Title

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ENVIRONMENTAL ASSESSMENT

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Abstract Past forest management practices, fire suppression, and climate change are increasing the need to actively manage California Sierra Nevada forests for multiple environmental amenities. Here we present a relatively low-cost, repeatable method for spatially parsing the landscape to help the U.S. Forest Service manage for different forest and fuel conditions to meet multiple goals relating to sensitive species, fuels reduction, forest products, water, carbon storage, and ecosystem restoration. Using the Kings River area of the Sierra Nevada as a case study, we create areas of topographically-based units, Landscape Management Units (LMUs) using a three by three matrix (canyon, mid-slope, ridge-top and northerly, southerly, and neutral aspects). We describe their size, elevation, slope, aspect, and their difference in inherent wetness and solar radiation. We assess the predictive value and field applicability of LMUs by using existing data on stand conditions and two sensitive wildlife species. Stand conditions varied significantly between LMUs, with canyons consistently having the greatest stem and snag densities. Pacific fisher (*Martes pennanti*) activity points (from radio telemetry) and California spotted owl (*Strix occidentalis occidentalis*) nests, roosts, and sightings were both significantly different from uniform, with a disproportionate number of observations in canyons, and fewer than expected on ridge-tops. Given the distinct characteristics of the LMUs, these units provide a relatively simple but ecologically meaningful template for managers to spatially allocate forest treatments, thereby meeting multiple National Forest objectives. These LMUs provide a framework that can potentially be applied to other fire-dependent western forests with steep topographic relief.

Keywords Ecosystem management · Fuels treatment · Prescribed fire · Restoration · Sierra Nevada · Threatened and endangered species

Introduction

California's Sierra Nevada forests, like most western montane forests in the United States, are highly modified from pre-European (c. 1865) settlement conditions (McKelvey and Johnson 1992). Fire suppression policies over the last century, harvesting practices, and expanding urban development have all influenced the structure, composition and function of these Sierra mixed-conifer forests. These practices have caused high levels of fuels to accumulate and more destructive fires to occur in many forest types (Skinner and Chang 1996; Taylor 2000; Miller and others 2009). While fuels management strategies can have significant public support from local residents and industry, environmental groups often challenge fuel treatments over possible impacts to threatened and endangered species (TES) (Laband and others 2006), many of which are associated with old-forest conditions (often referred to as old-growth forests). In addition, there has been a differential loss of other ecologically important, high net primary productivity vegetation communities such as riparian and wetland areas and increasingly expensive public demands to protect the wildland-urban interface from fire (Radeloff and others 2005).

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In response, forest management goals are evolving from an historic emphasis on natural resource extraction in the pre-1980s to a portfolio paradigm. Management of U.S. National Forests is now more driven by balancing wildlife, fuels reduction, forest products, ecosystem services (notably watershed function and carbon storage), ecosystem restoration, other non-extractive uses, and constrained by regulatory concerns such as the Endangered Species Act (ESA). Management approaches also need to be flexible enough to adapt to future uncertainties, such as climate change. To achieve these goals, various strategies have been proposed and implemented for managing the Sierra on a spatially-explicit basis: targeted timber and salvage sales, spotted owl and Pacific fisher protection zones, watershed protection areas, defense buffers around habitation sites, and delineated areas to achieve immediate fuels reductions and lessen the impact of large fires, such as Spatially Placed Area Fuel Treatments (SPLATS) (Finney 2001; North and others 2009). However, the potential contribution of individual forest stands to this range of management goals vary widely and are far from perfectly correlated.

In order to meet multiple management objectives and optimize the valuable services produced by public lands, an approach is needed which identifies the location and landscape context of spatial units best allocated to each use or management regime. For example, conserving habitat for certain sensitive wildlife species requires providing specific stand structures associated with preferred use sites (i.e., nests, dens, resting sites, etc.) as well as geographically broader foraging and movement habitat. Some of the sensitive species that most impact management in the Sierra Nevada prefer old-forest conditions that, with fire suppression, have developed high surface and ladder fuel loads. For instance, both the Pacific fisher (*Martes pennanti*) and California spotted owl (*Strix occidentalis occidentalis*) rest and nest, respectively, in dense stands with high canopy cover and large logs and snags (North and others 2000; Zielinski and others 2004). During wildfires, these sites are prone to high severity burns, which can incinerate canopy cover and kill many large old trees. Landscapes also need to provide foraging habitat that encompasses a range of forest conditions associated with different prey and movement corridors. In response, some agencies avoid active fuel treatments in threatened or endangered species (TES) use areas, leaving important habitat more susceptible to high-intensity fires, continued fuels accumulation, and perhaps a long-term creation of stands with densities and canopy closure levels outside the range of historical conditions. At the same time habitat needs to be managed for the full wildlife community, which requires the provision of diverse vegetation conditions within the same landscape. How can the provision of wildlife habitat be effectively integrated into other landscape level management objectives?

