Chapter 1:
Fuels and Fire at the Landscape Scale

Research Team

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Project Goals:

In this study, we are investigating how landscape-level fuels and silvicultural treatments affect potential fire behavior and fire effects across the forested landscape of the project area in the Plumas National Forest. This analysis is critical for assessing the potential of severe or extensive fire occurring on the landscape.

In addition, both fuels treatments and fire alter forest structure, pattern and composition and thereby modify wildlife habitat that depends on the vegetation. Our assessments of potential change to landscape-scale vegetation will be instrumental when coupled with assessments of wildlife habitat conducted by the owl research module. This linking of module research relies on an integrative analytical model developed by our team. That model is described here, as the last part of this study.

Objectives and Overview

Past management activities including fire suppression, timber harvesting, and livestock grazing have changed the structure and composition of many coniferous forests in the western United States, particularly those that once experienced frequent, low-moderate intensity fires (Biswell 1961; Hartesveldt and Harvey 1967; Parsons and Debenedetti 1979; Beesley 1995; Erman 1996; Menning 2003). These changes in vegetation have altered habitat for a variety of species. Correspondingly, changes in vegetation and fuel loading have changed the probability of fire spreading across the landscape.

The USDA Forest Service aims to actively manage vegetation with the goal of reducing the probability of large, intense, or severe fires while minimizing negative effects on wildlife habitat and ecosystem stability. Proposed treatments include group selections and defensible fuel profile zones (DFPZs). Group selection treatments involve the harvest of all trees smaller than 30” diameter at breast height (DBH) over a one to two acre area (Stine et al. 2002). DFPZs are areas with extensive forest thinning intended to reduce surface and canopy fuel loads. They are also known as shaded fuel breaks and are designed to allow access for active fire suppression. DFPZs are spatially-extensive, covering hundreds to thousands of hectares (Stine et al. 2002).

Currently, there is limited information on the effects of landscape fuels treatments on reducing severe fire behavior and effects, especially at the landscape scale (Erman 1996; Agee et al. 2000; Fites-Kaufman et al. 2001). Elsewhere in the Sierra Nevada, group selections have been shown to have little effect on the landscape-level behavior of fire (Stephens and Finney 2002); the proposed group selections in the Plumas, however, retain more large trees per acre than typical group selections. To date, the modeled effects of group selections with large tree retention have not been published for this forest type.

Assessing the effects of these vegetation management strategies—group selections and DFPZs—across the forested ecosystems of the Plumas and Lassen National Forests is the goal of the Plumas-Lassen Administrative Study (Stine et al. 2002). The study is composed of five research teams with distinct focuses: California spotted owls, small mammals, songbirds, fuels and fire, and vegetation. Due to practical considerations of a study as spatially extensive as this, we have to mix research with monitoring. The overall study does not comprise a formal scientific experiment in that the scientists involved have little control over actual treatments. The study amounts to far more than monitoring, however, in that we are independently assessing a large landscape and modeling changes to that landscape given a set of prescriptive treatments.

For the Fuels and Fire Module, which is the focus of this study plan, we aim to address the landscape-scale effects of the proposed forest treatments by answering a suite of questions: First, what are current conditions, in terms of fuel loads and vegetation, measured directly in the field? Second, what is the current potential fire behavior and effects given these measured fuel and vegetation conditions? Third, how would landscape fuels treatments affect vegetation condition and fire behavior and effects?

Fourth, in addition to these efforts to characterize fuels and fire relationships, it is essential to link results of our research with findings from the other research modules (figure 1).

It is clear that any landscape-level fuels or forest management strategy will affect many interrelated components of forest ecosystems (Erman 1996; Bahro 2004). Therefore, it is important to understand the synergistic effects between potential treatments and various areas of concern—forest conditions, risks of severe or extensive fire, and habitat alteration. Our goal in answering this fourth question is to produce an analytical model in which we integrate maps of current conditions with models that project responses of fire behavior and effects given prescriptions of treatment and weather scenarios. The vegetation component of the current conditions maps would act simultaneously as input to the Spotted Owl Module's habit suitability models. By coupling these data layers and models between research modules we will model the likely effect of a landscape fuels strategy on both fire and owl habitat given various prescriptions and weather scenarios.

Taken together, these four research goals form the top level of a hierarchical set of research goals that may be best expressed in a table. Hence, we have shown these research objectives and their supporting details and questions in table 1. Details supporting the modeling efforts follow the table.

Fig 1: Ecosystem Relationships Examined in PLAS
(Topics addressed in this module emphasized in bold)

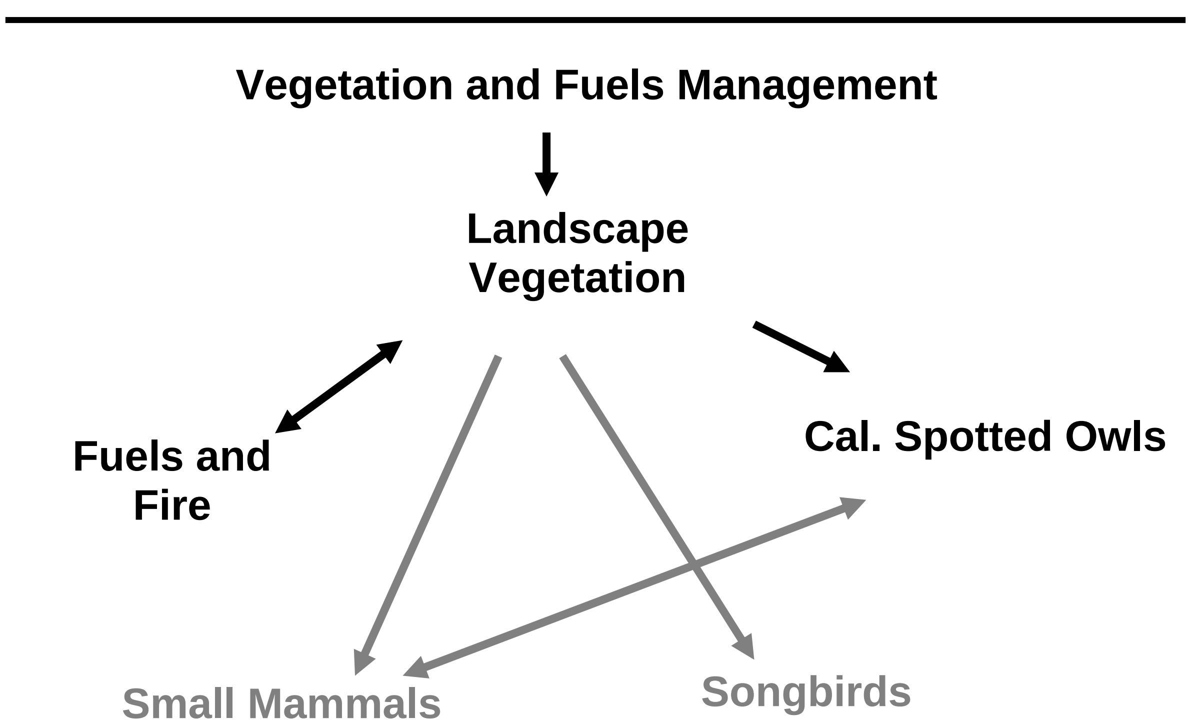


Table 1: Fuels and Fire Module: Summary of hierarchical arrangement of study topics

1.0 Current conditions: measurement of vegetation and fuels at the landscape scale
- 1.1 Current vegetation: What are current vegetation conditions prior to treatment?
  - 1.1.1 Forest sampling in the field (forest plots)
  - 1.1.2 Remote sensing of forest conditions
    - 1.1.2.1 Forest and vegetation classification (IKONOS imagery)
    - 1.1.2.2 Forest structural diversity analysis (IKONOS imagery)
- 1.2 Current fuels: What are current fuel loads prior to treatment?
  - 1.2.1 Fuels sampling in the field (forest plots)
  - 1.2.2 Ladder fuels: probability of fire ascending forest canopy (LaFHA)
  - 1.2.3 Integration of data sources into a fuel model/map for the study area

2.0 Fire modeling: how might current conditions (above) affect fire *behavior* and *effects*?
- 2.1 Fire *behavior*: What is the range of potential fire behavior given current conditions & a range of weather scenarios? (FARSITE & FlamMap models)
- 2.2 What are likely *effects* of fire behavior on these landscapes as determined by simulation models? (Stephens approach using FARSITE & FlamMap outputs)
- 2.3 Temporal dynamics of forest stands, including tree growth (FVS)

3.0 Effects of treatments: how might landscape-scale treatments change fire behavior and effects (using FlamMap)?
- 3.1 Group Selections (GS) and Defensible Fuel Profile Zones (DFPZs)
  - 3.1.1 Measure: how does the installation of GSs & DFPZs affect fuel loads?
  - 3.1.2 Model: how does the placement of GSs & DFPZs affect potential fire behavior? Do they reduce the probability of catastrophic fire under extreme weather conditions?
  - 3.1.3 Modeling: how does the installation of GSs & DFPZs affect fire effects such as mortality to different species and size classes of trees? Would the reduction in fire extent and intensity reduce the severity of canopy fires?
- 3.2 Spatial allocation and efficiency: DFPZs and Strategically Placed Landscape Area Treatments (SPLATs)
  - 3.2.1 How does the installation of alternative treatments affect fuel loading?
  - 3.2.2 How does the placement of alternative treatments affect potential fire behavior?
  - 3.2.3 How do different levels of management intensity (extent of treatment) affect the treatment's ability to reduce the size or intensity of fires?
  - 3.2.4 What effect would alternative treatments have on resulting fire *effects*?

4.0 Fire and habitat model integration
- 4.1 Correlate spectral entropy canopy diversity with habitat variables
- 4.2 Model interaction between vegetation management and both fuels and fire, and owl habitat given current conditions, prescriptions and weather scenarios

Study Area

Our study area is a subset of the Plumas National Forest in Northern California, USA. The Plumas and Lassen National Forests cover hundreds of thousands of acres, and sampling an area this size with a limited field crew and small remote sensing budget is beyond our capacity. As a result, we have chosen to focus on the study area's treatment units (TU) 2, 3 and 4 (Stine et al. 2002), which present widely varying topographical conditions and contain a variety of owl habitat quality. The total area of these three TUs is about 60,000 ha (150,000 ac) (Keane 2004). Vegetation varies widely through this region, presenting a good opportunity to examine fire behavior and end effects across a spectrum of conditions. The town of Quincy lies directly eastward of TU 4 and would be immediately affected by fire in this area and the resulting smoke. In addition, TU 2 has been evaluated to have high quality spotted owl habitat while areas 3 and 4 have lower qualities (Keane 2004). As a result, these three treatment units present a good range of conditions in which to conduct this research and test our model integration.

Vegetative cover in this area is primarily mixed conifer forest. The mixed conifer forest community comprises a mix of three to six conifers and several hardwoods (Barbour and Major 1995; Holland and Keil 1995; Sawyer and Keeler-Wolf 1995). Common conifers include ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), sugar pine (*P. lambertiana*), incense-cedar (*Calocedrus decurrens*), Douglas fir (*Pseudotsuga menziesii)* and white fir (*Abies concolor*). Red fir (*Abies magnifica*) is common at higher elevations where it mixes with white fir (Holland and Keil 1995; Sawyer and Keeler-Wolf 1995). At mid to lower elevations, common hardwoods include California black oak (*Quercus kelloggii*) and canyon live oak (*Q. chrysolepis*) (Rundel et al. 1995).

In addition, a number of species are found occasionally in or on the edge of the mixed conifer forest: western white pine (*P. monticola*) at higher elevations, lodgepole pine (*P. contorta*) in cold air pockets and riparian zones, western juniper (*Juniperus occidentalis*) on dry sites, California hazelnut (*Corylus cornuta*), dogwood (*Cornus spp.*) and willow (*Salix spp.*) in moister sites, California bay (*Umbellularia californica*) and California nutmeg (*Torreya californica*) in lower, drier areas (Griffen and Critchfield 1976; Holland and Keil 1995; Rundel et al. 1995).

A variety of vegetation types currently comprise the matrix of covers in which the mixed conifer forest is arrayed. Vegetation in the matrix ranges from chaparral on exposed, poorly watered south and west facing slopes to oak woodlands and riparian meadows. At higher elevations, particularly toward the Bucks Lake Wilderness, some red fir may be found in pure stands (personal experience).

