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RESEARCH ARTICLE

Using stochastic simulation to evaluate competing risks of wildfires and fuels management on an isolated forest carnivore

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Abstract Natural resource managers are often challenged with balancing requirements to maintain wildlife populations and to reduce risks of catastrophic or dangerous wildfires. This challenge is exemplified in the Sierra Nevada of California, where proposals to thin vegetation to reduce wildfire risks have been highly controversial, in part because vegetation treatments could adversely affect an imperiled population of the fisher (*Martes pennanti*) located in the southern Sierra Nevada. The fisher is an uncommon forest carnivore associated with the types of dense, structurally complex forests often targeted for fuel reduction treatments. Vegetation thinning and removal of deadwood structures would reduce fisher habitat value and remove essential habitat elements used by fishers for resting and denning. However, crown-replacing wildfires also threaten the population's habitat, potentially over much broader areas than the treatments intended to reduce wildfire risks. To investigate the potential relative risks of wildfires and fuels treatments on this isolated fisher population, we coupled three spatial models to simulate the stochastic and interacting effects of wildfires and fuels management on fisher habitat and population size: a spatially dynamic forest succession and disturbance model, a fisher habitat model, and a fisher metapopulation model, which assumed that fisher fecundity and survivorship correlate with habitat quality. We systematically varied fuel treatment rate, treatment intensity, and fire regime, and assessed their relative effects on the modeled fisher population over 60 years. After estimating the number of adult female fishers remaining at the end of each simulation scenario, we compared the immediate negative effects of fuel treatments to the longer-term positive effect of fuel treatment (via reduction of fire hazard) using structural equation modeling. Our simulations suggest that the direct, negative effects of fuel treatments on fisher population size are generally smaller than the indirect, positive effects of fuel treatments, because fuels treatments reduced the probability of large wildfires that can damage and fragment habitat over larger areas. The benefits of fuel treatments varied by elevation and treatment location with the highest net benefits to fisher found at higher elevations and within higher quality fisher habitat. Simulated fire regime also had a large effect with the largest net benefit of fuel treatments occurring when a more severe fire regime was simulated. However, there was large uncertainty in our projections due to stochastic spatial and temporal wildfires dynamic and fisher population dynamics. Our results demonstrate

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the difficulty of projecting future populations in systems characterized by large, infrequent, stochastic disturbances. Nevertheless, these coupled models offer a useful decision-support system for evaluating the relative effects of alternative management scenarios; and uncertainties can be reduced as additional data accumulate to refine and validate the models.

Keywords Fisher · *Martes pennanti* · Fuel treatments · Sierra Nevada · Fire suppression · Habitat suitability · LANDIS-II · PATCH · Habitat modeling · California · Wildfire

Introduction

Natural resource managers are challenged to balance requirements to maintain wildlife populations with the need to reduce the risk of catastrophic or dangerous fire in the western U.S. These goals are not mutually exclusive however, as wildlife may also be at risk from large, severe wildfires. Effects of past forest management actions, including logging and fire suppression, have altered fuel characteristics in many areas across the west (Schoennagel et al. 2004). Altered fuels coupled with projected climatic changes may increase the risk of large, severe wildfires (Westerling et al. 2006; Millar et al. 2007; Collins and Stephens 2007) and could negatively affect native species, such as those requiring older, denser, and more structurally complex forest conditions.

In the Sierra Nevada of California, significant efforts are underway to limit fire spread and fire severity through active fuel management, including mechanical thinning treatments and prescribed fire. A small population (probably <300 adults; Spencer et al. 2011) of the fisher (*Martes pennanti*) is isolated in the southern Sierra Nevada, concentrated within a fairly narrow band of mid-elevation forests along the western slopes of the range, south from Yosemite National Park to near the southern tip of the range. The fisher is a large member of the weasel family that is closely associated with the types of dense, structurally complex forest stands that are considered most in need of fuels treatments in the Sierra Nevada (Powell and Zielinski 1994; Zielinski et al. 2004; Zielinski et al. 2005; Davis et al. 2007; Spencer et al. 2011). The west coast population of the fisher (from California to Washington State) is a candidate for listing under the Endangered Species Act, and forest managers are under significant legal and societal pressure to maintain extant populations. Fuels treatments in fisher habitat are controversial, because they can reduce habitat quality by thinning forest canopy and removing constituent habitat elements used by fishers, such as large dead-wood structures used for denning and resting. Severe wildfires can also reduce forest canopy, kill larger trees, and remove large woody structures needed by fishers, and could potentially extirpate the isolated Sierra Nevada population through habitat degradation and fragmentation. The long, relatively narrow arrangement of suitable habitat means that one or more large fires could burn across it and isolate fishers on either side of the burn. Because both fuels treatments and wildfires can negatively impact fisher habitat, this system exemplifies a probabilistic, risk-minimizing balancing act for forest and wildlife managers.

There is large uncertainty regarding the long-term, landscape-scale effectiveness of fuel treatments to reduce the threat of large, high severity fires (Agee and Skinner 2005; Stephens and Moghaddas 2005a, b; Noss et al. 2006; Rhodes and Baker 2008; Syphard et al. 2011). Because fuel treatments are, by necessity, spatially and temporally restricted, it is possible that fires will burn into treated areas too infrequently to significantly modify the fire regime (Rhodes and Baker 2008). Therefore, fuel treatments may locally reduce fuel loads and fire severity (Schmidt et al. 2008) without reducing overall fire severity or area burned across the larger landscape (Stephens and Moghaddas 2005a, b). In the southern Sierra Nevada, Syphard et al. (2011) used a landscape modeling approach and found that the simulated area treated had a greater effect than treatment intensity on reducing fire severity. Treatment effectiveness was strongest at middle and high elevations where more fires intersected treatments and treatments were most effective under more severe weather conditions (Syphard et al. 2011).

