POTENTIAL IMPACTS OF CLIMATE CHANGE TO FISHER HABITAT IN CALIFORNIA: A PRELIMINARY ASSESSMENT

Hugh D. Safford
USDA-Forest Service
Pacific Southwest Region
1323 Club Drive
Vallejo, CA 94592
hughsafford@fs.fed.us

ABSTRACT

An assessment is made of the potential impacts of climate change on the habitat of the California fisher (*Martes pennanti*). Previous climate change and ecosystem response modeling results are combined with forest growth and disturbance simulations to provide insight into the likely outcomes of warming climates on vegetation floristics and structure in forests currently inhabited by fisher. In California, hardwoods (primarily oaks) have been found to be an extremely important source of denning and resting structures for fisher. GCM-coupled ecosystem modeling predicts that climate warming will drive an increase in the hardwood component of montane forests in California, especially where and if precipitation increases. Fire is predicted to become more frequent, and in some cases more intense, across much of the fisher's range as well. Greater activity of fire may negatively impact some of the structural habitat features that are key to fisher occurrence, such as large tree densities and high canopy cover. Rates of snag and surface woody debris creation may go up in the short term, but greatly increased frequencies of fire may ultimately reduce these important structural features over the long term. Little or nothing has been published on direct metabolic impacts of warming climates on fisher or its prey, and these types of effects may prove more important to future fisher distribution than indirect effects mediated through changing habitats. Complicated and synergistic interactions between factors are likely, and make any precise predictions of climate change impacts on fisher currently impossible.

Key words: California, climate change, fire, fisher, hardwoods, mixed conifer forest

INTRODUCTION

The fisher and its habitat

Fisher (*Martes pennanti*) is a mesocarnivore belonging to the mink family (Mustelidae). Fishers are habitat specialists and are considered to be among the western North American carnivore species most vulnerable to human disturbance and habitat alteration (Powell and Zielinski 1999, Harrison et al. 2004, Zielinski et al. 2005). Evidence is that fishers once ranged throughout the lower montane and montane zones of the Klamath Ranges and the Sierra Nevada (Zielinski et al. 2005), but today they are restricted to two disjunct populations separated by more than 400 km (Figure 1). Home ranges of fishers in California vary from 4-90 km^2, with males having significantly larger ranges; averages are about 15 km^2 for females and 40 km^2 for males (Powell and Zielinski 1994). In California, fishers are found from near sea level in the northwest, to as high as 2700 m (and above) in the Sierra Nevada; females generally remain at lower elevations than males (Zielinski et al. 2004a, 2005). The maximum documented dispersal distance for individual California fishers is about 100 km (Zielinski et al. 2005).

Floristic and structural characteristics of forests supporting fisher have been described by Powell (1993), Powell and Zielinski (1994), Seglund (1995), Klug (1997), Carroll et al. (1999), Mazzoni 2002, Zielinski et al. (2004a,b; 2006), Carroll (2005), and Yaeger (2005). In both California population areas, midseral conifer and mixed conifer-hardwood forests comprise the bulk of fisher habitat. In the Klamaths, fisher home ranges are primarily in Douglas-fir (*Pseudotsuga menziesii*) and/or white fir (*Abies concolor*) forest, with an important component of conifer-oak or pure oak stands; in the southern Sierra Nevada, the preferred floristic conditions range from mixed conifer to ponderosa pine (*Pinus ponderosa*) to montane hardwood. Oaks – chiefly black oak (*Quercus kelloggii*) - appear to be a key component of the habitat, especially in the southern Sierra Nevada (Carroll et al. 1999, Zielinski et al. 2004a). Forest structural characteristics within fisher home ranges are strongly skewed toward mid- to late-seral stands with high canopy cover; large, cavity-forming trees are required for resting and denning habitat (Seglund 1995, Zielinski et al. 2004b, Yaeger 2005). Geographic conditions correlated with core fisher habitat in California include complex topography, steep slopes, and proximity to water (particularly in the southern Sierra Nevada) (Zielinski et al. 2004b, Carroll 2005).

