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METHODOLOGY FOR SIMULATING FOREST GROWTH, FIRE EFFECTS, TIMBER HARVEST, AND WATERSHED DISTURBANCE UNDER DIFFERENT MANAGEMENT REGIMES[1]

ABSTRACT

The potential for large destructive fire is a major ecological, economic and social issue in the Sierra Nevada, especially in the mixed conifer zone where fire suppression and harvest have created fuel conditions believed to be unlike those of the past. Also, the health of late successional forests, watersheds, communities of people and the potential for timber production are important issues there. We have built a model to simulate forest structure and composition under different management objectives for the federal forests of the Sierra Nevada emphasizing the interaction of forests, fire, watersheds, and people. The purpose of this report is to explain our approach and to compare it to previous efforts.

Strategic forest planning models have traditionally focused on human alteration of forests to provide a sustained yield of timber output. Large scale disturbance processes, such as fire, have been ignored, subsumed into yield functions, or, more recently, recognized as another kind of "harvest" that could result in a recycling of acres back to earlier ages or different stand conditions.

We have undertaken a somewhat different approach to incorporating large scale disturbance, such as fire, into strategic forest planning. First, we divide each federal forest into approximately 200-400 polygons based on composition and structure to segregate the forest based on late-successional condition. Then we further subdivide each polygon into three zones based on distance from stream and other attributes to segregate the forest in terms of potential impacts of activities on aquatic environments. Finally, we further stratify each zone by vegetation type, tree size and density of vegetation, aspect and slope.

The potential for damage from fire under extreme weather conditions is calculated for each stand type based on likely flame length, crown density, height to live crown and other variables. This potential for damage is modified over time as the characteristics of the strata change and is used to estimate fire effects if a fire occurs.

We first attempt to achieve goals for these forests without recognition of fire. Goals for forest conditions and outputs over time that can guide the analysis include achieving a distribution of forest structure and composition that achieve late-successional goals, limiting watershed disturbance, limiting fire hazard, and achieving an even-flow of timber harvest volume. These goals can be achieved by applying two kinds of actions (prescribed fire and various intensities of timber harvest) or by leaving the forest to grow without intervention.

Given the planned actions that best meet the goals of an analysis and their outputs and effects over time, we allocate fires of different sizes onto the landscape in each period according to a historical profile of ignition probabilities and fire size in the polygons. The historical profile is described by the number of fires by size over the period of record. Also, a weather pattern is generated, in a probabilistic fashion, based on historical weather records. A fire of any size will have differing effects on the strata within the polygons where the fires occur based on strata condition.

In our analysis, fire behavior can be modified by human intervention in three ways: 1) alteration of fuels during commercial timber harvest, 2) fuel reduction treatments including mechanical treatment

[1]*Sierra Nevada Ecosystem Project: Final Report to Congress,* vol. II. *Assessments and scientific basis for management options.* Davis:University of California. Centers for Water and Wildland Resources. 1996.

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of fuels and prescribed burning, and 3) creation of shaded defensible fuel profile zones (fuel breaks). The first two methods affect fire severity; the third affects fire size.

Given the pattern of inputs, actions, outputs and effects that result, we then undertake a number of simulations to estimate the average impact of fire on the forest and also the variation in this impact. At the end of each period in a simulation, decisions are made whether to salvage and/or postpone green tree harvest depending upon watershed conditions in the local watershed (polygon).

We then summarize forest conditions, outputs, and effects over time from the intersection of planned actions, fire, and reaction to its effects. We also estimate the ending condition of the forest in terms of late-successional characteristics, watershed disturbance, potential for severe fire, and other measures.

We call this model Simulation and Analysis of Fire Effects in the FORESTS of the Sierra Nevada (SAFE FORESTS).

We believe that this approach advances the modeling of forests in fire-dominated landscapes in a number of ways. First, it enables us to place fire on a landscape. Thus, it overcomes a number of problems with previous approaches by allowing recognition of the place-related effects of fire. Second, the spatial nature of the fire simulation allows for the testing of fire control activities such as fuel breaks that have an inherent spatial nature. Third the "process" approach implied by calculation of fire hazard based on stand condition, recognition of weather patterns, and actual placement of fire on the landscape enables the dynamic calculation of fire effects. Fourth, it attempts to simultaneously recognize and relate goals for watersheds, late-successional forests, fuel treatment, and other values.

INTRODUCTION

The Need to Assess Strategies for the Conservation of Late-successional Forests in Fire-Prone Landscapes

The Sierra Nevada Ecosystem Project (SNEP) is an assessment of the entire Sierra Nevada ecoregion. It was commissioned by Congress in the 1993 Appropriation Act which authorized funds for a “scientific review of the remaining old growth in the national forests of the Sierra Nevada in California, and for a study of the entire Sierra Nevada ecosystem by an independent panel of scientists (Appendix A, Sierra Nevada Ecosystem Project, (1994)).” In addition, the Steering Committee guiding the work of SNEP charged the Science Team, in part, “to develop a range of alternative management strategies to maintain the health and sustainability of these ecosystems while providing resources to meet human needs (Appendix E, Sierra Nevada Ecosystem Project (1994)).” Thus, SNEP had the charge of both assessing the health of Sierra Nevada ecosystems and, where problems were detected, suggesting management strategies to maintain health and sustainability.

Documentation of the distribution and condition of old-growth forests in the Sierra Nevada and advice regarding the management of this resource are explicit responsibilities of SNEP. Congress provided this direction in language that was a part of two bills in the House of Representatives in 1992 (see Appendices A and C in Sierra Nevada Ecosystem Project (1994)): HR 5503 (passed), as mentioned above, called for a “scientific review of the remaining old growth in the national forests of the Sierra Nevada”; HR 6013 (proposed) called for, in part, "recommendations of alternative management strategies to protect and enhance . . . late-successional forests and their dependent and associated species, including a determination of whether late-successional reserves are necessary . . . and if such reserves are necessary, what lands should be included in such reserves." The charge from the SNEP steering committee to the SNEP Science Team linked the two bills: “The Forest Service’s recommended approach is to develop a study based on achieving the general requirements of HR5503 and attempt to meet the intent of the ecosystem study established in HR6013 (Appendix E of the Sierra Nevada Ecosystem Project (1994)).”

Toward that end, Franklin and Fites-Kaufmann (1996) assessed the state of late successional forests in the Sierra. They divided the entire federal ownership in the Sierra Nevada into polygons reflecting forest in different late-successional conditions. After analyzing the results from this inventory, they concluded that forest management on federal land had resulted in a significant decline in the amount and complexity of late-successional forest in the commercial forest types, especially the mixed conifer and east-side pine types. In the commercial forest types, they found that a significant reduction in big trees and big snags had occurred since imposition of federal forest management.

Next, Franklin, et al. (1996) proposed and evaluated the potential for a number of different conservation strategies for late-successional forests relative to their ability to: (1) provide sufficient, well-distributed high-quality late successional/old growth forest to sustain the organisms and functions associated with such ecosystems for the next century and (2) provide conditions which facilitate connectivity for organisms moving between old-growth forest areas.

These conservation strategies all involve increasing the general extent and complexity of late-successional forests in the Sierra Nevada. Some involve identifying relatively large Areas of Late Successional Emphasis (ALSEs) where late successional forests will be emphasized and also increasing the late-successional attributes of the intervening forest (called the "matrix"). Variations on this strategy call for more or less prescribed fire and mechanical treatment (timber harvest) in the ALSEs to accelerate development of these characteristics. Other strategies call for a more distributed late successional system. Finally, one strategy uses the concept of a "regulated forest" to achieve levels of late successional forests over the landscape without concern over concentration of the late successional areas in contiguous blocks.

From the beginning of the SNEP assessment of late-successional forests, it was clear that the threat of severe fire from the build-up in fuels and decrease in fire frequency in some types would be a major consideration in any strategy to rebuild the late-successional forests of the Sierra Nevada (Franklin and Fites-Kaufmann 1996, McKelvey, et al. 1996, Skinner and Chang 1996, Weatherspoon 1996, and Weatherspoon and Skinner 1996). While opinions may vary somewhat as to the degree of the current nature and extent of the threat of severe fire, it is clear that we need to understand the survivability of late-successional forests, and the forest in general, under different forest management strategies including strategies explicitly aimed at reducing fuels and limiting the damages to resources that do occur (Weatherspoon and Skinner 1996).

Therefore, we have undertaken the construction of a methodology to help assess the likelihood that various policies will achieve late-successional goals and what resources will be required to meet them, while explicitly acknowledging the potential for fire to influence attainment of these goals. We wish to be able to set late-successional goals for different parts of the landscape and test the length of time it will take to achieve them, the role for human intervention (control of wildfire, prescribed fire, timber harvest) to accelerate the achievement of late-successional goals, and the likelihood that severe fire will prevent their attainment. This paper discusses the models we have built to evaluate these concepts and strategies.

General Approach: Consideration of Integrated Conservation Strategies for Forests, Streams, and Watersheds

SNEP is assessing the state of Sierra Nevada ecosystems from a variety of perspectives. Numerous issues relative to the health and sustainability of these ecosystems have been identified beyond the issues mentioned above relative to late successional forests and fire. Some other issues identified in SNEP that are related to issues surrounding forest management relative to late-successional forests and fire are:

1) declines in aquatic biodiversity and existing and potential threats to riparian-associated species and ecosystems (Erman 1996, Kattelmann and Embury 1996, Knapp 1996, Kondolf, et al. 1996, Jennings 1996, Moyle 1996a, Moyle, et al. 1996a, Moyle, et al. 1996b, Yoshiyama, et al. 1996).
2) existing and potential difficulties from watershed disturbance (Berg, et al. 1996, Kattelmann 1996, Menning, et al. 1996).
3) declines in terrestrial biodiversity and existing and potential threats to terrestrial wildlife species and ecosystems (Graber 1996, Shevock 1996, Davis and Stoms 1996).
4) production of timber as an objective on federal lands including the sizes and species that might be harvested and the associated costs and revenues (Ruth 1996).
5) the potential effect of budget constraints on fuel treatments and other activities on federal lands (Ruth 1996).
6) management of existing roadless areas (Ruth 1996).
7) the intermingling of federal, state, and private lands (McKelvey et al. 1996, Menning et al. 1996)

We wish to consider strategies for addressing these issues simultaneously with strategies for late successional forests because the strategies to deal with the different identified issues potentially influence each other. Mechanical treatment to improve LS/OG rank, decrease fuel loadings, and/or produce timber can impact riparian areas and watersheds. Aquatic goals for riparian zones can affect the amount of LS/OG forest and the freedom to treat the zones to reduce fire hazard. LS/OG goals for ALSEs and the matrix can influence fire hazard there and the distribution of acres among seral stages and among different wildlife habitats. Creation of fuel breaks can possibly increase the survivability of the ALSEs and the forest in general and produce timber volume and value, but at the cost of reducing LS/OG rank and potentially negatively affecting the functioning of ecological systems within the fuel breaks. Wildlife goals can influence the amount and distribution of LS/OG. Budget constraints can influence the ability to undertake activities of any sort including the design of commercial entry.

Thus, we have built a policy analysis model that emphasizes the analysis of strategies for late-successional forests in fire-dominated landscapes, but that can also measure and limit effects on riparian areas and watersheds. The model can also accept goals for, or limits on, timber harvest and develop reports that can provide a basis for assessing the adequacy of wildlife habitat and seral stage representation. Also, it reports likely costs and revenues associated with different strategies.

The policy analysis model described here was applied in analysis of these issues on two national forests in the Sierra Nevada--Plumas and Eldorado. These national forests are located in the northern Sierra (Plumas) and central Sierra (Eldorado).

Problems Not Addressed

SNEP scientists identified many problems and issues with maintaining the health and sustainability of Sierra Nevada ecosystems beyond those addressed here. Some of these other problems are:

1) air pollution from outside the region or from urban areas inside the region (Cahill, et al. 1996). Suggestions for addressing air quality problems are discussed in Cahill, et al.
2) adverse effects on native aquatic organisms from changed water-flow regimes, introduction of exotics, and dumping of pollutants (Jennings 1996 and Moyle, et al.1996b). Suggestions for addressing these problems are discussed in Moyle (1996b).
3) fire and settlement issues on private land in the region (McKelvey, et al. 1996, Husari and McKelvey 1996, Weatherspoon and Skinner 1996, Duane 1996, McBride, et al. 1996). Suggestions for addressing these issues are covered in Weatherspoon and Skinner (1996) and Duane (1996).
4) potential vulnerability of some native plant communities, especially non-forest communities and native plant communities not represented on federal land, due to lack of areas dedicated to their maintenance (Davis and Stoms 1996). Procedures for selecting biodiversity management areas to address this problem can be found in Davis, et al. (1996).
5) condition of rangelands (Menke, et al. 1996). Options for improving rangelands conditions can be found in Menke, et al.
6) the leakage of value out of the region with little reinvestment (Stewart 1996). Options for addressing this issue can be found in Sierra Nevada Ecosystem Project, volume one (1996).
7) institutional capacity to implement the suggestions made in the options for solving the problems identified (Sierra Nevada Ecosystem Project, volume one, 1996).

As we develop models for incorporating these additional resource questions, we can further enhance our policy planning modeling.

FOREST-LEVEL OPTIMIZATION–PREVIOUS EFFORTS

Since the early days of the national forests, forest plans have guided the level of timber harvest and the scheduling of timber harvest activities. Relatively simple formulas were used to set the harvest levels based on controlling the volume harvested, the area cut, or both volume and area (Davis and Johnson 1987).

In both public and private forest planning, optimization models have become dominant in the development of forest plans (Davis and Johnson 1987). These models attempt to maximize or minimize some quantity subject to reaching specified policy goals, which are represented as constraints, given the choices for management that are allowed for each part of the forest. Typical objectives have been to maximize timber harvest, minimize cost, or maximize present net value. Typical policy goals have been to maintain a nondeclining yield of timber harvest over time, limit the rate of harvest in different portions of the forest, and attain some distribution of acres among age-classes or seral stages.

As the policy goals to be achieved have become more complex, the optimization models have often been reformulated as "goal programs." Then the policy goals that were previously represented as absolute constraints are transformed to allow for under- or over-achievement with an associated penalty. The overall objective is then to minimize the total penalty. This formulation has especially become popular as achieving a distribution of forest acres among seral stages over time has become a major policy goal.

A Classification of Forest Optimization Models

Johnson and Scheurman (1977), Clutter, et al. (1983), Johnson and Tedder (1984) and Davis and Johnson (1987) described the lineage of strategic planning systems based on forest-level optimization models where timber harvest is a major activity. Two major variables were: 1) the model formulation (Model I or Model II) and 2) the solution technique (linear programming or binary search).

In both model formulations, forest vegetation is classified according to certain variables such as species type, density, age, and other variables. Each unique combination of these classification variables forms a "stratum." Overlaying the classification system on the forest divides the vegetation into these strata. All instances of each stratum over some geographic area, such as the entire forest or a watershed, are aggregated into inventory categories in the analysis and are often called "analysis areas."

Johnson and Scheurman (1977) coined the terms "Model I" and "Model II" to label fundamentally different ways to define decision variables for the analysis areas for scheduling timber harvest and investment, the distinction being the way in which the regenerated (future) stands are handled. In Model I, regenerated stands are coupled directly to, and identified by, the existing stands to which they are associated. In Model II, regenerated stands are detached from the existing stands and new decision variables are defined for them.

Thus, Model I defines decision variables that follow the life history of an acre over all planning periods while Model II defines decision variables that follow the history of an acre over the life of a stand growing on the acre, from its birth (or start of the planning periods) through its death (or end of the planning periods). In Model I, a decision variable traces the activities on an acre over the entire planning horizon; in Model II, an acre may pass through several decision variables before reaching the planning horizon as stands are born, live, and die.

We describe below general mathematical formulations of Model I and Model II. We add one policy goal to the discussion--the need for an even-flow of timber harvest--to illustrate how policy goals are considered. In mathematical form, the basic structure of Model I is:

$$\text{Max} \sum_{s=1}^{S} \sum_{p=1}^{P_s} \sum_{t=1}^{T} B_{spt}\, x_{sp}$$

subject to:

Input constraints

$$\sum_{p=1}^{P_s} x_{sp} = \text{Area}_s$$

For s = 1....,S

$x_{sp} \geq$ zero s, p

Policy constraints

Even flow of timber harvest

1) Accounting rows

$$\sum_{s=1}^{S} \sum_{p=1}^{P_s} V_{spt}\, x_{sp} - H_t = 0 \qquad t = 1, \ldots, T$$

2) Even-flow requirement

$$H_t - H_{t-1} = 0 \qquad t = 2,\ldots.,T$$

where:

x_{sp} = acres assigned to prescription p of analysis area s, where analysis area s is a stratum on the forest

B_{spt} = contribution to objective function (per acre) in period t from prescription p of analysis area s.

V_{spt} = volume harvested in period t from prescription p of analysis areas s

S = number of analysis areas

p_s = number of prescriptions for analysis area s

Area s = size of analysis area s, in acres

T = number of periods

For an equivalent problem, the basic structure of Model II is:

ADDENDUM

$$\text{Max} \sum_{s=1}^{S} \sum_{p=1}^{P_S} \sum_{t=1}^{T} B_{spt}\, x_{sp} + \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{p=1}^{P_r} \sum_{t=1}^{T} C_{jrpt}\, y_{jrp}$$

subject to:

Input constraints

$$\sum_{P=1}^{P_s} x_{sp} = \text{Area}_s \qquad \text{for } s = 1....,S$$

$$\sum_{p=1}^{P_s} y_{jrp} - \sum_{s=1}^{S} \sum_{p=1}^{P_s} G_{jrqsp}\, x_{sp} - \sum_{j'=1}^{J} \sum_{r'=1}^{R} \sum_{p=1}^{P_r} H_{jrqj'r'p}\, y_{j'r'p} = 0$$

for r = 1....R
for j = 1....J $\qquad$ j'<j, j<q

Policy constraints

Even-flow of timber harvest

1) Accounting rows

$$\sum_{s=1}^{S} \sum_{p=1}^{P_s} V_{spt}\, x_{sp} + \sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{p=1}^{P_r} V_{jrpt}\, y_{jrp} = 0 \qquad t = 1, \ldots, T$$

2) Even-flow constraint

$$H_t - H_{t-1} = 0 \qquad t = 2,....,T$$

where:

x_{sp} = acres assigned to prescription p of analysis area s, where analysis area s is a stratum on the forest

B_{spt} = contribution to objective function (per acre) in period t from prescription p of analysis area s

V_{spt} = volume harvested in period t from prescription p of analysis areas s.

S = number of analysis areas

p_s = number of prescriptions for analysis area s

y_{jrp} = acres assigned to prescription p of regeneration class r initially recognized in period j.

C_{jrpt} = contribution to the objective function (per acre) in period t from prescription p of regeneration class r initially recognized in period j
P_r = number of prescriptions for regeneration class r

N = number of time periods

R = number of regeneration classes

G_{jrqsp} = a factor that gives the proportion of acres in prescription p of analysis area s that transfers in period q to regeneration class r initially recognized in period j. (G_{jrqsp} = 0,1)

$H_{jrqj'r'p}$ = a factor that give the proportion of acres in prescription p of regeneration class r' initially recognized in period j' that transfers in period q to regeneration class r initially recognized in period j. ($H_{jrqj'r'p}$ = 0,1)

T = number of periods

Any problem formulated with Model I can be formulated with Model II and visa-versa. It should be noted, though, that the power of Model II comes from its merging of acres of like characteristics from across the planning area as they are regeneration harvested. Through this process, fewer activities need be created to represent the problem, compared to Model I, but at the cost of losing some spatial definition in management of future stands. When the merging of acres as they are regeneration harvested is acceptable, Model II is a powerful tool; when such merging is not acceptable, Model I is usually preferable.

Incorporating Fire Effects into Forest Optimization

The models presented so far do not explicitly consider risk of loss from fire. Any effect of fire was handled through adjusted yield functions; the notion that fire could cause "premature" death of a stand was not recognized. Reed and Enrico (1986, 1989) broke from this tradition by creating a linear programming model of timber management in which the expected burned area was subtracted from each age class in each time period, and added along with the cutover area to the youngest age class in the following period. While describing their model as stochastic, they actually solved its equivalent "mean value problem", i.e., the random proportion burned was replaced with its expected value (Boychuk and Martell 1996).

Johnson, et al. (1986) built an extension of FORPLAN--the forest planning model used by the Forest Service--that would represent fire and other stochastic losses and changes deterministically in a manner similar to that proposed by Reed and Enrico. Johnson and Stuart (1986) showed the transfer of acres among stand ages and classes for reasons other than harvest could actually be represented as a generalized version of Model II, although this formulation is sometimes called Model III (Boychuk and Martell 1996). In terms of the Model II formulation above, this more general version of Model II allows the transfer coefficients ($G_{jrqsp}/H_{jrqj'r'p}$) to take values other than 0,1 as long as they sum to 1.

This mean value formulation of Model II is now in wide use, especially by the Forest Service in California as it has been made available in FORPLAN. The recent analysis of timber harvest levels on the national forests of the Sierra Nevada compatible with protection of the California Spotted owl used the version of FORPLAN that allows specification of fire mortality in terms of their equivalent mean values (USDA Forest Service, 1995). In their analysis, Forest Service planners estimated the expected rate of fire mortality by stand type and condition and embedded these mortality rates in their FORPLAN model. This mortality could be either complete or partial with the resulting transfer of the burned acres to another strata reflecting the fire effects.

While the mean value formulation is a major improvement toward incorporating fire risk, compared with the traditional approaches to timber harvest scheduling, some problems with this approach have been noted. Pickens and Dress (1988) and Hof et al. (1988) in their studies of the effect of stochastic technological coefficients on forest-level timber management models, found that attempting implementation of solutions from mean value problems in a stochastic system leads to infeasibility with high probability.

Gassmann (1989) formulated a version of the problem defined by Reed and Enrico as a multistage stochastic programming problem in which the proportion burned each period was stochastic. Boychuk and Martell (1996) compared the results of a stochastic programming problem (SPP) and the corresponding mean value problem when fire risk in considered in forest planning analysis. Since they felt that replanning is inevitable, they compared only the first period solutions. Boychuk and Martell found that the mean value solution generally gave a good approximation to the stochastic programming problem, but consistently over-harvested in cases where decision-makers wished to avoid declines in harvest and where there is little area in the older age classes. They felt that using a stochastic programming approach would be justified in areas lacking sufficient over mature areas and having high and highly variable fire losses, and where harvest quantity declines in the future are particularly unwanted.

In addition, the mean value formulation does not enable the measurement of the variability of the solution. In some cases, decision-makers may be as interested in this variability as in the mean value. With the mean value formulation, the problem can be resolved with different mortality rates to illustrate the implications of different assumed rates, but that shows the implication of different mean values rather than the variability associated with any particular mortality rate.

To assess the variability in forest plan outcomes, Boychuk and Martell (1996) formulated a stochastic programming version of the forest planning problem with risk of fire. As with the mean value formulations, they developed a model with linear objectives and linear constraints. They represented stochastic fire loss by a discrete two-point probability distribution that yielded the desired mean and coefficient of variation.

The use of stochastic programming to study forest planning under risk of fire enriches our understanding of the variability in outcomes and also of strategies which may avoid timber harvest level declines in the future. Even problems with few analysis areas, though, can result in very large linear programming formulations as shown in the work of Boychuk and Martell (1996). Thus, the technique is not currently practical for forest planning problems, like those in our study, where large numbers of analysis areas and a wide variety of outcomes from fire are the rule.