Methods

This study is conducted under a passive adaptive management framework administered by the USDA Forest Service; we have no control over the implementation of the landscape fuels treatments. The HFQLG Act outlines the landscape fuels treatment strategies, and defines the types of timber harvest to be implemented. Decisions on the timing and placement of fuels treatments will be determined at a local level by the Plumas National Forest.

We do have control over the data collection and modeling aspects of the project. Our research topics (table 1) can be divided into several methodological groupings. Here, we present summaries of methodologies for field data collection, remote sensing, and model integration. Data are collected from a series of field plots (discontinuous data) as well as from satellites (continuous forest canopy data). Additional data products are derived through modeling.

Methods: Field data collection

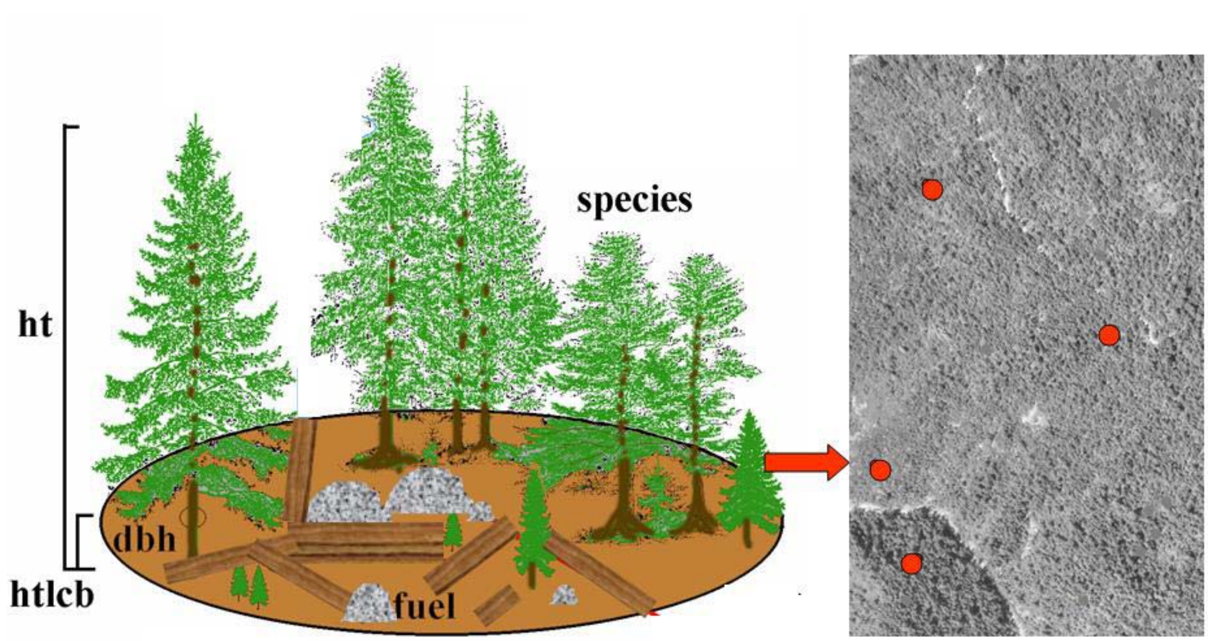
Plot Layout and Design

Data on forest cover and fuels is being collected in 0.05ha (0.125 ac) plots 12.6m (41.3 ft) in radius (figure 2). Plot locations are established using a stratified-random approach. Strata of elevation, aspect and vegetation type were defined using the layers previously supplied by the contractor VESTRA (Stine et al. 2002). This process identified over 700 plot locations in treatment units 2, 3 and 4. In addition to the randomly-stratified plot locations described above, similar data will be collected at locations identified by the other modules: plots are located at each owl nesting site and mammal study grid in the three treatment units.

Forest Structure and Composition; Site Data

We collect data on tree species, diameter at breast height (DBH), categorical estimate of height, and height to lower crown (see Appendix A for sample data sheet). Site data collected include location (using high-precision GPS), slope, and aspect. Canopy cover is assessed at 24 points (every 1 meter) along two linear fuels transects (described below).

Figure 2: Data sources: field plots and satellite imagery
(plots shown scattered on landscape on satellite image to right)



Ground based sampling of ladder, surface, and ground fuels

Surface and ground fuels are sampled in each plot using the line intercept method (Brown 1974; Brown et al. 1982). Ground and surface fuels are sampled along two transects radiating from plot center. The first transect is located along a random azimuth and the second falls 90 degrees clockwise from it. We sample 1 and 10 hour fuels from 10-12 meters along each transect, 100 hour fuels from 9-12 meters, and 1000 hour fuels data from 1-12 meters. Duff and litter depth (cm) are measured at 5 and 8 meters along each transect. Maximum litter height is additionally sampled at three locations from 7 to 8m (Brown 1974; Brown et al. 1982). Total fuel loads for the sites are occularly estimated using fuel photo series developed for the Northern Sierra Nevada and Southern Cascades (Blonski and Schramel 1993).

Ladder Fuel Hazard Assessment (LaFHA)

We have devised and implemented a mixed quantitative-expert system for assessing ladder fuels (submitted paper). The Ladder Fuel Hazard Assessment (LaFHA) requires a trained field crew member to rapidly assess the presence and continuity of fuel ladders in each of four quadrants in a plot using a flowchart. The first step is to determine the presence of low aerial fuels: the fuels that would create sufficient flame lengths to reach several meters from the forest floor. Sparse vegetation, or vegetation widely distributed, probably has too little fuel per volume of air to create and sustain large flames. Therefore, we define a clump of low aerial fuels to be brush or small trees covering an area of at least 4 square meters (2m x 2m) with gaps of less than 50cm. If it is particularly dense, or tall and brushy, a clump may cover a small area. A particularly dense clump may cover as little as $2m^2$ on the forest floor, for example. Branchy dead fuel or stems may be included in the assessment. The size and density of these clumps of fuel and vegetation are based upon personal experience (S. Stephens, K. Menning). If there is no clumping of low aerial fuels, the site would fall in the two lowest ladder fuel hazard categories (C, D); conversely, if there is a clumping of low aerial fuels, the site would fall in one of the two higher-risk categories (A, B). It is important to note that isolated clumps of low aerial fuels, well removed from any ladders, are discounted. Letters (A, B, C, and D) are assigned to hazard ratings instead of numbers to prevent confusion: categories are not of interval or ratio quality (e.g., "Is category 4 twice as risky as category 2?" No, we would not know the quantitative relationship without a direct test).

The second step is to make a determination about the vertical continuity of the fuel ladder from the ground to the canopy. Gaps of more than 2m might be enough to prevent the spread of flames vertically (S. Stephens). Vegetation with gaps of less than 2m from the ground to the upper canopy may present a good ladder to conduct flames. Sparse vegetation lowers the probability and reduces the quality of the ladder. The technician is expected to look at the vegetation and determine whether there are gaps of 2m or more. If the maximum gap is less than 2m, then the site would be categorized as the higher hazard of the two options.

After placing the site in one of the four categories (A, B, C, or D), the technician records the minimum height to live crown (HTLCB) and the size of the maximum gap in the best ladder. These two values may later be used to help verify the classification is correct. The process is repeated for each of the four quadrants of the plot.

The effect of slope is not considered during the hazard evaluation in the field, slope data are used later, to modify the hazard rating. Because the effect of slope on flame length is non-linear (Rothermel 1972), the slope must have a non-linear multiplicative effect on the hazard rating. Final analysis of the plot is performed in the laboratory by combining the ratings of the four quadrants and applying a non-linear slope factor. A plot with one quadrant of high ladder fuel hazard and three low hazard ratings is certainly not as great a risk as a plot with continuous, high-risk ladders in each quadrant. While this semi-quantitative, semi-qualitative process is experimental, and the exact numerical relationships between slope and hazard are yet to be determined, we feel the method has merit; importantly, the field crews report consistent ratings after training and repetition (K. Menning).

Methods: Remote sensing

Initial results of IKONOS imagery indicate that we will be able to use this imagery for classification of landscape vegetation. As a result, we have dropped the LANDSAT imagery analysis. Instead, all our effort in remote sensing goes into analyzing the IKONOS imagery. This high spatial resolution imagery is being used to provide information on continuous forest pattern, structure, cover and variability using methods developed by Menning (2003) including spectral entropy canopy diversity analysis (SpECDA—see appendix E of Fuel and Fire Study Plan). These data and analyses have the benefit of being linked to analyses of vegetation and wildlife habitat conducted by other researchers in the project (see model integration, below). In 2003, high-resolution (1-4m) IKONOS imagery of several treatments was collected covering treatment units 3 and 4. In 2004, IKONOS imagery covering TU 2 and 3—overlapping the data collected in 2003—was collected to provide additional coverage of the area with high owl population.

Methods: Data Processing, Analysis and Model Integration

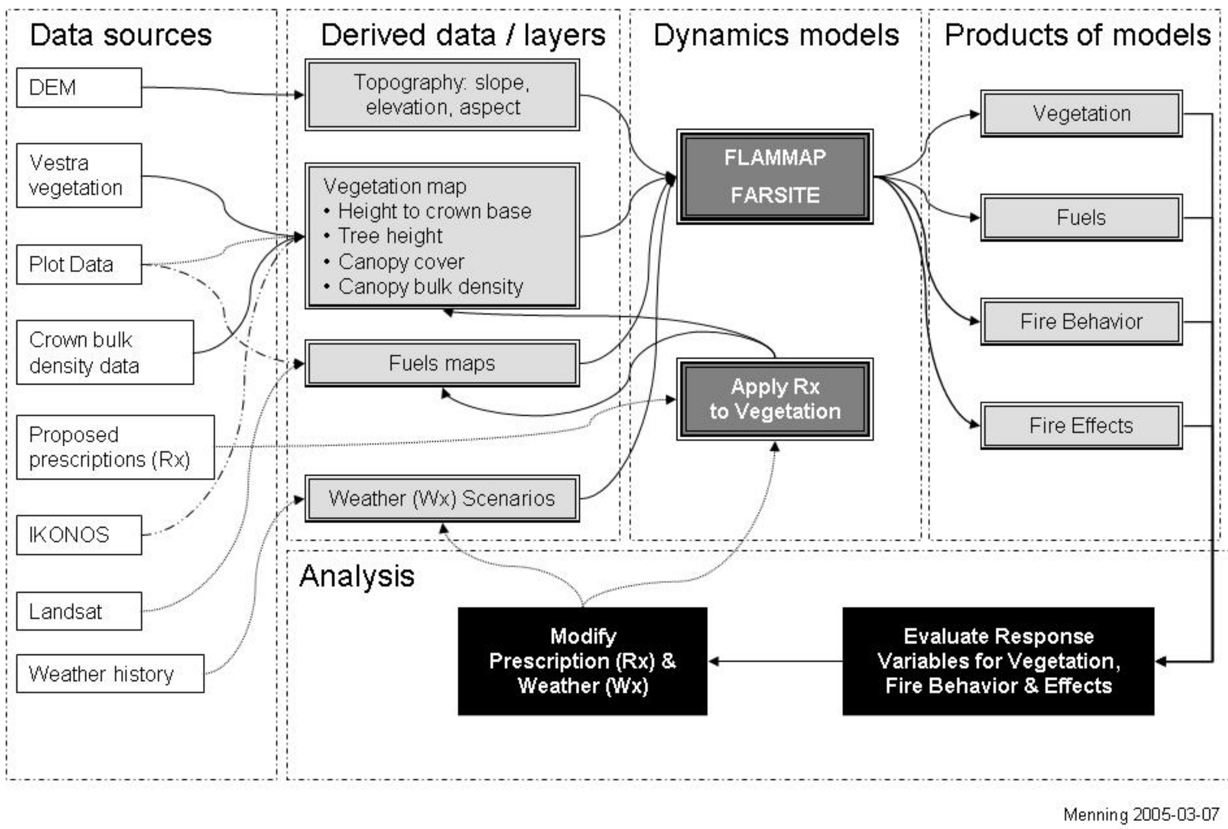
Fire behavior models require maps of vegetation, topography, and fuels, as well as weather scenarios, in order to model the spatial behavior of fire (figure 3). These data are integrated from a variety of different sources. Development of the vegetation map has been described above, in the remote sensing methodology. Topographic variables—slope, elevation and aspect—are mapped across the study area using pre-existing Digital Elevation Models (DEM) on a 30x30m grid. Assembling fuels maps requires that fuels be measured at select sites (a discontinuous set) and then extrapolated across the landscape where fire may burn (continuous coverage). Fire modeling will be conducted in two major phases: first, we will evaluate fire behavior and potential at one time, either the current condition or post-treatment, using Farsite and Flammap; second, we will use Forest Vegetation Simulator (FVS) to create a dynamic simulation of change through time at the stand level.