The relatively strict reliance of fisher on dense canopy forest and complex vegetation structure, and its preference for biologically productive landscapes at lower to middle elevations has led to increasing conflicts with human habitat use and management (Powell 1993, Harrison et al. 2004, Zielinski et al. 2005). Although much research has been carried out on fisher biology, fisher habitat, and fisher distribution, no assessment of the potential direct or indirect impacts of future climate change on the California fisher has yet been published. For example, climate-driven changes in tree species dominance at fisher sites may decrease - or increase - the amount of habitat available for foraging, denning or resting. Direct impacts of climate change on fisher metabolism and reproduction are also likely. The potential indirect impacts of climate-change through climate-driven changes in fire regimes are also important to evaluate. Fire regimes respond rapidly to changes in climate and – along with other ecological disturbances like insects and disease outbreaks – are likely to drive much of the short-term response in vegetation floristics and structure (Flannigan et al. 2000, Dale et al. 2001). If longer or more severe fire seasons are one outcome of climate warming, the probability of losing local populations of species that depend on late seral habitat will increase (McKenzie et al. 2004). This is particularly a concern for species like the fisher which have relatively small range sizes and low abilities or tendencies to disperse.

Future climate change in California

In this contribution, results from recent modeling efforts and scientific publications are used to provide some guidance as to the likely effects of future climate change on California fisher habitat. The intent of this treatment is not to focus on direct effects of climate on fisher (e.g., on metabolic rates), but rather to make an estimation of impacts we might expect to see on vegetation composition, fire frequency and intensity, forest structure, etc., all of which have important indirect effects on fisher survival. This contribution will not provide a general overview of climate change predictions for California or the West Coast: dozens of climate models and papers exploring their implications have been published, and it is not the intent nor the place of this paper to summarize these efforts for the reader (for general overviews, see, e.g., Field et al. 1999, NAST 2000, IPCC 2001, EPRI 2003, Wilson et al. 2003). In general, it can be said that California appears to be especially vulnerable to climate change impacts. This is due, among other things, to California's geographic location and longitudinal alignment along the Pacific Coast; its Mediterranean climate, which drives extreme contrasts in summer and winter precipitation patterns; its extremely high diversity of ecosystems and species; its large and rapidly growing human population; and its international importance as an economic and agricultural powerhouse (Field et al. 1999, Snyder et al. 2002, EPRI 2003, Wilson et al. 2003).

To this point, very few future-climate modeling efforts have treated areas as small as the State of California. The principal limiting factor is the spatial scale of the General Circulation Models (GCMs) that are used to game future climate scenarios. Most GCMs produce raster-based outputs with pixels that are 10,000's of km^2 in area; for example, the Hadley model referenced below produces output on a 2.5° by 3.75° (latitude by longitude) grid. To be used at finer scales, these outputs must be "downscaled" using a series of algorithms and assumptions – these finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCMs disagree with respect to the likely outcomes of climate change. For example, a recent comparison of 21 published GCM outputs that included the California region found that estimates of future precipitation ranged from a 26% increase per 1° C increase in temperature to an 8% decrease (Gutowski et al. 2000, Hakkarinen and Smith 2003). That said, there was some broad consensus: all of the reviewed GCMs predicted warming temperatures, and 13 of 21 predicted higher precipitation (three showed no change and five predicted decreases). Most models also agreed that summers will be drier than they are currently, regardless of levels of annual precipitation.

Currently the only modeling effort which has directly linked GCM outputs with subroutines modeling impacts on terrestrial vegetation and ecosystem processes across California is the effort conducted by the Electrical Power Research Institute ("EPRI") under commission to the California Energy Commission (EPRI 2003). The EPRI project is the most detailed and comprehensive study yet undertaken on the potential effects of climate change in California. EPRI coordinated a diverse group of researchers and modelers who carried out a series of studies focusing on climate change impacts on terrestrial vegetation, biodiversity, timber production, water resources, agriculture, energy and coastal resources. The EPRI project also considered a number of climate change scenarios, ranging from much warmer and wetter than today, to somewhat warmer and drier than today. The project was designed to help California natural resource managers and other policy makers better understand the potential effects of climate change on the state, so as to allow the development of adaptive land and resource management policies (EPRI 2003).