Summary and Discussion of Optimization Methods

Recent activity in forest optimization including fire risk effects has emphasized mean value and stochastic programming formulations, which can be viewed as variations in Model II, as discussed above. While these approaches have increased our understanding of how consideration of fire affects management plans, we did not choose these approaches for a number of reasons.

Despite its use in forest planning on SNEP forests (USDA Forest Service 1995), the mean value approach was not chosen for our modeling for four reasons:

1) The mean-value approach discussed above adjusts stratum condition for fire mortality. In reality, fires in the Sierra Nevada do not occur by strata; rather, they occur in a particular place and affect, to one degree or another, all strata they encounter. That is, fire is spatially explicit, while stratum designations are simply classes of like vegetation. Especially in the Sierra Nevada, with its fine scale mosaic, strata are intermingled to a significant degree. We felt that we needed to recognize the spatial aspect of fire and portray it as it occurs--a particular size in a particular place--which is not possible with the mean-value approach.
2) The mean-value approach works best when fires cause only a few different outcomes. When many different outcomes are possible, model size can explode. In our analysis, we uniquely tailored the effect of fire on stand condition in each stratum in each time period under each prescription, with most fires usually differentially killing different size classes but not entirely destroying the stand. We felt we would lose much of this fine detail by collapsing fire results into a form amenable to a mean value approach.
3) The mean-value approach does not explicitly consider the variability in fire occurrence in terms of time, place, and size. Fires in the Sierra Nevada have shown considerable variability in the amount of fire per decade although they have been consistently related to periods of drought. As an example, during the 60-year reference period the amount of fire per decade on the Eldorado National Forest varied from 3,500 to 32,000 acres; on the Plumas NF, it varied from 15,000 acres to 115,000 acres. Fires have shown some reliability in where they occur, such as the repeated burning along Highway 50 on the Eldorado NF, but the location of most fires from decade to decade is hard to pin down to particular LS/OG polygons. Finally, the frequency distribution of fire sizes varies from year to year and is best represented by a probability distribution.
4) We wanted to retain flexibility. Our modeling efforts began before the SNEP assessment had been completed. Anticipating that we might need to incorporate as yet unspecified nonlinear relationships into the simulations to reach wildlife or watershed goals, we chose a simulation approach that would maintain our options.

The stochastic programming approach (Boychuk and Martell 1996) has proven interesting and valuable for research insights. However, this approach is not practicable for applications with a large number of different starting conditions as in our analysis. The problem size simply becomes unmanageable.

Given the difficulties we see with using mean value and stochastic programming in our analysis, we have taken a different approach. As discussed below, we have taken a four-stage approach using a Model I formulation. First, we solve the strategic forest planning problem without fire given the goals of the alternative. Then we allocate fire onto the landscape using a number of stochastic variables including weather, fire size, and ignition probability. We simulate the fires and their effects for a number of periods as the fires sweep across LS/OG polygons, running through the strata found in the polygons, and leaving a differential mark on the landscape depending on vegetative condition (fuels, crown composition, and structure) in the different strata in each polygon burned. Finally, we rework the strategic plan, salvaging where permitted, and adjust the prescriptions previously chosen inside the LS/OG polygons that burn to allow for the fire that occurred and to make any needed change in post-fire activities to better achieve the goals of the prescription, much as a manager would react to an unforeseen activity. For fires that create conditions which exceed watershed disturbance limits, future activities which would create additional disturbance are postponed until watershed conditions improve. A number of simulations of fires, with the associated reactions, are done to help understand the mean and range of potential fires and their effects.

We do not, however, completely reoptimize the strategic plan that we develop for each alternative given the likely fire effects. Rather, we use these effects to help understand the likely influence of fire on the strategic plan.

Thus we do not claim that use of the SAFE FORESTS model will formulate strategic plans that are "best," given our goals and the likely fire effects, as might be claimed for mean value or stochastic programming. We can, though, have a much fuller understanding of the spatial effects of fire on large landscapes while recognizing the differential effect that fire can have on each area that burns.

Solution Techniques for Harvest Scheduling Problems

The formulations shown above for Model I and Model II have a linear objective function and linear constraints. As such, linear programming can be used to find the mathematically optimal solution, i.e., the solution that gives the maximum (or minimum) value for the objective function given the constraints (See Dykstra 1985 or Davis and Johnson 1987 for more discussion). Many harvest scheduling models, like FORPLAN, rely on linear programming as their solution technique.

Attempting to solve large problems with linear programming has led to a number of difficulties. First, linear programming software to solve these problems has often been costly or unavailable. Second, the size of the problem can easily exceed the capabilities of commercial software in terms of columns (choices for management of the analysis areas) or rows (number of acreage constraints and policy constraints).

A number of heuristics have been developed to solve these problems, with the most common approach called "binary search." Binary search uses a forest inventory data set and appropriate growth models to find the maximum even flow of volume or value that can be sustained over a finite planning interval subject to harvest flow and ending inventory constraints. The name "binary search" emerges because (1) there is only one decision variable per period (the level of harvest) and (2) there are only two choices in the problem, either increase the harvest or decrease it. All other needed decisions, such as what prescriptions to apply in each stand type and the priorities for selecting stands for intermediate harvest by thinning and for regeneration harvest, are decided external to the heuristic (Davis and Johnson, 1987).

Generally, binary search models are of a Model II form. Many have keyed on finding an equal volume through time, while others have keyed on equating net revenue through time. Binary search can sometimes obtain results similar to linear programming; other times, it can fall short of the linear programming results when the prescription for each stand and the priorities for thinning and final harvest are important to the solution and difficult to estimate. As policy constraints of different kinds are added to the formulation, estimation of the "best" prescriptions and priorities for harvest can become increasingly difficult; thus, binary search models are most useful when there are relatively simple policy constraint sets (Davis and Johnson 1987).

Recently, heuristics have been suggested that overcome some of the deficiencies associated with binary search. Hoganson and Rose (1984, 1987) developed a technique that allows consideration of alternative management intensities and finds the optimal stand priority for harvest, overcoming two major drawbacks of binary search. Given an objective of maximizing present net worth and a specified volume to harvest each period, Hoganson and Rose vary the price of stumpage in each period until they find a set of prices for the timber harvest such that the best time to harvest each stand to maximize its present net worth on an individual basis is also the best time to harvest the stands in aggregate to meet the overall harvest constraints. With relatively simple harvest flow requirements as the major policy constraints, this algorithm can give results approaching those of linear programming while being able to handle much larger problems.

Several general heuristic approaches have been applied to harvest scheduling problems when explicit spatial recognition is necessary which requires a large number of integer decision variables to model the objective function and constraints. In these cases the values of some decision variables cannot take on continuous non-negative values, but are restricted to zero or one. Such applications arise when harvesting on adjacent polygons is not permitted, when maintaining connections of polygons across the landscape is required, or when construction or obliteration of specific road segments must be recognized. Although algorithms (branch and bound, cutting plane) have been developed which sequentially solve a set of linear programming models to an exact solution, they are usually too slow for practical solutions to large harvest scheduling problems.

Three general heuristic approaches which have been used to solve large harvest scheduling problems involving integer variables are: 1) Monte Carlo methods, 2) TABU search, and 3) Lagrangian relaxation. Monte Carlo methods involve a neighborhood search using a criterion to accept non-improving solutions subject to a probability function as a way to avoid being trapped in local optima. Simulated annealing, a variant of the Monte Carlo method, accepts non-improving solutions with decreasing probability using the analogy of a cooling metal. Applications of Monte Carlo methods to harvest scheduling problems can be found in Nelson and Brodie (1990), Clements and Dallain (1990), Lockwood and Moore (1992), and Nelson and Liu (1995).

TABU search is a gradient algorithm which uses a collection of principles of intelligent problem solving to avoid being trapped in local optima. A fundamental element underlying TABU search is the use of a flexible memory where recency, frequency, quality, and influence of variables entering or leaving the solution is recorded and controlled. Applications of TABU search in harvest scheduling can be found in Murray and Church (1995), Bettinger (1996) and Boston (1996).

Lagrangian relaxation has been used to solve the integer programming problem using linear programming to solve a "relaxed" linear problem with few or no 0/1 variables to establish upper bounds on the exact solution. Applications in forestry include Guignard et al. (1993) and Torres-Rojo et al. (1996).

THE SAFE FORESTS MODEL

This paper describes the policy analysis model that we have constructed. We cover our classification of land, types of goals, measurement criteria, types of activities, mathematical formulation, and solution methodology. We call the model Simulation and Analysis of Fire Effects in the FORESTS of the Sierra Nevada (SAFE FORESTS).

The SAFE FORESTS model described here has been used in analysis of these issues on two national forests in the Sierra Nevada (Plumas NF and Eldorado NF) (Johnson, et al. 1996). We will use the Eldorado NF to illustrate the model, its data requirements, and its outputs.

Classification of Landof Land

Spatial UnitsSpatial Units

For the purposes of this model, spatial units include polygons and lines (vectors). Spatial units have geographic coordinates and associated attributes recognized in the modeling.

LS/OG Polygons/OG Polygons

Franklin and Fites-Kaufmann (1996) assessed late successional, including old growth (LS/OG), forest conditions for the Sierra Nevada using stand structural criteria as measures of the level of LS/OG forest function. Larger landscape units (polygons) which were relatively uniform in type and distribution of vegetation patches were mapped using imagery, maps, ground-based information, and the expert interpretations of resource specialists. This analysis resulted in 180 LS/OG polygons on the Eldorado NF and 216 on the Plumas NF.

Characteristics of the major patch types in each polygon were identified and tabulated and a composite late successional structural ranking was calculated for each polygon on a scale that extended from 0 (no contribution to LS/OG forest function) to 5 (very high level of contribution to LS/OG forest function). All six ranks are represented on the Eldorado NF (Figure 1). These polygons fell into four major forest types (Figure 2).

ALSEs

A subset of these LS/OG polygons have been identified as Areas of Late Successional Emphasis (ALSEs) (Figure 3). These LS/OG polygons generally have above-average levels of late-successional characteristics and are the focus areas for maintenance of high levels of late-successional characteristics in many of the analyses listed below. They were identified by Franklin and Fites-Kaufmann (1996).

Fuel BreaksBreaks (Defensible Fuel Profile Zones)

Eldorado and Plumas National Forest LS/OG polygons are overlain with a GIS coverage of potential fuel break polygons (defensible fuel profile zones). These zones would be 1/4 mile wide based on simulations by van Wagtendonk (1996) and were developed in cooperation with Forest Service personnel (Bahro 1996, Weatherspoon and Skinner 1996). They permit simulation of fire containment strategies. In alternatives that use fuel breaks, these strips of land have been modified to reduce flame length, fire intensity, spotting, and crown fire. The stand structure would provide a safe defensible area for fire suppression activities. They require periodic maintenance to remain effective. Fuel breaks are placed mainly on dominant ridge lines or strong intermediate ridges on the Eldorado NF (Figure 4) and on ridges or adjacent to major roads and/or large streams on the Plumas NF. In both cases, they have suitable access to facilitate safe fire suppression. They also provide anchor points for large scale prescribed burning programs.

Subdivision of LS/OG Polygons for Fire Simulation

The delineation of potential fuel breaks resulted in a subdivision of LS/OG polygons when a fuel break ran though it. In our fire simulations, an entire LS/OG polygon is burned when a fire enters it, with the effects of the fire varying within the polygon depending on the condition of the different vegetative strata within it. This resulted in increasing the number of LS/OG polygons (for simulation purposes) from 201 to 621 on the Eldorado NF (Figure 5). To increase the realism of the fire simulation, polygons larger than 1000 acres after recognition of potential fuel breaks were subdivided. This subdivision was first based on watershed boundaries from the Cal-Water GIS coverage. Any remaining 1000 acre or larger polygons are subdivided based on GAP vegetation polygon boundaries (Davis and Stoms 1996). These additional subdivisions result in 2315 LS/OG polygons for the Plumas NF. The combination of LS/OG polygons and fuel break polygons on the Eldorado NF yields appropriate size polygons for fire simulation. No further division of the 621 Eldorado LS/OG polygons along watershed or GAP boundaries was necessary.

Each LS/OG simulation polygon is linked to an attribute table containing descriptive information such as LS/OG rank, size, dominant forest type, designation as an Area of Late Successional Emphasis (ALSE), selection as a fuel break polygon, and other characteristics.

Non-spatial Information

In addition to the spatial information, we recognize a set of non-spatial strata within each LS/OG polygon. The geographic locations of non-spatial data are not recognized in the model. For example, we know that 60% of the area of LS/OG polygon 99 is north facing. However, we do not track precisely where within the polygon this north facing land is located. Non-spatial information used in this model include ownership, land-use zones, USDA Forest Service vegetation classification, slope, aspect, and roadless areas.

Land-use Zones-use Zones

We further subdivided each simulation polygon into up to four land use zones, three of which relate to potential influence on aquatic environments. First, we have a category called "reserved areas" which is composed of Wilderness areas and areas considered too unstable for road building or logging in nonwilderness areas. Next we recognize three aquatic influence zones that exhaustively divide the landscape outside of reserved areas. They are based on the aquatic and riparian system developed by D. C. Erman, N. Erman, L. Costick and S. Beckwitt and reported in Kondolf et al. (1996) and Kattelmann and Embury (1996).

Erman and his colleagues suggest that we recognize a number of overlapping zones that are defined in relation to their influence on the adjacent aquatic ecosystem. The Community Influence Zone is the area usually recognized as clearly riparian, with its distinctive flora and fauna and with many organisms that use both terrestrial and aquatic habitats on a regular basis. The Energy Influence Zone includes all the riparian area that is likely to contribute energy and structure to the aquatic ecosystem. It usually encompasses the Community Influence Zone and all land as far from the stream as the tallest tree that can be grown on the site. The Land Use Influence Zone is the region along a stream in which human activity is likely to influence the aquatic ecosystem by increasing nutrient and sediment inputs and other factors. It includes both other zones and may encompass much of the watershed, especially in smaller drainages.

The SNEP GIS team mapped three zones to capture the concepts: (1) a zone of approximately 150 feet (height of one site-potential tree) on each side of all streams to represent the Community Influence Zone and the Energy Influence Zone called the Community/Energy Zone, (2) a zone of variable width that begins approximately 150 feet from the stream, just outside the Community/Energy Zone called the Land Use Influence Zone. This zone is calculated on the basis of modeled stream width and adjacent slope steepness using methodology from Kondolf et al. (1996), and 3) the remainder of the watershed called the Uplands.

On both the Eldorado NF (Figure 6) and Plumas NF, the three zones divide the landscape approximately as follows: 1) Community/Energy Zone (13%), 2) Land Use Influence Zone (34%) and 3) Uplands (53%). Initial tests suggest that the stream layer used by SNEP underestimates the miles of stream that will be found on federal forests. We would expect that field work would result in less acreage in the uplands and more in the other two zones.

Strata

For each land-use zone within each LS/OG polygon, five strata are recognized: vegetative condition (50-60 choices), owners (2), slopes (2), aspects (2), and roaded or unroaded (2). One additional stratum occurs on the Plumas NF: whether the area falls into a fuel treatment zone.

Using GIS, areas that reflect unique intersections of these four land use and five stratum variables (six on the Plumas NF) are identified (nine total variables, 10 on the Plumas NF). The model does not spatially track these variables within the simulation polygons beyond their location in a land use zone in a simulation polygon. Rather, all occurrences of each unique intersection are grouped into a stratum.

Forest Condition In defining forest condition, we used the USDA Forest Service Region 5 forest classification of species type, size class, and percent of crown closure (USDA Forest Service 1994) to develop our vegetation classes. An aerial inventory of the Eldorado NF using this forest classification found approximately 40,000 polygons on federal land. Thus the average size of these stands is approximately 12 acres reflecting the fine scale mosaic of the Sierra Nevada (Figure 7).

We used Forest Inventory Analysis (FIA) plot information for each vegetation class to estimate existing forest condition in terms of a tree list by species and diameter class, and other information. Existing forest conditions are used as the starting point for developing silvicultural prescriptions to reach forest management goals appropriate for the different management strategies (see Cousar, et al. 1996).

Determining LS/OG Rank To determine starting LS/OG rank, we evaluated each vegetation class within each polygon using criteria of number of large trees, canopy closure, and intermediate canopy. We used the "rangewide structural standard" for rank determination of mixed conifer and ponderosa pine types. We used a "normalized structural standard" for red fir and sub alpine types, which modified the rangewide structural standard to account for the attributes of higher elevation forests (See Cousar et al. 1996 for more information).

In our modeling, we estimated LS/OG polygon rank as the acre-weighted average rank across all land types and conditions within the LS/OG polygon:

Polygon = ((Σ Acres * rank)/Total acres in a polygon)
rank all land
classes

We can then compare the LS/OG polygon rank determined by the modeling exercise (Figure 8) to the one created through expert opinion (the "mappers") (Figure 1). We made the comparison on the montane mixed conifer type of the Eldorado NF which contains the preponderance of the forest on the Eldorado and was the focus of the LS/OG mapping there. Both approaches to rank determination used the "rangewide structural standard."

One type of comparison looks at each LS/OG polygon and takes the difference in estimated rank by the two methods. We report this difference below by intervals of .5 for the Eldorado NF. We found on the Eldorado NF that the mapper's estimate exceeded the modeler's estimate by 0.5 to 1.0 rank in 16% of the LS/OG polygons. With perfect correlation, we would expect to find 0.0 difference for all polygons (100% of the polygon differences appearing in the 0.0 to 0.5 interval or the -0.5 to 0.0 interval). With no correlation, we would expect 10% of the polygons appearing in each interval from -5.0 to -4.5 to 4.5 to 5.0. On the Eldorado, we found a curve that might be described as "bell-shaped" centered on the low differences but with tails that go out as far as a difference of 3.0 to 3.5:

Difference (mapper - modeled)	Percentage of polygons
-5.0 to -4.5	0
-4.5 to -4.0	0
-4.0 to -3.5	0
-3.5 to -3.0	1
-3.0 to -2.5	2
-2.5 to- 2.0	4
-2.0 to -1.5	7
-1.5 to -1.0	9
-1.0 to -0.5	13
-0.5 to 0.0	17
0.0 to 0.5	10
0.5 to 1.0	16
1.0 to 1.5	9
1.5 to 2.0	6
2.0 to 2.5	3
2.5 to 3.0	2
3.0 to 3.5	0
3.5 to 4.0	0
4.0 to 4.5	0
4.5 to 5.0	0

In another approach, we can compare the rank estimates by summing the acres assigned to each rank in each exercise. Looking again at the montane mixed conifer type on the Eldorado National Forest, we see the modeled ranks more tightly distributed around the middle than the ranks determined by mappers and lacking ranks 4 and 5:

	Rank					
	0	1	2	3	4	5
	------------------------------thousand acres---------------------------					
Mappers	14	40	140	73	45	2
Modeled	7	33	171	105	0	0

Both approaches to classifying the forests of the Sierra Nevada relative to their LS/OG rank have their limitations. Neither can be seen as the "absolute truth" to be used as a standard of comparison. Obviously, more analysis is needed to understand the reasons for the similarities and differences of the approaches.

Owner groups Owners are grouped into federal and non-federal owners (see any of Figures 1-6). Although forest types are recognized on both federal and non-federal lands, forest management choices are modeled only on federal lands. Non-federal lands, mostly private land, are carried through the analysis for the purpose of reflecting an assumed contribution to watershed disturbance (see Menning, et al. 1996 for more discussion about these assumptions).

Slope Slopes are divided into two classes: 1) less than 40% 2) greater than or equal to 40 percent. Figure 9 shows an exaggerated shade relief map derived from the Eldorado National Forest Digital Elevation Model (DEM). The DEM was analyzed to determine slope and aspect. Slope classifications are recognized to reflect different fire behavior and to reflect different contributions of timber management and roading activities to watershed disturbance. The slope classification is also used to reflect different logging methods.

Aspect Lands are assigned an aspect of northeast or southwest depending upon azimuth. Northeast facing slopes have an azimuth of 315 to 134 degrees and southwest facing slopes have an azimuth of 135 to 314 degrees. Aspect is recognized to reflect different burning conditions due to fuel moisture and temperature. Aspect is also used to reflect different goals for late-successional forests.

Roadless Condition Lands are additionally classified depending on whether they are part of a currently unroaded area of 500 or more acres (Figure 10). This classification permits specification of limits on roads and timber harvest within roadless regions.

Fuel Treatments The Plumas NF has identified areas for fuel treatment with the assistance of the Quincy Library Group. They are continuous areas, often near defensible fuel profile zones (fuel breaks), strategically placed across the landscape. They differ from the fuel breaks in that the harvests are less intense.

Strata Characteristics

The miles of existing road and constructed roads within each stratum are also tracked. This enables the estimation of the amount of road that might be needed to accommodate different activities and to estimate watershed disturbance.

In addition, average distance to edge of the roadless area is recorded for roadless strata. This helps estimate logging cost under options that allows timber harvest, but not roads, in roadless areas.

Number of Strata

Many hundreds of strata can potentially occur in each land-use zone within each LS/OG polygon. Generally, though, each land-use zone within each LS/OG includes only a subset of the possible strata. On the Eldorado, the 620 simulation polygons contain approximately 83,000 strata considering all land-use zones, with more than 80 percent of the strata representing the federal land component. Strata, in turn, are composed of an average of three patches spread across a land use zone in the LS/OG polygon. Thus, average patch size for the Eldorado considering all five land use zones and all five strata layers is about 3 acres.

Fires and their Effects: Ignition, Fuel, Fire Size

Large fires account for most of the area burned in forest fires. Strauss et al. (1989) concluded in a study of several climatic regions of the western United States that the proportion of area burned by the top 1% of the largest fires ranged from 80%-96% of the area burned. In our simulations we model only large fires. Our definition of large fires varied by forest from 1000 acres on the Plumas NF to 3000 acres on the Eldorado NF (Bahro, 1996).

Ignition probabilities for large fires were estimated for each simulation polygon based on ignition history, ratio of large fires to ignitions, and three point estimates of fire size (mean fire) in nine vegetation strata (Sapsis, et al. 1996). Vegetative strata are based on three variables: 1) life form, 2) weather zone, and 3) population density class (Figure 11). These ignition probabilities are used in the SAFE FORESTS model as relative ignition probabilities and weighted to calibrate the model against historical fire data. After the model decides to burn a wildfire (based on weather probabilities) the relative ignition probabilities direct where the fire will be.

Custom fuel models were developed for all the vegetation types (Sapsis, et al. 1996) (Figure 12). Fuels are the energy source for fire. Fuel models are assigned to simulation polygons to estimate potential fire behavior under conditions conducive to large fire occurrence. These estimates of fire behavior—based on fuel model, topography, and weather conditions—drive the effects on forest resources expected to result from large fire occurrence.

Goals for the Analysis

Five goals can explicitly guide the analysis: 1) achieving late-successional forest conditions, 2) controlling watershed disturbance, 3) reducing risk of severe (stand-replacing) fire, 4) producing timber volume, and 5) ensuring a sustainable volume of timber products. In addition, other goals, such as minimizing disturbance to certain strata can be pursued by the types of activities that are allowed.

In each analysis, these goals are specified in hierarchical fashion such that achievement of the higher order goal cannot be compromised by attempting to achieve a lower order goal. As an example, assume that we are interested in the upper riparian zone in the matrix. In some analyses, the primary goal is control of watershed disturbance, the secondary goal is achievement of some late-successional rank, and the tertiary goal is achievement of an even-flow timber harvest. In all cases, the problem is structured such that we try to achieve as much of the secondary goal as possible given that achievement of the primary goal is not compromised and that we try to achieve as much of the tertiary goal as possible given that achievement of the secondary goal is not compromised. Ironically, the optimization problem is stated such that we try to "maximize" (or "minimize") the achievement of the lowest order goal after first achieving specified values for the higher order goals.