Region 5 of the U.S. Forest Service is considering implementing management guidelines that would vary forest treatments by topographic setting. Studies using fire history and tree age information have reconstructed nineteenth century forest landscape conditions under frequent fire conditions. These studies have found forest structure and composition varied with topography at both stand and landscape scales (Taylor and Skinner 2004; Hessburg and others 2007). Soil depth also often varies with topography in the Sierra Nevada. Many soils are formed from decomposed granitic parent material, where water holding capacity and site productivity are directly related to soil depth (Giger and Schmitt 1983; Urban and others 2000). This topographic variation in soil depth affects habitat conditions such as tree composition, density and canopy cover (Meyer and others 2007). Forests located higher on slopes and more southwesterly aspects are typically open, pine-dominated forests, in contrast to the higher stem density and canopy cover found in fir-dominated canyons and northeastern aspects. One approach to meet multiple management objectives is to build on previous spatial delineations of forested landscapes generated for singular purposes, and create units harboring different stand structures and fuel loads driven by changes in topography and aspect. In addition to the high correlation of topography with ecologically relevant variability in soils, water availability and vegetation characteristics, another advantage of delineating management boundaries using topography is that landforms are readily observable to field personnel (in contrast, say, to soil chemistry or depth to groundwater), making the delineations intuitive in emergency operations, for work crews in rugged landscapes, and in related situations where mapping support may be limited.

In this study we focus on the Kings River area of the Sierra National Forest, in the central Sierra Nevada and present a method for spatially parsing the landscape into units to be managed for different forest and fuel conditions relevant to sensitive species, fuels reduction and ecosystem restoration. First, we present a low-cost and repeatable method for creating units of relatively uniform topography, referred to as Landscape Management Units (LMUs). We describe the LMUs by their size, elevation, slope, aspect, wetness index, and solar radiation. Second, we assess the efficacy of these units using two approaches. We use existing vegetation data to characterize current stand condition and determine the stem and snag density per hectare and the composition of tree species across size classes. We then evaluate whether LMUs adequately delineate areas more or less used by two sensitive species by testing the null hypothesis that Pacific fisher telemetry points and spotted owl nests and sightings are uniformly distributed across LMUs. We examine the Kings River area as a pilot

site with potential regional application to the Sierra Nevada range, and possibly wider applicability to fire-prone landscapes with steep topographic relief in the western USA.

Methods

Study Area

The Sierra Nevada ecosystem spans 650 km along the eastern edge of California, encompassing mountain peaks and rugged foothills resulting in a variety of terrestrial and aquatic assemblages. Within this area, our study site encompasses the Kings River area and Teakettle Experimental Forest (totaling 54,323 ha) in the Sierra National Forest. The region is characterized by a Mediterranean-type climate (e.g., highly seasonal precipitation almost entirely limited to late fall and winter) and elevations ranging from 289 m in the foothills of the western edge of the study area to over 3230 m in the east. Fire is a natural ecological process occurring in the region, with historical (i.e., pre-European contact) fire events estimated to occur every 12–17 years (North and others 2005). By one estimate, extrapolating from the annual area burned, mixed-conifer forests in the Sierra Nevada now have a fire return interval greater than 600 years (McKelvey and others 1996) mostly because of aggressive fire suppression in the mid-to-late twentieth century.

The area contains a variety of vegetation communities which vary by elevation, ranging from chaparral dominant species in the lower elevations, to mixed conifer, California red fir (*Abies magnifica*), and lodgepole pine (*Pinus contorta*) at higher elevations (North and others 2002). Characteristic species of mixed-conifer forests include shade-intolerant species such as sugar pine (*Pinus lambertiana*) and Jeffrey pine (*Pinus jeffreyi*), and shade-tolerant species such as white fir (*Abies concolor*), California red fir, and incense cedar (*Calocedrus decurrens*). The Sierra mixed-conifer forest is the primary habitat for more vertebrate species than any other forest community in California (Mayer and Laudenslayer 1989), including rare old-growth dependent species, such as the Pacific fisher and California spotted owl, which are subjects of intensive conservation programs.

Landscape Management Units

A major goal of the project was to investigate the utility of a largely topographical strategy to delineate land-management categories for local forest managers. Previous studies have highlighted the predictive importance of topography in landscape management, for example Le Duc and others (1992) demonstrated a correlation between topography and other physical variables and patterns of vegetation, and others have shown topography to be one of a number of environmental surrogates for predicting species patterns (Carmel and Stoller-Cavari 2006) or identifying conservation areas (Kintsch and Urban 2002). More specifically, studies from other mixed-conifer forests (e.g., Taylor and Skinner 2004; Hessburg and others 2005; Hessburg and others 2007) have found patterns of forest condition and fire behavior are strongly affected by topographic and physiographic features. Within a stand, for example, areas with cooler microclimates (e.g., cold air drainages, seeps) often have lower historical fire intensity and frequency, and higher stem densities and canopy cover, producing forest habitat for some sensitive species. In contrast, upslope areas, particularly south or west facing, often have greater fire intensity and lower stem densities and canopy cover (Taylor and Skinner 2004; Hessburg and others 2007). While many factors can potentially influence forest conditions, water limitation and fire regime consistently have the greatest effect in the seasonally dry forest types in the Sierra Nevada (McKelvey and others 1996; Urban and others 2000). Based on these findings and input from Sierra Nevada ecologists, we use slope position (which impacts hydrology, fire behavior, and habitat potential) and aspect (which in part determines the degree of solar radiation, temperature and water demand) to create a repeatable method for developing Landscape Management Units (LMUs) based on a US Geological Survey 10 m Digital Elevation Model.