Based on the uncertain outcomes of climate change for California, one of the principal purposes of the EPRI project was to game a number of future scenarios using different estimates of change in temperature and precipitation. The EPRI team (EPRI 2003) found that the Hadley CM2 scenario (Johns et al. 1997; this model was also used in the U.S. National Assessment [NAST 2000]) produced one of the wettest future scenarios, and it was also the most accurate of the reviewed "wet future" models with respect to its ability to reproduce current precipitation patterns (Hakkarinen and Smith 2003). The Hadley CM2 GCM (hereafter "HAD") was therefore chosen to represent the wet end of the modeling spectrum. The National Center for Atmospheric Research parallel climate model (hereafter "PCM"; Dai et al. 2001) produced one of the driest future scenarios, and was chosen to represent the dry end of the spectrum; a number of intermediate scenarios were also generated to represent the middle ground of GCM predictions for California. Both the HAD and PCM models are "state-of-the-art" GCMs, and include the influences of ocean dynamics and aerosol forcing on the atmosphere (EPRI 2003). For calibration, both GCM models were run from the 1800s to 1995 using observed increases in greenhouse gas concentrations. Future scenarios were based on Intergovernmental Panel on Climate Change (IPCC) projections of a 1% increase in greenhouse gases per year (EPRI 2003).

Finally, the EPRI project used a standard downscaling methodology to create higher resolution (100 km^2) outputs from the coarse-scale GCM scenarios.

For the purposes of this study, the most germane results from the EPRI project are those pertaining to terrestrial ecosystems (Lenihan et al. 2003a,b). Lenihan et al. used a dynamic ecosystem model ("MC1") which estimates the distribution and the productivity of terrestrial ecosystems such as forests, grasslands, and deserts across a grid of 100 km^2 cells. To this date, this is the highest resolution at which a model of this kind has been applied in California. Based on their modeling results, Lenihan et al. (2003a,b) projected that, under all modeled climate change scenarios, forest types and other vegetation dominated by woody plants in California would migrate to higher elevations as warmer temperatures make those areas suitable for colonization and survival. For example, with higher temperatures and a longer growing season, the area occupied by subalpine forests and alpine vegetation was predicted to decrease as evergreen conifer forests and shrublands migrate to higher altitudes. Under their "wet future" scenarios, Lenihan et al. projected a general expansion of forests in northern California and grasslands in southern California. With higher rainfall and higher nighttime minimum temperatures, broadleaf trees were predicted to expand their distribution in many parts of the Sierra Nevada and Klamath Ranges, and conifer-dominated forests were predicted to decrease in extent in the same areas. Under their "dry future" scenarios, Lenihan et al. (2003a,b) predicted that grasslands would expand throughout the state, and that increases in the extent of tree-dominated vegetation would be minimal. Lenihan et al. also found that the frequency and the size of fires would increase under most of their climate scenarios; the change became most pronounced toward the end of the century. The drier climate scenarios resulted in more frequent fires and more area consumed by fires. Modeling based on the wetter climate scenarios suggested that fires under these conditions would tend occur at longer return intervals but at higher intensities due to greater productivity and more rapid growth of fuels.

Studies of fisher ecology have generally found that fisher survival is less tied to forest floristics than to forest structure (e.g., Powell 1993; Zielinski et al. 2004a,b, 2006). Due to the geographic scale of their effort, Lenihan et al. (2003a,b) were not able to assess likely changes in vegetation structure in their modeling effort. I used simulation modeling of forest growth and fire to assess the possible outcomes of high, mixed and low severity fire on the kinds of forest stands preferred by fisher in the southern Sierra Nevada. In this case, my interest was in quantifying possible changes in measures of forest structure that correlate closely with fisher presence and/or density (Seglund 1995, Klug 1997, Carroll et al. 1999; Zielinski et al. 2004a,b; Carroll 2005, Yaeger 2005). In this contribution, I summarize the results of the EPRI (2003) modeling efforts for the two areas currently inhabited by California fisher, present the results of vegetation growth and disturbance simulations, and discuss the possible outcomes of predicted climate change for the fisher and its habitat.