Measures of Goal Attainment

Late-successional Goals

Forest structure goals are measured by their contribution to LS/OG rank. This is measured primarily by number of large trees and canopy closure. Goals for westside mixed conifer for different ranks, as an example, are:

LS/OG Rank	Large Tree DBH	Min # Trees per acre	Canopy Closure
	(inches)		(%)
5	>40	10	55
4	>30/>40	12/6	55
3	>30/>40	6/2	40
2	>30/>40	2/2	20
1	>30	0.5	10

Achievement of late-successional goals can be assisted by stand growth, prescribed fire, or certain types of timber harvest. Much of the prescription development that we undertook was aimed at finding ways to accelerate the restoration of late-successional structures in the different types and forest conditions in the Sierra Nevada. Without attention to understory structure and canopy density, however, achievement of high levels of late-successional structural complexity can be associated with high likelihoods of severe fire (Agee 1996, Arno et al. 1996). Therefore attention was paid in prescription development to developing late successional structures that would have had moderate to low levels of basal area consumed with wildfire. This basically involved surface fuel treatment (hazard reduction) in conjunction with selective harvest of small diameter trees. These trees, in addition to being highly sensitive to fire-induced mortality, also constitute a significant portion of hazard by linking fire to the canopy. (Alexander 1988, Weatherspoon and Skinner 1996). Additional details of prescription development can be found in Cousar, et al. 1996.

Watershed Goals

Watershed goals are measured by the percentage of equivalent roaded acres (ERA) by land-use zone. For a discussion of the ERA method, see Menning, et al. (volume 2).

Assessing Initial Watershed Conditions

In our analysis, watershed conditions are controlled by LS/OG polygon. LS/OG polygons are of the appropriate scale (3000-10,000 acres) recommended by Chatoian (1995) for use with the ERA method.

The initial number of equivalent roaded acres (ERA) has five components:

1) ERA from existing roads
2) ERA from previously harvested areas on federal lands
3) ERA from assumed activities on private lands
4) ERA from previous wildfires
5) ERA from grazing activities

ERA from existing roads ERA from existing roads on federal lands is stratified by steep and gentle slopes. Roads on gentle slopes are assumed to contribute 3.6 acres per mile of road. Roads on steeper slopes (40%+) contribute 5.4 acres per mile of road.

Roads on private lands are not explicitly considered, but are lumped into general activity factors for private activity depending upon distance from stream.

ERA from previous harvesting activities All forested strata outside of plantations, roadless and wilderness areas are assumed to have a beginning ERA of 0.05 reflecting past salvage harvest. Young plantations (seedlings) outside of roadless and wilderness areas on gentle slopes are assumed to have a beginning ERA of 0.13 to reflect past ground-based harvesting with mechanical site preparation. Young plantations on steep slopes outside of roadless and wilderness areas are assumed to have a beginning ERA of 0.08 to reflect past cable logging and manual preparation.

The beginning ERA diminishes with time as described by Menning, et al. (1996).

ERA from activities on private lands Activities on private lands are assumed to make a total contribution of 0.1 in near-stream areas (150 ft) each side of streams and 0.2 on all other lands. This ERA figure assumes the lands are well-roaded, with frequent re-entries and mechanical site preparation.

ERA from previous wildfires Previous wildfires which have been artificially regenerated and classified as plantations are treated as discussed above. Forest types currently classified as non-stocked are assumed to be of fire origin and are assigned an ERA equal to the weighted first decade ERA contribution of stand terminating fire. Areas with seedlings in roadless and wilderness areas are assumed to have a beginning ERA of .075 from stand terminating fire in the past 10 years. Sapling stands in roadless and wilderness areas are assumed to have a beginning ERA of .025 from stand terminating fire in the past 20 years.The beginning ERA diminishes with time as described by Menning, et al. (1996).

ERA from grazing activities All federal lands in near-stream areas on gentle slopes with plantations are assumed to be grazed with an ERA contribution of 0.02 acres per acres. The 0.02 reflects a weighting to combine heavier use within the first 75 feet of the stream and less use in the rest of the zone.

Assessing Future Watershed Conditions

The contribution of future activities to watershed health (ERA) has seven components:

1) ERA from new roads
2) ERA from newly harvested areas
3) ERA from non-harvest mechanical fuel treatments
4) ERA from prescribed burning
5) ERA from wild fire
6) ERA from managed wildfire
7) ERA from new grazing areas

ERA from new roads If the road density in any polygon substratum exceeds four miles per square mile it is assumed that an adequate road system exists for timber harvest. If the existing road density is less than four miles per square mile and timber harvest is simulated, then additional miles of road are constructed to reach four miles per square mile. The only exceptions are in near-stream riparian zones and in roadless areas. In these two zones, ground-based systems are not used. Any timber harvest in a near-stream zone is assumed to be by skyline. In roadless areas, any timber harvest is assumed to be by helicopter. Treatment costs and ERA effects are adjusted appropriately.

ERA from wildfire ERA from wildfire is assigned by percent of basal area burned and slope. The ERA factors are derived from the Eldorado ERA handbook (Menning et al. 1996)

We control activities in the different land use zones to stay within the limits on ERA levels there. We do not, however, react to the limits by changing the proposed activity to one that accomplishes the objective but at lower impact. An example of this substitution would be to substitute intermediate support skyline for tractor logging. Because of the significant effect that watershed controls can have on pursuit of late-successional or fuel reduction goals (i.e., the model results indicate that solutions are often ERA limited), such substitution should be looked into.

Potential Damage From Severe Fire

Potential damage from extreme weather wildfire is measured by percent of basal area which would be killed if a fire should occur. Flame lengths greater than 6 feet in stands with greater than 70 percent canopy closure are assumed to kill all trees in the stand. Flame lengths less than 6 feet with ladder fuels in stands with greater than 70 percent canopy closure are also assumed to kill all trees in the stand (Cousar et al., 1996). Fire occurring under other conditions may kill all or part of a stand. For these conditions, the basal area which would die was derived by Bahro (1995) using the USDA Forest Service First Order Fire Effects Model (FOFEM) as a function of flame length, scorch height, dbh, and species. The flame length is based upon extreme weather assumptions developed by Bahro, forest personnel, and park personnel and the fuel loading under a management prescription (Bahro 1996, Sapsis et al. 1996).

We generally assume a fire that kills more than 60 percent of the basal area in a stand destroys the stand. Reducing the percent of basal area that will be killed in extreme wildfire can be done through prescribed fire and certain kinds of timber harvest. Fuel treatments through timber harvest, though, can retard achievement of late successional goals or cause excessive ERA values. Thus, the treatments are often limited by pursuit of other goals. To some degree, prescribed fire can be substituted for commercial harvest, but more treatments and years are needed to reduce the hazard.

Risk of severe fire in ALSE polygons is measured additionally by the percent of mixed conifer and ponderosa pine in the large size, high crown closure stands which undergo stand-terminating fire by ALSE cluster during a five-decade simulation. ALSE clusters are specific groups of contiguous ALSE polygons designed to promote redundancy (high chance of survivability) of high rank conditions in specific forest areas. As with the forest in general, prescribed fire and timber harvest, alone or in combination, can reduce the risk of severe fire here.

Sustainable Timber Harvest

The highest sustainable timber harvest for fifty years, compatible with watershed disturbance limits and late-successional target, can be specified as a goal. A wide variety of intensities and timing of harvest is available to help find the highest sustainable level given other goals. The highest sustainable level is calculated before wildfires occur. Stands that burn severely before their scheduled harvest are deducted from the estimated sustainable level.

Salvage after wildfire occurs if it is consistent with overall goals. Thus, the timber harvest volume available for any period is the sum of two components: 1) "green" timber harvest associated with the estimation of a sustainable timber harvest for fifty years, with the resulting level for a period reduced for stands scheduled for harvest in the period that burn severely, and 2) salvage timber harvest associated with reaction to wildfire. Thus, the overall expected harvest for a period can vary somewhat depending on the extent of severe fires.

Activities and their Effects

As discussed above, two general types of human intervention (activities) can be used to meet stated goals on the national forests: (1) timber harvest, and (2) prescribed fire. Depending upon topography, mechanical fuel reduction can be combined with timber harvest. Also, two types of activities are available to meet goals on the National Parks: 1) management of wildfire and 2) prescribed fire. Undisturbed growth is also considered a possible "activity." The development of prescriptions which can be used to meet the goals of an analysis are described in Cousar, et al.(1996).

Each activity is represented in the SAFE FORESTS model by its decadal contribution to forest structure (LS/OG rank), contribution to watershed disturbance (ERA), its flame length, and its contribution to timber production (board feet harvested). Activities are strung together for five periods to form what we call a "prescription." An example is shown below for two prescriptions in the mixed conifer strata with existing vegetative condition M3G on a gentle slope with a southwest aspect which had previous salvage harvesting: (1) let the forest grow without intervention "NNNNN" and (2) active vegetative management to maintain the forest structure at LS/OG rank 3, reduce the potential for severe wildlife, and provide timber harvest volume. This prescription consists of entries each 20 years (H) coupled with mechanical fuel reduction and prescribed burning in intervening periods (P):

Activity Name		“NNNNN”	“HPHPH”
LS/OG Rank			
Period	1	3	3
	2	4	4
	3	4	4
	4	4	3
	5	4	4
ERA			
Period	1	.08	.16
	2	.08	.13
	3	.08	.20
	4	.08	.13
	5	.08	.29
Harvest			
Period	1	0	6.2
	2	0	0
	3	0	10.7
	4	0	0
	5	0	26.3
Flame Length			
Period	1	3.7	3.7
	2	4.7	4.7
	3	5.7	2.7
	4	6.7	3.7
	5	7.7	2.0
Fire Hazard Index			
Period	1	99	99
	2	99	95
	3	99	15
	4	99	12
	5	99	15

Silvicultural Methods Employed

We have modeled all harvests, other than fire salvage, as individual tree selection. Each stratum is represented by a list of trees with different species, sizes, and characteristics. This list is compared to the desired condition, based on the goals of the alternative, to decide whether certain trees need to be removed. Even-aged regeneration harvest, such as shelterwood and clearcut harvest, in which the entire overstory is removed over a relatively brief period of time is not considered (except for fire salvage). Rather, all harvests retain a significant portion of the trees in the stratum after treatment.

We took this approach for two reasons. First, we used the work by Helms and Tappeiner (1995, 1996) done for SNEP that summarizes the state of silvicultural knowledge of Sierra Nevadan forests. They based this summary on a series of reports that they commissioned that summarized what has been learned from long-term studies of silvicultural treatments in the Sierra Nevada including studies from the University of California's Blodgett Forest Research Station (Olson and Helms 1996), Blacks Mountain, Swain Mountain (red fir type), Laacke and Tappeiner (1996), and Challenge Experimental Forest. Also they commissioned a study of stand density treatments and results (Oliver, et al. 1996). Helms and Tappeiner (1995, 1996) summarize the results from applying silvicultural methods of single tree selection, group selection, shelterwood, seed tree, and clearcutting with an emphasis on the mixed conifer type for which there is the most knowledge and to a lesser degree the red fir type. They state: "The major lessons learned from long-term studies on experimental forests are that Sierran forests of moderate to high site quality are capable of maintaining a high level of stocking and growth rate while at the same time sustaining a substantial harvest, if protected from catastrophic wildlife. Furthermore, these harvests would assist in preventing stands from losing vigor and becoming unhealthy due to excessive stocking. All silvicultural methods were shown to be similar in terms of their influence on growth and productivity (Helms and Tappeiner 1995, p. iv)."

We realize that, in practice, a combination of individual tree selection and group selection will be used depending on the distribution of the trees across the landscape. We do not, though, simulate even-aged regeneration harvest with removal of the overstory over a relatively brief period associated with establishment of the next stands except in the case of severe fire where stand replanting would be expected.

Second, we simulate individual tree selection because it enables us to address achievement of the late-successional goals associated with most alternatives. These goals call for a continuous presence of large trees across the landscape, to varying degrees, except for where fire has killed them (Franklin and Fites-Kaufmann 1996).

In our analyses, we rely on occasional waves of natural regeneration to replenished the supply of small trees (see Cousar, et al. 1996 for more discussion). Helms and Tappeiner (1995) express some concerns in relying solely on this approach. "Prompt natural regeneration of all species is sometimes adequate providing sufficient bare mineral soil is available for a seed bed. However, due to periodicity of seed crops and depredation by rodents and insects, it is often desirable to supplement natural regeneration with planting. Competing vegetation commonly needs to be treated in order to allow conifer regeneration to become rapidly established (Helms and Tappeiner 1995, p. iv)." Thus, as noted below, we may be underestimating the capital that will be needed to ensure adequate regeneration.

Stages in the SAFE FOREST Model

We have built a four-stage forest-level model to analyze the implications of different policies and objectives for managing the federal lands of the Sierra Nevada (Figure 13):

1) The first stage uses a Model I formulation for each ALSE polygon to maximize the achievement of LS/OG rank within the polygon subject to goals on watershed disturbance given the permitted activities.
2) The second stage uses a Model I formulation for the remainder of the forest (all non-ALSE LS/OG polygons) which sets goals for LS/OG rank and watershed disturbance for each LS/OG polygon and goals for timber harvest level (even-flow) over time for the entire forest. The timber harvest level includes the results from the first stage analysis. Subject to achieving these goals, the second stage maximizes timber harvest from the forest given the permitted activities.
3) The third stage simulates the stochastic application of fire to the forest for five decades. We assume that the planned schedule of activities, forest growth, and effects from stages one and two will occur. We then simulate the size, distribution, and intensity of wildfires for the forest for a series of randomly selected weather streams, with a weather stream identifying the distribution of weather between normal and extreme in each period.
4) Finally, we incorporate the implications of these fires for the actions on the forests, outputs, and effects. The effects of fire depend on the stand condition when the fire occurs. Salvage occurs when permitted. Then, the prescribed activities from the first two stages are adjusted to take the "next best" activities given that a fire has occurred. That is, in each burned strata, a substitute prescription is chosen which maintains the same pre-fire activities as the original prescription, but considers the fire effects over the decades remaining in the planning horizon. Both

in-strata and cumulative LS/OG polygon effects are considered in the post-fire prescription choice.

Modifying the prescriptions after a fire involves substituting a Model I vector (column) of activities which maintains the pre-fire activities while changing the post-fire activities to meet the goals of the prescription given that a fire has occurred. Following a fire, and evaluation of fire effects on forest structure, SAFE FORESTS draws from among a large number of pre-generated strata level prescriptions which represent pathways to strata level forest structure goals given that either a human-caused or natural disturbance occurs. The prescription chosen must maintain the emphasis (structure goal for the strata) and recognize the watershed goals for the LS/OG polygon. See Cousar et al. (1996) for additional details on the goal-oriented strata level prescription development used here.

Mathematical Formulations

Mathematical formulations used in the first two stages are:

First StageStage

Objective (for each ALSE polygon):

maximize the sum of the ranks for all strata in the polygon

$$\text{Max} \sum_{z=1}^{Z} \sum_{s=1}^{S_z} \sum_{p=1}^{P_s} \sum_{t=1}^{T} R_{zspt}\, x_{zsp}$$

subject to:
Input constraints

$$\sum_{p=1}^{P_s} x_{zsp} = \text{Area } s$$

$$\text{For } s = 1\ldots.,S_z, \quad z = 1,\ldots Z$$

$$x_{zsp} \geq 0 \qquad z,\ s,\ p$$

Entirely allocate each stratum to one timing choice in one prescription for the five periods

$$\sum_{p=1}^{P_s} u_{zsp} = 1 \qquad U = 0,1$$

$$\sum_{p=1}^{P_s} A_{zsp}\, u_{zsp} = x_{zsp}$$

$$\text{For } s = 1\ldots.,S_z, \quad z = 1,\ldots Z$$

Policy constraints

1) Do not exceed the ERA goal in any of the three ones defined in relation to the stream

$$\sum_{s=1}^{S_z} \sum_{p=1}^{P_s} E_{zspt}\, x_{zsp} \leq ERAMAX_z \qquad z=1\text{-}3$$

2) Evenflow of timber harvest

a) Accounting rows (for later use)

$$\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{p=1}^{P_s} V_{zspt}\, x_{zsp} - H_t = 0 \quad t=1,\ldots.,T$$

Also only allow prescriptions that display a rank from period to period that does not decline (nondeclining rank) and that reach a final rank of some specified level

where:

x_{zsp} = acres of prescription p of analysis area (strata) s of land use zone z.

R_{zspt} = LS/OG rank in period t of prescription p of analysis area s of zone z.

E_{zspt} = contribution to ERA in period t of prescription p of analysis area s of zone z

V_{zspt} = timber harvest volume in period t of prescription p of analysis area s of zone z

S_z = number of analysis areas in zone z

Z = number of zones in the LS/OG polygon

P_s = number of prescriptions for analysis area s

$Area_s$ = size of analysis area s, in acres

H_t = timber harvest volume in period t

Second Stage

Objective function:

maximize the timber harvest in all non-ALSE LS/OG polygons

$$\sum_{k=K+1}^{M} \sum_{z=1}^{Z_m} \sum_{s=1}^{S_z} \sum_{p=1}^{P_s} V_{kzspt}\, x_{kzsp}$$

subject to:

Input constraints

$$\sum_{P=1}^{Ps} x_{kzsp} = \text{Area } s$$

For s = 1....,S_z, z = 1,...Z_m, k= k+1,...M

$x_{zsp} \geq 0$ z, s, p

Entirely allocate each strata to one timing choice in one prescription for the five periods

$$\sum_{p=1}^{P_s} u_{kzsp} = 1 \quad U = 0,1$$

$$\sum_{p=1}^{P_s} A_{kzsp}\, u_{kzsp} = x_{kzsp}$$

For s = 1....,S_z, z = 1,...Z_m, m=1....M

Policy constraints

1) Do not exceed the ERA goal in any of the three zones defined in relation to the stream in each LS/OG polygon

$$\sum_{s=1}^{S_z} \sum_{p=1}^{P_s} E_{kzspt}\, x_{kzsp} \leq ERAMAX_{kz}$$

For z = 1,...Z_{km}, k=k+1....M

2) Evenflow of timber harvest

a) Accounting rows

$$\sum_{k=K+1}^{M} \sum_{z=1}^{Z_m} \sum_{s=1}^{S_z} \sum_{p=1}^{P_s} V_{kzspt}\, z_{kzsp} - U_t = 0$$

for t = 1,...,T

b) Even flow constraint

$$\sum_{k=1}^{K} H_{kt} + U_t - \sum_{k=1}^{K} H_{kt-1} - U_{t-1} = 0 \qquad t = 2,\ldots,T$$

3) Allow only prescriptions that meet some specified rank in each period

where:

x_{kzsp} = acres of prescription p of analysis area (strata) s of land use zone z of LS/OG polygon k.

R_{kzspt} = LS/OG rank in period t of prescription p of analysis area s of zone z of LS/OG polygon k.

E_{kzspt} = ERA contribution in period t prescription p of analysis area s of zone z of LS/OG polygon k.

V_{kzspt} = timber harvest volume in period t from prescription p of analysis area s of zone z of LS/OG polygon k

S_{kz} = number of analysis areas in zone z of LS/OG polygon k

Z_k = number of zones in LS/OG polygon k

P_s = number of prescriptions for analysis area s

L_t = total timber harvest volume from produced in period t from all ALSEs

$Area_s$ = size of analysis area s, in acres

H_{kt} = timber harvest volume in period t from ALSE polygon k

K = number of ALSE polygons

U_t = total harvest in period t from all nonALSE polygons

M = total number of LS/OG polygons

Problem Size

As discussed above, we represented the first two stages as Model I formulations of forest activity scheduling problems. Problem size for the Eldorado NF and Plumas NF was approximately as follows:

Stage 1 Plumas	Eldorado	
Number of linear models (no. of ALSE polygons)	52	53
No. of analysis areas(AA) per model	200	500
No. of prescription choices/AA	1-135*	1-135*
Number of policy constraints per model		
a. ERA	15	15

(Note: ensuring NDY of rank and ending rank was done by limiting the prescriptions that could be employed; * number of choices depends upon policy analyzed)

Stage 2	Eldorado	Plumas
Number of linear models	1	1
Num. of analysis areas	26,000	80,000
Num of prescription choices	1-700*	1-700*
Num. of policy constraints		
a. ERA (3/LS/OG/period)	1800	2400
b. NDY	5	5

(Note: ensuring that needed ranks are achieved is done through selection of permitted activities; *=number of choices depends upon policy analyzed)

Usually, linear programming is used to solve these formulations. We did not do that; rather, we developed a heuristic to enable rapid solutions for policy analysis (less than an hour to solve both stages for a forest).

Solution Methodology

A heuristic is used to assign activities to each strata of each land-use zone of each polygon to reach goals for the administrative unit. Only activities on federal land are simulated.

The solution procedure has four stages:

1) Assignment of activities to strata in ALSE polygons in the absence of fire (Figure 14).
2) Assignment of activities to strata in the nonALSE polygons in the absence of fire (Figure 15).
3) Simulation of fire (Figure 16)
4) Simulated management response to fire (Figure 17).

The heuristic has similarities to binary search in that strata are ordered in terms of priority for treatment. It improves on binary search, and has similarities to the approach used by Hogason and Rose (1984), in that it allows for consideration of multiple prescriptions for each strata instead of only one for each strata as done in binary search.

First and Second Stages

The first stage applies to each ALSE polygon. All strata are given an initial prescription of NOACTION. Rank is maximized subject to ERA limits. Prescriptions considered are limited to those that will satisfy certain tests for rank. Each of three zones that relate to distance from stream have a single limit on ERA; thus each strata has only one ERA limit in each period. All periods are considered simultaneously to stay within ERA controls over time. Given the order of consideration for the strata, prescriptions are identified that maximize rank, that is, reach the desired rank earlier than any other candidate prescription while not exceeding the cumulative ERA limit for the land zone of the ALSE polygon in any period. If more than one prescription can achieve the desired rank at the earliest time, the prescription which has the lowest average ERA is chosen.

The second stage applies to the nonALSE polygons, in terms of selection of activities, and to the entire forest in terms of the harvest flow goal. All nonALSE polygons are given an initial prescription of NOACTION. As with the ALSE polygons, each of three land zones that relate to distance from stream have a single limit on ERA and all periods are considered simultaneously to control on ERA.

Given the order of consideration for the strata, prescriptions are selected which meet LS/OG goals, any other limits on permitted activities and make the largest contribution to providing harvest in those periods that have lower than average harvest while not exceeding the ERA in any period. In the event of a tie, the prescription which has the lowest average contribution to ERA for the strata is chosen. Aggregate harvest is then updated and the calculations move to the next strata.

This heuristic uses binary search with an embedded gradient subsearch. The analysis begins with the existing forest structure and known condition of each watershed. The strata are ordered within each LS/OG polygon, land class, veg strata, aspect, and slope class. To guide the gradient subsearch toward a sustainable harvest flow, a forest wide objective function of minimizing decadal deviations from a trial decadal harvest volume is specified.

```
Specify trial decadal timber harvest volume:

For LS/OG polygon = Alse to NonAlse
 For aspect = south to north
  For slope = flat to steep
    For landclass = uplands to near stream
        For veg type = first to last
          For activity = first to last

           If polygon is ALSE polygon then

            identify contribution this activity would make
           to ALSE goal for strata while not exceeding
           watershed goal for landclass
           If polygon is not ALSE

           identify the maximum contribution this
           activity would make to reducing deviations to
           trial sustainable timber production goal while
           meeting LS/OG goal and not exceeding
           watershed goal for land class

           Next activity

           Update solution by allocating best activity to
           entire strata (0/1)

       Next veg type
     Next landclass
   Next slope
  Next aspect
Next LS/OG polygon
```

If trial volume not sustainable, then reduce trial volume and repeat procedure. If volume sustainable, increase trial volume and repeat procedure.

