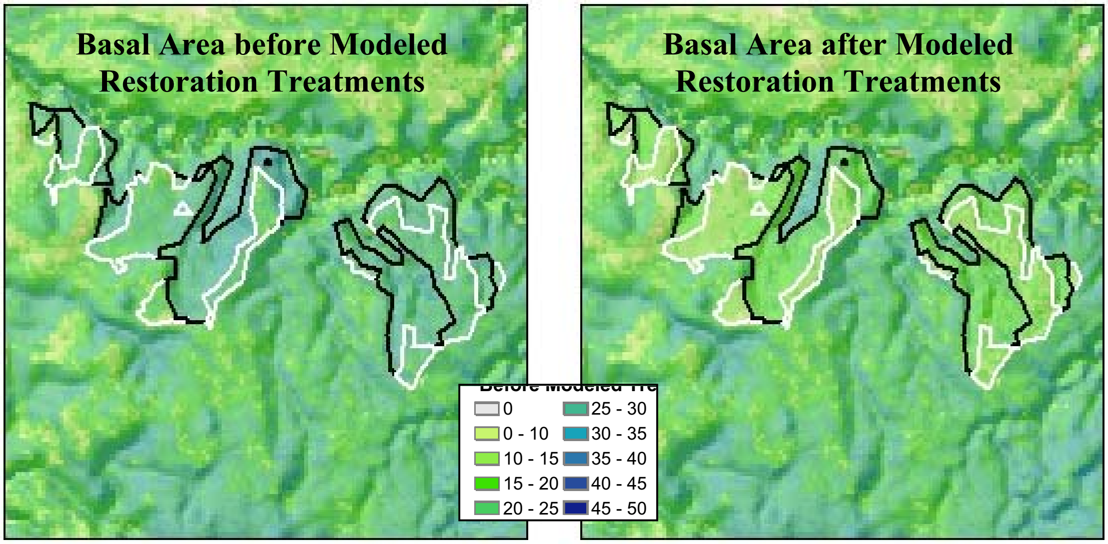


Figure 15. Basal area (m^2/ha) before and after modeled intermediate restoration (black) and full restoration (white) treatments.

Multi-Criteria Decision Making Analysis and Demonstration

ForestERA tools are designed to allow users to generate scenarios for guiding forest treatment planning. For ponderosa pine forests in the southwest, Allen et al. (2002) identified a suite of considerations important in the prioritization of restoration treatments, including crown fire potential, proximity to human communities and fire-sensitive watersheds, and protection of habitats of sensitive species. We developed the examples described in this paper to demonstrate the capacity of our tools to incorporate these and other factors in prioritizing treatments.

In this demonstration of the use of ForestERA tools, we step through the decision-making process with two examples, one with the dual objective of minimizing fire threat in and around human communities and minimizing negative restoration activity impacts to sensitive species and habitats (the "community protection prioritization") and the second with the goal of minimizing fire risk to the overall ecosystem with the same secondary objective of protecting habitats (the "ecosystem protection prioritization"). For simplicity, we only demonstrate the design of treatments to reduce negative impacts on a single wildlife species (Mexican spotted owl). However, our integrated models can be used to develop treatments that mitigate impacts on multiple species.

Defining decision problems and objectives is the first step of the multi-criteria decision-making process (Figures 2 and 16). Second, decision criteria are chosen for meeting the objectives. Third, the criteria are weighted according to user preferences. For example in this demonstration, we chose to weight fire hazard five times greater than fire risk to reflect the opinion that fuels are a more important factor than ignitions to consider in planning future treatments. In step four, spatial data is developed for each criterion. ForestERA tools are provided with a suite of spatial data for this purpose, although users can develop their own as well. Each data layer is standardized to a scale from zero to one for the purpose of combining them. In step five, the user has the option of defining spatial constraints on treatments to remove (mask out) areas unsuitable for treatments (Figure 17). For example, areas steeper than 30% slope may be deemed too steep for implementing some types of forest treatments, and therefore, removed from consideration. In step six, the criteria layers are combined (Figure 19) adhering to a set of specifications for the analysis (Figure 18) after applying the weighting factors defined in step three. More specifically, the standardized criteria layers of fire hazard (Figure 19, map 1), fire risk (Figure 19, map 2), community proximity and fire-sensitive watersheds (Figure 19, map 3), and areas upwind of communities and watersheds (Figure 19, map 4) are summed, while any areas excluded from treatment (Figure 19, map 5) are subtracted, to form a forest treatment prioritization layer (Figure 19, map 6). The treatment constraints include the target acreage for the treatment plan and a minimum treatment size. We selected a target acreage based on an estimate of the maximum area that could operationally be treated in 10-15 years in the 2 million acre "Flagstaff Region."