Calculation of Fuel Loads and Development of Fuel Models

Many fuel inventories done in the Sierra Nevada have assumed that the fuel particles being inventoried had similar properties to those found in the northern Rocky Mountains (Brown 1974) but Van Wagtendonk's work in quantifying Sierra Nevada surface and ground fuel properties allows custom fuel load equations to be developed for a site-specific project such as this. This methodology previously has been used to produce accurate estimates of fuel loads

(Stephens 2001). Additional validation of these fuel load coefficients are provided by Menning's research in Sequoia National Park (Menning 2003). As tree species in the northern Sierra Nevada are the same as those sampled by Menning and van Wagtendonk, the data should be relevant to this study site.

Figure 3: PLAS Landscape Vegetation, Fuels and Fire



Field measurements provide data on species mixes and fuel particle size distribution. Using these data, ground and surface fuel loads are calculated by using equations developed for Sierra Nevada forests (van Wagtendonk et al. 1996; van Wagtendonk and Sydoriak 1998; Menning 2003) as well as the production of fine fuels as determined by field measurements. Coefficients required to calculate all surface and ground fuel loads are arithmetically weighted by the basal area fraction (percent of total basal area by species) that are collected in the plots.

Plot based fuel measurements are being used to create a set of customized and spatially-extensive fuel models for the study area (Burgan and Rothermel 1984) for this area. Fuel model development includes a stochastic element to more closely model actual field conditions that have a large amount of spatial heterogeneity. Stochastic fuel models are being produced for each stratum identified using van Wagtendonk and Root's methods (forest type, aspect, seral stage, etc.). Plot data provide crown cover, height to live crown base, and average tree height at each site. Canopy bulk density estimates are based on previous work by Stephens (Stephens 1998). All of these spatially-discontinuous data derived from plot-specific measurements are extrapolated across the landscape using the remote sensing imagery maps of vegetation.

Simulations: Potential fire behavior

Potential fire behavior is being estimated using a similar technique developed by Stephens (1998) but at much broader spatial scales. The effectiveness of the different restoration treatments will be assessed with computer models such as FARSITE (Finney 1996; Finney 1998; Finney 2000) and FlamMap (Finney 2003). FARSITE is a deterministic, spatial, and temporal fire behavior model that requires as inputs fuel measurements and models; topographic data, including slope, aspect, and elevation; forest structural data including canopy cover, tree height, height-to-live crown base, and canopy bulk density; and weather. A historic fire occurrence map is being produced to estimate the probability of ignitions in the study area. Data come from the Plumas National Forest archives and current GIS layers. This derived map will be used to generate an actual ignition point in each FARSITE simulation. FlamMap is similar to FARSITE but does not use a user-determined ignition but burns the entire landscape using one set of weather data. These models will be used to quantify the potential fire behavior of the different treatment approaches.

The duration of each simulation would be seven days, a period that approximates the duration of many landscape-scale wildfires in the Sierra Nevada before they are contained (Stephens, personal experience). Weather scenarios using data from the 70th (moderate), 90th (severe) and 97th (extreme) percentile conditions is being used and this data is being collected from local weather stations. Fire simulations would be constrained by suppression activities. Constrained simulations will use realistic suppression elements (15 person hand crews, aircraft, bulldozers, etc.; Stephens, personal experience).

Outputs from the fire simulation include GIS files of fire line intensity (kW/m), heat per unit area (kW/square meter), rate of spread (m/s)**,** area burned (ha), emissions (tons) and if spotting and crowning occurred. Scorch height (m) would be calculated from fireline intensity, air temperature, and wind speed. This information will be used to compare the effects of the different landscape level restoration treatments on altering fire behavior.

Simulation: Fire effects

After the fire has passed, the effects of the fire linger: trees die, exposed soils erode, and insects invade. Some fire effects such as tree mortality are being modeled using the GIS outputs from the FARSITE and FlamMap simulations coupled to previously-tested quantitative models that estimate tree mortality (Stephens and Finney 2001). In addition to the tree-mortality measure of fire severity, the amount of bare mineral soil exposed by the simulated fires is being estimated for each 30m by 30m pixel.

Simulation: landscape dynamics over time

The second major phase of fire modeling takes advantage of the temporal dynamics of the Forest Vegetation Simulator (FVS) model. We will place the DFPZs on our virtual landscape at the probable time of their occurrence and use the model to grow trees in all other areas at the same time. The resulting landscape can then be evaluated for fuel loading and fire potential.

Analytical response variables for simulations

Landscape Fire Behavior

The differences in landscape-scale suppression efficiencies among fuels treatments is an essential aspect of this study (Agee et al. 2000; Bettinger et al. 2002). Defensible Fuel Profile Zones (DFPZs) should aid the ability of a wildfire suppression crew to successfully extinguish a fire during initial attack. FARSITE is being used with realistic suppression elements to determine if these landscape level fuel treatments will increase suppression efficiency when compared to the current untreated conditions. To test this efficiency in suppression, one landscape-scale fire response variable is the percentage of wildfires contained below 5 ha (12.5 ac) in size in one burning period before and after landscape fuel treatments.

Second, it is common for wildfires to be propagated by spotting and this can exponentially increase the size of the fire, particularly during the early periods such as the first 24 hours (Pyne et al. 1996). Treatments may reduce the spread of fire into a canopy where flaming brands may be carried into adjacent unburned areas(Pyne et al. 1996). Hence, the ability of a treatment to reduce the number of spot fires is an important measure of the treatment's ability to reduce fire severity or frequency. The number of spot fires is being estimated before and after treatments to determine if treatments reduce fire spread from spotting. Here, the second fire response variable is the percentage change in spot fire initiation before and after landscape level fuel treatments.

A third critical response variable focuses on escapements of fire across the landscape during a longer time period. We will report the probability of simulated fires escaping from or crossing DFPZs and spreading at least another 200 ha (500 ac). This probability will be defined as the percentage of fires given 90th percentile fire conditions. This will be an important measure of the effectiveness of the DFPZs at reducing the chance of fire spreading across the landscape.

The total spatial extent of fire, given treated or untreated areas, is the fourth response variable. Simulated fires will be allowed to burn either until they burn out or are contained. The extent of forested area burned will be compared between treated and untreated areas.

Fifth, ground and canopy fires are dramatically different in behavior, severity, intensity and likelihood to spread across a forested landscape (Pyne et al. 1996). Ground fires are often beneficial, reducing fuel from the ground and surface, and reducing competition for small trees (Stephenson et al. 1991; Stephenson 2000). The fifth response variable, therefore, is a simple ratio of the area of canopy fire to total fire extent.

Analyzing Spatial Efficiency of the Placement of Landscape-Level Fuels Treatments

Location of fuel breaks can play a significant role in the efficiency of fire suppression (Finney 1999; Finney 2001). This is discussed more thoroughly in our Study Plan. SPLATs are passive in nature—no active suppression is performed—and thereby differ markedly from DFPZs which are meant to be the base of active suppression. The efficacy of SPLATs, however, will be tested the same way as the DFPZs, as previously described with the same response variables and over the same time periods. SPLATs, like DFPZs, would be placed on the landscape over a period of years rather than being applied all in the same time period. Performing this analysis with the same base data layers of vegetation and topography will allow us to analyze the efficiency of these different landscape-scale forest fuels management strategies.

We plan to test SPLATs at several spatial extents. The first set of SPLATs tested will have the same spatial extent as the proposed DFPZs. We will test increasing increments of landscape treated by SPLATs by 5% until we find the level of treatment that corresponds with similar degrees of suppression efficiency with the DFPZ network.

Further, we will try re-allocating the DFPZ treatment areas spatially to see if we can improve their efficiency for suppressing large or severe fires. A response variable here would be the percentage of the landscape burned given different configurations given the same weather scenarios and suppression efforts.

Landscape Vegetation and Habitat Response to Fire

A primary concern of this study is the effect of fires on forest structure, pattern and condition. Of particular concern are the older, late-successional forest remnants (Erman 1996). These provide essential habitat to the spotted owl. Wildfires in the Sierra Nevada are commonly low to moderate severity events with patches of high severity fire (Stephenson et al. 1991). Low severity fires may kill only the smallest pole or seedling size-class trees while moderate severity fire may kill both small and moderately sized trees. Fire in the high severity patches—or landscapes in the case of an extensive high severity fire—kills the majority of the small and medium sized and many of the large trees within the perimeter. High severity fire and the corresponding large tree mortality will significantly reduce canopy cover.

Many wildlife species such as California spotted owls prefer diverse forest structure for foraging and breeding and the presence of such variation may affect the success of reproduction (Hunsaker et al. 2002; Blakesley et al. In Press; Lee and Irwin. In press). Telemetry studies indicate that owls prefer to nest in areas with high canopy cover. Some areas of lower cover can also be included in the foraging habitat but this should probably only comprise a fraction of the area. Reduction of canopy cover may reduce the nesting habitat quality for the owl.

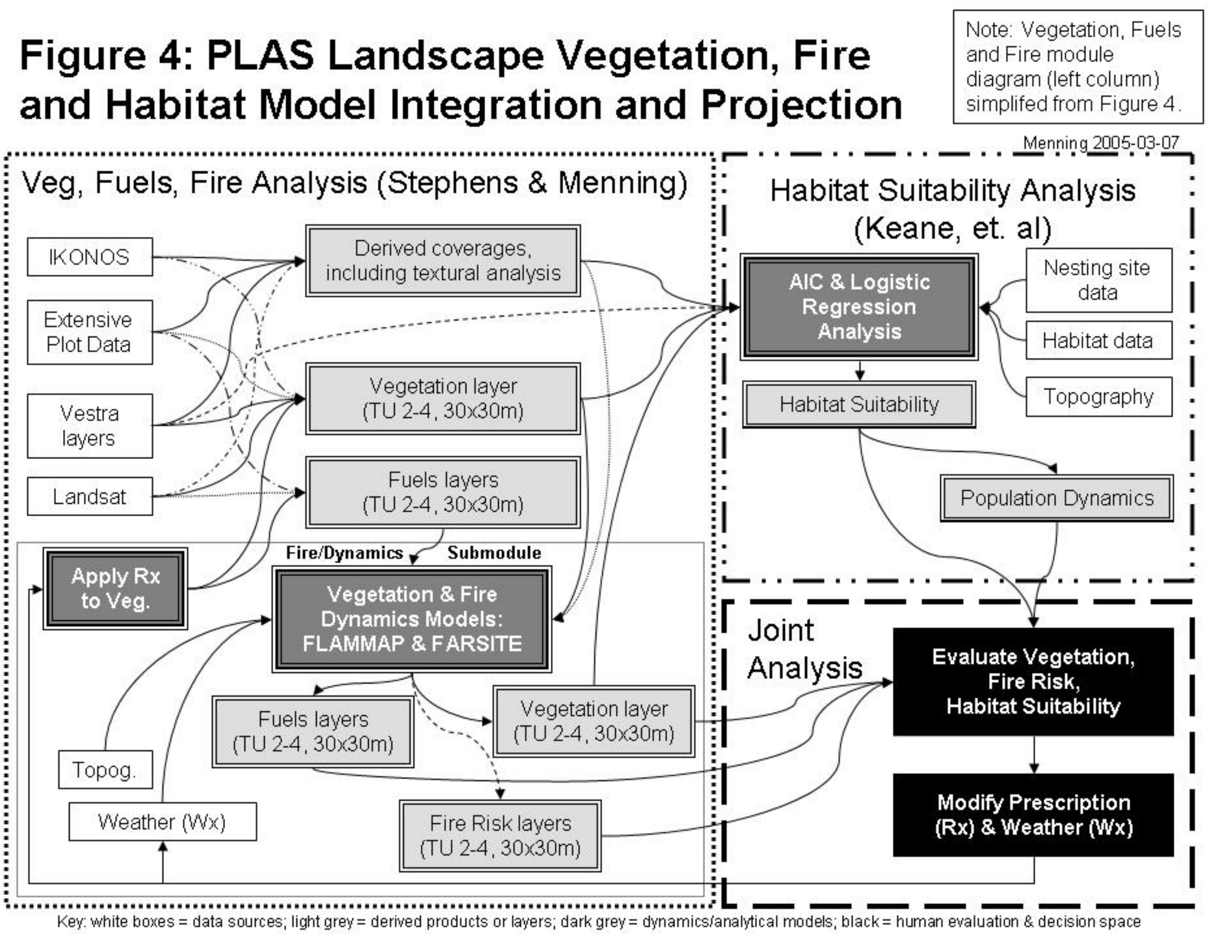
While there is a certain link between vegetation structure, pattern and composition and spotted owl core areas and home ranges (Keane and Blakesley 2005) exact measures of vegetation condition or change are not yet well defined. In addition, the link between different spatial scales of vegetation—extent and variation—and habitat selection is unknown. As a result, the definition of meaningful measures of vegetation condition and change, including appropriate scales of analysis from $30m^2$ to hundreds of hectares, will evolve along with the active analyses conducted in the Spotted Owl module (Keane and Blakesley 2005).