These procedures are not guaranteed to find the solution that yields the highest value of the objective function given the constraints, as does linear programming. We have not systematically compared these solutions to those that would result from using linear programming as the solution technique. In early use of the model, however, we did take a second pass through the strata to see whether the solution could be improved with little effect. A positive feature of the model is that the solution is closely tied to the ground through the large number of polygons, spatially defined riparian land classes within polygons, and slope and aspect classes. Experience with management plans developed with more coarse land stratifications indicated as much as a 30% deviation between the linear programming solution and the actual harvest plan.

The priorities for consideration of different strata recognize a number of objectives. In terms of slope and steepness, the priority generally is south flat, north flat, south steep, north steep. These priorities reflect both cost of treatment and risk of fire. The priority for treatment of the major species groups are mixed conifer, ponderosa pine, red fir, and hardwood. Alpine receives only the NO ACTION prescription.

Third and Fourth Stages -- Fire Simulation

A sequential approach has been taken to simulate the occurrence, extent and effects of fire. Following assignment of activities, fire ignitions occur based upon historical probabilities within polygons and spread into contiguous areas.

Fire effects are then estimated using the vegetation structure and composition in each strata at the time of the fire along with the topographic variables of slope and aspect. The simulations are then repeated a number of times to obtain an estimate of the variability of the outcomes.

The solution from part 1 is then subjected to a set of weather streams, fire ignitions, and fire spread. The fire effects are calculated and management reaction is simulated.

The fire simulation procedure is:

```
For decade = first to last
  For year = 1 to 10
    For subpolygon = first to last

      IF this is an extreme weather year

                 test random number against probability of
a large fire starting under extreme weather conditions
in this polygon

     IF this is a normal year

          test random number against probability of a
          large fire starting under extreme weather
          conditions in this polygon

     IF fire starts then

          IF polygon has already burned in this period do
          not reburn
```

identify fire size from a list of historical fire sizes for administrative unit using frequency distribution of historical fire sizes

grow fire by burning entire polygon fire starts in

update veg status for burned strata by selecting new activity which maintains management emphasis for that veg type given that a fire has occurred.

IF ERA for LS/OG polygon is not exceeded, then salvage

IF ERA for LS/OG polygon is exceeded, postpone green harvest for other strata while maintaining same
management emphasis

IF fire has not reached target fire size, spread fire to adjacent polygon according to prevailing winds for that area (administrative unit or subunit).

IF adjacent polygon is a fuel break then calculate average weighted flame length for strata in burned polygon and average weighted flame for strata in fuel break

test random number against probability of fire crossing fuel break given approaching flame length and fuel break flame length

IF random number less than probability of crossing fuel break then burn fuel break and fire stops

Update polygon veg type

IF fire has not reached target fire size, spread fire to adjacent polygon according to prevailing winds for that area (administrative unit or subunit).

Next subpolygon
Next year
Next decade

See Bahro (1996) for specific coefficients used in modeling fire behavior.

An Example of SAFE FOREST Analyses

In our analysis of management options for the federal forests of the Sierra Nevada, we are examining a number of different strategies. We show here the results of one simulation for one management strategy for the Eldorado NF: actively manage the forest using prescribed fire, fire breaks, and timber harvest in both the ALSEs and matrix to achieve a high late-successional rank for late-successional forests in the ALSEs and a mid late successional rank in the matrix; reduce fire hazard; limit watershed impacts in the near-stream, stream influence (midslope), and uplands zones; and produce a sustainable timber harvest. We chose this strategy because it illustrates the full use of management tools and policy goals.

We will focus here on five aspects of the analysis for the Eldorado NF: 1) LS/OG rank, 2) potential for severe fire, 3) fires during the simulation periods and their effects, 4) ERA levels, and 5) timber harvest levels. We show the spatial distribution over time of LS/OG rank, potential for severe fire, and fires during the simulation periods.

All information is available for the entire forest and also for the two major components (ALSEs and matrix).

LS/OG Rank

In this alternative, LS/OG rank increases over time, especially in mixed conifer polygons (Figures 18-19 and Tables 1-3). Tabular information is provided on LS/OG rank in a number of ways: 1) average rank by forest type and period (Table 1), 2) average rank by forest type, land allocation, and period (Table 2), and 3) distribution of each type among different ranks by period (Table 3). The distribution of each type among different ranks is especially valuable as a guide to how activities and fires affect the production of high, medium, and low ranks.

The maps show rank by LS/OG polygon based on the area weighted average of different strata within the polygon. The tables show ranks for the strata in different forest types ignoring nonforest, i.e., the tabular information is one source of the LS/OG polygon ranks along with nonforest elements. Thus, the map for the first period shows no rank 4 and 5 mixed conifer polygons while the tables show that 27% of mixed conifer in the first period is rank 4.

From period to period, the rank can decline even if the objective is to increase rank. This is mainly due to the destructive influence of wildfire.

Potential for severe fire

The potential for severe fire is measured through the proportion of the basal area in a stand that would be killed if the stand burned under severe weather. By this measure, potential for severe fire decreases significantly over time, especially in the mixed conifer polygons (Figures 20-21). Tabular information partitions each forest type in each period among classes reflecting different amounts of basal area damage if the stand burns and also breaks this information down by LS/OG rank for mixed conifer (Tables 4-5). We consider severe damage to occur if more than 60% of the stand basal area is killed by fire. By this measure, mixed conifer decreases from 68% having the potential for severe damage in period 1 to 12% in period 5. Looking at rank 4 mixed conifer, the amount of it increases from 35,000 acres in period 1 to 51,000 acres in period 5 while the proportion of rank 4 that would burn severely decreases from 100% in period 1 to 16% in period 5. In sum, the policy scenario involving significant hazard reduction measures appears to result in greater fire resiliency over time.

Fires during the simulation period

The amount and location of fire varies over the five periods (Figures 22-23 and Table 6).

Tabular information is given for the amount burned by severity class in each type in each period (Table 7) and the amount burned by severity class in each LS/OG rank in mixed conifer in each period (Table 8). Over time, the proportion of the fire acreage that burns severely declines sharply.

The amount of severe fire in ALSE polygons is measured additionally by the percent of mixed conifer and ponderosa pine in the large size, high crown closure stands which undergo stand-terminating fire by ALSE cluster during the five decades. ALSE clusters are specific groups of contiguous ALSE polygons designed to promote redundancy (high chance of survivability) of high rank conditions in specific forest areas.

The frequency with which various LS/OG polygons burned during the next 50 years can be tabulated from the 10 simulations run for each management strategy. As expected, the lower elevation polygons have a much higher-than-average frequency of burning (McKelvey and Bussey, 1996).

ERA levels

ERA levels over time are reported separately for the three different stream influence zones for both ownerships together and for public and private components individually (Table 9). In this analysis, zone 1 was limited to .10, while zones 2 and 3 were not constrained. The ERA for zone 1 stayed roughly constant over time while that of zones 2 and 3 gradually rose over time.

Timber harvest

Timber harvest is composed of "green" volume from planned activities and salvage volume from fire salvage activities (Table 10).

Other reports

We create a number of other periodic reports:

1) Flame length potential by forest type
2) Flame length potential for mixed conifer by LS/OG rank
3) Flame length of mixed conifer of each LS/OG rank that burned
4) Acres of prescribed burn by forest type
5) Distribution of forest types among different Wildlife Habitat Relationship categories
6) Acres of different habitat quality (poor, medium, good) for 20 wildlife species.
7) Distribution of forest acres among categories reflecting different numbers of trees over 30".
8) Gross value, cost, and net value of the harvest over time by type of harvest (selection, salvage)
9) Inventory volume by species in different DBH classes for the mixed conifer types
10) Harvest volume by species in different DBH classes for the mixed conifer types

A summary report is also available which shows the number of harvest entries over 50 years in each land allocation in each forest type.

Future Development

The SAFE FORESTS model should be considered a work in progress. Improvements could be made in almost all areas. The spatial incorporation of wildfire has been a central part of this model. Improved ways of distributing fire on the landscape should undoubtedly be made. More explicit spatial recognition of the strata within polygons may be required.

There has been no linkage between suppression effort and fire size. Although cumulative effects of wildfire on watershed disturbance and forest stocks of both live and dead wood are tracked, the financial costs of wildfire suppression are not addressed so tradeoffs between presuppression efforts, suppression efforts, and forest condition cannot be made.

An attempt has been made to recognize weather as a major driver in natural disturbance. But, although normal and extreme weather years are generated during simulations, the ignition frequency probabilities have been assumed constant with time and fuel conditions associated with weather do not specifically recognize the cumulative effects of multi-year drought on tree stress, insect cycles, and the dynamics of forest mortality. There has been no accounting of forest smoke from both presuppression and suppression activities to gauge the effectiveness of management activities.

The development of the SAFE FORESTS model has concentrated upon forest structure, fire hazard, watershed condition, and timber output as measures of ecosystem health and sustainability. Explicit relationships between these measures of ecosystem condition and performance and wildlife remain to be incorporated. Additional development will be needed if spatial relationships between types of wildlife habitat are desired.

In summary, numerous useful improvements could be made. The efforts in this study should be considered an initial attempt.

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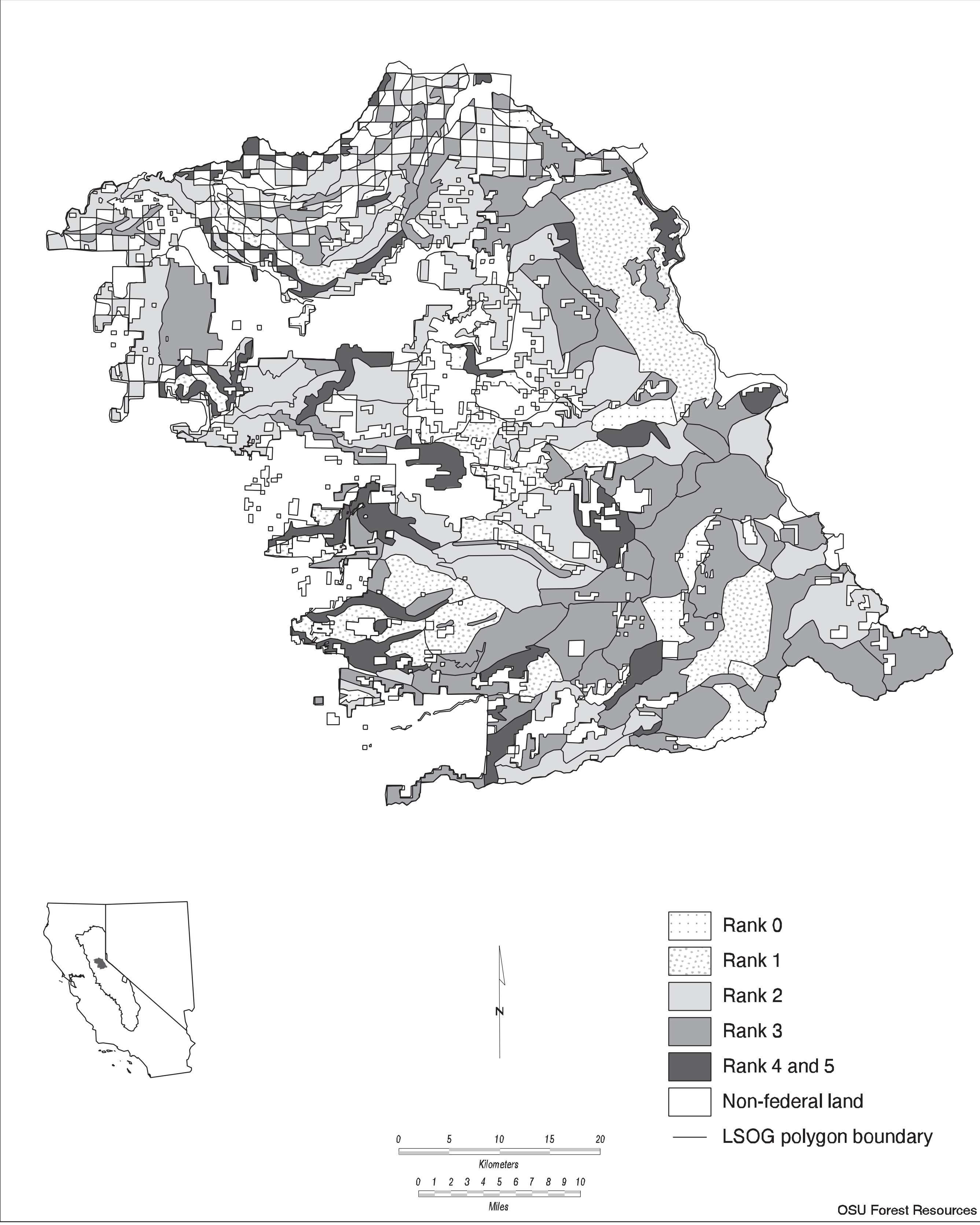

Figure 1

LS/OG polygons ranked by local experts as to their degree of LS/OG structural complexity and contribution to late successional forest function (rangewide structural standard).

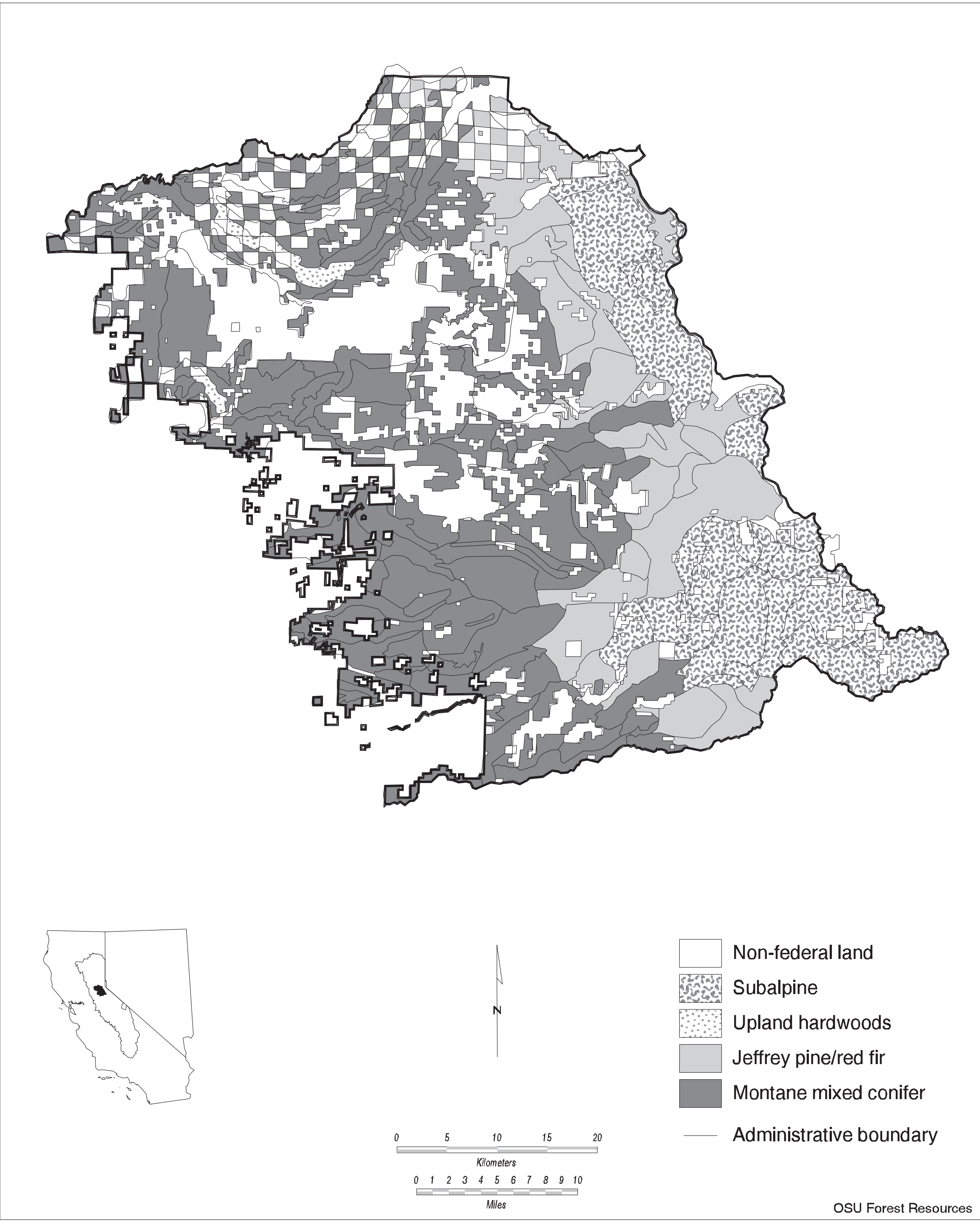

Figure 2

Eldorado National Forest: forest types used in the LS/OG mapping.

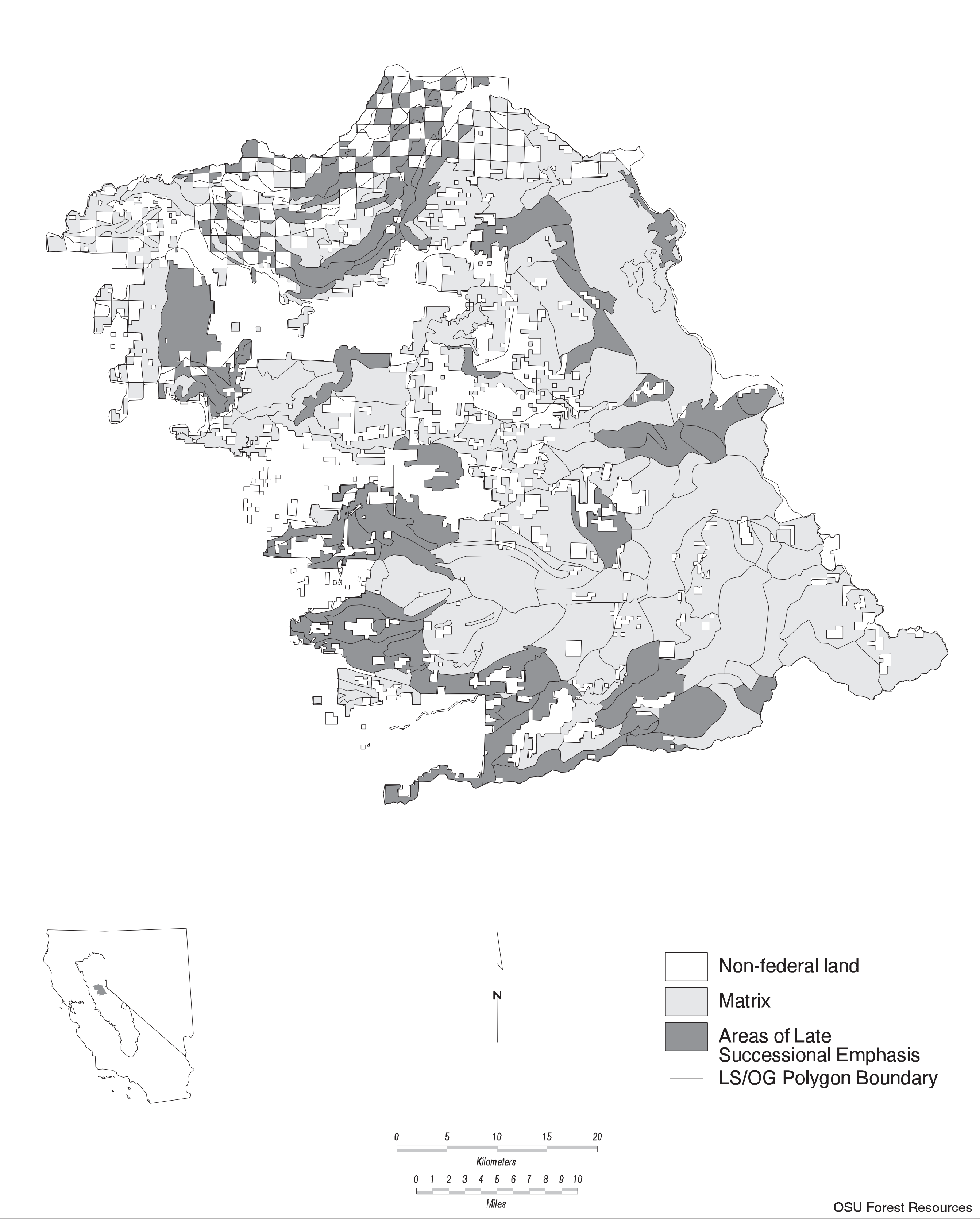

Figure 3

Eldorado National Forest: Areas of Late Successional Emphasis (ALSE).

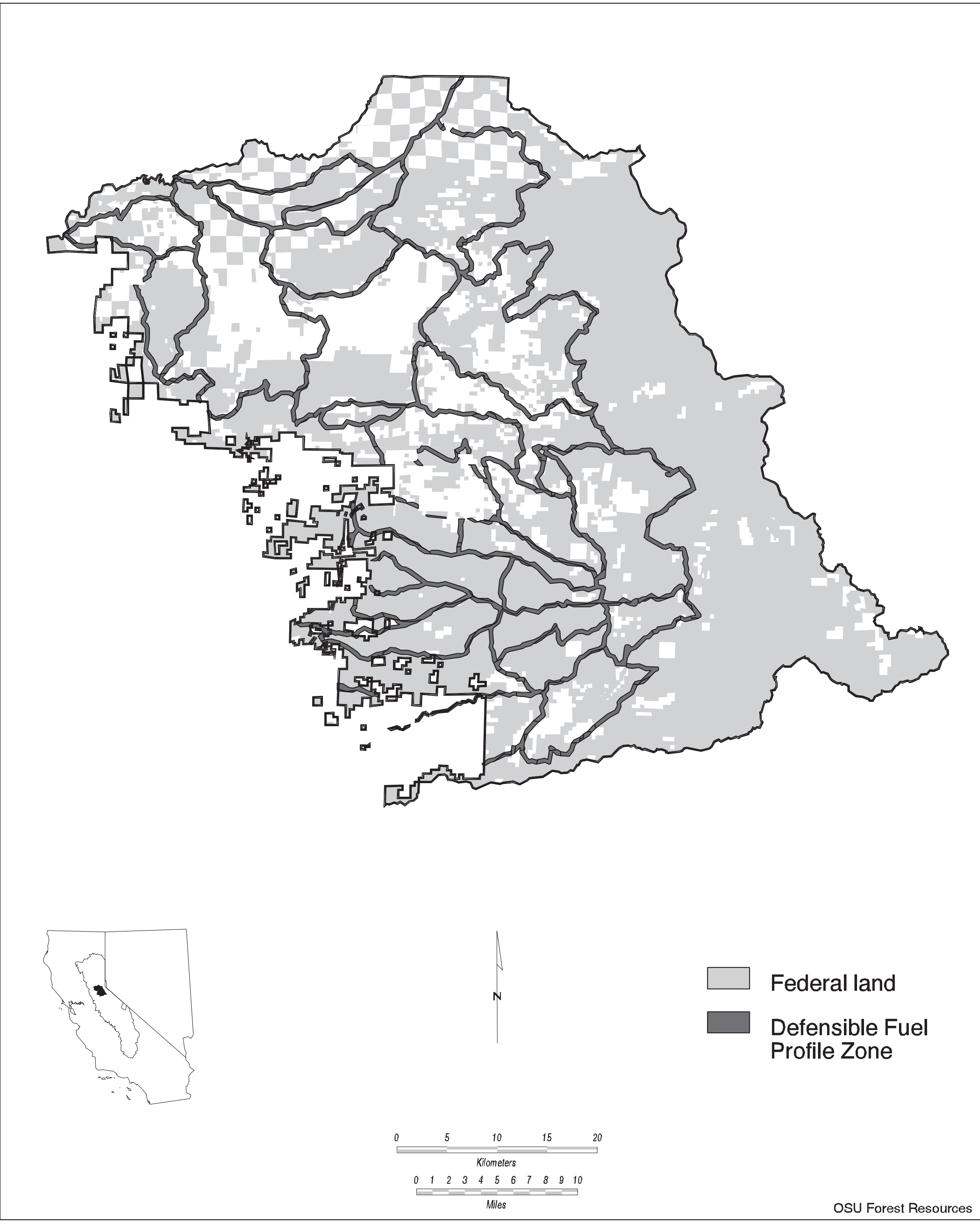

Figure 4

Eldorado National Forest: defensible fuel profile zones (Fuel Breaks).