Three classes of slope position were generated: canyon, mid-slope, and ridge-top. The thresholds defining each class were selected in consultation with experts familiar with the study area to best represent the locations of typical transitions from either riparian to mid-slope vegetation characteristics, or upper slope to exposed ridge conditions. A suite of spatial analysis routines in ArcGIS (v. 9.2 ESRI, Redlands, CA) were used to compare the elevation of each cell (10 m pixel) in the landscape with the average of the surrounding cells in a 50 m radius neighborhood. If the target cell was 25 m higher than the average cell, it was classified as a ridge. If the target cell was 20 m lower then it was classified as canyon. All remaining cells were assigned to the mid-slope class. In contrast to other methods for defining canyons, such as a uniform buffer created around all streams, our method identifies pockets of lower elevation away from drainages that are important sinks of cool air and moisture. These locations have higher canopy cover, fuel moistures, and more snags and logs than the surrounding forest, thereby providing contrasting forest microclimate and wildlife habitat with the surrounding upland forest (North and others 2002).

The aspect data layer was reclassified into three classes: northerly, southerly, and a neutral class. To approximate the thermal inertia experienced by slopes receiving

afternoon sun we orientated these classes with the coolest (northerly) slopes centered at northeast (45°) and the warmest (southerly) centered at southwest (225°) (McCune and Keon 2002). We included a neutral class to capture slopes which only receive sun at sunrise and sunset (120°– 150° and 300°–330°), and are assumed to be cooler than southwesterly slopes (although the size of this class is arbitrary, it reflects a range over which heat load rapidly changes [McCune 2007]). We confirmed these three classes were unique by comparing the aspect strength of the three groups (Tukey–Kramer) and found them to be significantly different ($P < 0.05$).

To create the Landscape Management Units we combined the slope position and reclassified aspect data to produce a 3×3 matrix containing nine possible classes (Table 1). While the number of classes for both slope position and aspect could have been more finely segmented (e.g., Macmillan and others 2000), we limited the number of classes in each to be practical from an ecological and management point of view. For example an analysis of mixed-conifer forests found similar stand structures within a watershed based on three basic slope positions due to slope's influence on fire intensity (Beaty and Taylor 2008). Managers have also employed the same basic slope position and aspect categories we use here when assessing potential soil moisture in Sierra Nevada forests (Parker 1982). The resulting grid was generalized by using a minimum threshold of 4 ha (or approximately 10 acres) which for the Teakettle Experimental Forest has been shown to be large enough to contain the three main patch components of mixed conifer forest: closed canopy, gap, and shrub patches (North and others 2002). All LMU areas less than this size threshold were replaced with the values of the neighboring cells using a nearest-neighbor Euclidean adjacency function (i.e., the "nibble" function in ArcGIS).

We characterized the LMUs using standard GIS summary techniques to calculate their average elevation, size, mean slope, mean aspect and aspect strength of each unit. Mean aspect strength measures the average relative strength of pixels within a polygon oriented in a particular direction (ranging from 0–1). For example, a mean aspect strength of '1' for an LMU would mean all cells are oriented between 330°–120° and that the slopes of individual pixels are equal to the mean of the polygon. In other words, the net mean aspect is adjusted by the ratio of the slope of each cell to the mean slope of the LMU to reflect the homogeneity or 'strength' of the terrain within the area of interest. We also calculated two indices which, in part, reflect the different growing conditions within the LMUs. First, a topographic wetness index for each LMU, based on the amount of water flow received from upslope by each cell in the LMU from the broader watershed (Beven 1997). Wetness indices are valuable predictors of potential tree

Table 1 Summary data on area, elevation, slope, and aspect of Landscape Management Units in the Kings River area, Sierra National Forest, California