Despite the potential benefits of fuel treatments to mitigate against the risk of crown fires, these treatments could have a cumulative, adverse affect on wildlife habitat over time (Tiedemann et al. 2000; Apigian et al. 2006; Lehmkuhl et al. 2007). If fuel treatments reduce the quantity or quality of fisher habitat (by removing large trees or reducing canopy density or structure) without significantly reducing the risk of high severity fire, the net effect will likely be a reduction in fisher population size. Alternatively, if treatments are effective at a landscape scale, a policy of sustained fuel management may prevent the sudden loss or fragmentation of fisher populations due to extreme fire events, as may occur under climate change.

Our objective was therefore to determine how the probabilistic interactions among fuel treatments, wildfire, and post-fire and post-treatment forest succession could influence fisher population size under alternative future fire regime and fire management scenarios. We used a model toolkit approach that incorporated a landscape dynamics model (Syphard et al. 2011), a landscape-level fisher habitat model (Spencer et al. 2011), and a fisher population dynamics model (Spencer et al. 2011). Our approach explicitly considered the spatial interactions among multiple processes (succession, wildfire, and fuel treatments) and the relative strength of direct and indirect effects of fuel treatments on fisher population size in the southern Sierra Nevada for the next 60 years.

To address our objective, we explored these interactions in terms of three direct effects and one indirect effect that together influence fisher population size (Fig. 1). These four interactions defined four hypotheses that were explicitly tested:

H1 *Fuel treatments reduce wildfire severity and extent on the landscape* The explicit assumption behind all fuel treatments is that they will effectively reduce fire severity (mortality of trees) and, by slowing fire spread, allow faster fire suppression efforts, thereby reducing fire size.

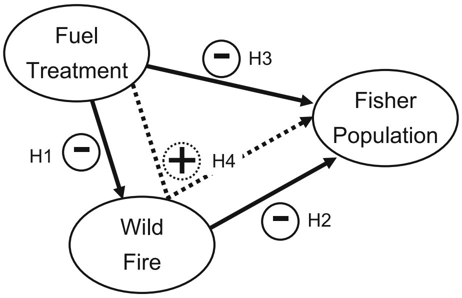

Fig. 1 Expected interactions among fuel treatments, wildfire, and fisher populations in the southern Sierra Nevada. *Solid lines* represent direct effects; the *dashed line* represents an indirect effect

H2 *Wildfire directly and negatively affects fishers* All wildfires reduce aboveground biomass, albeit with differential effects for different tree species, ages, or fuel types. Above-ground biomass of trees is positively associated with habitat quality of fishers in the southern Sierra Nevada (Spencer et al. 2011). Because wildfire reduces aboveground biomass, it also reduces habitat quality for fishers. The degree to which habitat quality is reduced by fire depends on the extent of area burned and fire severity, which determines whether only smaller, understory trees are killed or whether fires also remove larger, overstory trees.

H3 *Fuel treatments directly and negatively affect fishers* Because fuel treatments reduce aboveground live biomass of trees, canopy density, and dead-wood structures, like wildfire they have the potential to reduce habitat quality for fishers. The amount of tree biomass removed and its distribution among tree species and size classes determines the magnitude of effects on fisher habitat quality.

H4 *Fuel treatments indirectly and positively affect fishers* Because fuel treatments are intended to reduce fire severity and fire spread, and thereby reduce threats of large, intense, or stand-replacing fires, they may also prevent the loss and fragmentation of fisher habitat. H4 is the net indirect effects of H1 and H2 combined.

Whether the indirect positive effect of fuel treatments on fishers (H4) outweighs the expected direct negative effect of fuel treatment (H3) is a critical question for determining whether and where fuel treatments should be deployed. Our goal was to assess this potential trade-off between the positive and negative effects of fuel treatments on fishers and to assess how this balance is affected by changes in the fire regime and the location of fuel treatments.

Methods

Study area

The study area (~2.2 million ha of forest) includes portions of the Sierra, Sequoia, and Stanislaus National Forests and Yosemite and Sequoia-Kings Canyon National Parks as well as some industrial timber lands and tribal lands (Fig. 2). This area