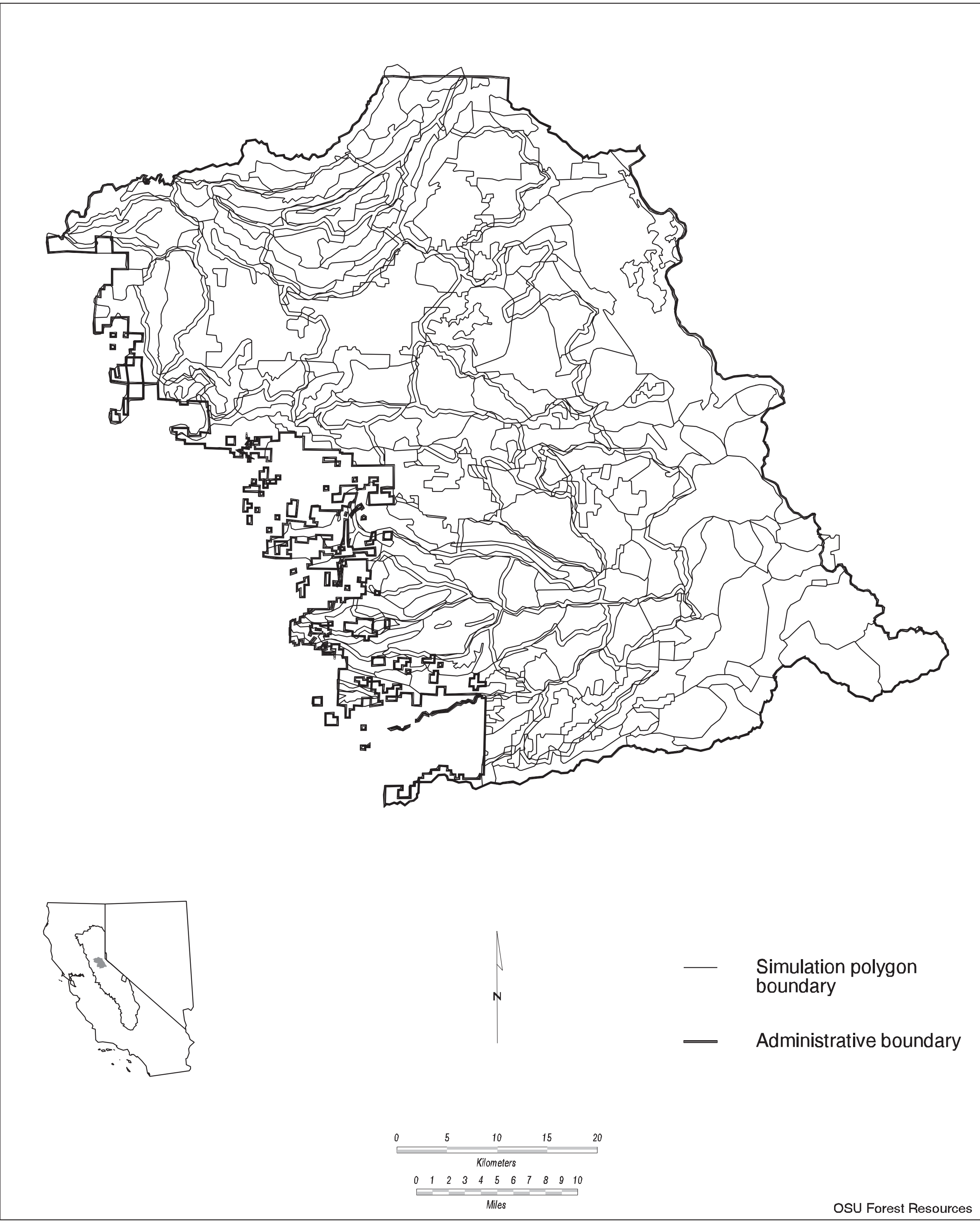

Figure 5

Eldorado National Forest: simulation polygon boundaries.

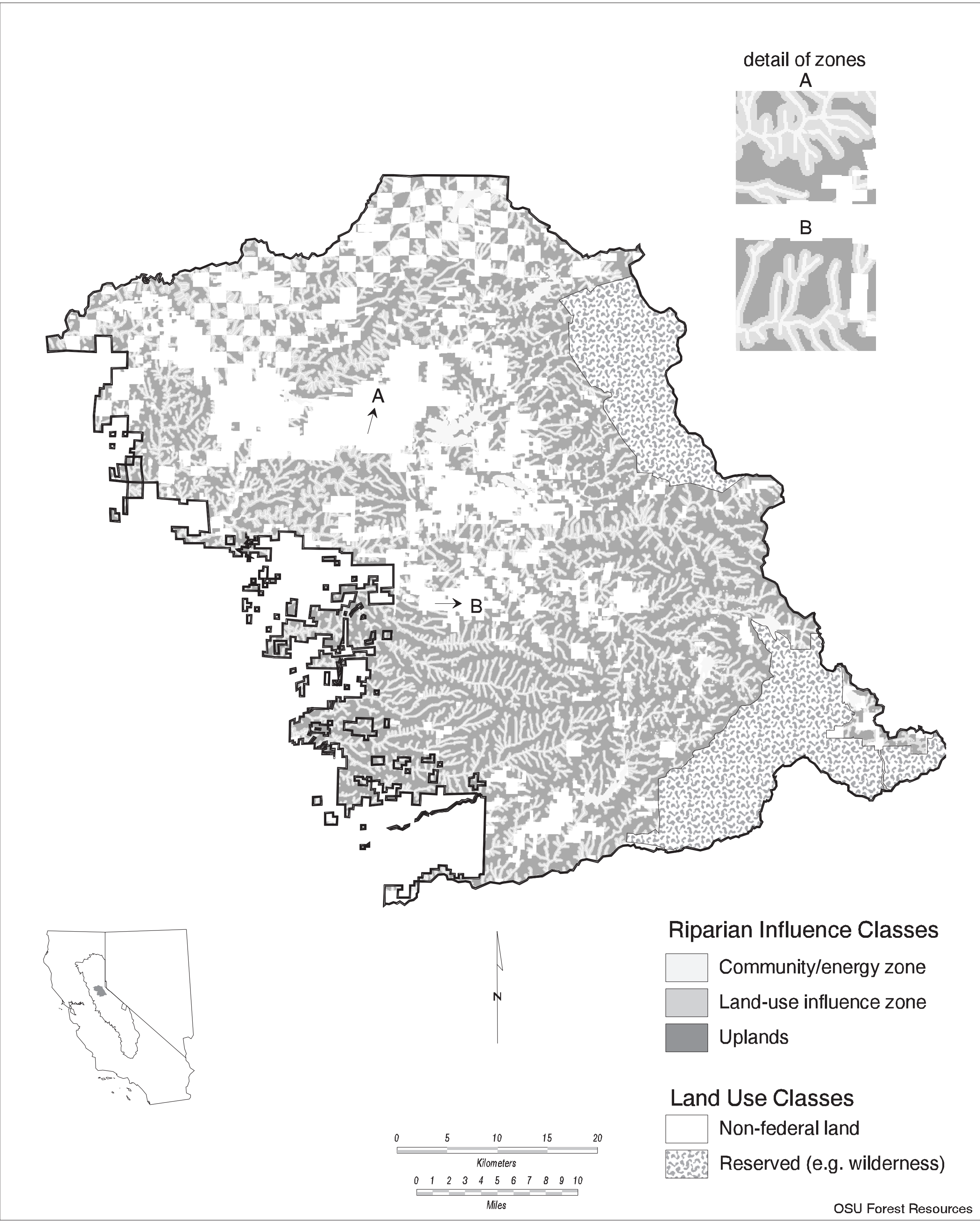

Figure 6

Eldorado National Forest: riparian influence zones.

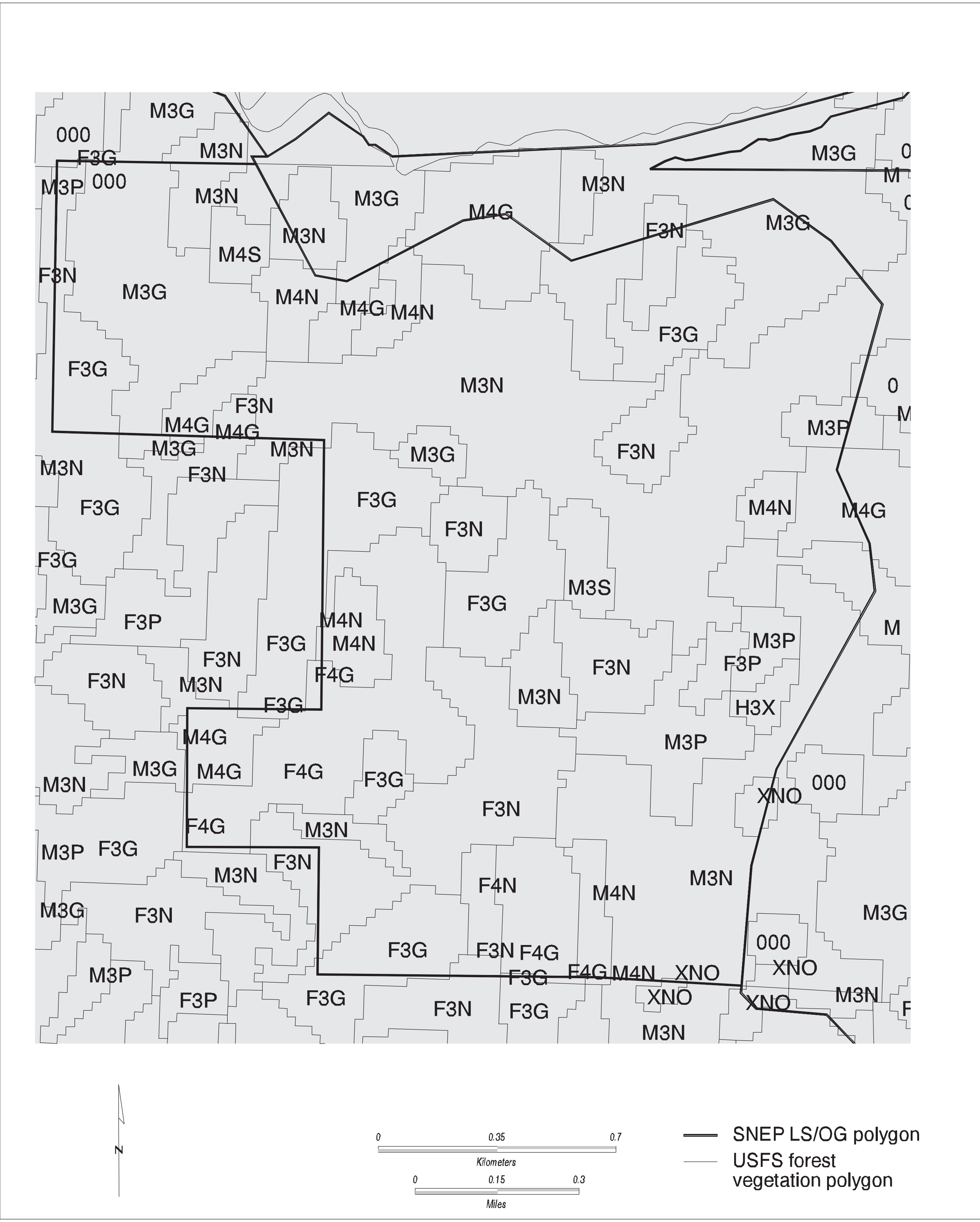

Figure 7

Eldorado National Forest: Example of USDA Forest Service strata vegetation polygons.

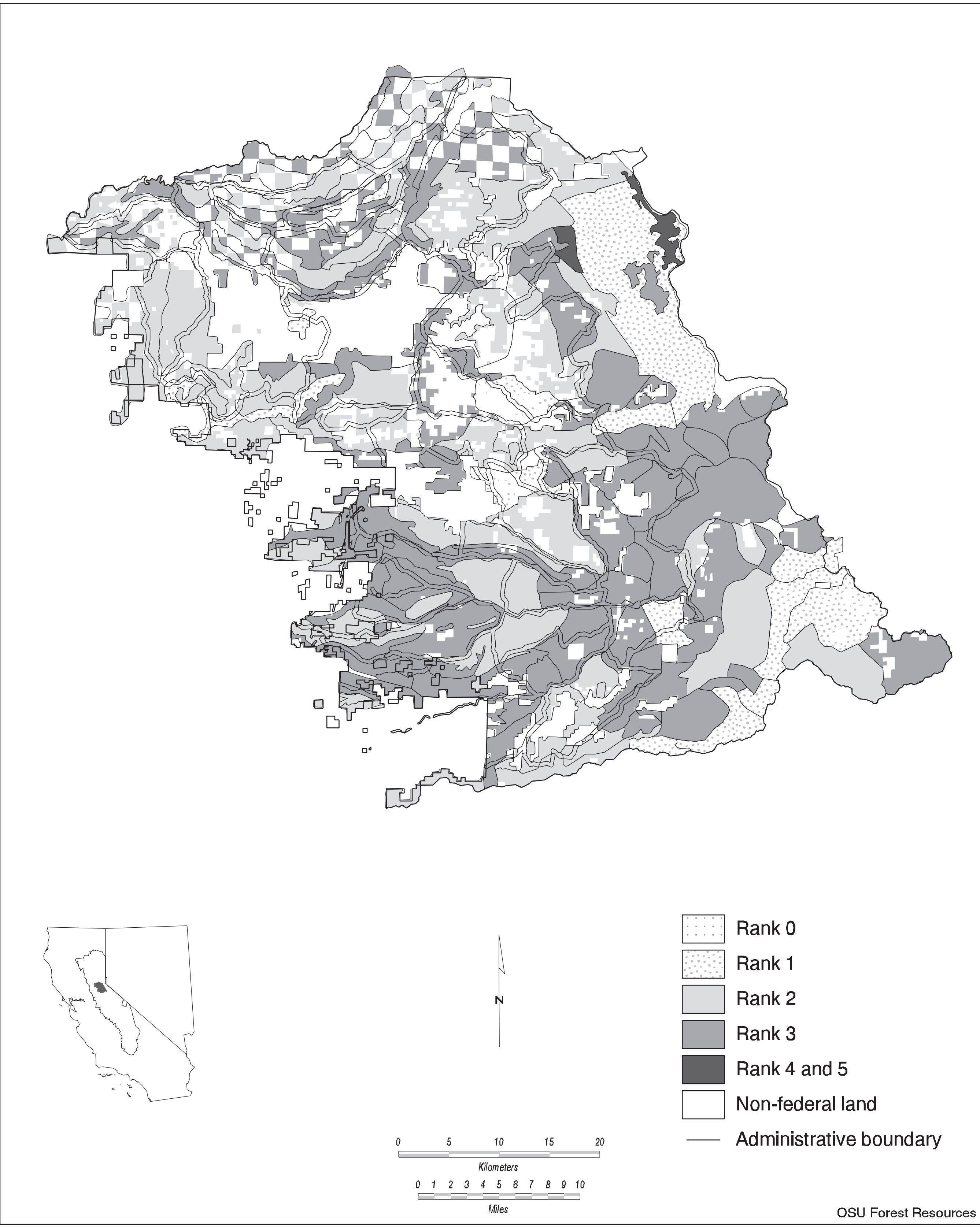

Figure 8

LS/OG polygons ranked as to degree of LS/OG structural complexity and contribution to late successional forest function by evaluating each vegetation class within each polygon (rangewide structural standard for mixed conifer and ponderosa pine types and series-normalized structural standard for higher elevation types. Note: the series-normalized standard generally ranks LS/OG polygons higher than does the rangewide standard).

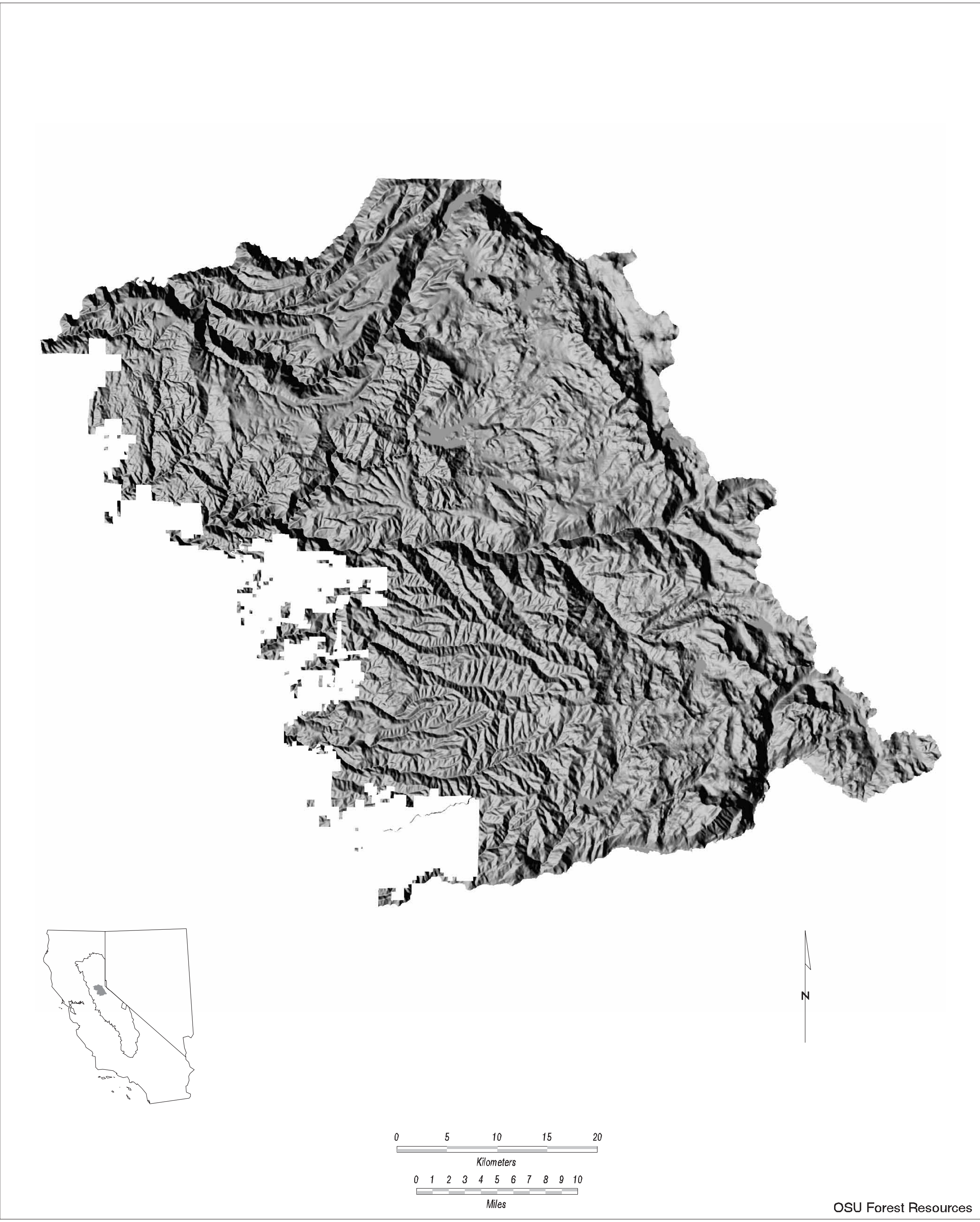

Figure 9

Eldorado National Forest: exaggerated shade relief.

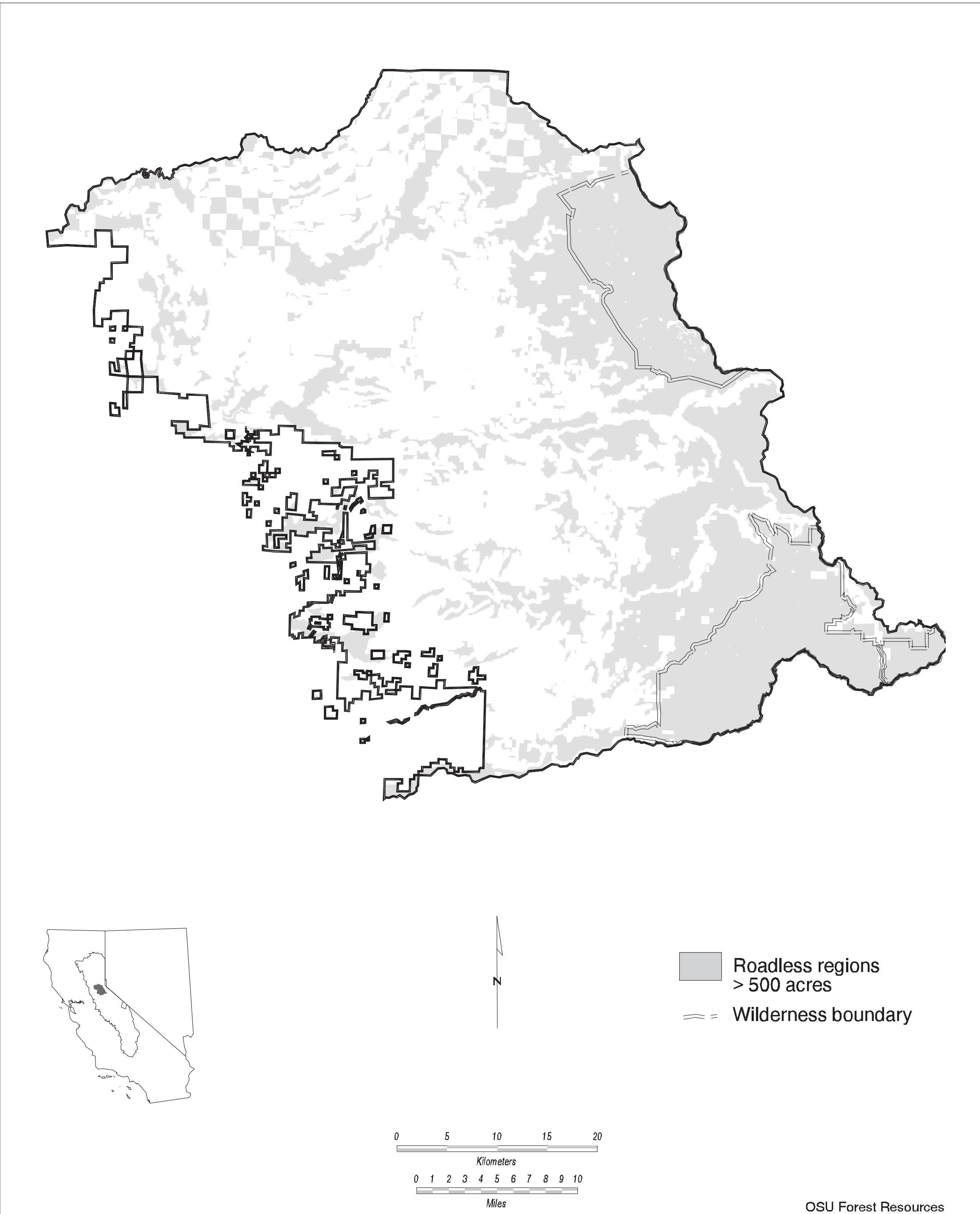

Figure 10

Eldorado National Forest: roadless regions.