Fire and Habitat Model Integration

The final goal of the Fuels and Fire Module research is to coordinate with the Spotted Owl Module to produce a system in which an input of landscape-scale vegetation layers, weather scenarios, and fire events can be used to derive simultaneous assessments of fire and owl habitat. This effort requires separate but linked analyses by both our module and the Spotted Owl

Module analysts (Keane and Blakesley 2005). The fuels and fire module will use inputs of IKONOS imagery (described above, and in appendix E of Study Plan), extensive plot data, and pre-existing VESTRA vegetation classification data to produce derived coverages, including base vegetation layers. These vegetation layers will be passed to both the Owl Module and the fire behavior and effects part of this module's study. Analysts in the Owl Module use the layers in their Akaike Information Criteria (AIC) and regression analyses to determine owl habitat suitability (Keane and Blakesley 2005).

These paired analytical efforts—fire and wildlife habitat—will yield results covering the same landscape at the same time given the same weather and treatments. Fire behavior and effects and habitat will be evaluated jointly. Revised prescriptions for landscape fuels treatments (such as DFPZs) will be drafted along with a defined set of potential weather scenarios. These prescriptions and scenarios will be used to update the base vegetation layer to a post-treatment condition. Then, the whole process is repeated, with emphasis on analysis of the results (figure 4, Appendix B).



The net result of this collaborative effort will be an integrated analysis of the landscape-level effects of any potential fuels treatments and weather scenarios on both fire and owl habitat. We anticipate that other modules—Small Mammals and Songbird—may be able to develop habitat suitability analysis from vegetation layers that will enable them to integrate with this model, as well. As an interim step, we can probably crudely assess habitat of songbirds and small mammals using the California Wildlife Habitat Relationships system which links vegetation characteristics to the known habitat needs of different wildlife species. Eventually, empirical models derived from the research of the Songbird and Small Mammal Modules could supplant these coarser models.

Coordination with Interested Parties

We plan to work closely with Mark Finney, a fire-modeling expert in Missoula, Montana on FARSITE and FlamMap fire assessments. In addition, we anticipate close coordination with fire management offices at the Forest Service districts. In 2003, for example, we supplied forest structural data to the Plumas National Forest to use in its forest management planning.

Accomplishments in 2006: Results

Field

A field crew of two seasonal workers—Bridget Tracy and Nicholas Delaney—were trained in field work by Kurt Menning. Tracy and Delaney worked in the field for three months, from late May to late August. The field crew collected data from 178 plots this summer. Seventy of the sites had previously been inventoried: 51 plots were revisits of previously established plots (2003) and 19 were replacement plots for those that were eradicated by logging operations. An additional 108 new plots were established throughout the study area (TUs 2-4). In contrast to the previous plots, which were stratified random, these new plots were located at true random locations across the forest without bias for vegetation type, elevation or aspect. The total number of plots inventoried through 2006 is 602 (Table 2). Of these, 494 plots are stratified by slope, elevation, aspect and vegetation type. The other 108 comprise a true random sampling of the same area.

Table 2: Differences between random and stratified plot data. The differences are not significant due to high variability.

Plot type	#	Trees per hectare	Standard dev. (sd)	Trees per acre	sd	Basal area (m^2/ha)	sd	Basal area (f^2/acre)	sd
random	108	651.7	363.2	263.7	147	42.7	24	186.1	105
stratified	494	569.6	362.0	230.5	146	41.6	24	181.3	107

Table 3: Composition of 17,583 trees in 602 plots sampled, including snags. Trees under 10 cm (4 inches) diameter at breast height (DBH) are not included in this table.

Species	Count	Percent	% Without snags
White fir	4963	28.2	30.9
Douglas-fir	4319	24.6	26.9
Incense-cedar	2433	13.8	15.1

Snag	1503	8.5	na
Ponderosa pine	1475	8.4	9.2
Black Oak	1272	7.2	7.9
Sugar pine	930	5.3	5.8
Canyon Live Oak	240	1.4	1.5
Other hardwoods	160	0.9	1.0
Jeffrey pine	156	0.9	1.0
Red fir	132	0.8	0.8
	17583	100.0	100.0

Table 4: Fuel averages over 602 plots.

	Litter Depth	Duff Depth	0-3" fuels	3-9" fuels	9-20" fuels	20"+ fuels	Total
	(cm, in)		(metric tons/ha, tons/acre)				
Metric	3.8	3.3	3.6	2.5	2.7	3.0	11.8
Standard	1.5	1.3	3.2	2.3	2.4	2.7	10.5

Remote Sensing

Remote sensing imagery was acquired for TU 3&4 (2003) and TU 2&3 (2004) (see Figures 5 & 6). These images have been orthorectified and radiometrically enhanced. Orthorectification entails mathematically correcting the geometry of the imagery to remove geographic error and distortion due to the topography. A suite of points located in the field using a high-resolution GPS allowed us to make this set of corrections. We performed radiometric corrections to eliminate haze scattering of blue light and adjust the differences in total illumination due to the angle of the sun given the time and date. With these changes, the imagery is completely pre-processed.

Our next phase of image analysis was creating interpretive coverages of the imagery for use in landscape habitat analysis by the rest of the study team. These coverages include spectral entropy canopy diversity analysis (Figures 7 & 8), supervised classifications (Figure 9), and object-oriented classifications of vegetation (Figure 10 & 11). Spectral Entropy Canopy Diversity Analysis (SpECDA, Menning 2003) measures variability in NDVI (normalized difference vegetation index) values in a local area. The result is an assessment of the heterogeneity in canopy cover both by type (vegetation versus non-vegetated) as well as variability within vegetation type (conifer, chaparral, oak).

Figure 5: Five scenes of IKONOS imagery from 2003 and 2004 arrayed over a digital elevation model (DEM) of the landscape.

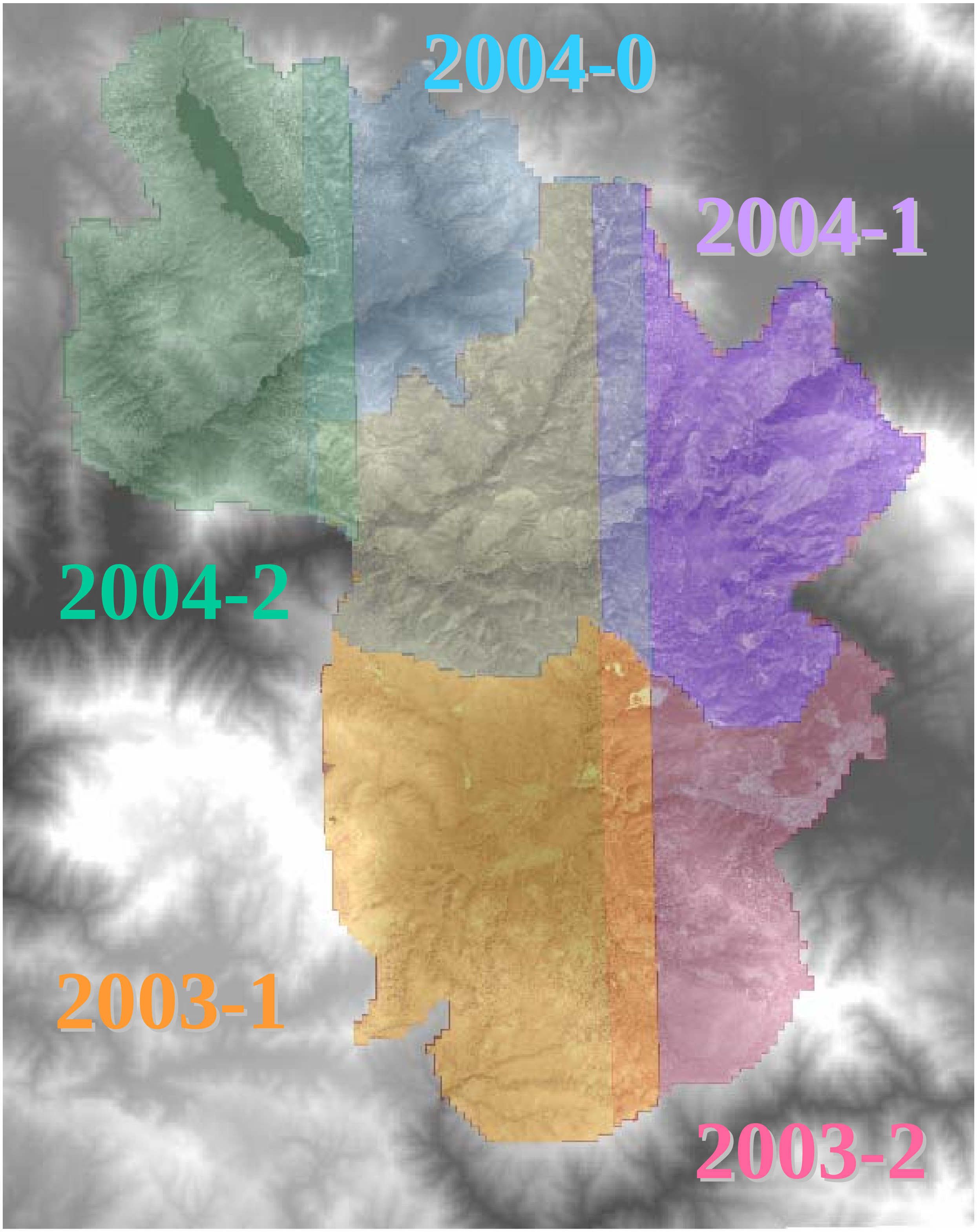


Figure 6: Three scenes of IKONOS imagery from 2004 displayed in true color.

Figure 7: One area, around Butt Valley Reservoir, shown with NDVI (Normalized Difference Vegetation Index), spectral entropy canopy diversity analysis (at plot scale), and SpECDA at the landscape scale.