As discussed in the fire modeling section, FlamMap does not model the likelihood of fire spreading from one place to another. In order to incorporate fire spread in our analysis we use a spatial layer representing areas upwind of values at risk (Figure 19, map 4). Another optional decision criteria layer we have considered for the purpose of incorporating fire spread, although have not yet implemented, is to include a spatial layer with values from high to low (standardized from one to zero) starting a the windward edges of the study area and traversing to the lee edges to represent the benefit of the protection to leeward areas offered by treating windward locations.

As could be expected, the treatments in the "community protection prioritization" are mainly located adjacent to and upwind of urban areas and fire-sensitive watersheds, while the "ecosystem protection prioritization" treatments are more evenly spread throughout the study area in higher fire hazard areas (Figure 20). The impacts of these treatment plans on fire hazard and wildlife are modeled in step seven, by selecting from a suite of provided treatment definitions. In this demonstration the full restoration treatment is selected for the entire planning areas of both prioritizations (options 1 and 4) and the fire hazard and wildlife models are rerun.

Two additional treatment options are explored in step eight to address the second objective defined in step one of mitigating negative impacts of treatments on Mexican spotted owls. Mexican spotted owl habitat was predicted to decrease by 33,000 ha from a starting value of 265,000 ha in the "community protection prioritization" treatment plan, and by 45,000 ha in the "ecosystem protection prioritization." To reduce impacts on owl habitat in options 2 and 5 (Figure 21), treatments were reduced in intensity to an intermediate level when a full-restoration treatment would result in loss of owl habitat. Imposing this constraint resulted in slightly over 40% of the treatments shifting to an intermediate level (Figure 24). Reflecting a second strategy to reduce treatment impacts on owls, treatments were restricted completely from owl habitat in options 3 and 6 (Figure 22). The overlap between the treated areas from options 1 (and 2) and the alterative option 3 (Figure 23, map on left) and options 3 and 4 and option 5 (Figure 23, map on right) show that a significant shift occurred in the location of treatments (Figure 23).

In order to explore the tradeoffs between alternatives, ForestERA tools can be used to generate a decision matrix (Figure 25). Weighting factors are applied to each criteria based on user preferences.

	Decision Problem	Objective	Criteria	Weight
1	Forest ecosystems are inadequately protected from high intensity crown fires	Minimize fire threat to overall ecosystem	➢ Fire hazard (crown fire potential) ➢ Fire risk (based primarily on ignition density)	5 1
2	Human communities and resources are inadequately protected from high intensity crown fires	Minimize fire threat in and around human communities and resources	➢ Fire hazard ➢ Fire risk ➢ Prevailing winds ➢ Proximity to urban areas ➢ Municipal watersheds ➢ Power lines ➢ Viewsheds ➢ Travel corridors ➢ Communications towers	5 1 1 2 1
	Focal species habitats are inadequately protected from high intensity crown fires	Minimize fire threat in and around focal species habitats	➢ Fire hazard ➢ Fire risk ➢ Prevailing winds ➢ Proximity to focal species habitats	
	Special areas of concern are inadequately protected from high intensity crown fires	Minimize fire threat to specially designated areas	➢ Fire hazard ➢ Fire risk ➢ Prevailing winds ➢ Roadless areas ➢ Wilderness areas ➢ Other specially designated areas	
1,2	Sensitive species and habitats may be harmed by impacts of restoration activities	Minimize negative restoration activity impacts to sensitive species and habitats	➢ Potential forest management sites ➢ Responses to forest management of: • Mexican spotted owl • Pronghorn antelope • Northern goshawk • Merriam's turkey • Tassel-eared squirrel • Passerine birds • Small mammals • Black bear	N/A
	Invasive plant species distribution may be altered by forest management activities	Minimize spread of noxious weed species	➢ Potential forest management sites ➢ Presence of leafy spurge, yellow star thistle, knapweed, scotch thistle,…	

Figure 16. Decision problem and criteria table (values in blue mark demonstration of community protection prioritization [1] and full ecosystem protection prioritization [2])

Constraints on Treatment Location
Forest treatments must take place in areas with slope < 30%.
Forest treatments must take place outside of urban areas.
Forest treatments must take place in areas dominated by ponderosa-pine.
Forest treatments must take place outside of specially-designated areas: • Wilderness areas • National Monuments • Roadless areas
Forest treatments should not take place within designated sensitive areas for focal species (used in options 3 and 6 only).