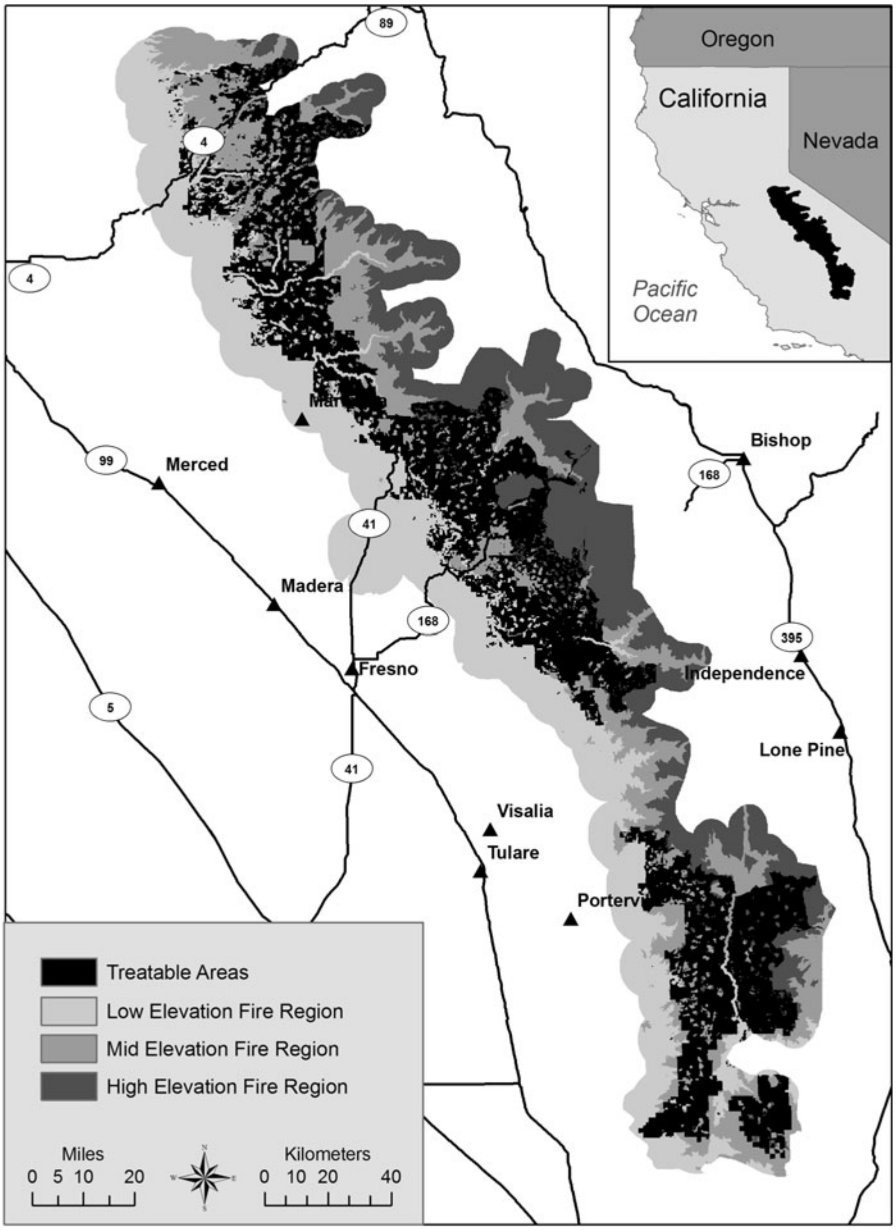

Fig. 2 Study area in the southern Sierra Nevada, California

comprises all known occupied fisher habitat in the southern Sierra Nevada plus additional potential, but apparently unoccupied, habitat that may be important to sustaining or expanding the current fisher population (Spencer et al. 2011). The study area ranges in elevation from 31 to 4,409 m and supports a diversity of vegetation types, from low elevation grassland, hardwood and chaparral to subalpine and alpine coniferous forests and tundra.

Fisher habitat, fisher population, and forest landscape models

Our goal was to encapsulate all of the substantial sources of inherent uncertainty (Clark et al. 2001). Inherent uncertainty represents the externalities that generate spatial and temporal variability. For the fisher population in the southern Sierra Nevada, inherent uncertainty arises primarily from (a) infrequent, potentially large wildfires that destroy fisher habitat, (b) the dispersal and colonization of fisher into available habitat, and (c) the probability of individual fishers surviving and reproducing as a function of habitat quality.

Landscape model

We used the LANDIS-II forest landscape model (Scheller et al. 2007) to simulate succession, fuel treatments, and wildfire and to estimate total aboveground live biomass (Syphard et al. 2011). LANDIS-II is a stochastic, spatially dynamic model of disturbances and succession; trees and shrubs are represented as species and age cohorts (Scheller et al. 2007). Disturbances are probabilistic and dependent on location and spatial context. LANDIS-II is designed and optimized for large spatial scales (>1 million ha) and therefore emphasizes broad interactions among disturbances and succession while sacrificing smaller-scale mechanistic detail.

Succession and growth of vegetation was simulated using the Biomass Succession (v2.1) extension (Scheller and Mladenoff 2004; Syphard et al. 2011). To simulate fire regimes, we used the Dynamic Fire and Fuels extension (v1.0) in which fire is a function of fire weather, fuels, and topography (Sturtevant et al. 2009; Syphard et al. 2011). We divided the landscape into three principle fire regions defined by elevation (which strongly correlates with fuel moisture and the major ecological zones in the region): low-elevation (<1190 m), mid-elevation (1190–2120 m), and high-elevation (>2120 m) (Fig. 2). These elevations created bands of approximately equal area. Fuel treatments were implemented via the Biomass Harvest (v1.0) extension.

Fisher habitat model

Spencer et al. (2011) generated and tested a landscape-level fisher probability of occupancy model using General Additive Modeling (GAM) methods applied to multi-year, systematically collected fisher detection-nondetection data (highly predictive of fisher presence-absence) provided by Region 5 of the USDA Forest Service (2006) and a wide array of spatial environmental variables. The model provided a strong fit to the fisher detection-nondetection data, with an area under the receiver operating curve (AUC) value of 0.941 and a mean fivefold cross-validated AUC of 0.905 ± 0.071. It used three variables averaged over a 5-km^2 moving window to predict probability of fisher occupancy: total aboveground live-tree biomass, latitude-adjusted elevation, and annual precipitation. Assuming that probability of fisher occupancy reflects fisher habitat value, the model suggests that fishers preferentially select those areas with the greatest aboveground biomass (i.e., many large trees), at intermediate elevations (~1300–2400 m), that also have relatively low annual precipitation. More details concerning the model and its interpretation are provided by Spencer et al. (2011).