METHODS

Summary of climate and terrestrial vegetation modeling outputs

Mapped outputs from the EPRI (2003) and Lenihan et al. (2003a,b) modeling efforts were imported into a graphics program. The following outputs were accessed: temperature and precipitation; vegetation type (see Table 1), fire return interval (FRI, in years and % change over time), and fireline intensity (in btu/ft/sec and % change over time). Polygons representing the approximate extent of the two California populations of fisher (drawn based on information in Zielinski et al. 2004a and 2005b) were overlain onto the EPRI and Lenihan et al. maps (Figure 1). In the graphics program, a grid was created to match the grid size in the map outputs (10 km by

10 km). Using the grid, map pixels within the boundaries of each fisher population were counted and tallied as to attribute. Pixels which fell on the polygon edge were counted as ¾, ½, or ¼, depending on approximate area within the polygon. The number of pixels of each mapped attribute was divided by the total number of pixels and multiplied by 100 to give percent-of-mapped-area. Outputs for each fisher population area were graphed, using the PCM and HAD climate model results (see above) in order to bracket the range of reasonably probable future climate scenarios.

Fire effects simulations

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhart and Crookston 2003) was used to model fire effects on the structure of late-seral conifer vegetation in the southern Sierra Nevada. Base data were the set of FIA plots sampled on the Sierra and Sequoia National Forests, stratified to represent two vegetation types: mixed conifer stands (multiple conifer species with black oak) with cover ≥40% and overstory trees averaging 24-39 inches (61-99 cm) diameter-at-breast-height; and fir-dominated stands with cover between 40 and 69% and overstory trees averaging 24-39 inches. California Forest Service codes for vegetation classes making up the two types are: "M4N" and "M4G" for the mixed conifer type (I will refer to this type as "M4N/G"), and "F4N" for the fir type. The sample size for each vegetation type was 9.

Computer simulations were used to grow trees in each plot for 40 years, beginning in 2006, running simulations for high (13 ft [4 m] flame length), mixed (6.5 ft [2 m]) and low (3.3 ft [1 m]) severity fire in the first year (i.e., fires were simulated only in 2006). As a control, the same stands were also simulated without fire. The following outputs were tracked: tree canopy cover; number of "large trees" (dbh ≥30 inches [76 cm]) per acre; number of hardwood trees (dbh ≥11 inches [28 cm]) per acre; number of large snags (dbh ≥30 inches [76 cm]) per acre; and down logs ≥12 inch (30 cm) diameter, measured as tons per acre. Each of these variables has been shown to correlate with occupied fisher habitat in California and elsewhere (Powell 1993, Zielinski et al. 2004a,b, 2006). FFE-FVS pools plots within each class before simulating growth and disturbance, which results in a single output prediction and makes statistical comparisons among plot outcomes difficult. Given the broad, informational purposes of this contribution, I will rely on simple description of the simulation differences.

RESULTS

Review of EPRI (2003) climate and ecosystem modeling results for California fisher population areas

Climate

Temperature and precipitation predictions for both climate change scenarios for the period 2000-2099 are presented in Figure 2. On the scale of the entire state, the HAD model predicts a 3.3° C average rise in temperature by 2099, while the PCM model expects a 2.4° C rise. Averaged across the state, the HAD model predicts an increase of about 58% in mean annual precipitation, the PCM model a 21% decrease (Figure 2; EPRI 2003). Within the fisher population areas, the HAD model predicts increases of about 3.1 to 3.2° C (with slightly more warming in the southern Sierra Nevada), and the PCM model predicts increases of 2 to 2.2° C. Predicted values for mean annual precipitation are very different between the two GCMs: by 2099, the HAD model expects a 30-50% increase in precipitation in the general Klamath region, and a 50-70% increase in the southern Sierra Nevada (with increases rising to the south). The PCM model predicts decreases of 10-15% in the Klamaths (with some small patches of 16-20% decreases), and 5 to 15% in the southern Sierra Nevada (EPRI 2003).