Figure 17. Constraints for excluding treatments from particular locations (values in blue mark constraints used in both demonstration of community protection prioritization and full ecosystem protection prioritization)

Constraints on Individual Treatments and Total Area Treated
Area of analysis: ForestERA-defined "Flagstaff Region" (2 million acres)
Target acreage for forest treatments is 180,000 acres.
Minimum size of treatment polygon: 250 acres

Figure 18. Overlay analysis options setting limits on treatment size and analysis area (values in blue mark constraints used in both demonstration of community protection prioritization and full ecosystem protection prioritization)

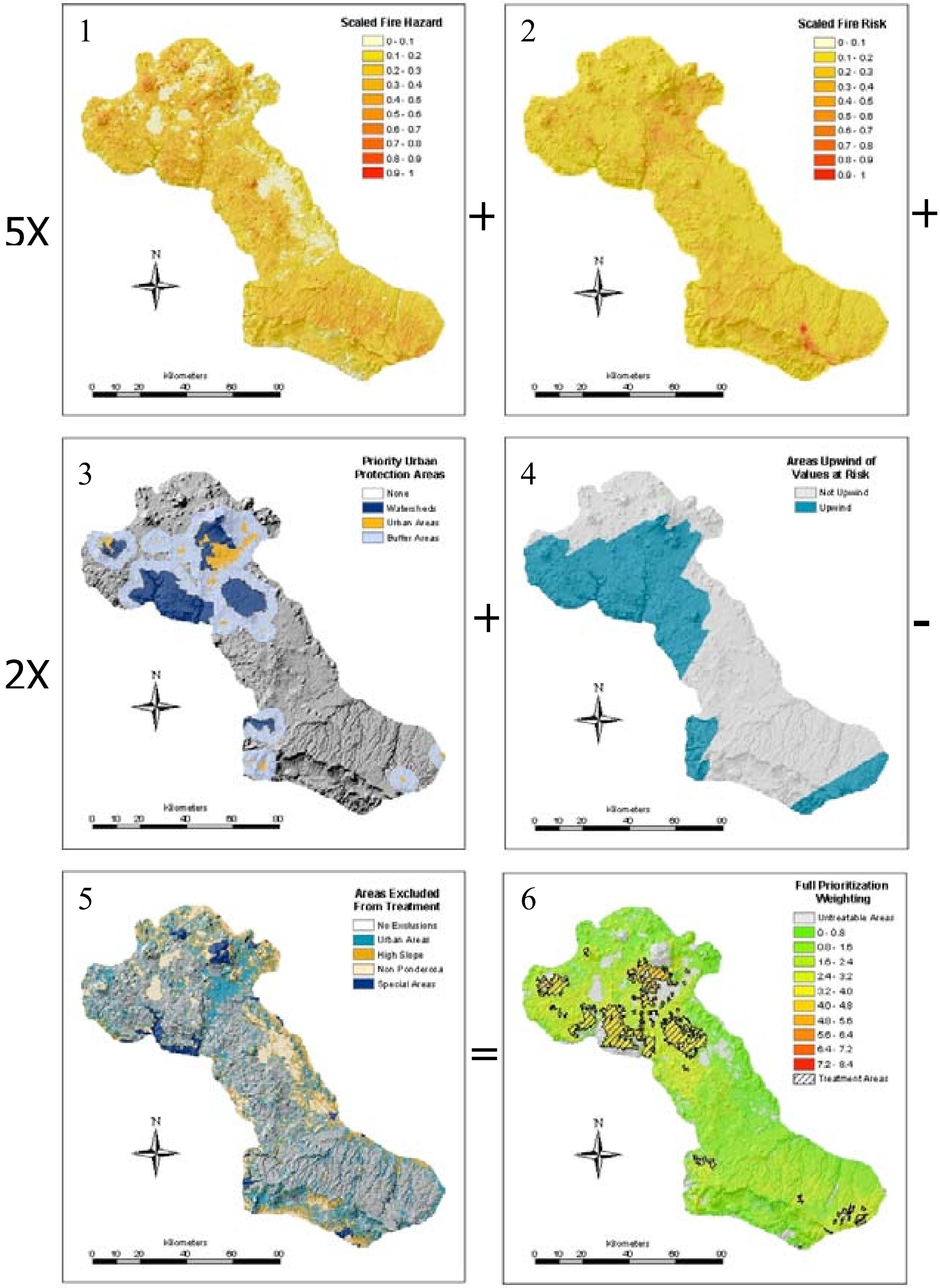


Figure 19. Additive weighting process for prioritizing forest treatments (in map 3, the weighting factor of two is only applied to urban areas and not fire-sensitive watersheds)