Fisher population model

Fisher population dynamics were simulated using PATCH, a spatially dynamic, stochastic population model (Schumaker 1998) that allows demographic parameter values (age-specific fecundity, mortality, and dispersal) to vary with spatially explicit habitat values (Spencer et al. 2011). PATCH simulates occupancy of territories by individual females over time within hexagons set to average female territory size. Occupancy dynamics are functions of mean habitat value within each territory, species' dispersal characteristics, and age-specific survival and fecundity rates drawn from an age-based population projection matrix (Leslie matrix). Stochasticity is generated using a random-number algorithm that modifies outcomes from the mean expected parameter values for each individual at each time step.

We assumed a maximum dispersal distance of 50 km, consistent with the limited literature on fisher dispersal (Lewis and Hayes 2004), and found that simulated population dynamics were very insensitive to this parameter (tested from 25 to 100 km) (Spencer et al. 2011). Assuming that fisher probability of occupancy predicted by the GAM correlates closely with habitat value, the highest mean annual survival (0.90) and fecundity (1.62) rates were assigned to adult female territories with probability (i.e., value) >0.75 and scaled these values linearly with habitat values below 0.75, such that model fishers had essentially no probability of surviving and reproducing in territories with values approaching zero (Spencer et al. 2011). This parameterization yielded a simulated population at carrying capacity that fit closely with the patterns of fisher occupancy observed in the multi-year fisher detection-nondetection data, with an intrinsic population growth rate (λ) = 1.0, and with "source" territories (where births exceed deaths) in higher-value habitat areas, and "sink" territories (deaths exceed births) in lower-value areas.

The age-specific demographic parameter values assumed by Spencer et al. (2011) are close to those subsequently measured by two intensive field studies of fisher population biology within the study area, although annual survivorship is lower than assumed. During the years 2009–2011, the Sierra Nevada Adaptive Management Project (SNAMP) fisher study measured annual survivorship of adult females at 73% and annual fecundity at 1.6 (ranging from 1.5 to 1.8 in different years; total $N = 46$ adult females) (Sweitzer, unpublished data; http://snamp.cnr.berkeley.edu/documents/386/). During 2007–2010, the Kings River Project fisher study measured survivorship and fecundity at 76% and 1.7, respectively, also with low annual variability ($N = 45$) (C. Thompson, personal communication). These measured survivorship rates are 16–19% lower than the 90% assumed for the highest-value habitat areas, whereas the measured fecundity rates are strongly concordant with the assumed (1.62) value. The lower annual survivorship measured by these recent field studies suggests that the population may be less robust than suggested by Spencer et al. (2011). Spencer et al. (2011) showed that lowering survivorship by 15% or more from the 90% rate initially assumed could prevent the population from expanding into suitable but unoccupied habitat in Yosemite National Park. These latest field study data support the hypothesis of Spencer et al. (2010) that elevated fisher mortality in currently occupied areas due to human influences is preventing population growth and expansion.

Experimental design

To evaluate the relationships among wildfire, fuel treatments, and fisher populations, we developed a factorial experimental design that allowed us to systematically explore the effects of fuel treatment rate, fuel treatment intensity, and fire regime on simulated fisher populations. The objective of this approach was to structure our understanding of how the complex interactions between the fuel treatments and wildfires may cumulatively affect fisher habitat and population size. We examined the following factors: (1) fire regime, (2) fuel treatment rate, and (3) fuel treatment intensity.

Fire regime

We simulated two fire regimes. The 'baseline' fire regime was calibrated to fire sizes, fire rotation periods, and the fire severity distribution from the previous 20 years of fire and weather data and represents a continuation of recent conditions (Syphard et al. 2011). We also simulated a 'high' fire regime designed to produce larger, more severe fires (Syphard et al. 2011). The high fire regime is a coarse approximation of potential climatic change effects (Westerling et al. 2006; Lutz et al. 2009; Overpeck and Udall 2010) and was designed to encapsulate the high degree of uncertainty pertaining to future fire weather conditions (Stainforth et al. 2005). The high fire regime was created by selecting a subset of historic weather records that reflected the most severe weather conditions from the last 20 years (Syphard et al. 2011).

Fuel treatment rate

We treated 4 or 8% of the treatable landscape (including lands inside of national forests but excluding non-treatable designations, such as existing and recommended Wilderness Areas, existing and recommended Wild and Scenic River areas (Wild and Scenic Rivers Act, 1968), Research Natural Areas, non-vegetated land, and spotted owl (*Strix occidentalis*) Protected Activity Centers; Fig. 2) managed at 5-year intervals. Stands to be treated were randomly chosen and treatments ranged from 20 to 50 ha in size. The 8% treatment rate was designed to approximate the proportion of the landscape that should be treated to reduce wildfire (Finney et al. 2006; Syphard et al. 2011). The 4% treatment rate approximates current treatment goals (although actual treatment levels are often lower due to external constraints, e.g., weather, economic, legal, and air quality constraints.

Fuel treatment intensity

We simulated two treatment types or intensities, designated 'light' and 'medium', designed to capture the contemporary range of fuel treatments. Although heavier treatments are possible, they are unlikely given existing policy restrictions. Both intensities were conducted as ‘thin from below’ treatments, in which the youngest cohorts (smaller or understory tress) are preferentially targeted for removal. In the light intensity treatment, biomass from cohorts up to 30.5 cm in diameter was removed (Syphard et al. 2011). In the medium intensity treatment, biomass from cohorts up to 76 cm in diameter was removed. Both treatments were followed by a simulated prescribed fire with a 0.6-m flame length which substantially reduced subsequent rate of spread and fire intensity. On slopes ≥30%, a prescribed fire treatment was simulated alone with 1.2-m flame lengths. Following each treatment, a stand was assigned a fuel type with an assumed efficacy (reduced rate of fire spread and severity) and duration of efficacy (10 or 15 years) (Syphard et al. 2011). Following this efficacy period, stand fuel type was reassigned based on stand structural characteristics alone.