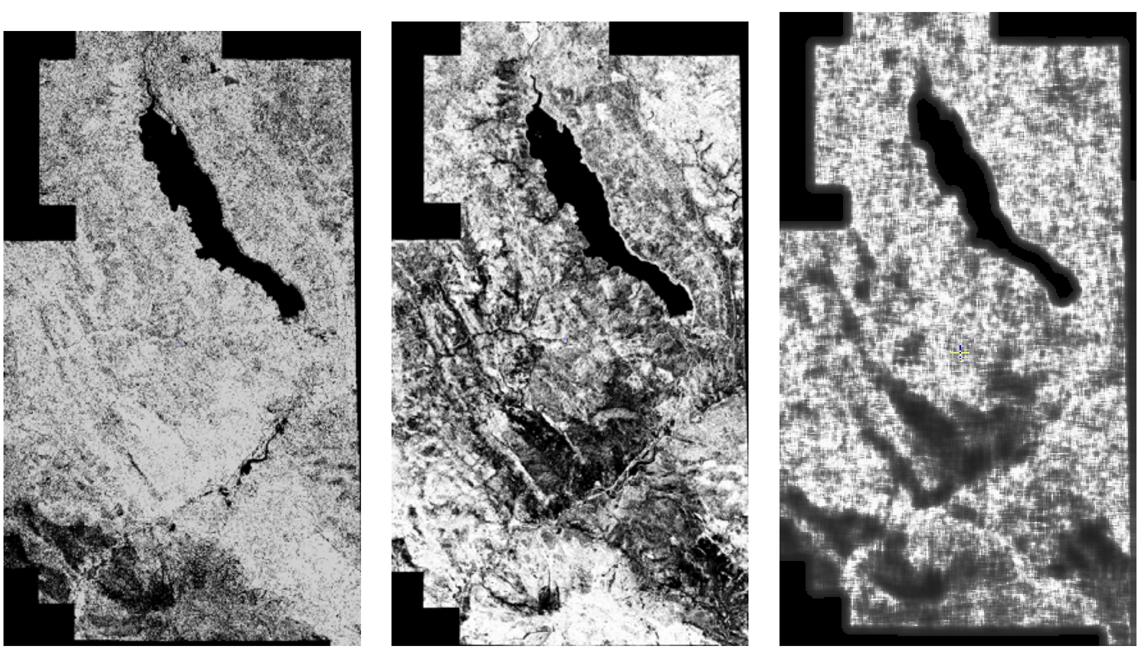


Figure 8: Close up of an area off Highway 70 showing NDVI (left) and SpECDA (right).

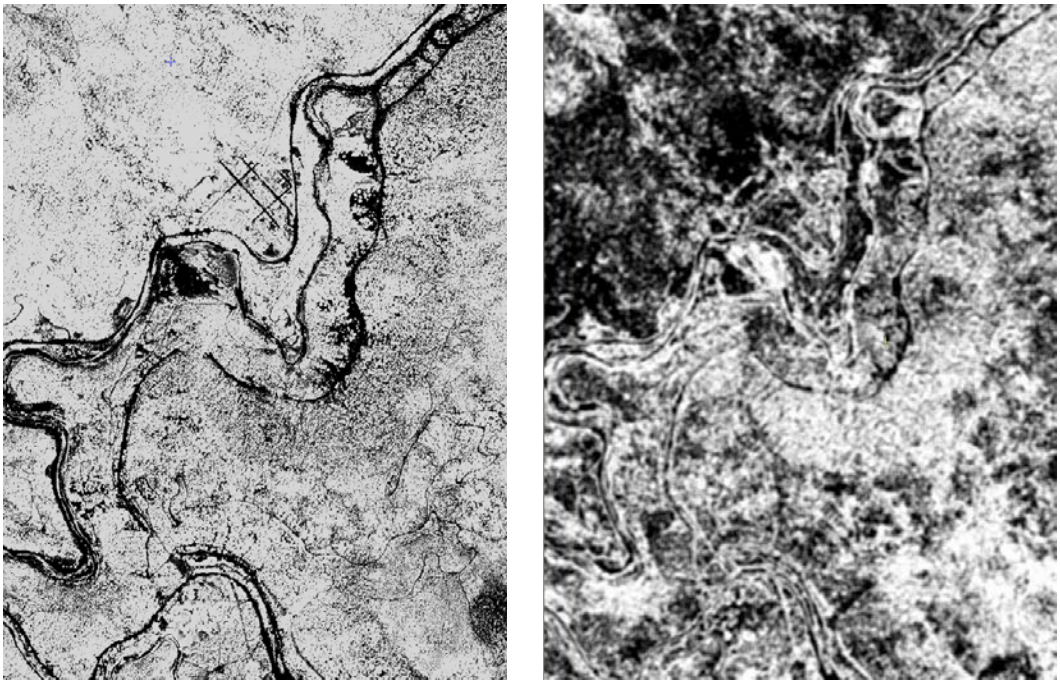


Figure 9: Pixel-based supervised classification of area around Butt Valley Reservoir. Dominant classification separates denser northern aspect forest from sparser southern aspect forest.

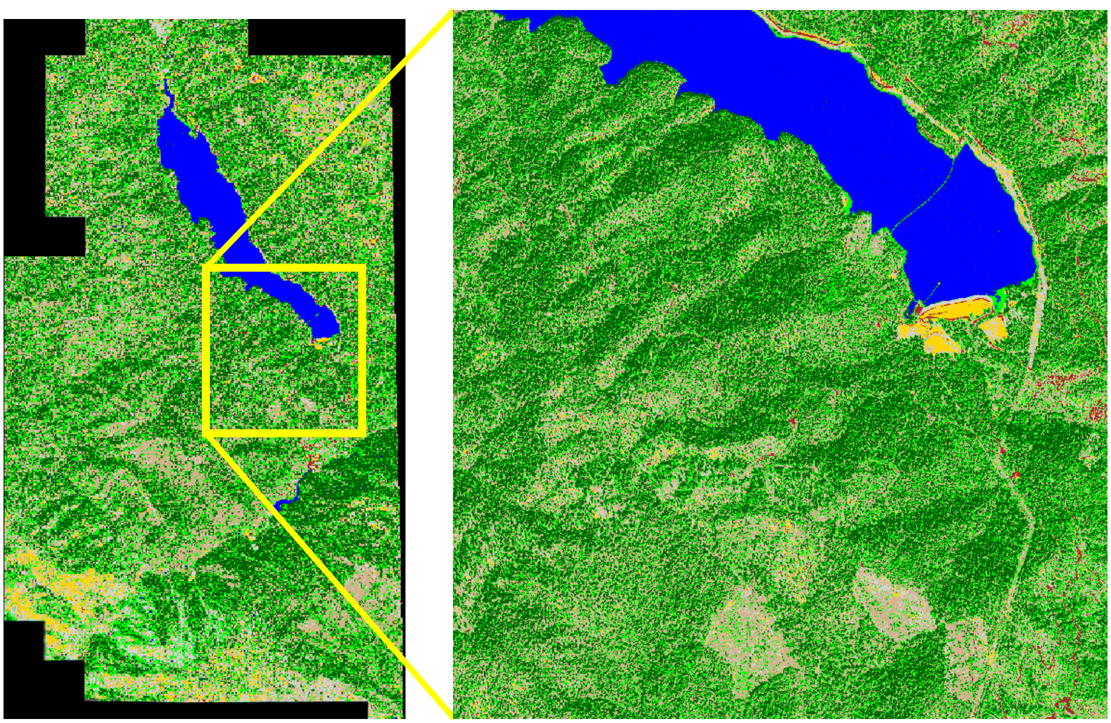


Figure 10: Object-oriented classification in eCognition of vegetation in the Butt Valley Reservoir area.

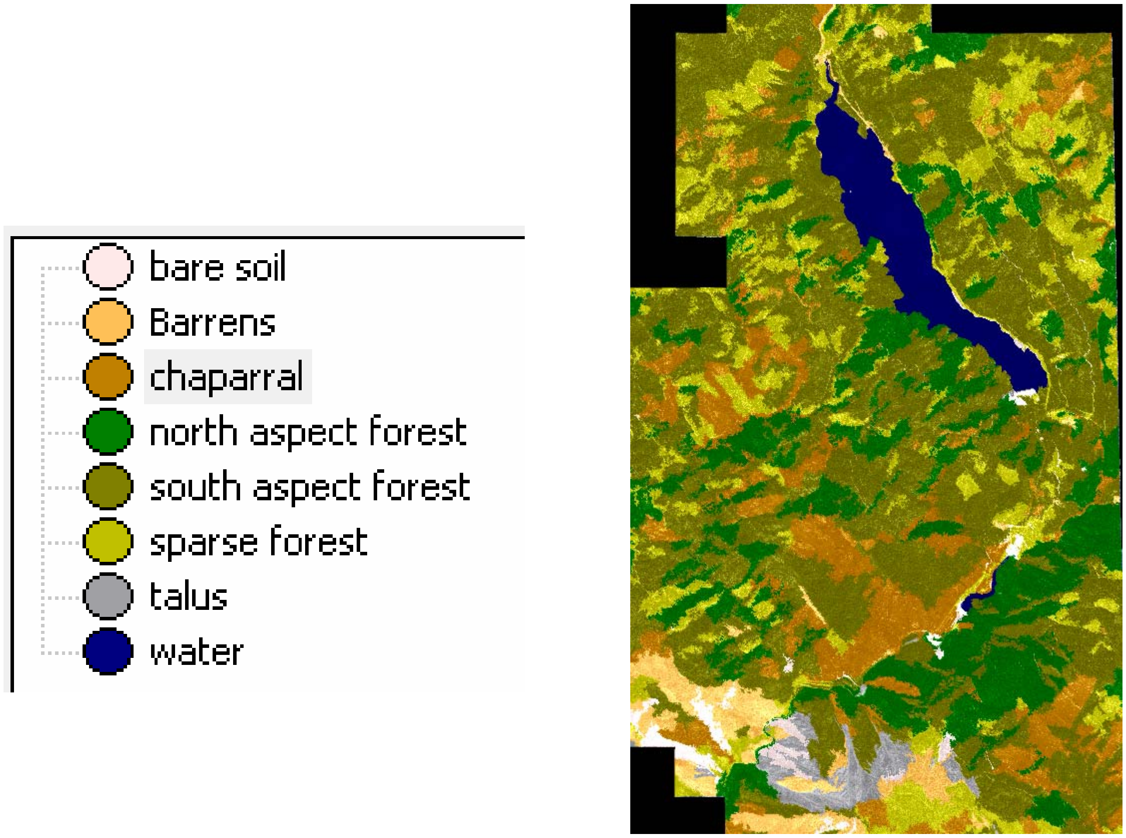
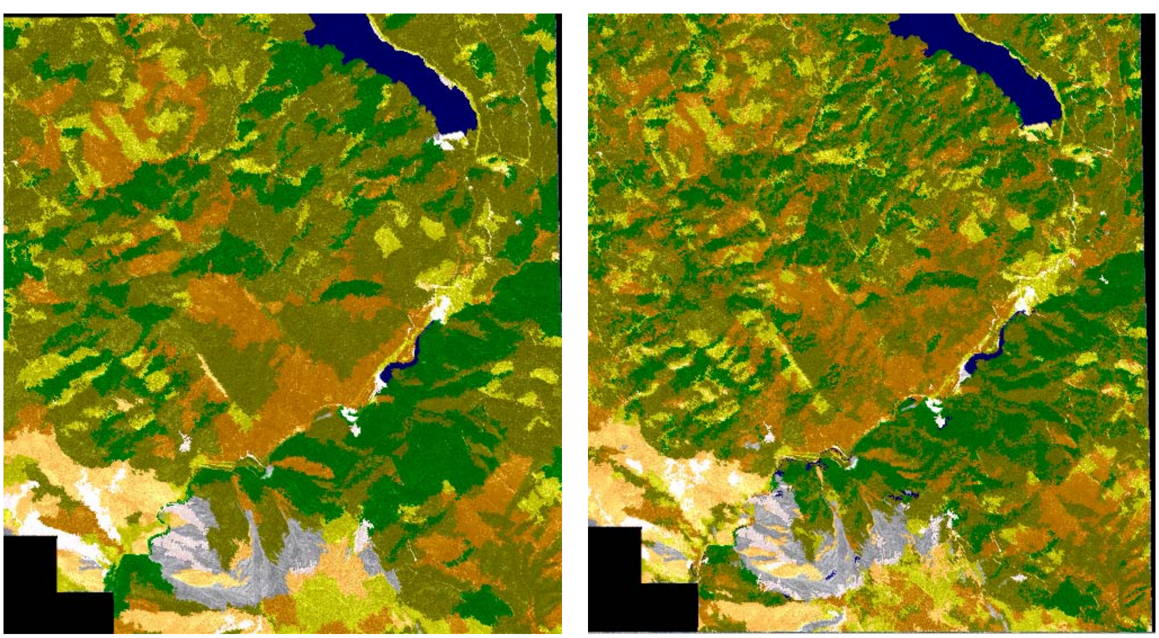


Figure 11: Close up of two different spatial scales of object-based classification.



Our next steps in the remote sensing analysis include performing accuracy assessment of classes using our extensive network of plots, verifying classes (north forest, south forest, rock, dirt, water, chaparral, etc.), identifying and extracting oaks from scenes and performing spatial analysis of classified images.