	Canyon				Mid-Slope				Ridge			
	Area (ha) & % of area	Mean elevation (m)	Mean slope (deg)	Mean aspect (degrees) & strength	Area (ha) & % of area	Mean elevation (m)	Mean slope (deg)	Mean aspect (degrees) & strength	Area (ha) & % of area	Mean elevation (m)	Mean slope (deg)	Mean aspect (degrees) & strength
Northern	3,626 (7%)	1,446	18.4	48.53 (0.72)	9,717 (18%)	1,745	15.8	52.55 (0.72)	2,947 (5%)	1,685	19.4	49.59 (0.73)
Neutral	1,721 (3%)	1,616	18.9	162.85 (0.01)	4,883 (9%)	1,872	15.8	140.84 (0.11)	1,322 (2%)	1,856	19.15	299.83 (0.03)
Southern	6,860 (13%)	1,655	18.4	226.46 (0.76)	18,192 (33%)	1,866	16.6	227.79 (0.77)	5,057 (9%)	1,846	19.1	228.99 (0.77)
Total	30,163 (22%)				81,028 (60%)				23,045 (17%)			

growth rates, vulnerability to wildfires, and suitable habitats for a number of vertebrate species. Low wetness locations may be particularly susceptible to the higher temperatures, decreased snowpack, and possibly lower rainfall predicted for the Sierra over the coming decades (Hayhoe and others 2004). Second, we calculated and compared the mean annual solar radiation of LMUs, again associated with tree growth rates and vulnerability to wildfires with the assumption that particular units would receive relatively more radiation (using ArcGIS Solar Analyst).

To evaluate current stand conditions of the LMUs, we used existing vegetation transect data ($n = 164$) collected by the Kings River Experimental Watershed study, part of a collaboration between the Pacific Southwest Research Station and the Sierra National Forest that has collected data since 2002 (Dolanc and Hunsaker 2007). The vegetation data component involved walking a 20 m line and recording the diameter at breast height (dbh) of every tree or snag > 2 m tall, within 5 m to the left or right of the transect (resulting in a 20 m × 10 m, or 0.02 ha, plot). To assess the stand condition and composition, we calculated the proportion of shade-intolerant and shade-tolerant species across seven different dbh size classes. Shade-intolerant species such as Jeffrey pine and sugar pine dominate the canopy and thus should have higher proportion of trees in the larger dbh categories (North and others 2007). In contrast, the proportion of shade-tolerant species, growing below the canopy, such as white fir and incense cedar, should be higher in the smaller dbh size classes. Although there is an imbalance in the distribution of transects vis-à-vis LMUs and also in their distribution across the study site (Fig. 1), findings from the analysis provide a qualitative picture of LMUs with respect to their utility in a variety of forest management settings.

To test whether LMUs adequately captured differences in species' preferences for various habitats, we used both Pacific fisher (21 females and 13 males) radio telemetry points ($n = 622$) collected between 2008 and 2009 and spotted owl nests and sightings ($n = 425$). Again, these data were collected in the study area for other purposes, but provide an opportunity to test whether LMUs can contribute to identifying areas for forest vertebrates of management concern. Fisher locations were taken by field technicians who search an area until they hear a signal and then take 5–7 bearings on the individual over the course of 1–2 h. These points are screened, and the actual location is then triangulated using the telemetry program LOCATE II. To ensure that the recorded points were independent, we removed the points that were less than 24 h apart (the time estimated to move across their home range (C. Thompson, USFS Pacific Southwest Research Station, pers. comm.). Of the remaining locations, 95% were acquired between 2
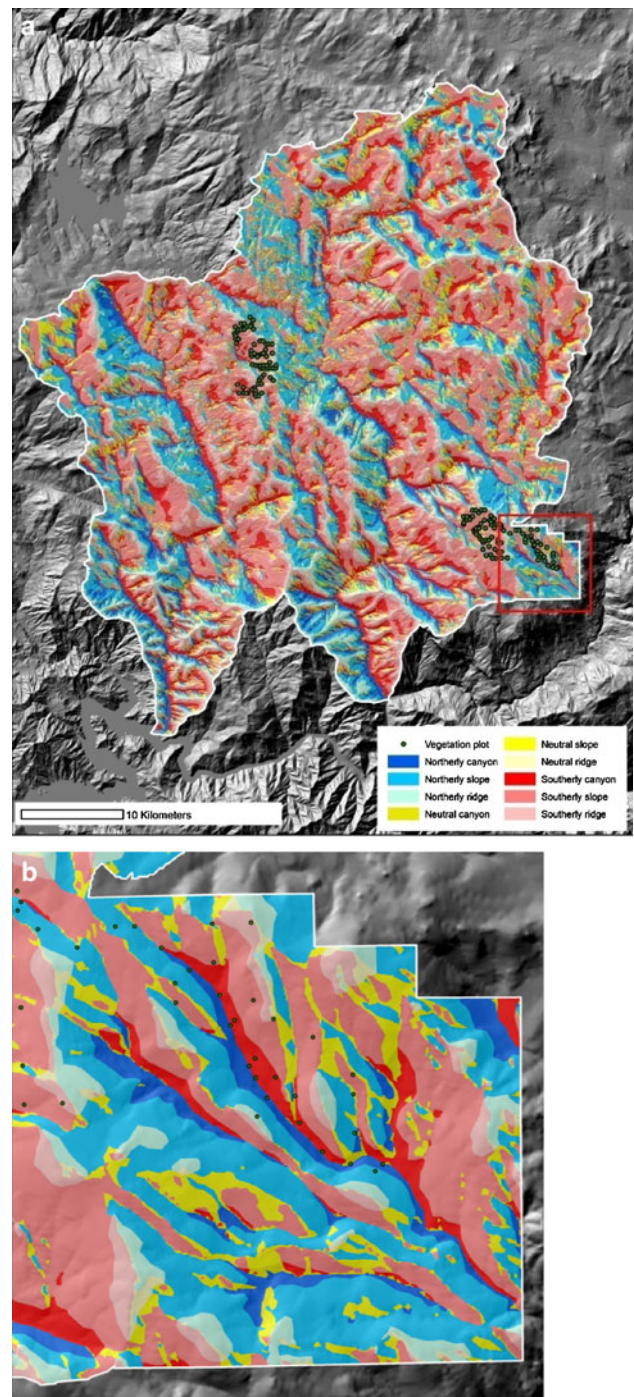