The EPRI (2003) outputs allow the differentiation of predicted changes in precipitation into seasonal components (Figure 3). Within the area of the two California fisher populations, the HAD future climate scenario (warmer and wetter) expects significant increases in wet-season (November-March) precipitation ranging from 150 to 200% by the period 2080-2099. Within (most of) the Klamath area, dry season (June-August) precipitation during this period is predicted by the HAD model to be between 75 and 100% of current, but dry season precipitation is expected to increase in the southern Sierra Nevada due to increased thunderstorm activity (Figure 3; EPRI 2003). The PCM scenario (warmer and drier) for the Klamath area predicts slightly decreased precipitation for the wet season, but only 50-75% of current precipitation during the dry season. The PCM predictions for the southern Sierra are similar, but expect less relative loss in summer precipitation than in the Klamaths (Figure 3; EPRI 2003).

Vegetation

Figure 4 gives modeling results from Lenihan et al. (2003a,b) for vegetation types within the two fisher population areas. In the Klamath area, current vegetation is modeled by MC1 as about 78% evergreen conifer forest, which includes a wide variety of conifer-dominated vegetation types (Table 1), and about 16% mixed evergreen forest (oaks and other hardwoods in combination with Douglas-fir or Ponderosa Pine); the remaining 5% is modeled as shrublands or "mixed evergreen woodland" (mostly xeromorphic oak-dominated vegetation, such as blue oak savanna or canyon live oak stands). The HAD future climate scenario (warm and wet) predicts a reversal in the dominance of conifer- versus hardwood-dominated vegetation types in this part of California: evergreen conifer forest suffers a +/- 90% loss in area and mixed evergreen forest increases by almost 450%. The PCM future climate scenario (warm and dry) also predicts losses in evergreen conifer forest (70% loss in area) and gains in hardwood-dominated vegetation (250% increase), with significant gains in shrublands and mixed evergreen woodland as well (Figure 4A).

In the southern Sierra Nevada, MC1 models about 25% of the current landscape as evergreen conifer forest, about 22% as mixed evergreen woodland, 18% as subalpine/alpine, 17% as shrubland, 16% as grassland, and 2% as mixed evergreen forest (Figure 4B; Lenihan et al. 2003a,b). Under the HAD future climate scenario, the area occupied by mixed evergreen forest rises dramatically, to more than 60% of the landscape, replacing evergreen conifer forest at higher elevations (which drops by 50% in area) and mixed evergreen woodland at lower elevations (which loses 42% of its current area); all of the other vegetation types also drop in area. Under the PCM scenario, the amount of mixed evergreen forest also rises, but only to about 10% of the area; the big winner is grassland, which expands dramatically due to higher temperatures, greater drought and higher fire frequencies (Figure 4B; Lenihan et al. 2003a,b).

Fire return intervals (FRI)

Under the HAD climate change scenario, the MC1 model (Lenihan et al. 2003a,b) predicts that about 40% of the Klamath landscape will experience fire less often than under "current" (mean of 1895-1994) conditions, with most of this landscape seeing increases in FRI of 10-25%; under this scenario about 50% of the landscape will see no significant change in FRI (Figure 5A). For the same area, the drier PCM scenario results in more frequent fire over about half of the landscape, with most of these areas seeing decreases of about 10-25% in FRIs (Figure 5A; Lenihan et al. 2003a,b). The HAD and PCM climate change scenarios make much more congruent predictions for the southern Sierra Nevada: in both cases MC1 expects around 65% of the landscape to experience similar FRIs to "current" conditions, and in both cases most of the remaining landscape is predicted to see more frequent fire; under the HAD scenario about 11% of the southern Sierra Nevada area sees less fire (Figure 5B).