Modeling Fire and Integrating with Wildlife Habitat Analysis

We have begun the fire modeling with Farsite and Flammap. Initial results are being presented at the March meeting in Quincy. In January 2007, we attended USFS training in FVS software to perform the later phase of fire modeling. Test runs on real data are shown below. We are not presenting fire behavior data yet as thresholds and values are still being calibrated.

Figure 12: Actual data from plot 0014 inventoried in 2006 shown in Stand Visualization System (SVS). This is a very sparse plot with fair clearance from ground to lower live crown on most trees.

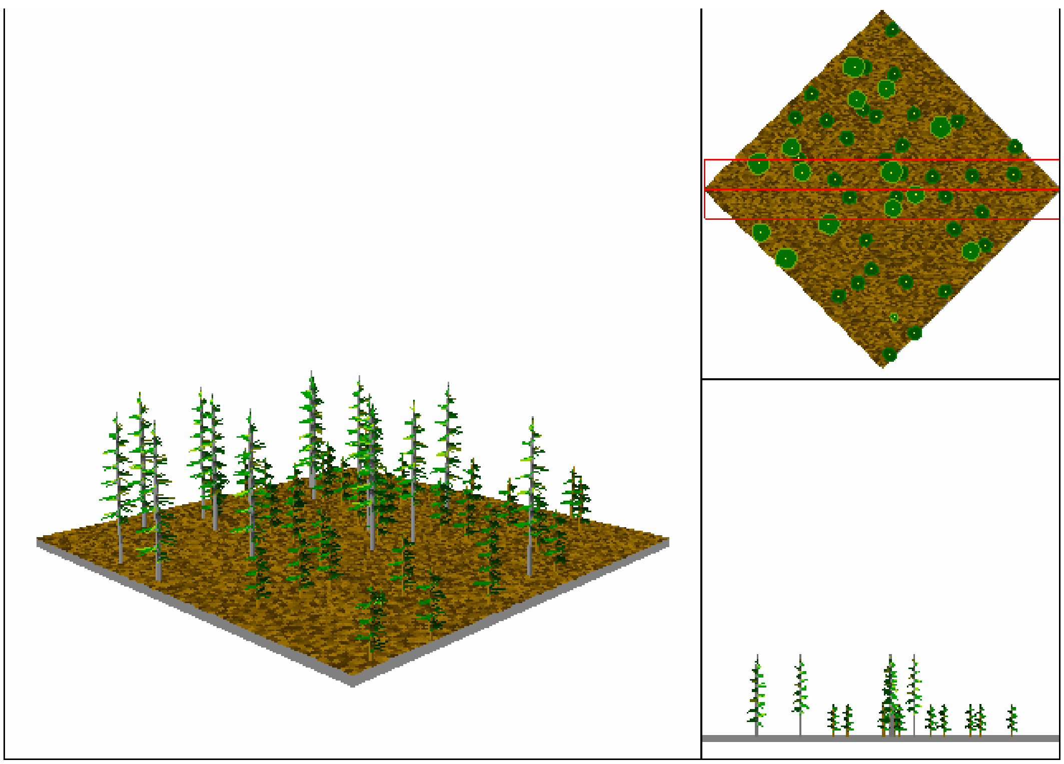


Figure 13: Actual data from plot 0014 shown burning under severe autumn conditions. Most trees survive but a number of small trees with canopy reaching to the ground torch.

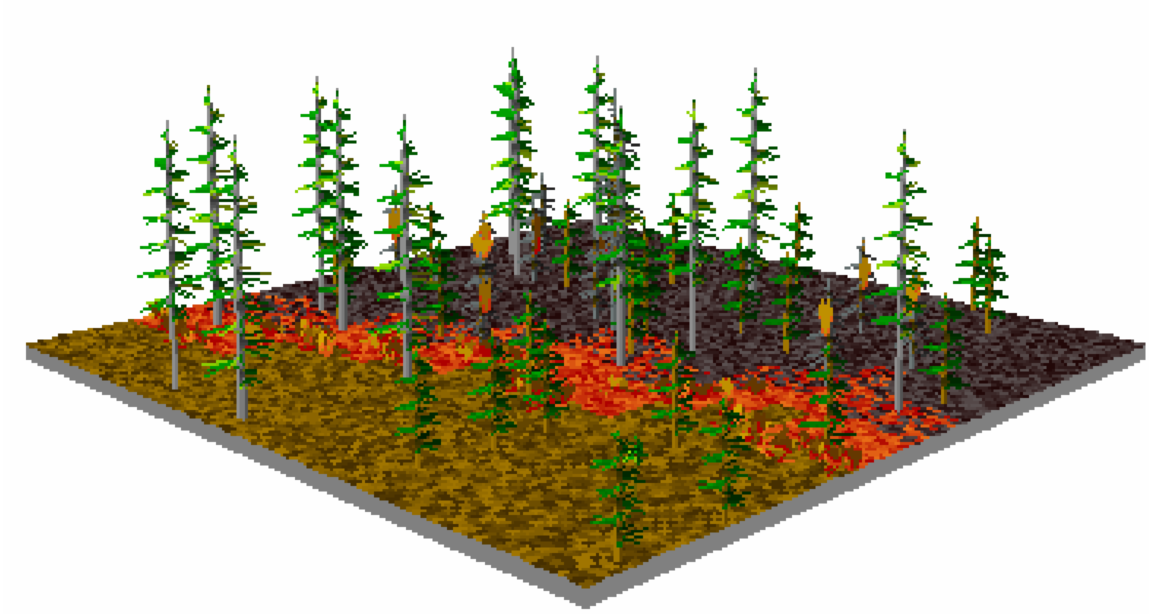


Figure 14: Actual data from plot 1172 inventoried in 2006. This is a dense stand of young trees overtopped by a single larger tree.

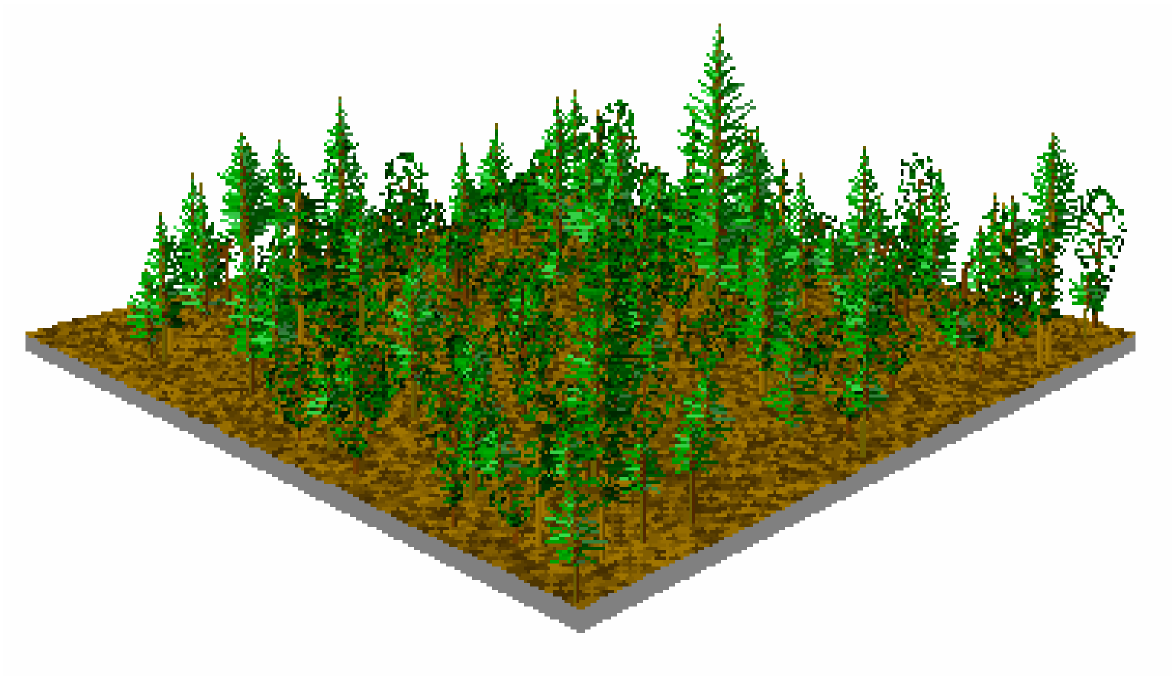


Figure 15: Plot 1172 experiencing moderately severe fire.

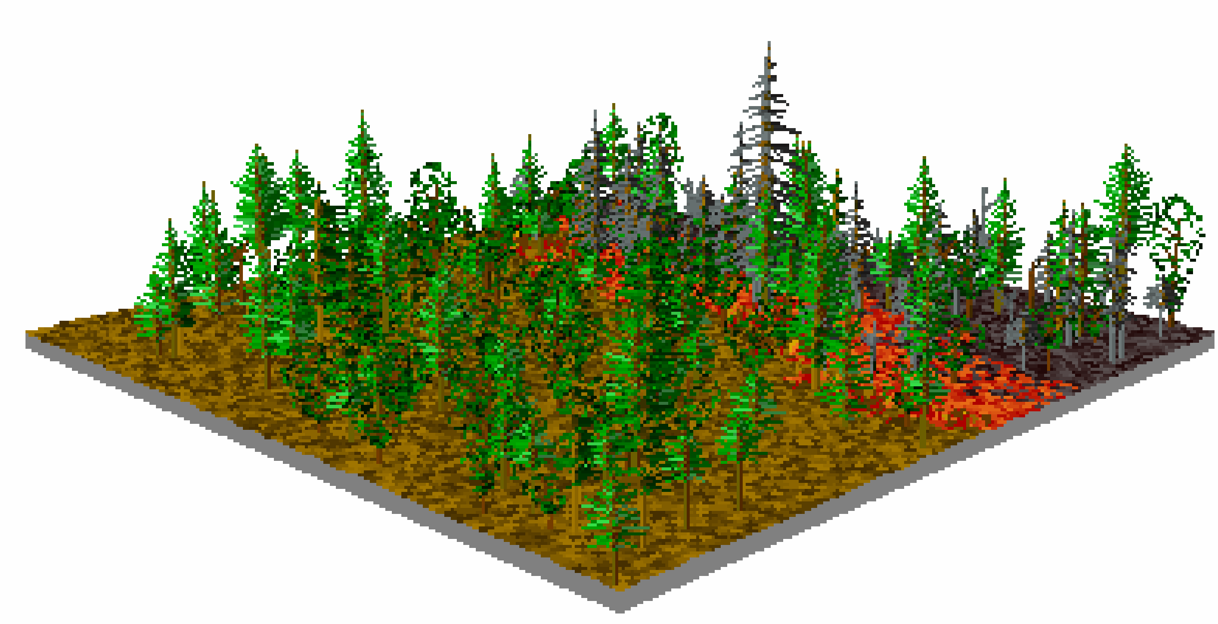


Figure 16: Projected data from plot 1172 shown 50 years in the future assuming standard rates of growth for this region of the Plumas.

Publications and Presentations 2005-7

- Menning, K.M., and S.L. Stephens (in press: 2006-7) Fire Climbing in the Forest: a semi-qualitative, semi-quantitative approach to assessing ladder fuel hazards, Western Journal of Applied Forestry.

- Menning, K. M. and S. L. Stephens (2007) Modeling potential fire based on current conditions across 60,000 ha in the northern Sierra Nevada (California, USA). US Branch International Association of Landscape Ecology Annual Meeting.

- Menning, K. M. and S. L. Stephens (2007) Comparing two populations of a Sierra Nevadan (California, USA) forest community as arrayed across elevational, aspect and slope gradients. US Branch International Association of Landscape Ecology Annual Meeting.

- Menning, K. M. and S. L. Stephens (2006). Modeling Landscape Fire Behavior and Effects in the Northern Sierra Nevada. 3rd International Fire Ecology and Management Congress, San Diego, CA.

- Menning, K. M. and S. L. Stephens (2006). Landscape-scale Fire Risk Wildlife Habitat Considered Jointly. 21st Annual Symposium of the United States Regional Chapter of the International Association for Ecology (US IALE), San Diego, CA.