Fig. 1 a Landscape Management Units for the Kings River area, Sierra National Forest based on three aspect classes and three slope position classes. *Green dots* represent location of vegetation plots; **b** Zoom into the Teakettle Experimental Forest identified by *red box* in Fig. 1a (Color figure online)

and 24 days apart. The owl data includes confirmed nests of owl pairs ($n = 37$) collected between 2000 and 2003, and one representative spotted owl point for each year from 1990-2002 based on, in order of desirability, nest location, roosting location, or an estimated location based on

nighttime vocal imitation surveys ($n = 388$) (Hunsaker and others 2002). We used a contingency table to test the probability that the owl or fisher observations within a polygon are independent of LMU type, by comparing the ratio of observation to no observation polygons within an LMU. We also used a goodness of fit analysis to test the null hypothesis that the density of fisher and owl observations within an LMU is the same as the density expected given the spatial area of the LMU.

Results

LMUs General Characterization

Across the study area, over 43,000 subunits within the LMUs were identified, with the greatest number on neutral aspect mid-slopes and fewest on south facing ridges and canyons. South facing units comprised the largest spatial area (55%), followed by north facing (30%) and neutral aspects (15%), while the mid-slope class had the largest area, accounting for 60% of the study area, followed by the canyon and ridge class (22 and 17% respectively) (Fig. 1a, b, Table 1).

The mean elevation for the nine LMU classes ranged from an average low of 1,446 m for northerly canyons to an average high of neutral mid-slopes at 1,872 m (Table 1). Although the canyon classes were consistently lower than the mid-slope classes as one might expect, the mid-slopes were not consistently lower than the ridges. This reflects the heterogeneous distribution of LMUs across the landscape, since ridges can occur both in the lower elevation western part of the study area as well as in the higher eastern elevations. The mean aspects of the northerly LMUs were clustered around 45° (with an average aspect strength of 0.7, meaning that almost three-quarters of the pixels within these LMUs were oriented between 330°–120°), reflecting the 45° offset incorporated to capture the thermal inertia of southwest facing slopes (Table 1). The mean southerly aspects ranged from 226–229° (average aspect strength of 0.8), however the mean aspect of the neutral LMUs varied considerably because of the two neutral classes centered on 135° and 315°, with consequently a low average aspect strength of 0.05.

To compare the nine LMU classes in terms of their growing conditions, we found the canyon classes of all three aspects had a higher wetness index than mid-slopes and ridges had the lowest wetness index (Table 2). The mean annual solar radiation was lowest in the canyons, with all mid-slopes receiving more than the canyons (Table 2). Radiation was greater on mid-slopes than ridges with northerly and neutral orientations, but southerly ridges received the greatest amount of radiation in part due to

Table 2 Physical and stand characteristics of Landscape Management Units grouped by aspect in the Kings River area, Sierra National Forest, California

	Canyon					Mid-slope					Ridge				
	Mean wetness index	Solar radiation (Watt h/m²)	No. veg. transect	Stem density (per ha)	Snag density (per ha)	Mean wetness index	Solar radiation (Watt h/m²)	No. veg. transect	Stem density (per ha)	Snag density (per ha)	Mean wetness index	Solar radiation (Watt h/m²)	No. veg. transect	Stem density (per ha)	Snag density (per ha)
Northern	8.4	1,416,500	9	4,611	678	8.0	1,571,660	20	1,688	190	7.1	1,529,040	1	3,550	150
Neutral	8.1	1,557,170	6	6,150	892	7.8	1,696,750	13	2,788	335	7.0	1,673,320	2	625	175
Southern	8.6	1,676,250	36	3,611	331	8.0	1,778,890	70	3,191	293	7.2	1,786,830	8	3,125	419

Vegetation transect area is 0.02 ha (200 m²)

their orientation. As might be expected, across the classes within each aspect, the summed mean radiation received by southerly aspects was highest, followed by neutral aspects and lowest in northerly aspects.

Current Stand Condition and Composition

The number of vegetation transects occurring in each LMU type ranged from 1 on a northerly ridge to 70 located on southern mid-slopes and their distribution across the study site was in two main areas (Fig. 1). The stem density occurring in the LMUs was consistently highest in the canyon LMUs (e.g., 6,150 stems/ha for neutral canyons), and lowest stem density on neutral ridges (625 stems/ha, Table 2). Snag density followed a similar pattern, being highest in northerly and neutral canyon LMUs and lowest on neutral and northerly ridges (Table 2).