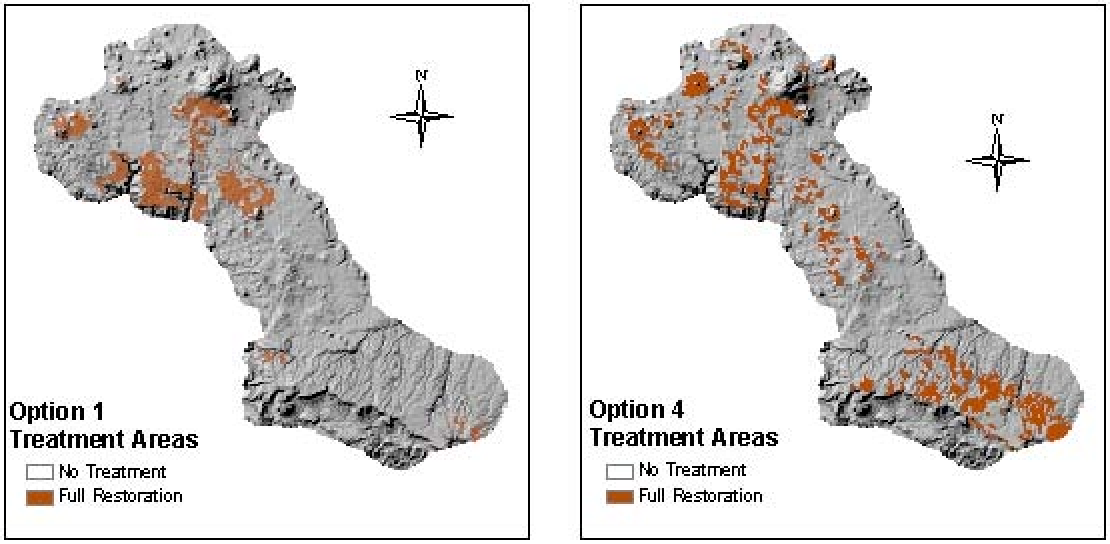


Figure 20. Full restoration treatment plans with **no owl habitat mitigation** for community protection prioritization (option 1) and full ecosystem protection (option 4).

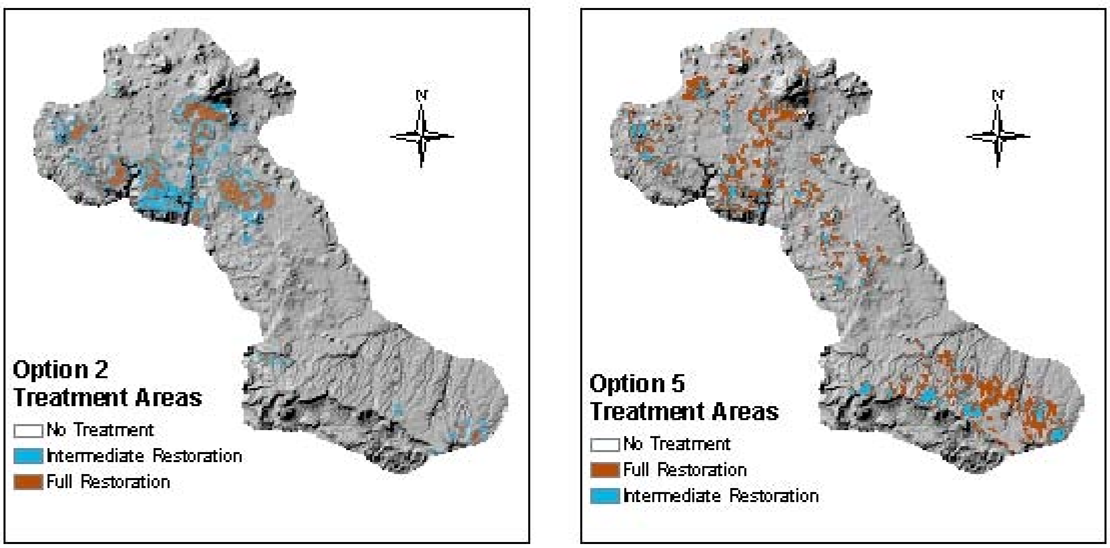
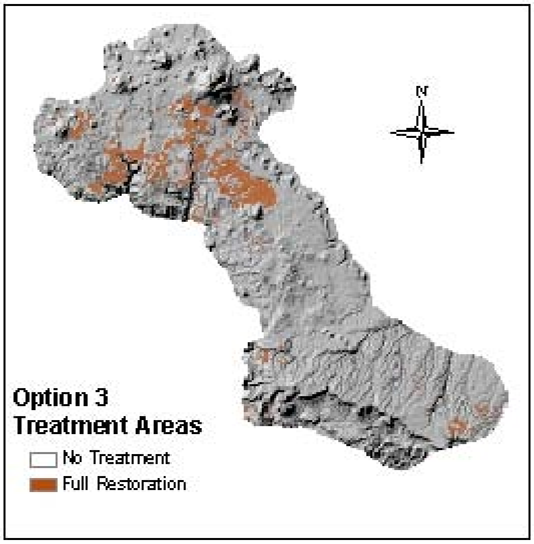


Figure 21. Full restoration treatments designed with **moderate owl habitat mitigation** for community protection prioritization (option 2) and full ecosystem protection (5).