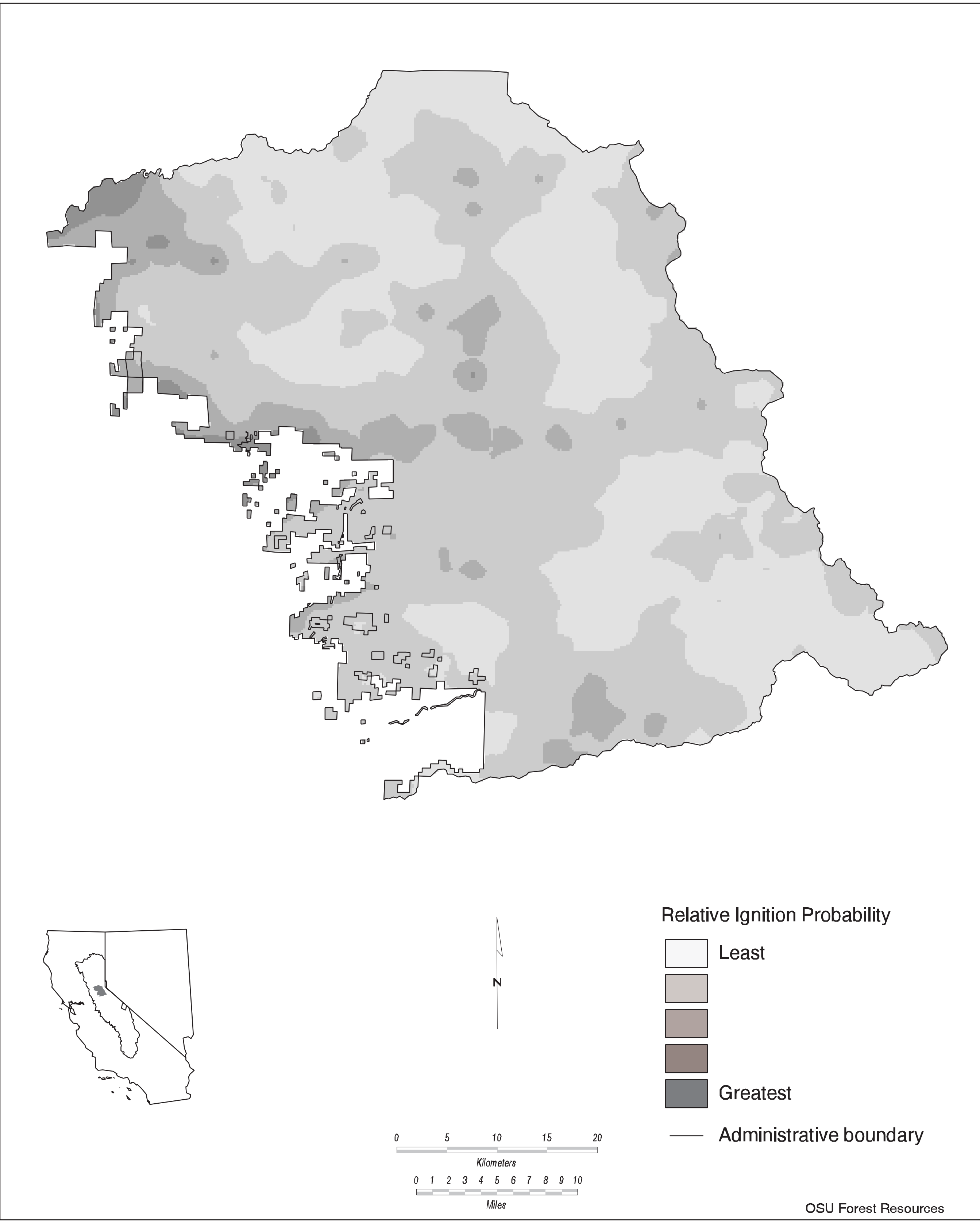

Figure 11

Eldorado National Forest: relative ignition probabilities.

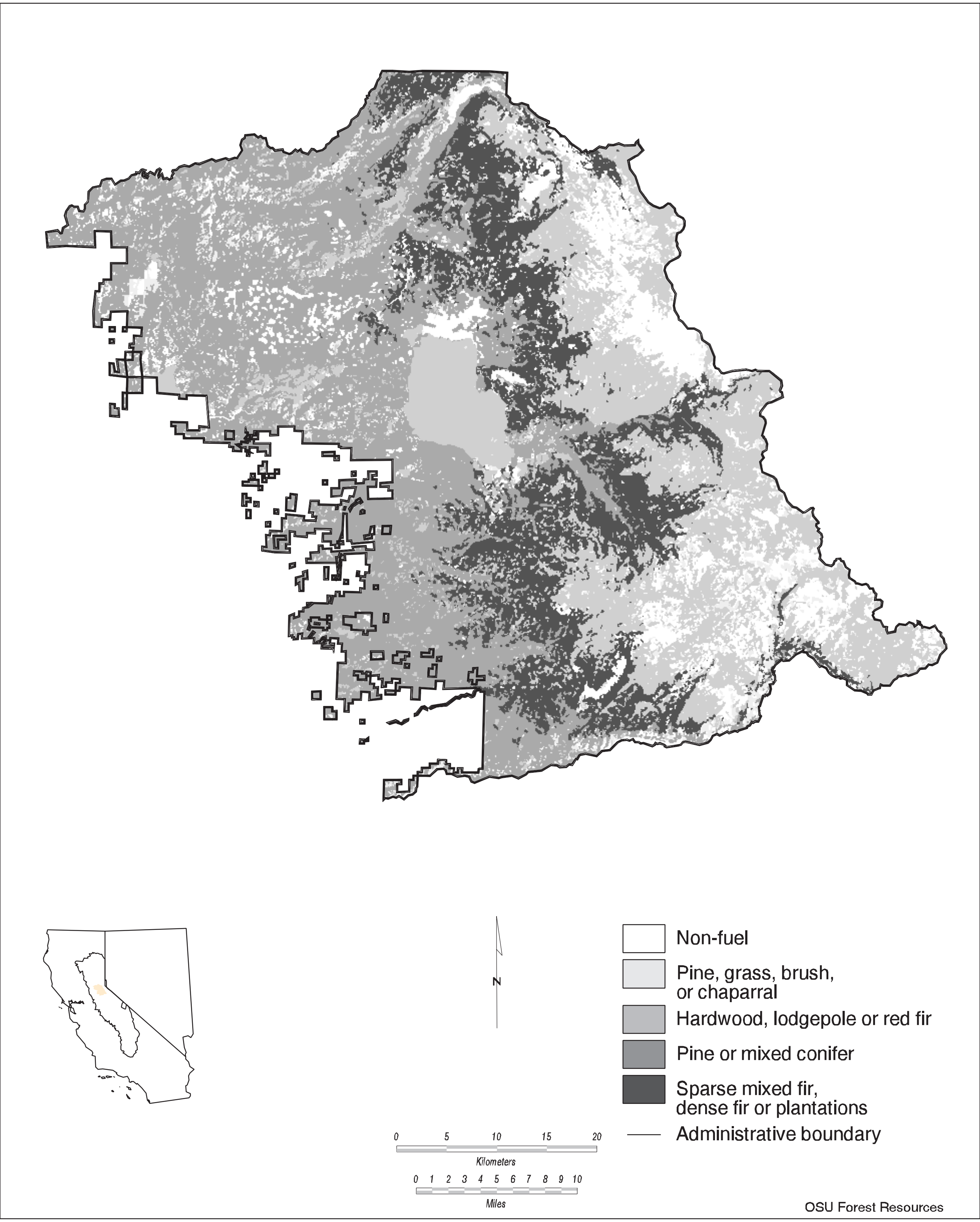

Figure 12

Eldorado National Forest: fuel models.

Figure 13. Stages in the SAFE FORESTS model.

Stage 1.	Find the set of activities that best meets the goals for each ALSE polygon
Stage 2.	Find the set of activities that best meets the goals for the non-ALSE polygons and forest goals for a sustainable timber harvest.
Stage 3.	Simulate the fires across the landscape for the planning periods after randomly selecting weather and a number of other stochastic variables.
Stage 4.	Adjust the schedule of activities, outputs, and effects from stages 1 and 2 for the fires.

Figure 14. Flowchart for Stage 1.

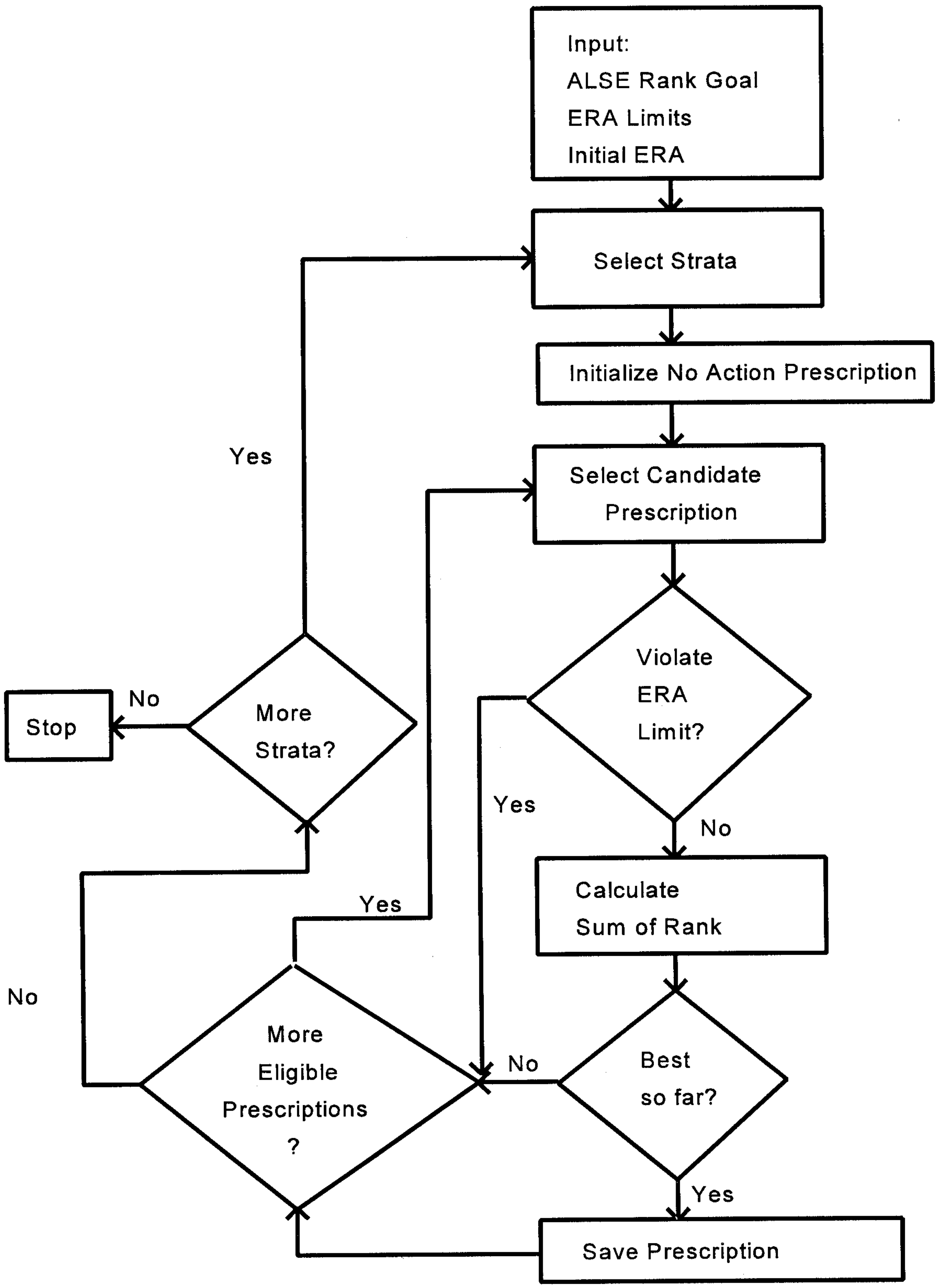

Figure 15. Flowchart for Stage 2.

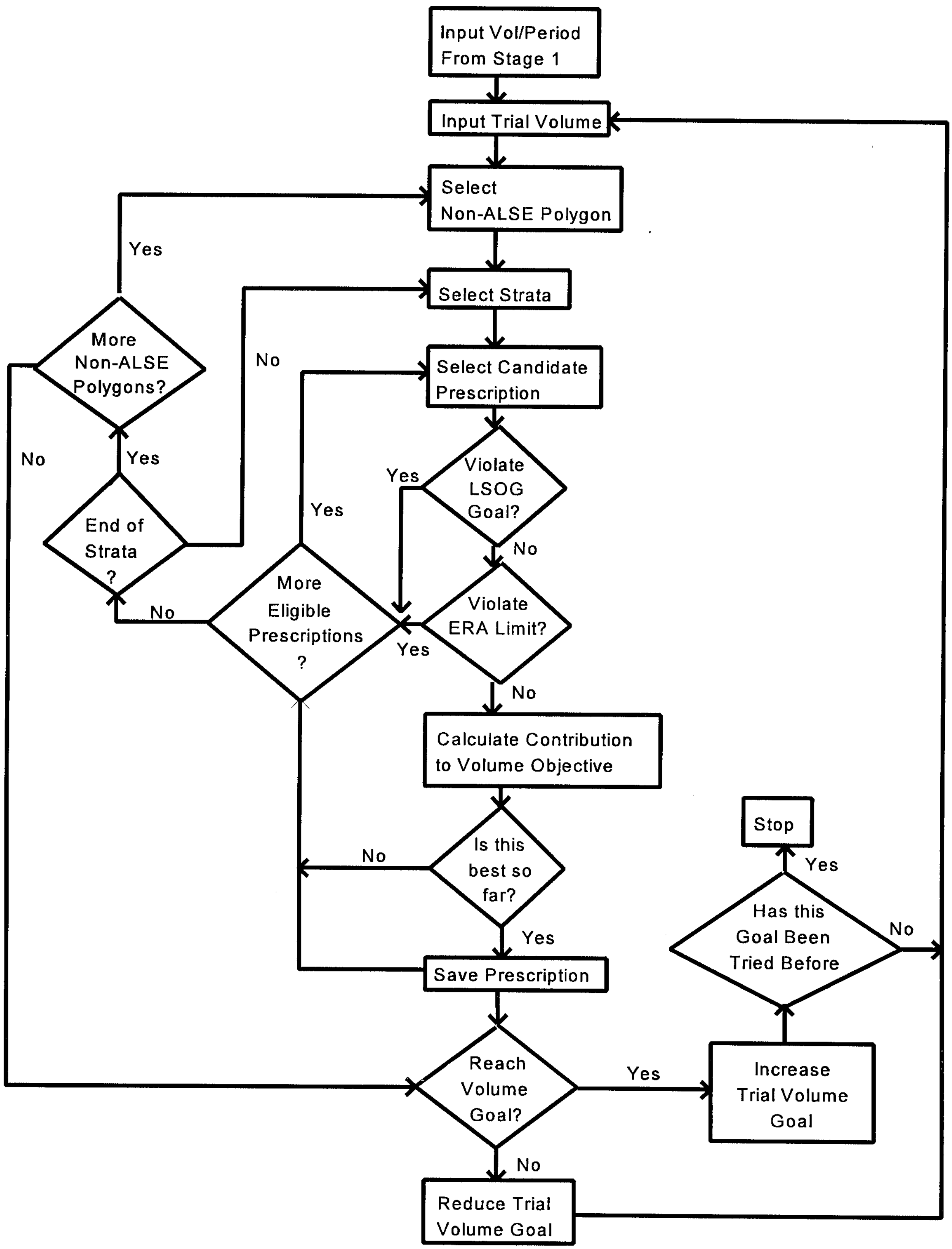

Figure 16. Flowchart for Stage 3.

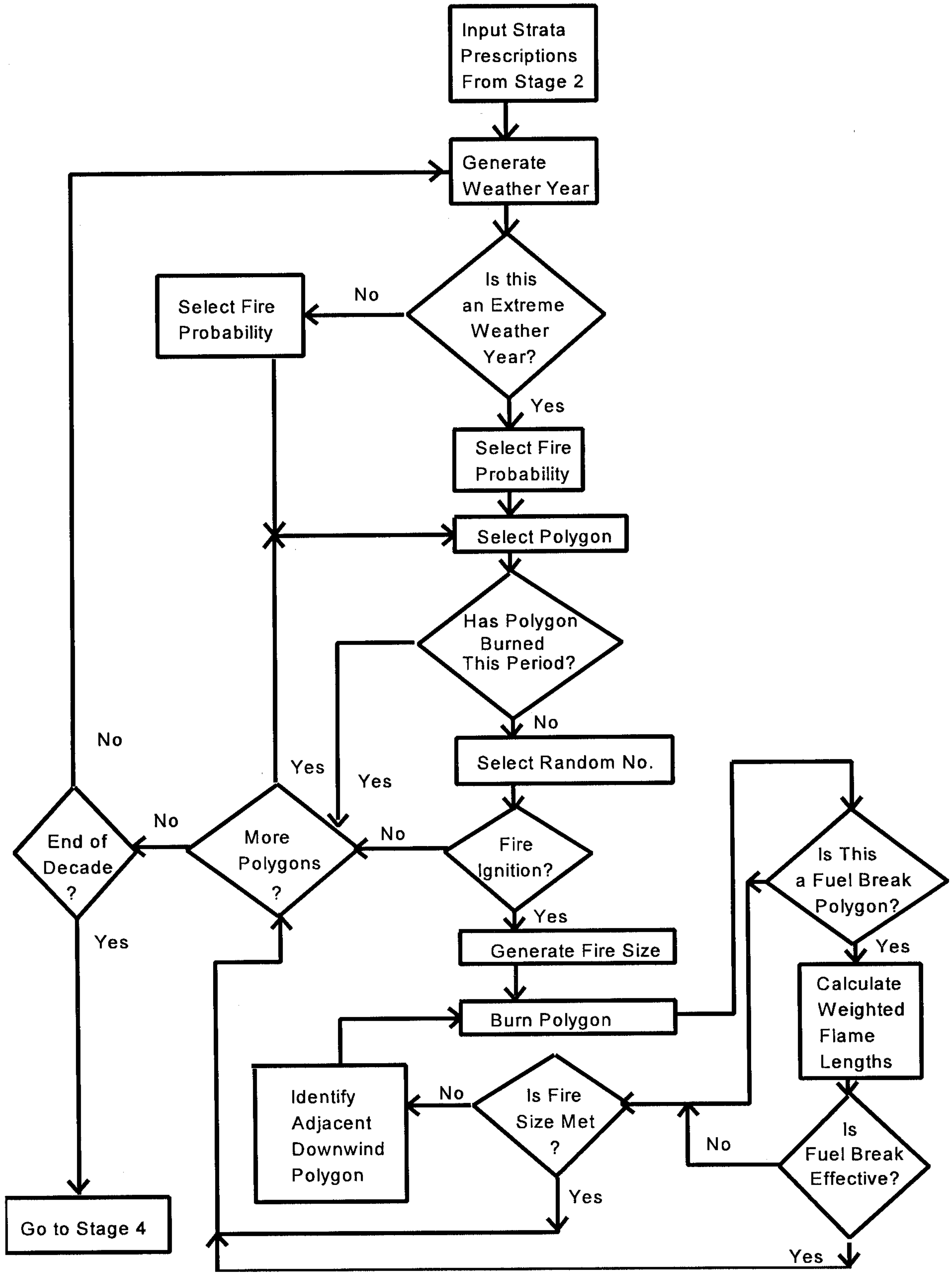

Figure 17. Flowchart for Stage 4.

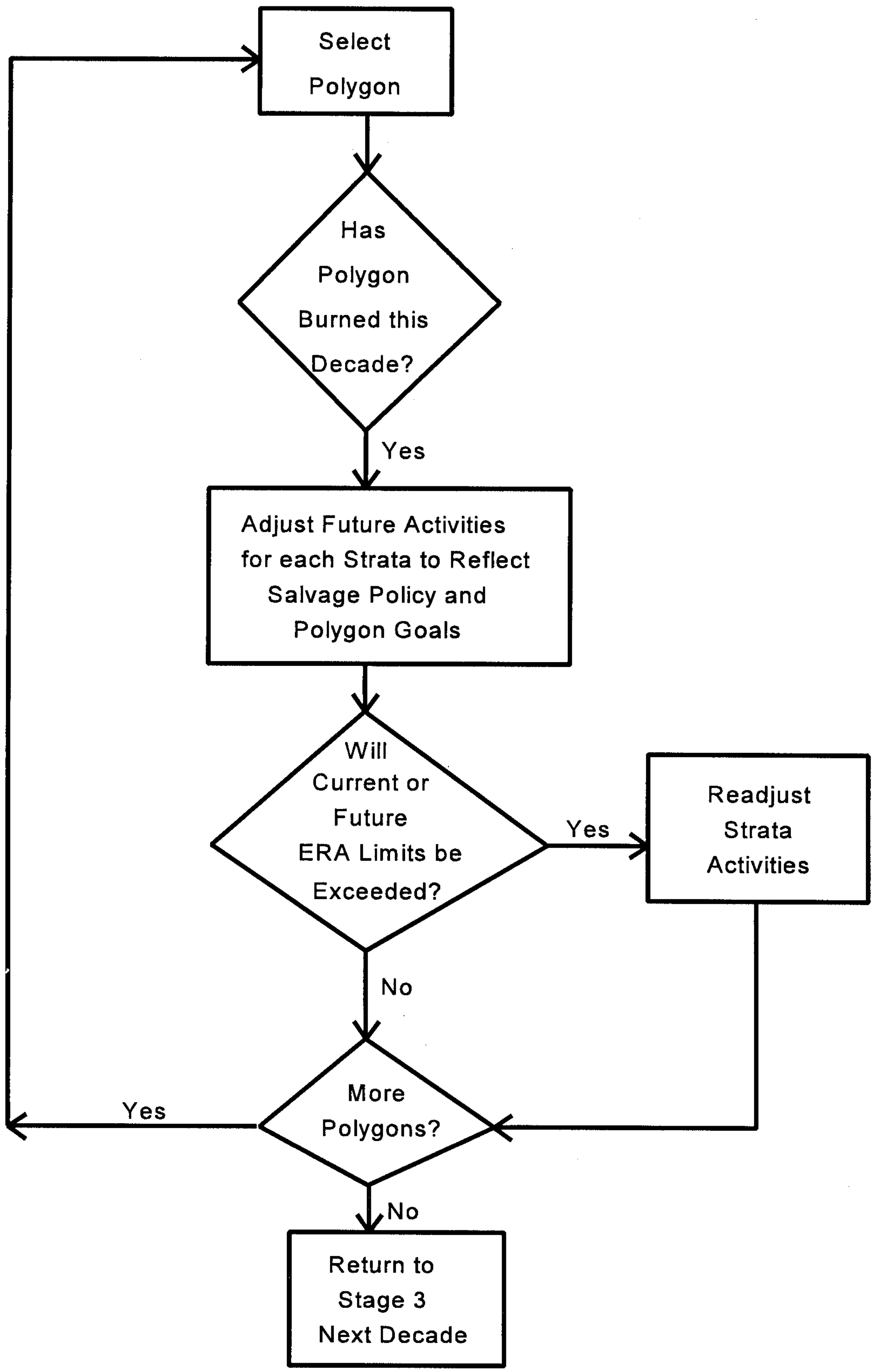

Table 1. Rank by forest type on federal land before harvest for decades (periods) 1-5.