Simulations of landscape and fisher population change

We created eight combinations of fire regimes (baseline and high fire), fuel treatment rate (4 and 8%), and fuel treatment intensity (light and medium), and simulated landscape change and fisher population change for each combination over 60 years. In addition, we simulated an additional four combinations of treatments alone without fire. For each combination, we projected aboveground biomass every 10 years for 50 years using LANDIS-II. To determine the effects of fuel treatments *alone* on fisher population size, we also applied our models to the full range of fuel treatments without fire on a sub-set of the total landscape (the central region occupying ~30% of the forested area) (Table 1). These simulations were conducted separately from those defined above.

Each combination was replicated 10 times for a total of 120 LANDIS-II simulations (Table 1). Because of the large size of our study area, the requisite computational resources, and the number of subsequent habitat maps and population simulations produced, 10 replicates per scenario was the maximum possible. Only one known published study (~ 195,000 ha) included more LANDIS-II simulations (Xu et al. 2010).

For each of the 120 LANDIS-II simulations, we imported the total aboveground live biomass outputs from LANDIS-II into the fisher habitat model every 10 years, thus producing 60-year sequences of changing habitat-value maps on which to simulate fisher population dynamics using PATCH. Pilot simulations demonstrated that changing the habitat value map more frequently than once per decade had little influence on changes in fisher population size over longer time periods. Fisher population dynamics were simulated for 60 years on this dynamic habitat-value map, which reflected the simulated effects of disturbance, fuel treatments, tree growth and succession, and subsequent biomass changes on the landscape. PATCH simulations were initialized with the mean equilibrium number of adult females within the study area (135) estimated using simulations based on contemporary habitat conditions (Spencer et al. 2011). PATCH was first run for 10 years based on current conditions to allow fisher age classes to equilibrate; results of this PATCH equilibration phase were discarded. Population simulations extended 10 years beyond the last habitat map (to simulation year 60).

Table 1 Matrix of scenarios tested to test the effects of wildfire and fuel treatments on fisher populations in the southern Sierra Nevada, CA

Treatment intensity	Fire regime			Treatment rate
	No Fire	Baseline	High	
Light	10–60–100	10–60–100	10–60–100	Low (4%)
	10–60–100	10–60–100	10–60–100	High (8%)
Medium	10–60–100	10–60–100	10–60–100	Low (4%)
	10–60–100	10–60–100	10–60–100	High (8%)

Numbers indicate: LANDIS-II replicates—number of habitat model maps—PATCH replicates. *Note* the scenarios without fire were conducted on ~30% of the total landscape occupying the central region

Because fisher dispersal, colonization, survival, and reproduction are stochastic, we replicated each PATCH simulation 10 times in order to capture variation in projected population change, resulting in 1200 population estimates (Table 1). Ten replicates is sufficient, because stochastic variability in fisher population size or demographic rates is relatively low for any given set of habitat conditions relative to variability imposed by changes in habitat value (Fig. 3). This relatively low demographic stochasticity reflects the fairly long-lived and "K-selected" nature of fishers, which experience low annual mortality and relatively consistent year-to-year fecundity in adult females within suitable habitat. Variation due to differences among scenarios (assumptions about fires, management, and fire regime) was larger than stochastic differences within scenarios. In addition, Spencer et al. (2011) found that population extinctions are unlikely under current habitat conditions unless females experience very high mortality rates, despite the small size of the population.

Statistical analyses

We used Structural Equation Models (SEM) to test our hypotheses about the interactions that cause simulated fisher population size to increase or decrease (Fig. 1). SEMs test whether the hypotheses are consistent with the available data (but cannot prove causation) and test for indirect interactions (Grace and Pugesek 1998). SEMs are confirmatory rather than exploratory and are suited for multivariate problems and interactions, because more reliable estimates of path coefficients (and thus, the relative importance of the factors being explored) are estimated (Grace and Pugesek 1998). SEM was conducted using the Stata statistical package. SEMs can be either standardized or unstandardized, which can potentially lead to different conclusions. Therefore, we report both standardized and unstandardized coefficients.

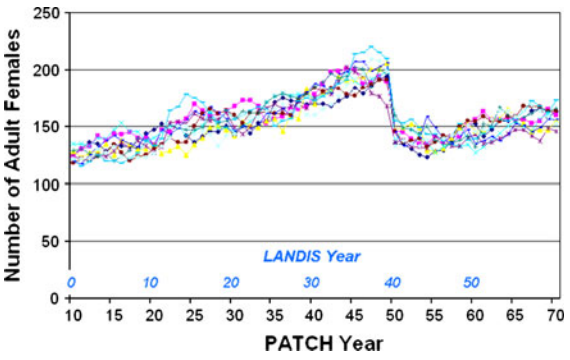

Fig. 3 Example fisher population dynamics from 10 PATCH replicates run for one LANDIS-II replicate (replicate 7 from the High Fire scenario with no fuel treatments). LANDIS-II aboveground biomass maps are used to generate habitat probability maps, via the GAM model LAND8, every 10 years. These maps are input into PATCH at 10 year increments, excluding the PATCH initialization period (not shown). In this example, all replicate populations steadily increased for about 40 years (presumably due to vegetation growth) followed by a crash after major fire(s) in about simulation year 50