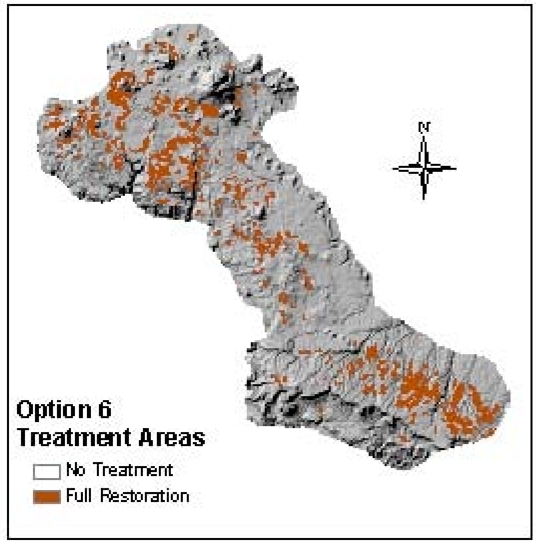
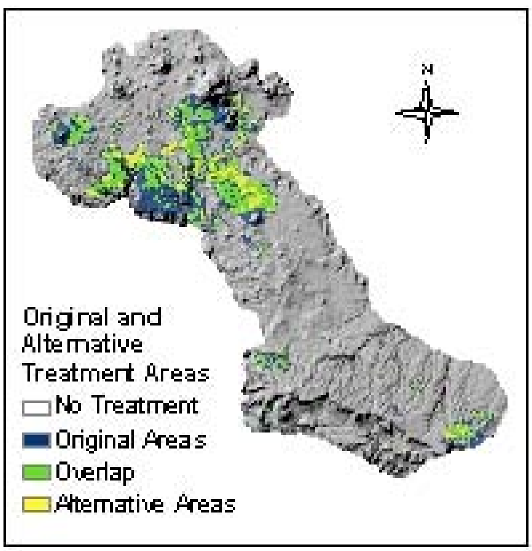


Figure 22. Full restoration treatments designed with **no treatments in owl habitat** for community protection prioritization (option 3) and full ecosystem protection (option 6).



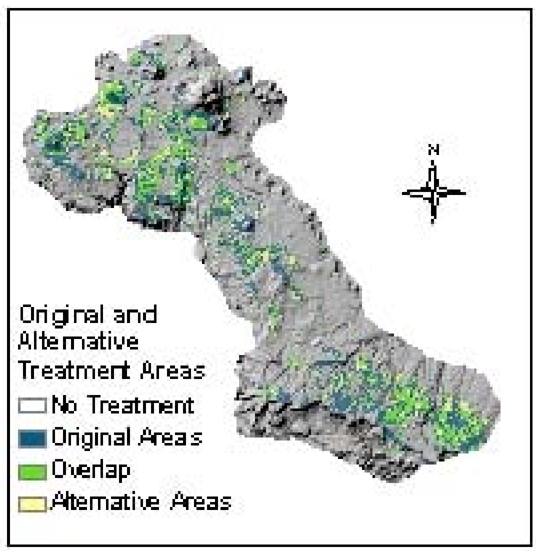


Figure 23. Overlap of **no owl habitat mitigation** treatments (blue areas; options 1 and 4) and **no treatments in owl habitat** treatments (yellow areas; options 3 and 6)

	Community protection prioritization			Ecosystem protection prioritization		
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
	No owl mitigation	Reduced treatments	Treatments restricted from owl habitat	No owl mitigation	Reduced treatments	Treatments restricted from owl habitat
Full Restoration (acres)	178,000	102,000	170,000	183,000	108,000	176,000
Intermediate Restoration (acres)		77,000			75,000	
Untreated (acres)	1,903,000	1,903,000	1,911,000	1,898,000	1,898,000	1,905,000

Figure 24. Acres treated in each hypothetical treatment option.

Results

Treatment Effects on Fire Hazard and Wildlife Taxa

Evaluation criteria performance characteristics vary considerably between options 1-6 (Figure 25). Overall fire hazard reduction rates are generally higher in the "ecosystem protection" options (4-6) than in the "community protection" options (1-3), as the ecosystem protection options maximize fire hazard reduction irrespective of community proximity. Performance characteristics vary considerably within each option, illustrating varied responses to restoration by the species evaluated. Treatments have a positive effect on pronghorn in all cases. Pronghorn antelope are shown to respond positively to all treatment options because the quality of pronghorn habitat is higher in open areas. Conversely, tassel-eared squirrels are shown to respond negatively. Western wood-pewee respond negatively to options 1-3, and positively to options 4-6.