The composition of stands within LMUs grouped by slope position class (canyon, mid-slope, ridge) all demonstrated a declining density of trees with increasing dbh size. Highest stem density per hectare was found in the smallest dbh class (0–25 cm) with the second class (25–50 cm) having four times fewer stems in canyons and mid-slope, and six times fewer in ridge groups (Fig. 2). The proportion of shade-intolerant species (*P. jeffreyi* and *P. lambertiana*) was low, accounting for 4% in canyon and ridge LMUs and 2% on mid-slopes. By size class, they accounted for 15 and 13% or less of all stems on canyons and ridges respectively, and less than 7% in five of the 7 size classes of mid-slopes (in the remaining classes they accounted for 6 out of 23 stems between 100–125 cm and half of the 12 stems between 125–150 cm) (Table 3). In contrast, the proportion of shade-tolerant species (*A. concolor* and *C. decurrens*) accounted for over 50% of stems across each LMU. By size class in canyon and mid-slope LMUs they accounted for
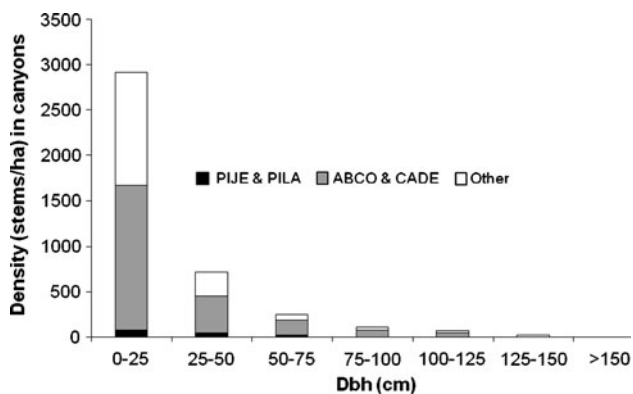

Fig. 2 An example of stem density per hectare in *canyon* Landscape Management Units by seven size classes. Shade-intolerant species: PIJE = *Pinus jeffreyi* and PILA = *Pinus lambertiana*; shade-tolerant species: ABCO = *Abies concolor* and CADE = *Calecedrus decurrens*

Table 3 Stem density per hectare in landscape management units by seven size classes of dbh (cm) in the Kings River area, Sierra National Forest, California

	Canyon							Mid-Slope							Ridge						
	0–25	25–50	50–75	75–100	100–125	125–150	>150	0–25	25–50	50–75	75–100	100–125	125–150	>150	0–25	25–50	50–75	75–100	100–125	125–150	>150
PIJE & PILA	75	45	19	8	6	3	0	19	17	9	6	6	6	0	68	18	0	14	0	0	0
ABCO & CADE	1,593	409	172	73	43	2	0	1,046	288	137	39	7	1	6	1,223	145	68	0	0	0	0
Other	1,250	264	58	26	23	15	4	964	163	79	42	10	4	0	714	159	182	95	0	18	0
Total	2,918	718	248	107	72	20	4	2,029	467	224	87	23	12	6	2,005	323	250	109	0	18	0

Species codes are given in Fig. 2

over 55 and 30% respectively (with the exception of the 125–150 cm class), and on ridges 27% or more in the three size classes where present (Table 3).

Sensitive Species Locations

We examined the ratio of known fisher observations to no observations across LMU polygons and rejected our null hypothesis, finding more fisher presences in some LMUs than others ($G2 = 109.54$, $df = 8$, $P < 0.0001$). We also found that the density of fisher telemetry points within LMUs was significantly different than that expected given the spatial area of each LMU ($\chi^2 = 103.98$, $df = 8$, $P < 0.0001$). The majority of fisher points were acquired on southerly mid-slopes and northerly mid-slopes, 30 and 20% respectively (reflecting the greater proportion of spatial area in these classes). As we might expect given the habitat preferences of fishers, there were more observations of fishers in canyons and fewer observations of fishers on ridges, than expected given the spatial area of these LMUs (Fig. 3). These findings were still significant when all telemetry points (i.e., those less than 24 hours apart) were included in the analysis.