In order to capture all model interactions and significant sources of variability, our SEM dependent variables were chosen to reflect emergent model behaviors and to be sensitive to both the vegetation-fire model and the fisher population model. We used the predicted number of adult females at simulation year 60 as our principle dependent variable in our SEMs. Simulated fire rotation periods (FRP; the amount of time necessary to burn an area equivalent to each fire region) for each fire region were used as both a dependent SEM variable (to evaluate fuel treatment efficacy at a landscape scale) and an independent SEM variable to evaluate how fire affected fisher populations. We used total aboveground live biomass removed by fuel treatments as an independent SEM variable because it integrates and combines the effects of both fuel treatment area and treatment intensity; therefore the effect of treatment area and intensity were collapsed into this single variable for the final analyses. In our SEM, dependent variables are regressed against individual independent variables to calculate estimates for hypotheses 1–3. The SEM calculated the estimate for hypothesis 4 by subtracting the direct effect on fishers (H1) from the full model (number of adult female fishers regressed against both FRP and biomass removed). The 'no treatment' scenarios were excluded from our SEM analysis because their inclusion would create an unbalanced dataset.

We evaluated the effects of the two fire regimes, baseline and high fire, separately. We also spatially stratified our analysis by elevation and focused on the mid and high-elevation fire regions as these two areas contained the vast majority of suitable fisher habitat (Spencer et al. 2011). To determine whether treatment effectiveness spatially varied with location relative to high-quality fisher habitat, we also stratified by two habitat quality classes. We defined high-quality (primary) versus low-quality (marginal) fisher habitat for each fisher habitat map as greater or less than 0.5 fisher occurrence probability, respectively. The assignment of a treated cell to either high-quality or low-quality fisher habitat changed over time due to simulated wildfires, fuel treatments, and succession. For these habitat analyses, we calculated the simulated fire rotation period based on whether wildfires were within high or low-quality fisher habitat during any given period.

Finally, we regressed fisher population size against biomass removed by fuel treatments on the sub-set landscape to estimate the effect of fuel treatments alone.

Results

Interactions among fuel treatments, fires, and fishers

Based on simulations conducted over a subset of the study area, we confirmed that, *without fire*, fuel treatments would directly reduce potential fisher population size due to the immediate reduction in habitat quality (linear regression: slope $= -0.08$, intercept $=$ 324.8, $P = 0.004$, adj. $R^2 = 0.88$). Although this analysis is unrealistic (because fire cannot be completely excluded from the landscape), it demonstrates a significant negative correlation between biomass reduction by fuel treatments and fisher populations. This negative correlation between fuel treatments and fisher populations served as a null hypothesis against which we compared the same relationship when fire was simulated.

The complete structural equation models (SEMs) for mid- and high-elevation, baseline and high fire regimes, were significant except for baseline fire in low-quality habitat (Table 2). Only the second hypothesis—fire negatively affects fisher populations—was significant for all models (excluding baseline fire, low-quality habitat), for both standardized and unstandardized coefficients (Table 2). Our first hypothesis—fuel treatments reduce fire—was significant in all cases except baseline fire at mid-elevations. Hypothesis three—fuel treatments are *directly* negatively correlated with fisher populations—was never significant (Table 2). The strength of the relationships between wildfire, fuels management and fisher population varied between areas classed as low-quality (marginal) and high-quality (primary) fisher habitats (Table 2).

Indirect and direct effects compared

We compared the negative direct effect of fuel treatments—equivalent to hypothesis three—to the positive indirect effects of fuel treatments, hypothesis four (hypotheses one and two combined). When stratified by elevation, the positive indirect effect (standardized and unstandardized) was significantly different than zero in all cases except for the mid-elevation fire region under the baseline fire regime (Fig. 4). The negative direct effects of fuel treatments were never significantly different from zero (Fig. 4). In all cases, the positive indirect effect had a higher absolute value than the negative direct effect. However, in no case was the difference significant, and the total effect (positive plus negative effects) was never significant (Fig. 4).

Next, our results were stratified by the quality of fisher habitat. Under the baseline fire regime and within low -quality fisher habitat, neither the direct effect of fuel treatments on fisher nor the indirect effects were significantly different than zero (Fig. 5). Under the high fire regime and within low-quality fisher habitat, only the positive indirect effects were significantly different than zero. However, under either the baseline or high fire regime and with treatments within high-quality fisher habitat, both effects were significantly different than zero. Again, in all cases, the positive indirect effect was larger than the negative direct effect, although the absolute differences between negative and positive effects were not significant. Fuel treatments in low-quality fisher habitat under the high regime had the highest ratio of positive to negative effects (Fig. 5).