Pronghorn typically inhabit very open areas and avoid areas that have high canopy cover or tree densities. They also avoid areas of high slope. The pronghorn habitat quality model is based on slope and canopy cover. Areas where canopy cover exceeds 60% are considered "non-habitat" for pronghorn, while areas below 20% are considered optimal. Therefore treatments that reduce canopy cover by a greater percentage tend to result in the greatest increase in pronghorn habitat quality. Options 4-6 treat more area with canopy cover >60%, so these options result in greater increases in habitat quality than options 1-3.

The tassel-eared squirrel model is based on a strong linear relationship between basal area and squirrel densities (Dodd et al. 1998; Dodd, unpublished data). As basal area decreases, squirrel density also decreases. Therefore treatment effects on squirrels are always negative. Treatment options 4-6 tend to have higher impacts on squirrels since the treated areas tend to have higher basal area than do options 1-3. Options 2 and 4 have less significant effects than do the other options in their respective groups since the intermediate restoration treatments reduce basal area less than full restoration treatments.

Reduction in overall area of predicted Mexican spotted owl habitat corresponds to the level of mitigation incorporated within each option. The Mexican spotted owl model is also based on relationships with basal area. Areas with basal area below 17 m^2/ha are considered "non-habitat" for the owl. Therefore, the patterns resulting from the treatment depend on how much owl habitat has basal area reduced below this minimum threshold. Options 4 and 5 have more impact than options 1 and 2 due to the larger amount of owl habitat that is included in treatment areas. Options 3 and 6 have minimal impact because treatments take place outside of owl habitat. However, the model is partially based on a majority filter that excludes areas where the majority of pixels in a 5X5 pixel area do not meet the threshold requirements. Therefore, some owl habitat is lost along the edges of treatment areas.

Unlike the other species considered in these examples, the western wood-pewee shows a variable response to treatments. Pewees are generally absent from areas with <100 trees/ha or >600 trees/ha. Therefore, in areas where treatments reduce tree density from 100-600 trees/ha to below 100 trees/ha, the probability of detecting pewees generally decreases. In contrast, where tree densities are reduced from >600 trees/ha to 100-600 trees/ha, the probability of detecting pewees generally increases. In options 4-6, more of the treatments take place in areas of high tree density, permitting the probability of detecting pewees to increase in most of the treated areas. For options 1-3, more of the treatments take place in areas of moderate tree densities, and many of these areas are reduced to densities below 100 trees/ha. Therefore, pewees are less likely to be detected in most treatment areas in options 1-3.