We also found more spotted owl observations (both on and off nests) in polygons of certain LMUs ($G2 = 98.89$, $df = 8$, $P < 0.0001$), again rejecting our null hypothesis and indicating that owl observations are not independent of LMU type. Similar to the fisher observations, there was also a greater density of observations in certain LMUs than that expected given the spatial size of the LMU ($\chi^2 = 105.24$, $df = 8$, $P < 0.0001$). There was a disproportionate number of sightings in northerly canyons (55 compared to the expected 28) and southerly canyons (99 compared to 54), but they occurred on southerly mid-slopes
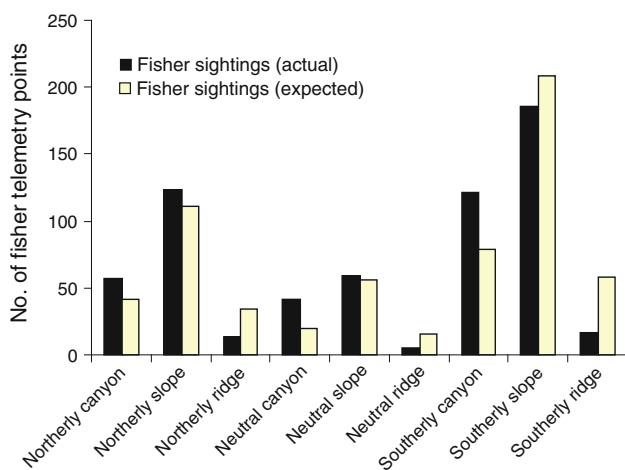

Fig. 3 Comparison of the distribution of 622 telemetry points for Pacific Fisher compared to the distribution expected given the size of the Landscape Management Units, for the Kings River area, Sierra National Forest
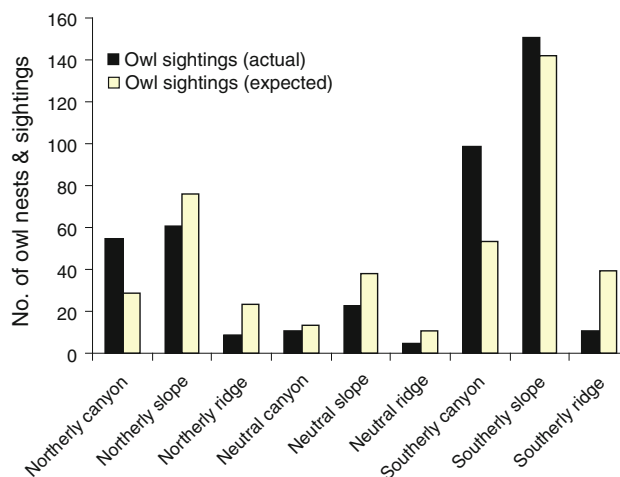

Fig. 4 Comparison of the distribution of 425 nests, roosts and sightings for California spotted owl compared to the distribution expected given the size of the Landscape Management Units, for the Kings River area, Sierra National Forest

in roughly expected numbers (152 compared to 142) (Fig. 4). All ridges and northerly and neutral mid-slopes had fewer sightings than expected given their spatial area.

Discussion

Our objective was to delineate Landscape Management Units based on slope and aspect attributes that might parse the forest into units with distinct stand structure and wildlife habitat attributes. A classification strategy for LMUs based primarily on topography appears to have promise in differentiating the various communities and conditions created in canyons, or other topographic sinks, that trap water and cold air, versus the drier and more fire-prone settings of mid-slopes or ridges. Similarly, the aspect, relative to the maximum heating and drying conditions experienced on southwest-facing slopes, also appears to be a useful classification variable. Even over a range of elevations, and sometimes rather different mixes of dominant conifers, the resulting topographic categories consistently predicted patterns of forest structure and wildlife habitat. We believe that the use of LMUs represents a simple but robust, ecological model for parsing the landscape and representing the inherent spatial heterogeneity that was found in the Sierra under an active fire regime. This spatial variability will not only provide diverse habitat conditions but function to break up the fuels on the landscape and thus interrupt the spread and intensity of future wildfires.

The LMUs we describe may offer a relatively simple but ecologically meaningful method of parsing a forest landscape into areas with distinct moisture conditions, fire regimes, forest structures, and wildlife habitat. Current

U.S. Forest Service plans in fire-prone forests often focus on managing landscapes delineated by 'burnshed' boundaries, strategic fuel treatment placement (i.e., SPLATS [Finney 2001]), and different zones for levels of fire suppression (Aplet and Wilmer 2010). Litigation over forest management often arises because these plans allegedly do not account for ecosystem restoration or the provision of wildlife habitat (Laband and others 2006). In contrast, the LMU approach is based on identifying and managing the landscape based on local ecosystem characteristics. For forest managers the LMUs are easy to delineate in the planning stage using GIS information and readily recognized in the field for implementing different management practices. This simplicity does mean that the described LMU method may not be appropriate for all wildlife species or ecological processes, but is more suited to those closely associated with soil moisture and fire intensity. The approach has higher predictive value in the high-relief landscapes typical of the central Sierra Nevada than in low-slope settings. Landscape analyses with finer categories and better spatial resolution often require extensive field measurements of forest, microclimate and physiographic conditions and more complex spatial statistics that may not be analytically practical for many National Forests to undertake. We believe the topographically-driven LMUs may provide a practical template for stratifying management practices in the next round of 10-year plans for National Forests in California's Sierra Nevada.