- Menning, K. M. and S. L. Stephens (2006). Assessing Ladder Fuels in Forests. 3rd International Fire Ecology and Management Congress, San Diego, CA.

- Menning, K.M., and S. L. Stephens (2005) "Fire rising in the forest: Ladder fuel hazard assessment using a mixed qualitative and quantitative approach," Ecological Society of America, August 7-12, 2005, Montreal Canada. (Abstract attached to end of report).

- Menning, K. M. and S. L. Stephens (2005). (Invited speaker:) *Linking fire and wildlife habitat in California: Spectral entropy canopy diversity analysis*. UK Centre for Ecology and Hydrology, Monks Wood, Cambridgeshire, England, UK. November 21, 2005.

- Menning, K. M. and S. L. Stephens (2005). (Invited speaker:) *Spatial Ecological Links Between Fire, Forests and Habitat in the Plumas-Lassen Administrative Project*. Geographic Information Centre Seminar: City University, London, London, England UK. November 22, 2005.

- Menning, K. M. and S. L. Stephens (2005). (Invited speaker:) *Forest Structural Diversity: Spectral Entropy Canopy Diversity Analysis*. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland. December 5, 2005.

Goals for 2007

Spring

Furthering the remote sensing processing and analysis and fire behavior and effects modeling are our primary goals in spring. Integrative modeling of fire and habitat scenarios with John Keane and the owl module has been planned at a January 2007 meeting.

Field Season

We are not planning on putting a field crew out in the Plumas in 2007. We will be performing fire modeling and remote sensing analyses given current data instead.

Autumn

Autumn goals include publishing remote sensing and modeling analyses (please see the publications list).

Expected Products (Deliverables)

Results will be published regularly in the Plumas-Lassen Administrative Study Annual Reports. We will present results directly, as they are derived, to interested parties. More formal scientific publications are targeted covering a variety of areas including the LaFHA approach being piloted in this study, SpECDA analyses of forest structure and its variability, fire behavior and effects, integrated model results with the Owl Module, and assessments of the efficiency of DFPZs and other treatments in moderating the landscape-level effects of fire.

Additional Publications Planned for 2007

- Menning, K. M. and S. L. Stephens. "Spectral Entropy Canopy Diversity Analysis (SpECDA) used to Assess Variability in Forest Structure and Composition" submitted to Photogrammetric Engineering and Remote Sensing.
- Menning, K. M., S. L. Stephens, J. Keane, D. Kelt, and others. "Integrated modeling of fire and California Spotted Owl habitat conditions given different weather and landscape treatment scenarios" To be submitted to a journal mutually agreed upon.
- Menning, K. M. and S. L. Stephens. "Fire Behavior and Effects as a Result of Defensible Fuel Profile Zones" To be submitted to International Journal of Wildland Fire.
- Menning, K. M. and S. L. Stephens. "Landscape Forest Variability across the Northern Sierra Nevada" To be submitted to Landscape Ecology.

Additional publications based on analysis of the field data, remote sensing products, and results of integrative modeling with Keane.

Data Management and Archiving

All data will be archived with the USDA Forest Service's Sierra Nevada Research Center (SNRC) in Davis, California, as well as the Fire Science Lab (Stephens Lab) at the University of California, Berkeley. Some derived products will be put on-line by the SNRC or Stephens Lab.

Appendix A: Datasheet for field data collection, page 1 of 2

Plumas Veg Module — Data sheet

3/4/2004

Data for the whole plot								50m radial plot		Logs	
Plot		Date	UTM-E		UTM-N			Habitat typ		Snags <10	
			Aspect		Slope			Water Y/N		Snags 10-30	
			Recorders		Photo #			% Road		Snags >30	

Variable Radius (50m) Plot Species Tallies (panama angle gauge)

Species (live)											
Number stems											

50m Plot Layers + ---> Species and their percent cover

	Herb (+seed) (<50cm)	Real Shrub (0.5-5m)	Small tree (Tree shrub)	All veg 0.5-5 (Tot. shrub)	Big tree (Tree)
%cover					
Low Bnd					
Low Bnd Sp					
Up Bnd					
Up Bnd Sp					
DBH min					
DBH min sp					
DBH max					
DBH max sp					

Real shrub (0.5-5m)		Small Trees (tree shrub, 0-5m)		
Species	% Cover	Size class	Species	% Cover
		Small Tree		
		(Tree Shr)		
		(<5m)		
			total	100%
		Big Tree		
		(Tree, >5m)		
total	100%		total	100%

12.6 m Radial Plot Fuels & Fire Risk Assessments

Fuel Photo Series		LaFHA			
Fuel size	Count	Quadrants	Haz. Rating	Min Cr Ht	Max Lad Gap
0-3"		N (1)			
3-9"		E (2)			
9-20"		S (3)			
>20"		W (4)			

Brown's Transects 12.6m

Tallies	1 hr (0-0.6cm)	10 hr (0.6-2.5)	100 (2.5-7.6)	Litter @ 5	Duff @ 5	Litter @ 12	Duff @ 12	max depth 1	max depth 2	max depth 3	Sight tube
A											
B = A+90											
A: 1000hr	Diam										
	Sound/Rot										
Shrubs	Species										
	Length										
	Ht class										
B: 1000hr	Diam										
	Sound/Rot										
Shrubs	Species										
	Length										
	Ht class										

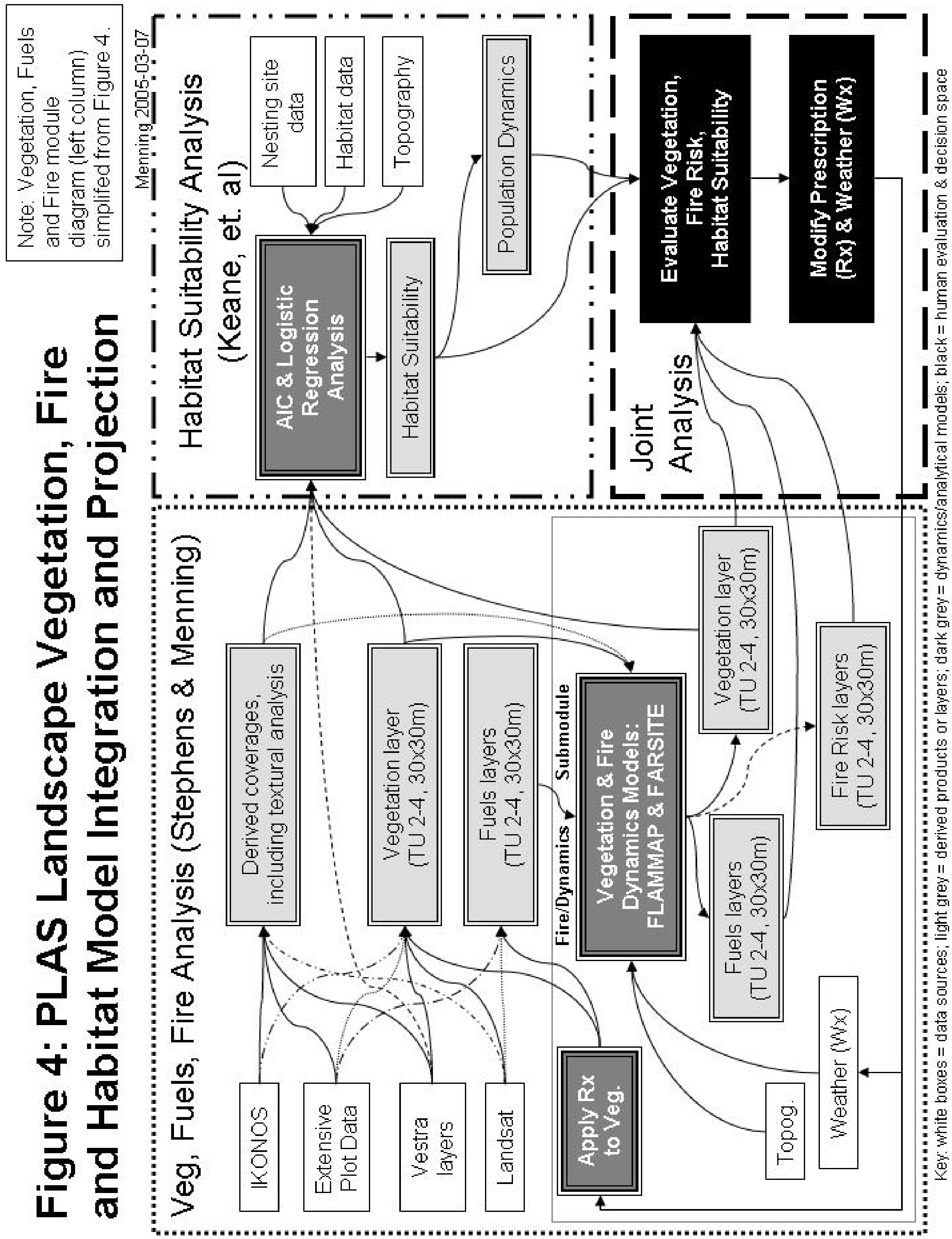
Appendix A (continued): Datasheet for field data collection, page 2 of 2

Plot ______

Sheet 2

Trees in 12.6m radius plot								Snags in 12.6m radius plot			
Species	DBH	Height	Ht. Low Cr.	Cr. Width	Shape	Mistletoe 0-6		DBH	Ht. Class	Decay class	Cav>10cm

Appendix B: Model integration with California Spotted Owl team (Keane)



Literature Cited

Agee, J. K. (1998). "The Landscape Ecology of Western Forest Fire Regimes." Northwest Science **72**(Special Issue): 24-34.

Agee, J. K. (2003). Personal communication.

Agee, J. K., B. Bahro, et al. (2000). "The use of shaded fuelbreaks in landscape fire management." Forest Ecology and Management **127**(1-3): 55-66.

Bahro, B. (2004). Hazardous Fuels and Vegetation Treatment Processes and Tools Under Development by R5, PNW Research Station and RM Research Stations, USDA Forest Service.

Barbour, M. G. and J. Major, Eds. (1995). Terrestrial Vegetation of California: New Expanded Edition. Davis, California Native Plant Society.

Beesley, D. (1995). Reconstructing the Sierra Nevada Landscape: An Environmental History 1820-1960, Sierra Nevada Ecosystem Project (SNEP).

Benkelman, C. A., D. Verbyla, et al. (1992). Application of high resolution digital imagery to forest studies. Proceedings of the 1992 ASPRS-ACSM Annual Meeting.

Bettinger, P., D. Graetz, et al. (2002). "Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems." Silva Fennica **36**(2): 561-584.

Birky, A. K. (2001). "NDVI and a simple model of deciduous forest seasonal dynamics." Ecological Modelling **143**(1-2): 43-58.

Biswell, H. H. (1961). "The Big Trees and Fire." National Parks and Conservation Magazine **35**: 11-14.

Blakesley, J. A., B. R. Noon, et al. (In Press). "Site occupancy, apparent survival and reproduction of California spotted owls in relation to forest stand characteristics." Journal of Wildlife Management.

Blonski, K. S. and J. L. Schramel (1993). Photo series for quantifying natural forest residues: Southern Cascades, Northern Sierra Nevada. Boise, Idaho, National Interagency Fire Center.

Bongers, F. (2001). "Methods to assess tropical rain forest canopy structure: An overview." Plant Ecology **153**(1-2): 263-277.

Bonnicksen, T. M. and E. C. Stone (1980). "The Giant Sequoia-Mixed Conifer Forest Community Characterized Through Pattern Analysis as a Mosaic of Aggregations." Forest Ecology and Management **3**: 307-328.

Bonnicksen, T. M. and E. C. Stone (1982). "Managing vegetation within U.S. National Parks: A Policy Analysis." Environmental Management **6**: 101-102, 109-122.

Bonnicksen, T. M. and E. C. Stone (1982). "Reconstruction of a presettlement giant sequoia-mixed conifer forest community using the aggregation approach." Ecology **63**: 1134-1148.

Brown, J. K. (1974). Handbook for inventorying downed woody material. Ogden, Utah, Intermountain Forest and Range Experiment Station Forest Service U.S. Dept. of Agriculture.

Brown, J. K., R. D. Oberheu, et al. (1982). Handbook for inventorying surface fuels and biomass in the interior West. Ogden, Utah, U.S. Dept. of Agriculture Forest Service Intermountain Forest and Range Experiment Station.