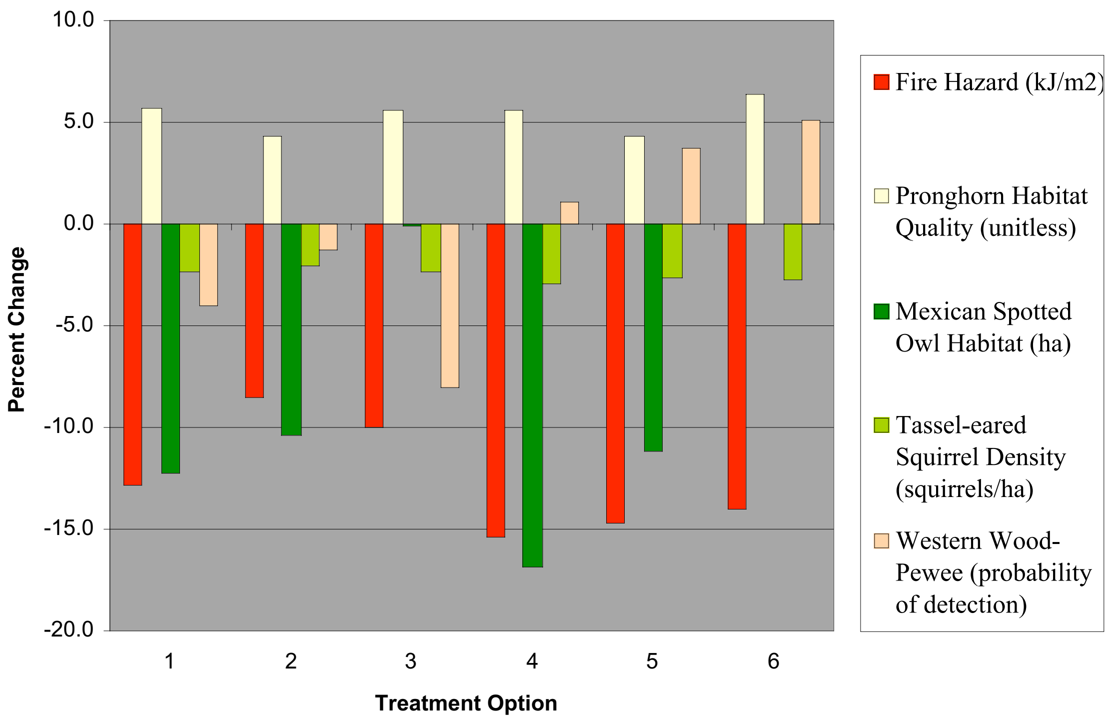


Figure 25. Performance bar chart for treatment options showing percent change from pre-treatment levels.

Decision Matrix Results

Patterns in performance characteristics for options 1-6 may also be compared within a "decision matrix" (Malczewski 1999). A decision matrix is a spatial multi-criteria decision analysis (MCDA) tool for assessing the relative value of user-defined restoration scenarios. Evaluating performance characteristics within a decision matrix allows decision-makers to compare the "overall" performance of options, and assign decision-maker preference-based values to each evaluation criteria through a weighting process. With MCDA tools, restoration stakeholders "weight" evaluation criteria and use decision rules to rank alternatives being considered.

The matrix shown in Figure 26 illustrates the comparison of the six options using weighting values hypothetically representative of a group of stakeholders prioritizing: 1) no preference or without explicitly considering decision-maker preferences, 2) community protection from crown fire with consideration to wildlife impacts, 3) overall ecosystem protection from crown fire with consideration to wildlife impacts, 4) fire hazard reduction to communities only, and 5) fire hazard reduction to overall ecosystem. By not explicitly considering decision-maker preferences (see totals using equal weighting factors), options 4, 5, and 6 are better able to maximize fire hazard reduction and minimize impacts to species and thus receive higher overall scores (highest value of 3.1 for option 6). Incorporating community protection weighting values shifts the preference to options 1-3, which were designed to protect communities in the initial prioritization. With full ecosystem protection weighting values, options 4-6 rise to the top, as these options were designed for this purpose.

If community fire hazard reduction is only considered in the weighting factors, option 3 ranks higher than option 1. This somewhat surprising result occurs because, when treatments prioritized for community protection were removed from owl habitat in option 3, a greater amount of treatments happened to shift into lower fire hazard areas upwind of communities, thus resulting in a greater amount of treatments upwind than in option 1. Finally, if fire hazard reduction to the overall ecosystem only is considered in the weighting factors, option 4 becomes the preferred choice. This use of user preferences in both the initial prioritization and, later, in comparing alternatives, demonstrates that the decision matrix can be used to compare various treatment plans, and possibly find compromises, regardless of the assumptions that went into initially developing them. Although the alternative options (2, 3, and 5, 6) to the highest priority treatment areas designed for community protection (option 1) and ecosystem protection (option 4) were designed to mitigate impacts to owls, it is possible to consider the impacts to other wildlife species using the decision matrix weighting factors, even though the weights do not change the treatment design of any option.

	Community protection prioritization			Ecosystem protectionprioritization			Weighting Factors				
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6					
	No owl mitigation	Reduced treatment intensity	Treatments restricted from owl habitat	No owl mitigation	Reduced treatment intensity	Treatments restricted from owl habitat	Equal	Comm-unity	Eco-system	Comm. Fire Hazard Only	Eco-sytem Fire Hazard Only
Reduction in Fire Hazard (kJ/m^2)											
in Areas Upwind of Urban	9.3%	8.3%	9.8%	8.4%	8.0%	7.7%	4	50	11	100	22
in Areas Not Upwind of Urban	3.5%	0.2%	0.2%	7.0%	6.7%	6.3%	16	0	39	0	78
MSO Habitat (Ha)	-12.3%	-10.4%	-0.1%	-16.9%	-11.2%	0.0%	20	25	25	0	0
Pronghorn Habitat Quality (Unitless)	5.7%	4.3%	5.6%	5.6%	4.3%	6.4%	20	15	15	0	0
Squirrel Density (Squirrels/Ha)	-2.4%	-2.1%	-2.4%	-2.9%	-2.6%	-2.7%	20	5	5	0	0
Wood-Pewee (Prob of Detection)	-4.0%	-1.3%	-8.0%	1.1%	3.7%	5.1%	20	5	5	0	0
TOTAL-equal weighting	-1.6	-1.5	-0.5	-1.2	0.2	3.1	100	100	100	100	100
TOTAL-community weighting	2.1	2.0	5.2	0.7	1.9	4.9					
TOTAL-ecosystem weighting	-0.2	-1.1	1.4	0.2	1.4	4.4					
TOTAL-community fire hazard only	9.3	8.3	9.8	8.4	8.0	7.7					
TOTAL-ecosystem fire hazard only	4.8	2.0	2.3	7.3	7.0	6.6					

Figure 26. Decision matrix (Note: upwind of urban areas make up 20% of the total study area, so an equal weighting a factor of 4 is given to upwind [20% of 20]).