Our analysis of current stand conditions and composition (albeit with a greatly uneven number of plots in each LMU) showed greatest stem density in canyons. Water is the most limiting resource in many Sierra Nevada forests (Stephenson 1998; North 2006) strongly affecting net primary productivity and total biomass. Consequently, the wetter, cooler growing conditions found in the canyon LMUs support more stems and riparian hardwoods than drier, upslope conditions. Our analysis of stand composition also showed that current conditions vary greatly from estimates of historical (pre-European) conditions that experienced low-intensity, frequent fire events. Stem density per hectare is currently 2,848 stems/ha on mid-slopes for all stems >2 m tall, which is two orders of magnitude greater than stem densities associated with mid-slope pre-European forest conditions (North and others 2007). In addition, pre-European forests had a higher density of large trees and a high proportion of shade-intolerant pine species (e.g., *P. jeffreyi* and *P. lambertiana*). Our analysis indicated that trees with the smallest dbh (0–25 cm) dominated the density of forest stands, with tree density decreasing as dbh increased. This density of small size-classes, especially in the canyons, caused by fire suppression is a significant change compared to the nearly flat diameter distributions of historic frequent fire forest conditions that have been suggested by reconstruction studies (Taylor and Skinner 2004; North and others 2007). We also found a low proportion of shade-intolerant species, less than 4% across all size classes in canyon, slope and ridge LMUs, which contrasts with studies which suggest shade-intolerant pines used to account for 30–50% of the stems (Sudworth 1900; Moore 1913).

To test the ability of the LMU classification to identify preferred use areas for two prominent mesocarnivores that have influenced policy for protecting old growth forests in the Sierra Nevada, we used existing data on Pacific fisher and California spotted owl. Given the association of these species with closed canopy forests for resting, denning, roosting, and nesting, their protection is of particular management concern because their habitats have been heavily impacted by logging and modified fire regimes. We found the probability of fisher and spotted owl nests and sighting presences are influenced by LMU type. We also found that the number of observations recorded in canyons was 37% to over 100% higher than expected given their spatial area and less than expected on ridges, although both species were observed across all LMU types. Although we did not examine causality, for fisher this result may reflect their habitat association for resting and denning in large trees and snags surrounded by dense canopy (Zielinski and others 2004). Accordingly, analysis of the transect data showed canyons were characterized by greater stem density, which often is associated with higher canopy cover, and, in general, higher snag density. Similarly, more spotted owl nests and sightings occurred in northerly and southerly canyons, which may in part reflect their preference for snags and closed canopies. In both cases, it may also be related to greater abundance and diversity of potential prey (e.g., northern flying squirrels) in wet or riparian conditions (Meyer and others 2007).

For both species there is less information about foraging habitat preferences or how different forest conditions might be optimally distributed within an animal's home range. Our research cannot address these important questions. Many western forests are being extensively treated to reduce fuels and produce a more open canopy stand structure. Without these treatments, high-severity fire can eliminate most or all live canopy cover over several watersheds. In this context, our research is focused on identifying areas in fuels treated landscapes where high canopy cover conditions for sensitive species might be most effectively retained. Nineteenth century historical records of fisher and spotted owls suggest some portion of active-fire forest landscapes still provided the large snags, logs, and high canopy cover associated with resting, denning, and nesting sites for these species. Microclimate studies (Rambo and North 2009) and historic reconstructions of fire history (van de Water and North 2010) and

forest structure (Dwire and Kauffman 2003) suggest riparian areas may have provided mesic, high canopy cover even in forests where much of the upslope landscape burned every 10–25 years.

Our results from the species analyses, however, should be viewed with some caution. Current forest conditions in the Kings River area have been produced not only by the effects of fire suppression, but also by past management practices which included logging. Beginning in the 1880s most of the area has been selectively logged, moreover this practice did not follow a consistent prescription over time, e.g., varying based on the shifting commercial value of different species (Rose 1994). Although we cannot detect a consistent pattern in past forest logging we also cannot dismiss the effects as completely random. Some of the differences in forest conditions and sensitive species use patterns may be due to these past logging practices. Consequently, fisher and owl use patterns may reflect the best forest conditions currently available after nearly a century of fire suppression and selective logging, rather than optimal habitat.

In responding to location, management, and climate change, the properties of a forest evolve over time, often at quite different rates from place to place. Therefore, a scientifically sound medium-term approach (e.g., 40 years), and associated adaptive management cycles, requires the effects of location and climate be assessed on predicted future states of forests as well as on the present stand structure. Software to run these models is available and has been validated in the Sierra Nevada, for example, the Forest Vegetation Simulator (Johnson and others 1998), ZELIG (Miller and Urban 1999), and wildlife-habitat models (Mayer and Laudenslayer 1989), but have not been integrated into a scale-predictive framework, such as the Landscape Management Units presented here. The current confluence of changing environmental conditions and need to manage forest resources for multiple objectives requires a flexible place-based strategy to guide future decisions both in the Sierra Nevada as well as other fire-dependent western forests with steep topographic relief. Tomorrow's forests are not likely to resemble those of the recent past; however, management strategies can leverage our knowledge about landscapes to meet wildlife and fuel treatment needs in a post fire-suppression environment.

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