Burgan, R. E. and R. C. Rothermel (1984). BEHAVE: fire behavior prediction and fuel modeling system - Fuel modeling subsystem. USDA Forest Service General Technical Report INT-167., Intermountain Research Station, Ogden, Utah.**:** 126p.

Cohen, W. B. (1994). GIS applications perspective: Current research on remote sensing of forest structure.

Cohen, W. B. and T. A. Spies (1992). "Estimating structural attributes of Douglas-fir / Western Hemlock forest stands from Landsat and SPOT imagery." Remote Sensing of Environment **41**: 1-17.

Conners, R. W. and C. A. Harlow (1980). A Theoretical Comparison of Texture Algorithms. IEEE Tr. on Pattern Analysis and Machine Intelligence. **PAMI-2, No. 3**.

Duncan, B. W. and P. A. Schmalzer (2004). "Anthropogenic influences on potential fire spread in a pyrogenic ecosystem of Florida." Landscape Ecology **19**(2): 153-165.

Erman, D., Ed. (1996). Summary of the Sierra Nevada Ecosystem Project Report (SNEP). Davis, California, Centers for Water and Wildland Resources.

Finney, M. A. (1996). FARSITE: Fire Area Simulator. Users' Guide and Technical Documentation. Missoula, Montana (USA), Systems for Environmental Management**:** 116.

Finney, M. A. (1998). FARSITE: Users Guide and Technical Documentation. Missoula, Montana (USA), USDA Forest Service Research Paper**:** 47.

Finney, M. A. (1999). Some effects of fuel treatment patterns on fire growth: A simulation analysis of alternative spatial arrangements. Appendix J: Fire and fuels. Herger-Feinstein Quincy Library Group Forest Recovery Act Final EIS, USDA Forest Service, PSW.

Finney, M. A. (2000). Efforts at Comparing Simulated and Observed Fire Growth Patterns. Missoula, Montana (USA), Systems for Environmental Management.

Finney, M. A. (2001). "Design of regular landscape fuel treatment patterns for modifying fire growth and behavior." Forest Science **47**: 219-228.

Finney, M. A. (2003). FlamMap: Fire Behavior Mapping and Analysis Model. http://fire.org/.

Finney, M. A. and K. C. Ryan (1995). Use of the FARSITE fire growth model for fire prediction in US National Parks. The International Emergency Management and Engineering Conference, Sofia Antipolis, France.

Fites-Kaufman, J. A. (2004). Personal communication, USFS Adaptive Management Services Enterprise Team.

Fites-Kaufman, J. A., D. Weixelman, et al. (2001). Forest Health Pilot Monitoring Report: Vegetation, Fuels, Wildlife Habitat, USFS Adaptive Management Services Enterprise Team.

Forman, R. T. T. (1995). Land Mosaics: The ecology of landscapes and regions. Cambridge, England, Cambridge University Press.

Forman, R. T. T. (1995). "Some general principles of landscape and regional ecology." Landscape Ecology **10**(3): 133-142.

Franklin, J. (1986). "Thematic mapper analysis of coniferous forest structure and composition." International Journal of Remote Sensing **7**: 1287-1301.

Fujioka, F. M. (2002). "A new method for the analysis of fire spread modeling errors." International Journal of Wildland Fire **11**(3-4): 193-203.

Gamon, J. A., C. B. Field, et al. (1995). "Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types." Ecological Applications **5**(1): 28-41.

Gong, P. (1995). Remote Sensing and Image Analysis. Berkeley, California.
Griffen, J. R. and W. B. Critchfield (1976). The Distribution of Forest Trees in California. Berkeley, CA, USDA Forest Service.
Hall, F. G., Y. E. Shimabukuro, et al. (1995). "Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models." Ecological Applications **5**(4): 993-1013.
Haralick, R. M. (1979). Statistical and Structural Approaches to Texture. Proceedings of the IEEE. **67 no. 5:** 786-804.
Haralick, R. M., K. Shanmugan, et al. (1973). Textural Features for Image Classification. IEEE Tr. on Systems, Man, and Cybernetics. **SMC-3, No. 6:** pp. 610-621.
Hartesveldt, R. J. and H. T. Harvey (1967). The fire ecology of sequoia regeneration. Proceedings of the 6th Tall Timbers Fire Ecology Conference, Tallahassee, FL.
Holland, V. L. and D. J. Keil (1995). California Vegetation. Dubuque, Iowa, Kendall/Hunt Publishing Company.
Hunsaker, C. T., B. B. Boroski, et al. (2002). Relations between canopy cover and the occurrence and productivity of California spotted owls. Predicting Species Occurrences: Issues of Accuracy and Scale. J. M. Scott, P. J. Heglund and M. L. Morrison. Washington, DC**:** 687-700.
Jensen, J. R. (1996). Introductory digital image processing: a remote sensing perspective. Upper Saddle River, N.J., Prentice Hall.
Johnson, E. A., K. Miyanishi, et al. (2001). "Wildfire regime in the boreal forest and the idea of suppression and fuel buildup." conservation biology **15**(6): 1554-1557.
Keane, J. (2004). Annual Report on the Spotted Owl Module (Appendix E) in the Plumas-Lassen Administrative Study, Sierra Nevada Research Center, USDA Forest Service, Davis, CA.
Keane, J. J. and J. A. Blakesley (2005). California Spotted Owl Module: Study Plan, Sierra Nevada Research Center, USDA Forest Service, Davis, CA.
Keane, R. E., P. Morgan, et al. (1999). "Temporal patterns of ecosystem processes on simulated landscapes in Glacier National Park, Montana, USA." Landscape Ecology **14**(3): 311-329.
Kolasa, J. (1989). "Ecological Systems in Hierarchical Perspective: breaks in community structure and other consequences." Ecology **70**: 36-47.
Latham, P. A., H. R. Zuuring, et al. (1998). "A method for quantifying vertical forest structure." Forest Ecology and Management **104**(1-3): 157-170.
Lee, D. C. and L. L. Irwin. (In press). Assessing risk to spotted owls from forest thinning in fire-adapted forests of the western United States.
Lillesand, T. M. and R. W. Kiefer (2000). Remote sensing and image interpretation. New York, John Wiley & Sons.
Linn, R., J. Reisner, et al. (2002). "Studying wildfire behavior using FIRETEC." International Journal of Wildland Fire **11**: 233-246.
Maus, P. E., M. L. Golden, et al. (1996). Guidelines for the use of digital imagery for vegetation mapping. Washington, DC U.S. Dept. of Agriculture, Forest Service, Engineering Staff,.
Mbow, C., K. Goita, et al. (2004). "Spectral indices and fire behavior simulation for fire risk assessment in savanna ecosystems." Remote Sensing of Environment **91**(1): 1-13.
Menning, K. M. (2003). Forest Heterogeneity: Methods and Measurements From Extensive Field Plots, Fire Modeling, and Remote Sensing of the Mixed Conifer Forest of the

Southern Sierra Nevada, USA (Ph.D. Dissertation). Wildland Resource Science, University of California, Berkeley.
Menzel, J. P. and W. W. Covington (1995). "Changes in forest structure since fire regime disruption in the Walnut Canon area, northern Arizona." Bulletin of the Ecological Society of America **76**(2 SUPPL. PART 2): 181.
Musick, H. B. and H. D. Grover (1991). Image textural analysis as indices of landscape pattern. Quantitative Methods in Landscape Ecology. M. G. Turner and R. H. Gardner. Ann Arbor, Springer**:** 77-104.
Parker, G. G. and M. J. Brown (2000). "Forest canopy stratification: Is it useful?" American Naturalist **155**(4): 473-484.
Parsons, D. J. and S. H. Debenedetti (1979). "Impact of fire suppression on a mixed-conifer forest." Forest Ecology and Management **2**: 21-33.
Peddle, D. R. and S. E. Franklin (1991). "Image texture processing and data integration for surface pattern discrimination." Photogrammetric Engineering and Remote Sensing **57**(4): 413-20.
Pyne, S. J., P. L. Andrews, et al. (1996). Introduction to Wildland Fire. New York, John Wiley & Sons, Inc.
Ricotta, C., G. C. Avena, et al. (1996). "Analysis of human impact on a forested landscape of central Italy with a simplified NDVI texture descriptor." International Journal of Remote Sensing **17**(14): 2869-2874.
Rothermel, R. C. (1972). A mathematical model for fire spread predictions in wildland fuels, USDA Forest Service**:** 40.
Roy, D. P. (1997). "Investigation of the maximum Normalized Difference Vegetation Index (NDVI) and the maximum surface temperature (T-s) AVHRR compositing procedures for the extraction of NDVI and T-s over forest." International Journal of Remote Sensing **18**(11): 2383-2401.
Rundel, P. W., D. J. Parsons, et al. (1995). Montane and Subalpine Vegetation of the Sierra Nevada and Cascade Ranges. Terrestrial Vegetation of California: New Expanded Edition. M. G. Barbour and J. Major. Davis, California Native Plant Society.
Rykiel, E. J. (1996). "Testing ecological models: the meaning of validation." Ecological Modelling **90**: 229-244.
Sawyer, J. O. and T. Keeler-Wolf (1995). A manual of California vegetation. Sacramento, CA, California Native Plant Society.
Stephens, S. L. (1998). "Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests." Forest Ecology and Management **105**(1-3): 21-35.
Stephens, S. L. (2001). "Fire history of adjacent Jeffrey pine and upper montane forests in the Eastern Sierra Nevada." International Journal of Wildland Fire **10**: 161-176.
Stephens, S. L. (2004). Personal communication.
Stephens, S. L. and M. A. Finney (2002). "Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion." Forest Ecology and Management **162**(2-3): 261-271.
Stephenson, N. L. (1988). Climatic control of vegetation distribution: the role of the water balance with examples from North America and Sequoia National Park, California. Ithaca, NY, Cornell University.

Stephenson, N. L. (2000). Overview of Sierra Nevada Forest Dynamics: Pattern, Pace, and Mechanisms of Change.

Stephenson, N. L., D. J. Parsons, et al. (1991). Restoring Natural Fire to the Sequoia-Mixed Conifer Forest: Should Intense Fire Play a Role? Proceedings 17th Tall Timbers Fire Ecology Conference, High Intensity Fire in Wildlands: Management Challenge and Options, Tall Timbers Research Station, Tallahassee, FL.

Stine, P., M. Landram, et al. (2002). Fire and Fuels Management, Landscape Dynamics, and Fish and Wildlife Resources: An Integrated Research Plan on the Plumas and Lassen National Forests, Sierra Nevada Research Center, USDA Forest Service, Davis, CA.

Sturtevant, B. R., P. A. Zollner, et al. (2004). "Human influence on the abundance and connectivity of high-risk fuels in mixed forests of northern Wisconsin." Landscape Ecology **19**(3): 235-253.

Taylor, A. H., Q. Zishen, et al. (1996). "Structure and dynamics of subalpine forests in the Wang Lang Natural Reserve, Sichuan, China." Vegetatio **124**: 25-38.

USDA Forest Service (2002). Cone Fire Burns Experimental Forest, Lassen National Forest.

USDA Forest Service (2004). Cottonwood Fire Update, Plumas National Forest.

van Wagtendonk, J. W., J. M. Benedict, et al. (1996). "Physical properties of woody fuel particles of Sierra Nevada conifers." International Journal of Wildland Fire **6**(3): 117-123.

van Wagtendonk, J. W. and R. R. Root (2003). "The use of multi-temporal Landsat Normalized Difference Vegetation Index (NDVI) data for mapping fuel models in Yosemite National Park, USA." International Journal of Remote Sensing **12 (in press)**: 1-29.

van Wagtendonk, J. W. and W. M. Sydoriak (1998). "Fuel Bed Characteristics of Sierra Nevada Conifers." Western Journal of Applied Forestry **13**(3): 73-84.

Wang, L. (2002). Automatic Extraction of Ecological Parameters for Individual Trees from High-Spatial Resolution Remote Sensing Images. UC Berkeley ESPM Colloquium Series, November 18, 2002.

Wessman, C. A., G. Asner, et al. (2001). "Remote sensing of forest structure and biophysical properties indicating forest response to chronic nitrogen deposition." Ecological Society of America Annual Meeting Abstracts **86**: 232.