Discussion

Large, severe wildfires pose a potentially large risk to the remaining fisher population in the southern Sierra Nevada. Our simulations indicate that if fuel treatments reduce fire effects and area burned across the landscape (Syphard et al. 2011), they also have the potential to reduce the loss of fisher habitat. In general, under the assumptions of our models, the positive effects of treatment on fisher habitat exceeded the short-term negative effects and these potential benefits

Table 2 Structural equation model results for Hypotheses 1–4 for two fire regimes stratified by elevation and by treatment location relative to fisher habitat quality

	Baseline fire		High fire	
	Mid-elevation	High-elevation	Mid-elevation	High-elevation
H1 STD	0.212	**0.542**	**0.409**	**0.520**
H1 UST	0.079	**0.210**	**0.122**	**0.109**
H2 STD	**0.700**	**0.563**	**0.769**	**0.727**
H2 UST	**0.423**	**0.398**	**0.699**	**1.206**
H3 STD	−0.076	−0.224	−0.196	−0.222
H3 UST	−0.017	−0.062	−0.053	−0.077
H4 STD	0.149	**0.305**	**0.315**	**0.378**
H4 UST	0.034	**0.084**	**0.085**	**0.132**

	Baseline fire		High fire	
	High-quality habitat	Low-quality habitat*	High-quality habitat	Low-quality habitat
H1 STD	**0.492**	0.027	**0.468**	**0.586**
H1 UST	**0.188**	0.002	**0.105**	**0.028**
H2 STD	**0.878**	0.134	**0.947**	**0.604**
H2 UST	**0.454**	0.386	**1.046**	**2.643**
H3 STD	**−0.305**	0.014	**−0.359**	−0.223
H3 UST	**−0.060**	0.002	**−0.089**	−0.047
H4 STD	**0.432**	0.004	**0.443**	**0.354**
H4 UST	**0.085**	0.001	**0.110**	**0.074**

Fuel treatments were assigned to being either low-quality or high-quality fisher habitat based on temporally dynamic probabilities of fisher occupancy (using a 0.5 probability cut-point) estimated at 10 year time steps. For each hypothesis, standardized (STD) and unstandardized (UST) coefficients are given. Significant coefficients ($\alpha = 0.05$) are indicated by bold type. All SEMs were significant ($P < 0.001$) except baseline fire with low-quality habitat ($P = 0.86$)

* SEM not significant

to fisher habitat may be particularly important if wildfires become larger and more severe due to climate change (Westerling et al. 2006; Lutz et al. 2009; Kim et al. 2009).

Our simulations projected that the ability of fuel treatments to preserve fisher habitat will vary by elevation with the best results occurring at higher elevations. These results are inconsistent with the conclusion that fuel treatments are more effective at reducing the extent and severity of fire (by reducing the mortality of large, old trees) at mid-elevations (1190–2120 m) (Syphard et al. 2011). Treatments are more effective under more severe fire regimes (Kim et al. 2009; Syphard et al. 2011).

Similarly, the placement of fuel treatments relative to high-quality habitat (>0.5 fisher occurrence probability) significantly improved fisher habitat. Under the baseline fire regime, the placement of simulated fuel treatments within primary fisher habitat provided the greatest net benefit to fishers. Under a heightened fire regime, fuel treatments in marginal fisher habitat also benefited fishers as fires spread more readily between high- and low-quality habitat. These results indicate that the negative effects of treatment are more localized than the indirect positive effects, and location should be an important consideration when determining where to place fuel treatments to protect fisher habitat. If treatments are placed too far from fisher habitat, they may only affect fires locally and not provide the indirect positive benefits that would occur from reducing the spread of severe fire near fisher habitat. Identification of the best locations for fuels treatments will require a better understanding of why fire patterns vary across the landscape (Dellasala et al. 2004). There have been a number of approaches developed for mapping fire risk and probability using

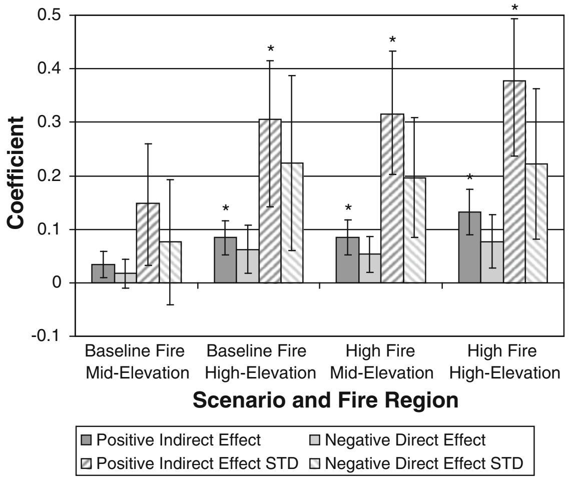

Fig. 4 Coefficients from a structural equation model test of the indirect and direct effects of simulated fuel treatments on estimated fisher population sizes for baseline and high fire regimes at mid and high-elevations. Direct negative effects are absolute values. The structural equation model was drawn from treatment combinations using high and medium fuel treatment rates and medium and low fuel treatment intensities ($N = 40$). Error bars represent standard errors. *Values significantly different than zero

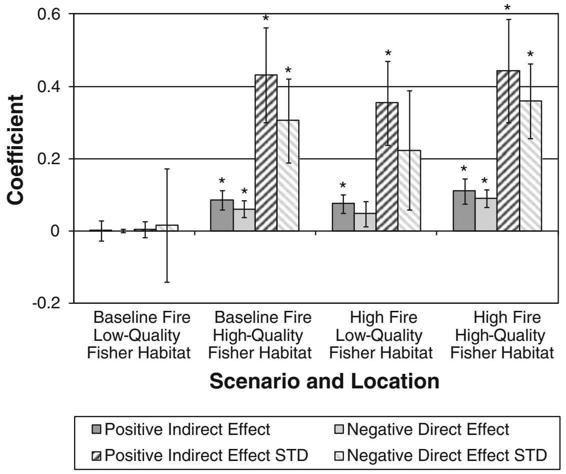

Fig. 5 Coefficients from a structural equation model of the indirect and direct effects of simulated fuel treatments on estimated fisher population sizes for baseline and high fire regimes. Direct negative effects are absolute values. Fuel treatments were assigned to being either within low-quality or high-quality fisher habitat based on temporally dynamic probabilities of fisher occupancy (using a 0.5 probability cut-point) estimated at 10 year time steps. The structural equation model was drawn from treatment combinations using high and medium fuel treatment rates and medium and low fuel treatment intensities ($N = 40$). Error bars represent standard errors. *Values significantly different than zero

biophysical, climatic, and anthropogenic variables (e.g., Preisler et al. 2004). If treatments are placed in areas with a greater fire risk, the efficiency of the treatment in regards to fisher population size will also likely increase.