	Period				
forest type	1	2	3	4	5
subalpine	3.94	4.20	4.22	4.34	4.51
white fir mx cf	2.34	2.40	2.40	2.49	2.52
ponderosa pine	2.43	2.61	3.06	3.18	3.35
westside mx cf	2.69	2.71	2.67	2.80	2.90
red fir	3.34	3.34	3.31	3.28	3.41
hardwood	2.91	2.91	3.43	3.84	4.18
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	2.24	2.30	2.35	2.42	2.50

Table 2. Rank by period and land allocation for each decade (period). Withdrawn category is Wilderness, ripzone-1 category is the Community/Energy Zone, ripzone-2 is the Land Use Influence Zone, fuelbreak category is the area within fuelbreak polygons, and the uplands category is the remainder of the federal land

period - 1 overall forest rank is 2.24

	withdrawn (1)	ripzone-1 (2)	ripzone-2 (3)	fuelbreak (4)	uplands (5)
subalpine	3.82	4.14	4.07	3.94	4.03
white fir mx cf	2.24	2.42	2.35	2.25	2.34
ponderosa pine	2.24	2.48	2.65	1.95	2.26
westside mx cf	2.14	2.77	2.78	2.55	2.65
red fir	3.30	3.44	3.39	3.20	3.34
hardwood	2.17	2.61	2.89	3.17	2.98
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	1.57	2.23	2.47	2.31	2.39

period - 2 overall forest rank is 2.30

	withdrawn (1)	ripzone-1 (2)	ripzone-2 (3)	fuelbreak (4)	uplands (5)
subalpine	4.16	4.29	4.25	4.09	4.22
white fir mx cf	2.59	2.73	2.29	2.18	2.40
ponderosa pine	2.72	2.71	2.92	1.52	2.46
westside mx cf	2.32	2.97	2.89	1.71	2.79
red fir	3.39	3.41	3.45	3.02	3.32
hardwood	2.17	2.61	2.89	3.17	2.98
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	1.68	2.39	2.55	1.94	2.47

period - 3 overall forest rank is 2.35

	withdrawn (1)	ripzone-1 (2)	ripzone-2 (3)	fuelbreak (4)	uplands (5)
subalpine	4.17	4.31	4.28	4.14	4.26
white fir mx cf	2.84	2.89	2.28	2.25	2.31
ponderosa pine	2.79	3.25	3.32	1.56	3.02
westside mx cf	2.97	3.03	2.76	1.73	2.74
red fir	3.67	3.45	3.27	3.24	3.12
hardwood	3.17	3.37	3.45	3.17	3.49
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	1.76	2.54	2.58	2.01	2.48

period - 4 overall forest rank is 2.42

	withdrawn (1)	ripzone-1 (2)	ripzone-2 (3)	fuelbreak (4)	uplands (5)
subalpine	4.30	4.39	4.38	4.29	4.38
white fir mx cf	3.45	3.03	2.40	1.94	2.39
ponderosa pine	3.23	3.47	3.43	1.44	3.15
westside mx cf	3.19	3.07	2.92	1.78	2.88
red fir	3.67	3.58	3.08	3.39	3.07
hardwood	4.09	4.09	4.07	0.83	4.06
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	1.83	2.64	2.66	1.94	2.56

period - 5 overall forest rank is 2.50

	withdrawn (1)	ripzone-1 (2)	ripzone-2 (3)	fuelbreak (4)	uplands (5)
subalpine	4.45	4.66	4.59	4.44	4.55
white fir mx cf	3.99	3.02	2.43	2.10	2.35
ponderosa pine	3.23	3.44	3.59	1.63	3.43
westside mx cf	3.72	3.21	3.00	1.91	2.97
red fir	4.00	3.74	3.09	3.69	3.11
hardwood	4.09	4.30	4.44	0.83	4.49
ns/brush/barren	0.00	0.00	0.00	0.00	0.00
total	1.97	2.70	2.74	2.10	2.63

Table 3. Percent of forest type on federal land by rank and total acres by forest type for each decade (perio

period - 1 overall forest rank is 2.24

	% of forest type by rank 0	1	2	3	4	5	total acres
subalpine	.00	.00	.00	.41	.25	.34	38,431
white fir mx cf	.09	.01	.54	.17	.18	.00	110,281
ponderosa pine	.07	.00	.48	.33	.12	.00	66,673
westside mx cf	.07	.02	.32	.31	.27	.00	129,525
red fir	.02	.00	.02	.56	.41	.00	82,461
hardwood	.00	.00	.54	.00	.46	.00	4,522
ns/brush/barren	1.00	.00	.00	.00	.00	.00	107,021
total	.25	.01	.25	.27	.20	.02	538,914

period - 2 overall forest rank is 2.30

	% of forest type by rank 0	1	2	3	4	5	total acres
subalpine	.00	.00	.00	.14	.52	.34	38,431
white fir mx cf	.10	.01	.49	.22	.19	.00	110,281
ponderosa pine	.08	.01	.49	.08	.35	.00	66,673
westside mx cf	.09	.02	.38	.10	.41	.00	129,525
red fir	.00	.00	.03	.60	.37	.00	82,461
hardwood	.00	.00	.54	.00	.46	.00	4,522
ns/brush/barren	1.00	.00	.00	.00	.00	.00	107,021
total	.25	.01	.26	.18	.28	.02	538,914

period - 3 overall forest rank is 2.35

	% of forest type by rank						total
	0	1	2	3	4	5	acres
subalpine	.00	.00	.00	.12	.53	.34	38,431
white fir mx cf	.10	.01	.50	.20	.20	.00	110,281
ponderosa pine	.06	.03	.11	.38	.42	.00	66,673
westside mx cf	.09	.03	.33	.22	.33	.00	129,525
red fir	.00	.00	.03	.64	.33	.00	82,461
hardwood	.00	.00	.03	.51	.45	.01	4,522
ns/brush/barren	1.00	.00	.00	.00	.00	.00	107,021
total	.25	.01	.20	.25	.27	.02	538,914

period - 4 overall forest rank is 2.42

	% of forest type by rank						total
	0	1	2	3	4	5	acres
subalpine	.00	.00	.00	.00	.66	.34	38,431
white fir mx cf	.01	.10	.50	.20	.20	.00	110,281
ponderosa pine	.05	.05	.08	.30	.52	.00	66,673
westside mx cf	.09	.03	.26	.25	.37	.00	129,525
red fir	.00	.00	.02	.68	.30	.00	82,461
hardwood	.04	.00	.03	.00	.86	.07	4,522
ns/brush/barren	1.00	.00	.00	.00	.00	.00	107,021
total	.23	.03	.18	.24	.29	.03	538,914

period - 5 overall forest rank is 2.50

	% of forest type by rank						total
	0	1	2	3	4	5	acres
subalpine	.00	.00	.00	.00	.49	.51	38,431
white fir mx cf	.00	.10	.49	.19	.22	.00	110,281
ponderosa pine	.03	.06	.10	.16	.65	.00	66,673
westside mx cf	.04	.05	.29	.22	.39	.01	129,525
red fir	.00	.00	.01	.57	.42	.00	82,461
hardwood	.04	.00	.03	.00	.52	.41	4,522
ns/brush/barren	1.00	.00	.00	.00	.00	.00	107,021
total	.21	.04	.18	.20	.32	.04	538,914

Table 4. Forest type on federal land by fire severity class potential by decade (period). The severity class potential is the percent of basal area which would die if strata were to burn.

period - 1

	fraction of forest type by severity class potential (beginning of period)						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.69	0.31	0.00	0.00	0.00	38,431
white fir mx cf	0.00	0.06	0.42	0.48	0.01	0.03	110,281
ponderosa pine	0.00	0.00	0.00	0.07	0.10	0.83	66,673
westside mx cf	0.00	0.00	0.00	0.32	0.10	0.58	129,525
red fir	0.00	0.02	0.96	0.02	0.00	0.00	82,461
hardwood	0.00	0.00	0.46	0.54	0.00	0.00	4,522
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	107,021
total	0.20	0.06	0.26	0.19	0.04	0.25	538,914

ADDENDUM

period - 2

	fraction of forest type by severity class (beginning of period)						potential total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.71	0.29	0.00	0.00	0.00	38,431
white fir mx cf	0.00	0.14	0.72	0.14	0.00	0.00	110,281
ponderosa pine	0.00	0.02	0.07	0.08	0.07	0.76	66,673
westside mx cf	0.00	0.12	0.44	0.14	0.07	0.23	129,525
red fir	0.00	0.57	0.41	0.02	0.00	0.00	82,461
hardwood	0.00	0.01	0.86	0.03	0.00	0.10	4,522
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	107,021
total	0.20	0.20	0.35	0.07	0.03	0.15	538,914

period - 3

	fraction of forest type by severity class (beginning of period)						potential total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.65	0.35	0.00	0.00	0.00	38,431
white fir mx cf	0.00	0.39	0.50	0.11	0.00	0.00	110,281
ponderosa pine	0.00	0.06	0.31	0.07	0.03	0.53	66,673
westside mx cf	0.00	0.49	0.24	0.07	0.01	0.19	129,525
red fir	0.00	0.56	0.43	0.02	0.00	0.00	82,461
hardwood	0.00	0.13	0.84	0.00	0.00	0.03	4,522
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	107,021
total	0.20	0.34	0.30	0.05	0.01	0.11	538,914

period - 4

	fraction of forest type by severity class (beginning of period)						potential total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.57	0.43	0.00	0.00	0.00	38,431
white fir mx cf	0.00	0.57	0.31	0.06	0.03	0.03	110,281
ponderosa pine	0.00	0.47	0.31	0.04	0.00	0.18	66,673
westside mx cf	0.00	0.60	0.24	0.03	0.01	0.13	129,525
red fir	0.00	0.40	0.57	0.01	0.02	0.00	82,461
hardwood	0.00	0.43	0.53	0.00	0.00	0.04	4,522
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	107,021
total	0.20	0.42	0.28	0.03	0.01	0.06	538,914

period - 5

	fraction of forest type by severity class (beginning of period)						potential total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.20	0.68	0.12	0.00	0.00	38,431
white fir mx cf	0.00	0.64	0.25	0.02	0.05	0.03	110,281
ponderosa pine	0.00	0.67	0.28	0.00	0.00	0.05	66,673
westside mx cf	0.00	0.64	0.22	0.03	0.01	0.11	129,525
red fir	0.00	0.52	0.33	0.14	0.02	0.00	82,461
hardwood	0.00	0.32	0.57	0.00	0.00	0.11	4,522
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	107,021
total	0.20	0.46	0.24	0.04	0.02	0.04	538,914

Table 5. Fraction of Mixed Conifer on federal land by fire severity potential by rank for each decade (perioc Severity class potential is the percent of basal area which would die if strata were to burn. Total Acres are th total acres in each rank at the beginning of the decade (period).

period - 1

fraction of MIXED CONIFER by severity class potential (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.00	0.00	0.00	0.24	0.67	0.09	9,162
rank 1	0.00	0.00	0.00	0.86	0.00	0.14	2,918
rank 2	0.00	0.00	0.00	0.62	0.14	0.24	42,023
rank 3	0.00	0.00	0.00	0.27	0.01	0.72	40,293
rank 4	0.00	0.00	0.00	0.00	0.00	1.00	35,129
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 2

fraction of MIXED CONIFER by severity class potential (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.00	0.00	0.01	0.74	0.02	0.22	11,587
rank 1	0.00	0.00	0.19	0.69	0.00	0.12	3,150
rank 2	0.00	0.24	0.40	0.12	0.17	0.07	49,097
rank 3	0.00	0.26	0.46	0.07	0.06	0.14	13,152
rank 4	0.00	0.00	0.58	0.00	0.00	0.42	52,539
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 3

fraction of MIXED CONIFER by severity class potential (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.00	0.00	0.72	0.00	0.03	0.25	11,540
rank 1	0.00	0.00	0.72	0.15	0.00	0.13	4,119
rank 2	0.00	0.74	0.08	0.11	0.01	0.06	42,688
rank 3	0.00	0.42	0.30	0.14	0.00	0.14	28,396
rank 4	0.00	0.47	0.18	0.00	0.00	0.35	42,782
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 4

fraction of MIXED CONIFER by severity class potential (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.00	0.00	0.71	0.00	0.03	0.27	11,323
rank 1	0.00	0.02	0.80	0.03	0.00	0.15	3,417
rank 2	0.00	0.96	0.04	0.00	0.00	0.00	34,214
rank 3	0.00	0.41	0.37	0.10	0.01	0.11	32,014
rank 4	0.00	0.64	0.16	0.00	0.01	0.19	48,557
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 5

	fraction of MIXED CONIFER by severity class (beginning of period)						potential total
	0	1-20	21-40	41-60	61-80	81+	acres
rank 0	0.00	0.00	0.39	0.01	0.04	0.56	5,215
rank 1	0.00	0.03	0.93	0.02	0.02	0.00	6,826
rank 2	0.00	0.90	0.10	0.00	0.00	0.00	37,000
rank 3	0.00	0.52	0.28	0.11	0.00	0.09	28,579
rank 4	0.00	0.68	0.16	0.00	0.01	0.15	51,070
rank 5	0.00	0.00	0.00	0.00	0.00	1.00	835

Table 6. Total public and private forest acres burned each decade (period). The average fire per decade for t simulation was 19,981 acres.

Period	Acres
1	10,798
2	32,848
3	9,338
4	25,749
5	21,170

Table 7. Fraction of forest type on federal land burned by severity class. Severity class is the percent of basa area estimated To die when strata burned in this simulation.

period - 1

	fraction of forest type (federal) which burned by severity class						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.64	0.36	0.00	0.00	0.00	2,110
white fir mx cf	0.00	0.21	0.44	0.35	0.00	0.00	63
ponderosa pine	0.05	0.00	0.00	0.00	0.00	0.95	429
westside mx cf	0.06	0.00	0.00	0.29	0.08	0.57	3,800
red fir	0.00	0.03	0.97	0.00	0.00	0.00	945
hardwood	0.08	0.00	0.71	0.22	0.00	0.00	79
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	2,170
total	0.25	0.14	0.18	0.12	0.03	0.27	9,596

period - 2

	fraction of forest type (federal) which burned by severity class						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.56	0.44	0.00	0.00	0.00	120
white fir mx cf	0.57	0.04	0.30	0.09	0.00	0.00	8,006
ponderosa pine	0.80	0.00	0.04	0.00	0.00	0.16	4,893
westside mx cf	0.51	0.02	0.30	0.02	0.01	0.15	9,788
red fir	0.62	0.23	0.14	0.01	0.00	0.00	3,602
hardwood	0.88	0.00	0.11	0.00	0.00	0.02	114
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	2,214
total	0.63	0.05	0.21	0.03	0.00	0.08	28,737

period - 3

	fraction of forest type (federal) which burned by severity class						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.00	0.00	0.00	0.00	0.00	0
white fir mx cf	0.95	0.03	0.03	0.00	0.00	0.00	305
ponderosa pine	0.95	0.01	0.04	0.00	0.00	0.00	2,029
westside mx cf	0.64	0.20	0.10	0.01	0.00	0.06	2,340
red fir	0.85	0.00	0.00	0.15	0.00	0.00	205
hardwood	0.62	0.00	0.36	0.00	0.00	0.03	960
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	1,723
total	0.82	0.06	0.09	0.01	0.00	0.02	7,562

period - 4

	fraction of forest type (federal) which burned by severity class						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.00	0.00	0.00	0.00	0.00	0
white fir mx cf	0.93	0.02	0.04	0.02	0.00	0.00	1,040
ponderosa pine	0.86	0.06	0.00	0.02	0.00	0.06	8,369
westside mx cf	0.97	0.02	0.01	0.00	0.00	0.00	4,979
red fir	0.78	0.00	0.04	0.15	0.02	0.00	413
hardwood	0.95	0.05	0.00	0.00	0.00	0.01	131
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	3,022
total	0.92	0.03	0.01	0.02	0.00	0.03	17,954

period - 5

	fraction of forest type (federal) which burned by severity class						total
	0	1-20	21-40	41-60	61-80	81+	acres
subalpine	0.00	0.00	0.00	0.00	0.00	0.00	0
white fir mx cf	0.54	0.00	0.01	0.13	0.25	0.07	376
ponderosa pine	0.95	0.02	0.00	0.00	0.01	0.02	6,286
westside mx cf	0.71	0.10	0.08	0.03	0.01	0.06	7,444
red fir	0.88	0.00	0.00	0.04	0.08	0.00	412
hardwood	0.58	0.00	0.03	0.00	0.00	0.39	284
ns/brush/barren	1.00	0.00	0.00	0.00	0.00	0.00	2,574
total	0.84	0.05	0.04	0.02	0.01	0.04	17,376

Table 8. Fraction of Mixed Conifer on federal land by rank burned by severity class for each decade (peric Severity class is the percent of basal area estimated to die when the strata burned. Total Acres are the total a of the Mixed Conifer by rank which burned in this simulation.

period - 1

fraction of MIXED CONIFER burned by severity class (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.00	0.00	0.00	0.00	1.00	0.00	212
rank 1	0.46	0.00	0.00	0.34	0.00	0.20	35
rank 2	0.05	0.00	0.00	0.60	0.06	0.28	868
rank 3	0.07	0.00	0.00	0.35	0.02	0.56	1,612
rank 4	0.07	0.00	0.00	0.00	0.00	0.93	1,073
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 2

fraction of MIXED CONIFER burned by severity class (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.95	0.00	0.00	0.00	0.05	0.00	816
rank 1	1.00	0.00	0.00	0.00	0.00	0.00	227
rank 2	0.88	0.00	0.07	0.04	0.00	0.01	3,671
rank 3	0.08	0.15	0.71	0.00	0.00	0.06	1,358
rank 4	0.16	0.00	0.47	0.00	0.00	0.36	3,716
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 3

fraction of MIXED CONIFER burned by severity class (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	1.00	0.00	0.00	0.00	0.00	0.00	42
rank 1	1.00	0.00	0.00	0.00	0.00	0.00	6
rank 2	1.00	0.00	0.00	0.00	0.00	0.00	937
rank 3	0.14	0.62	0.20	0.04	0.00	0.00	655
rank 4	0.60	0.07	0.14	0.00	0.00	0.19	700
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 4

fraction of MIXED CONIFER burned by severity class (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	1.00	0.00	0.00	0.00	0.00	0.00	1,772
rank 1	1.00	0.00	0.00	0.00	0.00	0.00	320
rank 2	1.00	0.00	0.00	0.00	0.00	0.00	1,980
rank 3	0.84	0.10	0.01	0.03	0.00	0.02	430
rank 4	0.80	0.09	0.09	0.00	0.00	0.01	477
rank 5	0.00	0.00	0.00	0.00	0.00	0.00	0

period - 5

fraction of MIXED CONIFER burned by severity class (beginning of period)

	0	1-20	21-40	41-60	61-80	81+	total acres
rank 0	0.98	0.00	0.00	0.00	0.02	0.00	459
rank 1	1.00	0.00	0.00	0.00	0.00	0.00	399
rank 2	1.00	0.00	0.00	0.00	0.00	0.00	1,825
rank 3	0.70	0.07	0.10	0.13	0.00	0.01	1,843
rank 4	0.47	0.23	0.15	0.00	0.01	0.15	2,882
rank 5	0.00	0.00	0.00	0.00	0.00	1.00	36

Table 9. Percent ERA Report by decade (period) by zone by owner group. Units are equivalent roaded acre acre.

zone 1 = 150 ft each side of stream (Community/Energy Zone)
zone 2 = variable buffer outside of 150 ' (Land Use Influence Zone)
zone 3 = uplands

zone		period 1	2	3	4	5
1	federal	.08	.08	.08	.08	.08
2	federal	.10	.11	.12	.12	.11
3	federal	.12	.12	.13	.13	.13
1	other	.10	.10	.10	.10	.10
2	other	.20	.20	.20	.20	.20
3	other	.20	.20	.20	.20	.20
1	average	.08	.09	.08	.09	.09
2	average	.13	.13	.14	.14	.14
3	average	.14	.14	.15	.15	.15
	overall	.13	.13	.14	.14	.14

Table 10. Federal harvest volumes by period and type.

Period	Green Timber mmbf/yr	Salvage mmbf/yr	Total Harvest mmbf/yr
1	76.9	2.0	78.9
2	70.8	2.8	73.6
3	78.8	0.4	79.2
4	81.2	1.1	82.3
5	78.1	2.2	80.3

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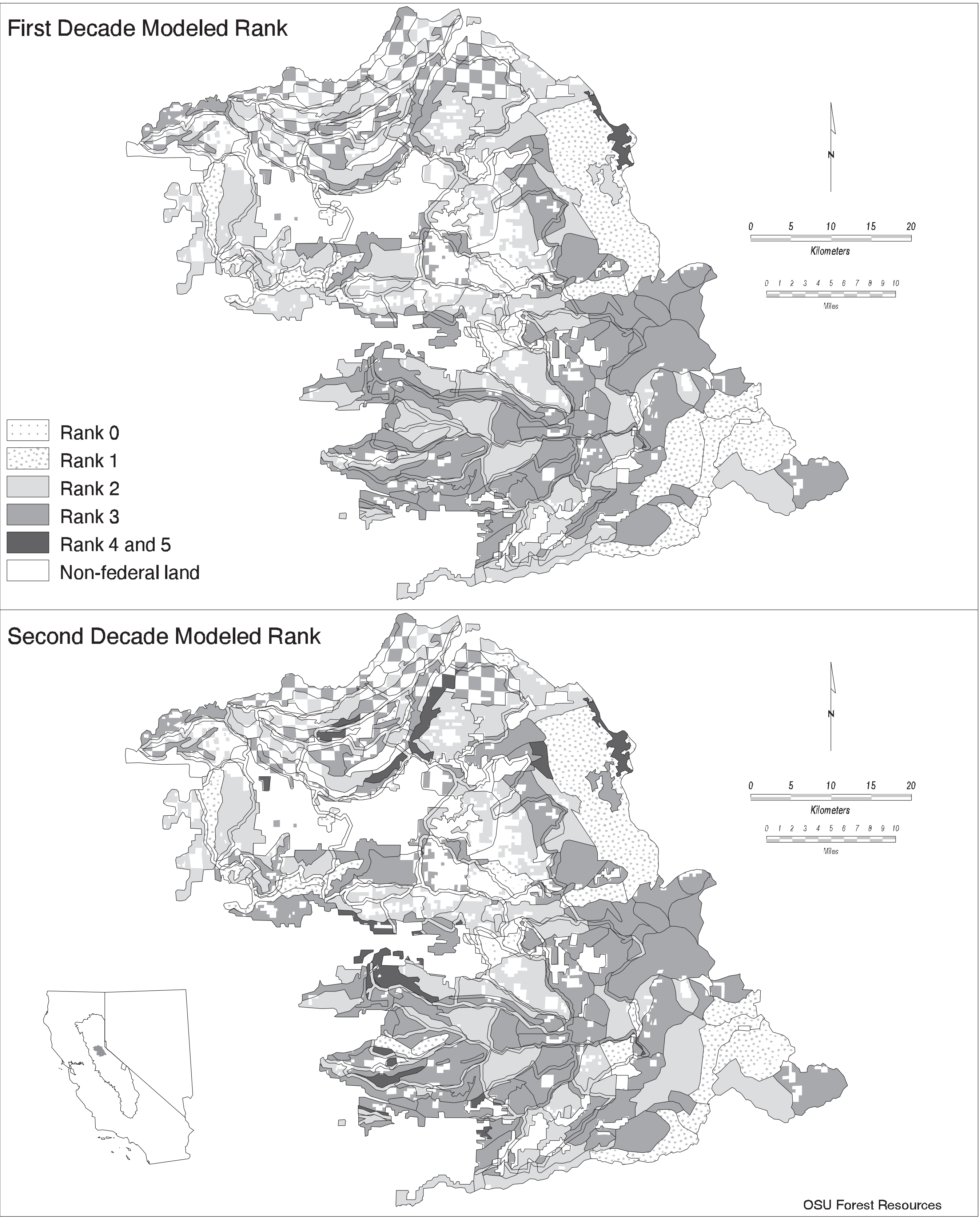


Figure 18

Eldorado National Forest: LS/OG polygon rank through time. LS/OG polygons ranked as to degree of LS/OG structural complexity and contribution to late successional forest function by evaluating each vegetation class within each polygon (rangewide structural standard for mixed conifer and ponderosa pine types and series-normalized structural standard for higher elevation types).