Scaling Treatment Effects

The magnitude of a change in one of the criteria in the weighted matrix can have a substantial impact on the results of the matrix analysis. The change from pre-treatment to post-treatment for any factor can be determined in two different ways: an absolute amount of change in relationship to some actual or defined maximum value for the factor, or, a relative change between pre and post-treatment values.

As an example of the differences between relative and absolute scaling, consider pronghorn habitat quality. This factor is rated on a scale of zero to one. If the habitat quality changes from a value of 0.1 pre-treatment to a value of 0.2 post-treatment, the absolute change (in relation to the maximum possible value) is a 10% increase in habitat quality since 0.1 is 10% of the maximum and 0.2 is 20% of the maximum possible value. On the other hand, the relative change between 0.1 and 0.2 represents a 100% increase in habitat quality since 0.2 is double 0.1.

Difficulties arise in trying to apply either relative or absolute scaling to different factors. For some factors an absolute maximum or minimum value cannot be defined (e.g., the maximum squirrel density is not known with any certainty even though we could make some assumptions and calculate one), and absolute scaling then must be based on some chosen minimum or maximum. On the other hand relative scaling can lead to quite different values depending on the range of variation between factors. A factor with a pre-treatment value of 0.1 on a scale of zero to one will have a greater relative (%) change than a factor with a pre-treatment value of 0.5 for any increment of increase.

No matter what scaling is used there is always the chance for considerable differences in percent change among factors in the matrix. In addition, some factors may show a high percentage of change that is not very meaningful in reality. Other factors change by relatively small, but highly significant amounts. Because some factors cannot be weighted in absolute terms, relative change is used in the matrix. It is important, however, that those applying weights to different criteria understand the importance of the magnitude of the change for each factor, and adjust their weights accordingly (Malczewski 1999).

We decided to rate the Mexican spotted owl and pronghorn with the highest weighting factors (25 and 15, respectively) because they are relatively large organisms with small populations. Squirrels and wood-pewee population sizes across the study area are in the thousands or tens of thousands, while owls and pronghorn number only in the hundreds. Therefore small percentage changes in population size could potentially impact owls and pronghorn to a greater degree than they would squirrels or wood-pewees. The higher weights on owls and pronghorn are meant to account for this larger relative impact.

Next Steps

•Develop vegetation maps for full study area complete with formal accuracy assessment.
•Build remaining wildlife models (northern Goshawk, black bear, small mammals, Merriam's turkey) including accuracy assessments when sufficient data exists.
•Refine spatial layer depicting fire-sensitive watersheds.
•Finalize characterization of post-treatment forest structure.
•Complete encoding models into integrated ArcGIS spatial tools (wildlife, invasive plants, fire threat and risk, forest treatments, and multi-criteria decision-making).
•Organize training workshops in use of ForestERA products and tools.
•Assemble database and tools for distribution in late 2003/early 2004.

Discussion and Conclusions

Comparison of treatment options with performance charts or decision matrices is not meant to rank alternatives completely and finally. It is, however, meant to support an ongoing evaluation process in which stakeholders can iteratively assess different restoration scenarios, using different evaluation criteria and weighting strategies. By exploring scenarios in this manner, stakeholders will be better able to identify and understand the trade-offs and areas of agreement that should inform and guide restoration planning.

The ForestERA project will also allow restoration planners to explicitly define and assess impacts of proposed restoration scenarios, thereby facilitating the quantitative assessment of a treatment scenarios' cumulative effects – a critically important component of landscape-scale restoration planning, and an analysis required by the National Environmental Policy Act (NEPA) of 1969.

The evaluation criteria responses shown here are necessarily generalizations of complex ecosystems and their predicted response to several hypothetical restoration scenarios. Temporal dynamics, such as forest successional change over time, are not demonstrated here, but are critical elements of forest restoration planning. The ForestERA project continues to develop and qualify additional evaluation criteria (i.e., responses of additional passerine birds, black bear, northern goshawk, and Merriam's turkey to restoration treatments). By using ForestERA tools for predicting the cumulative effects of multiple restoration treatments and scenarios, managers can more informatively develop alternative treatments plans that mitigate negative impacts and address landscape and regional concerns associated with forest restoration.

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