In general, the most efficient fuel treatments would minimize biomass removed while maximizing their ability to reduce overall fire effects. Our simulated fuels treatments removed biomass primarily from surface fuels and smaller trees and shrubs (ladder fuels). In relying on total biomass as a proxy variable in determining fisher habitat value, our analyses do not account for local determinants of fisher habitat quality. Thus, although total biomass enabled us to draw conclusions about the factors controlling fisher populations at broad scales, it also limits our ability to make projections at finer (<100 ha) scales, where a different set of variables are likely to serve as better predictors of fisher habitat value (Zielinski et al. 2004; Zielinski et al. 2005; Zielinski et al. 2006; Thompson et al. 2011).

The deployment of fuel treatments across large landscapes has the potential to reduce the risk of severe fires and to protect habitat for wildlife populations associated with forest conditions prone to removal by fire. However, fuel treatments may also have unforeseen consequences for other wildlife (Tiedemann et al. 2000; Apigian et al. 2006; Lehmkuhl et al. 2007) and may serve as vectors for the introduction of exotic species (Collins et al. 2007). Future research should consider a broader range of management scenarios, more mechanistic estimates of climate change effects, the effects of insects and drought, and additional wildlife species. Combining these elements will allow a better assessment of the risks and benefits of fuels management.

Our simulations show that although the mean effects of fuel treatments on fishers are positive, there is substantial variation in these effects, posing challenges to managers who must deal with this uncertainty. By incorporating large uncertainties to the degree possible, our approach and results exemplify the challenges of conducting predictive science, including ecological forecasting (Clark et al. 2001), and of managing rare or threatened species across large landscapes. The results strongly suggest a precautionary approach whereby fuel treatments should only be applied when and where they are maximally effective at reducing fire and/or minimally reduce the quality of fisher habitat. Intensive and ongoing monitoring will be required

(Brashares 2010) and a more focused analysis of fuels management prescriptions would help to define the optimal treatment to minimize risks to fisher habitat while maximizing fire management goals.

Our approach could be adapted to address the potential trade-offs inherent to management actions for a variety of species. With sufficient information about habitat needs of more species at a landscape scale, such an approach may also enable an assessment of the optimal spatial variation and configuration of management activities necessary for restoring wildlife (Scott et al. 2001) and/or maximizing overall biodiversity (Manley 2004). Ongoing intensive studies of the fisher population in the Sierra Nevada, and of the local effects of fuels treatments on fishers, are accumulating significant new data that could be used to improve parameterization of our models and reduce uncertainties in our assumptions. For example, the most recent field data suggesting reduced annual survivorship would be expected to amplify the importance of protecting the highest quality habitat; the next iteration of modeling could test this hypothesis. Refined models could also be used to produce hypotheses for testing by such field studies in an adaptive management context.

Our simulations incorporated many of the largest sources of uncertainty, and the generally low statistical significance of our results reflects a system that is inherently stochastic and unpredictable. Furthermore, our conclusions are predicated on our model choices and parameterization (Higgins et al. 2003); these additional sources of uncertainty are not reflected in the results and deserve additional testing. For example, we assumed conditions that reflected a history of fire exclusion and fire suppression, leading to more severe fires than occurred prior to European settlement (SNEP Science Team and Special Consultants 1996). These assumptions were implicit in both the baseline and high fire regimes. If a fire regime with more frequent, lower intensity fires can be restored, both the direct negative effects of fire and the indirect positive effects of fuel treatments would be reduced and the need for mechanical treatments would be reduced.

Conclusions

In summary, the small, isolated fisher population in the southern Sierra Nevada is at risk of extirpation by stochastic events, including uncharacteristically large or severe wildfires that could fragment habitat and isolate fishers in smaller areas. Fuels management could potentially reduce the risk of these catastrophic fire events. Although fisher habitat quality is reduced in the near term, our simulations suggest that this reduction is local and temporally limited (as the remaining trees grow more vigorously and recover lost biomass) and is compensated for by the longer-term reduction in fire risk. Taking into account that fires will burn on this landscape, the simulated fuel treatments we examined generally increased landscape-scale habitat quality and lead to larger fisher populations. However, the system is highly stochastic with a large degree of inherent uncertainty. If conducted, fuel treatments should prioritize treatments in areas at highest risk of large, severe wildfire that could move through the relatively narrow band of higher-quality fisher habitat. We could expect these patterns to hold true for any population dependent upon limited late-seral habitat that is at risk due to large, severe fires.

The need to balance multiple, often competing, objectives across large landscapes, i.e., landscape sustainability, is now widely recognized. However, the science to support management decisions is too often still focused on the local scale, such as the localized effects of individual fuels treatments on habitat or wildlife populations, without considering the broader, cumulative, and spatially dynamic context of these actions. Moving forward, we need to emphasize landscape inter-connectedness and realistically incorporate the stochastic and unpredictable nature of landscapes and populations in assessing how best to balance competing, probabilistic risks of various disturbances on the long-term sustainability of forest ecosystems and wildlife populations.

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