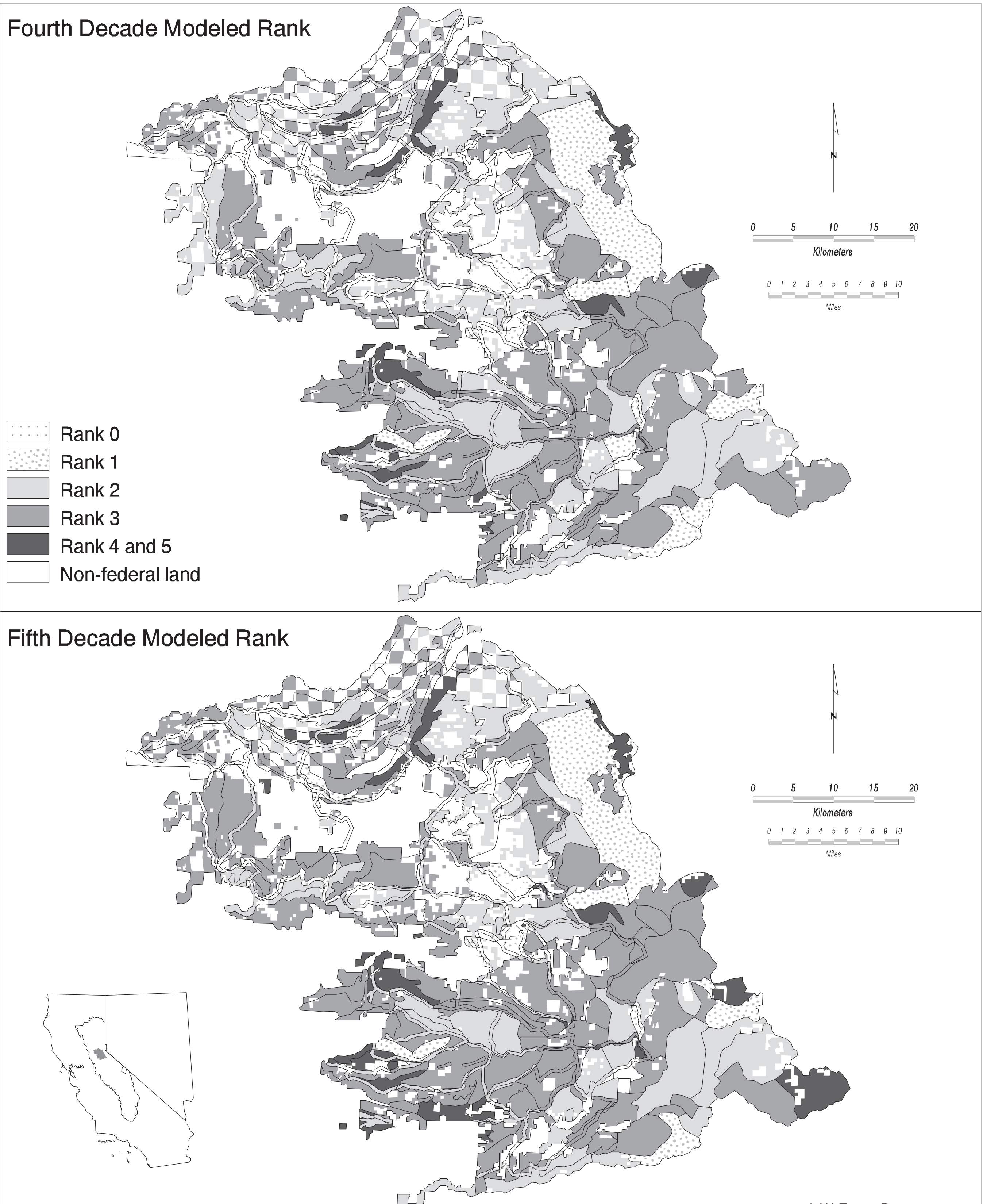


Figure 19

Eldorado National Forest: LS/OG polygon rank through time. LS/OG polygons ranked as to degree of LS/OG structural complexity and contribution to late successional forest function by evaluating each vegetation class within each polygon (rangewide structural standard for mixed conifer and ponderosa pine types and series-normalized structural standard for higher elevation types).

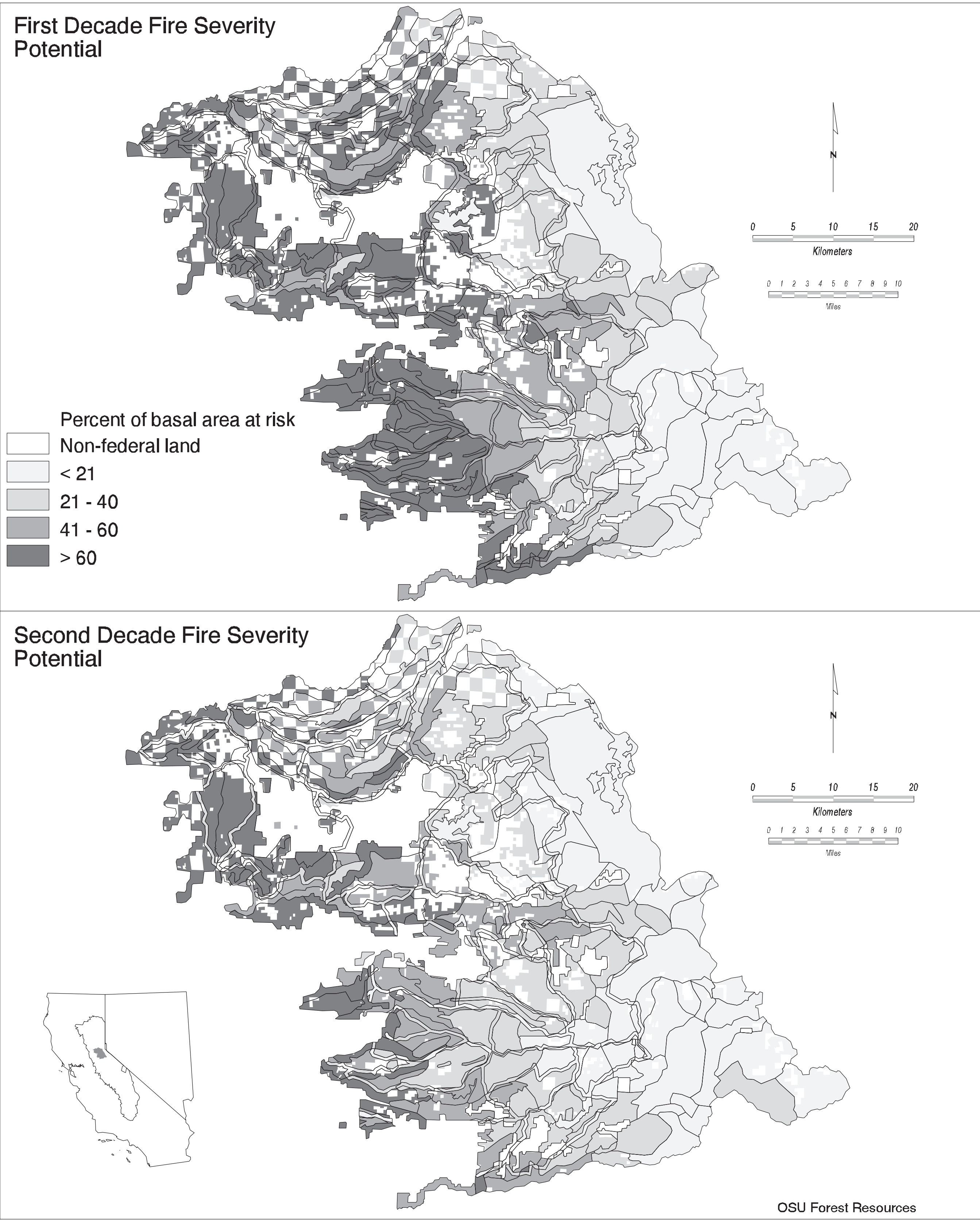


Figure 20

Eldorado National Forest: fire severity potential.

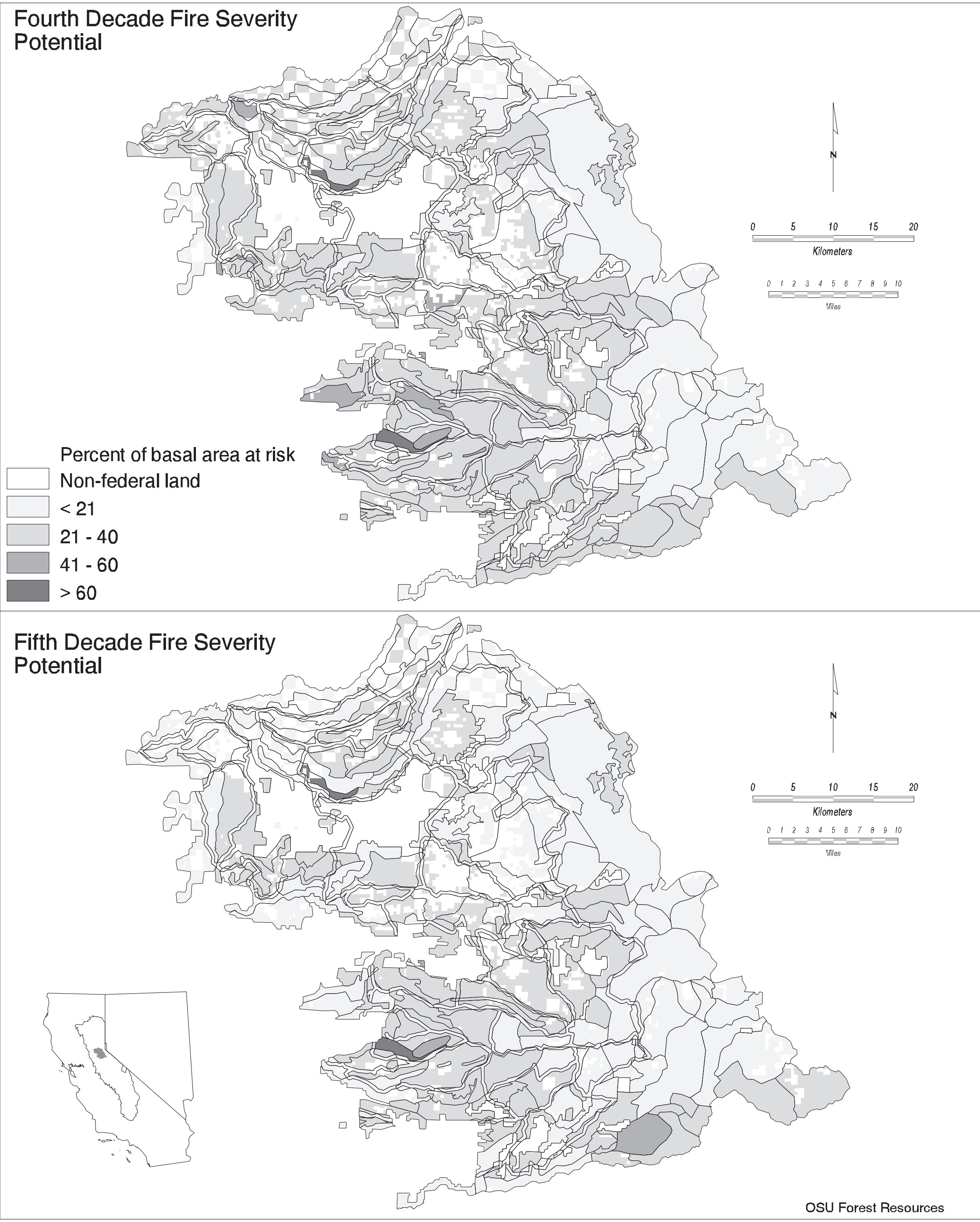
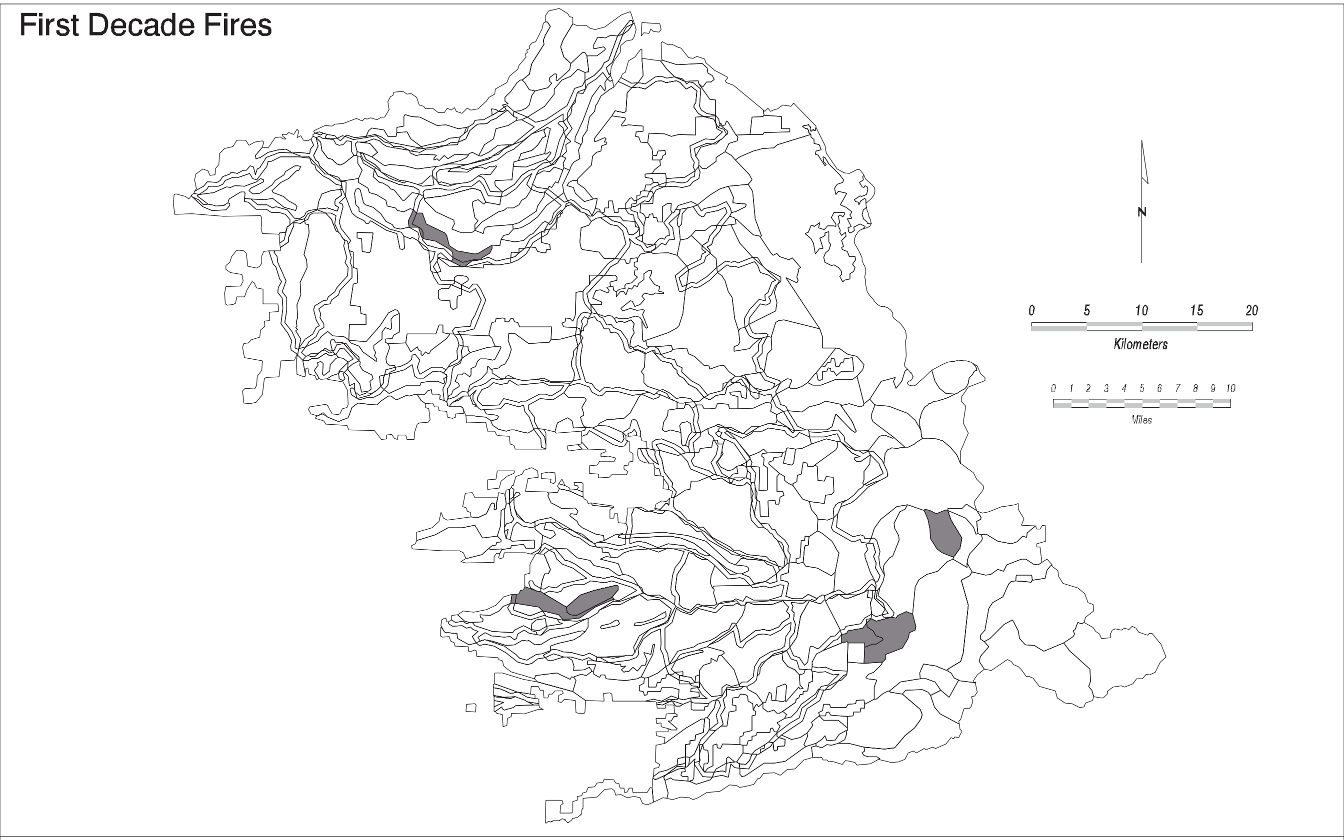


Figure 21

Eldorado National Forest: fire severity potential.



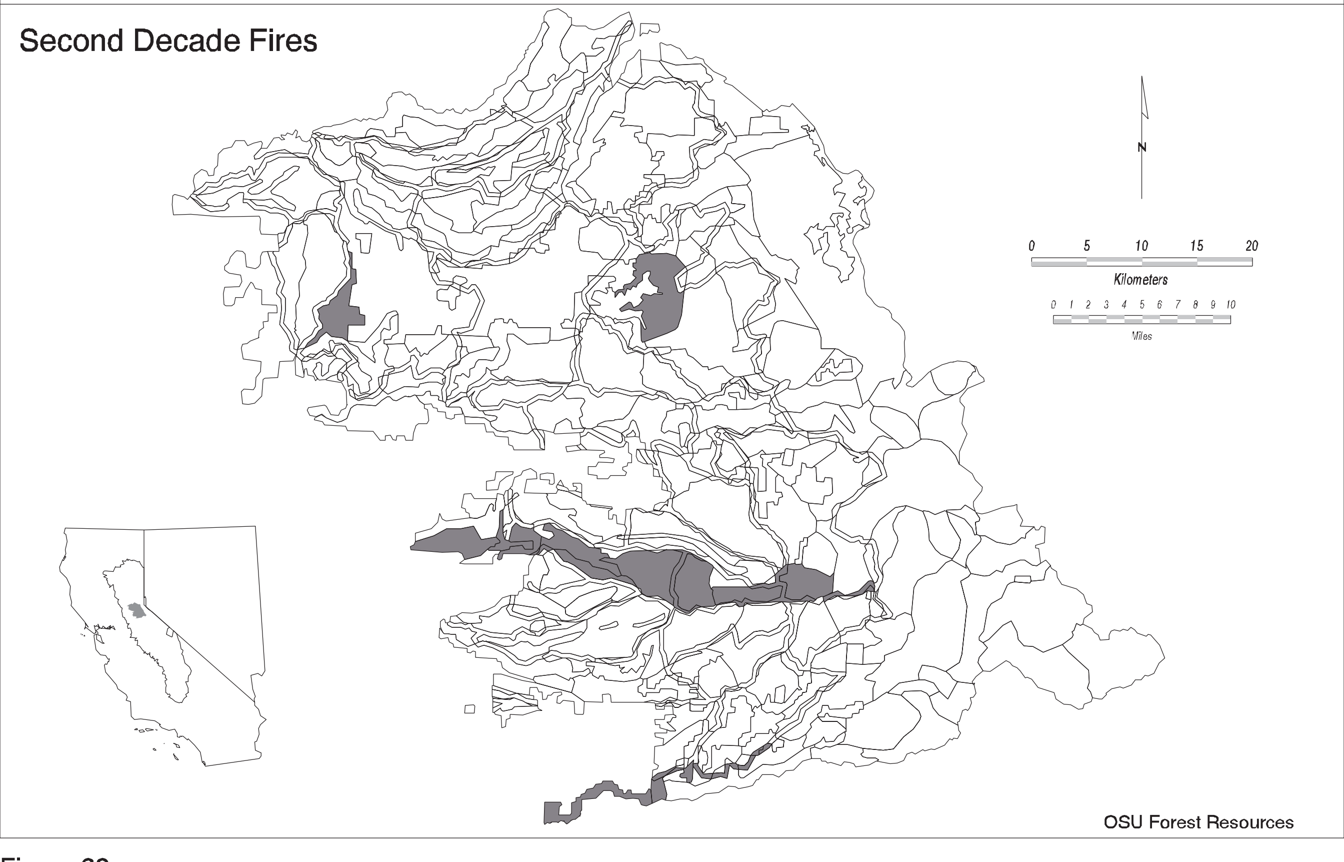


Figure 22

Eldorado National Forest: fire occurrence.

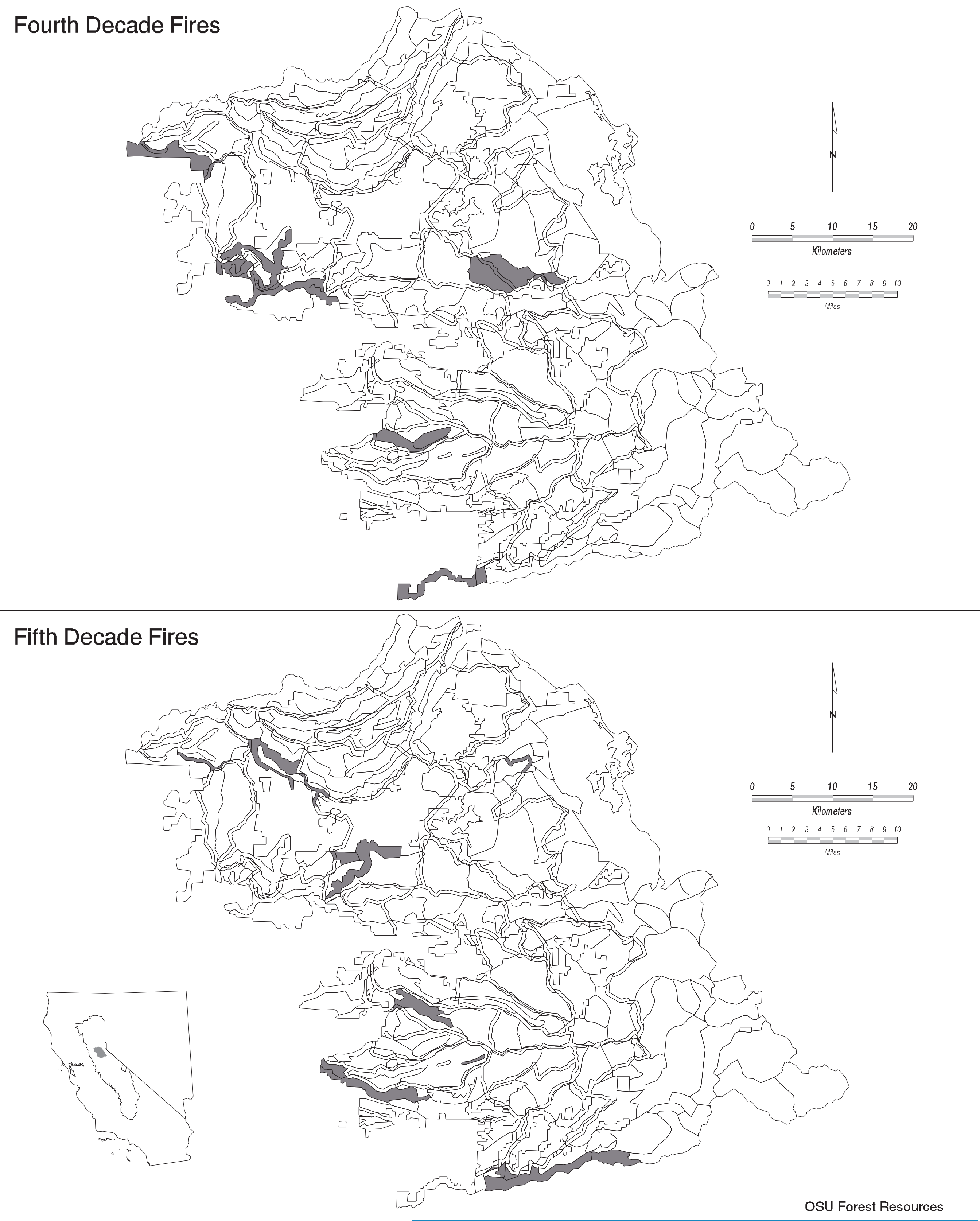


Figure 23

Eldorado National Forest: fire occurrence.

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