Fireline intensities

As with FRIs, the HAD and PCM scenarios within the MC1 model generated disparate outcomes for the Klamath area but more or less similar outcomes for the southern Sierra Nevada (Figure 6). In the Klamaths, MC1 predicts that – under the HAD climate scenario – about ¼ of the area will see increased fire intensities by 2099 (due primarily to more fuels growth under wetter conditions), about 60% of the area will see more or less no change, and about 10% will see decreased fire intensities; the PCM-based outputs for the same area predict that about 50% of the area will see decreased fire intensities due to more frequent fire and vegetation type shifts to more flammable fuels (Figure 6A). In the southern Sierra Nevada, the HAD scenario results in about 40% of the area seeing increased fire intensities, 21% experiences decreased intensities, and 38% experiences no measurable change. Landscape patterns under the PCM scenario are very similar: 35% of the southern Sierra Nevada area is predicted to have fires of greater intensities by 2099, 13% of the area has lower intensities, and about ½ the area is unchanged (Figure 6B; Lenihan et al. 2003a,b).

Growth and Fire Effects Simulations

Figures 7 and 8 report quantitative results from the FFE-FVS simulations for the mixed conifer type (classes M4N/G); results for the fir type (F4N) are not shown, as they were very similar. It is important to remember that the results are dependent on the original set of plots entered into the simulation – the reader should focus on the relative changes between years and "treatments" rather than on the actual values. Figure 7 reports results for large trees, canopy cover, and hardwood trees. The number of large trees (≥30 inch dbh) was reduced to nearly zero by the high severity burn, mixed severity fire resulted in a 50% loss of large trees, while low severity caused a minor loss in large tree density (Figure 7A). Based on the modeled growth rates, it will be many decades beyond 2046 before there is any recovery in large tree density in the high severity simulation. In 40 years, overstory cover increased from 61% to 78% in the undisturbed simulation; rates of cover increase were much more rapid in the burned simulations. Even with an 82% loss in canopy after fire, the high severity simulation matched the undisturbed simulation in cover after 30 years; the low and mixed severity simulations were not far behind (Figure 7B). Canopy cover in the high severity simulation was contributed almost entirely by small trees. Between 2026 and 2046, ratios between tree size classes went from 56:1:0.2, to 1:1:0.2, to 1:2:0.2 (6-11 inch dbh:12-24 dbh: >24" dbh); smaller trees contributed most cover to the mixed severity simulation as well (data not shown). The results for hardwoods (Figure 7C) are difficult to extrapolate and of limited usefulness, as the mixed conifer plots used in the simulation had no hardwoods greater than 11 inch dbh before the simulated disturbances. As a result, both high and mixed severity fire removed all hardwood trees from the simulated plots and recruitment and growth was not rapid enough to replace any of this loss before 2046 (Figure 7C); even low severity fire reduced the hardwood density by 2/3. Had there been larger hardwood trees in the plots, low and mixed severity fire would have reduced conifer cover and likely resulted in a positive hardwood growth response. Hardwood numbers in the undisturbed simulation actually dropped over time, due to increased density of conifers; again, this is also partly the result of the small sizes of hardwoods in the M4N/G plots.

Figure 8 reports simulation results for large snags (≥30 inch dbh) per acre and down logs (≥12" dbh), measured in tons per acre. Burning of all kinds increased snags and down logs over the undisturbed simulation. Based on background rates of large tree mortality, the undisturbed simulation predicted between 4 and 5 large snags per acre by 2046. Snag creation was greatly enhanced by fire, especially high intensity fire, but the total snag numbers began to converge across simulations as time passed and snags fell. Even so, 40 years after fire the high severity simulation still had 75% more snags than the undisturbed simulation (Figure 8A). As snags fall, they become down woody debris. Figure 7B shows that falling trees after fire significantly increased the amount of woody debris through the period of the simulation. The different simulations were approximately equal immediately after fire, but had diverged significantly by 2016. The rate of woody debris creation was dependent on the severity of fire (Figure 8B), and peaked about 20 years after the event, when there was about 14 times as much down woody debris in the high severity simulation as in the unburned simulation (14.6 tons vs. 1.2 tons per acre).

Figure 9 shows stand-level results of the FFE-FVS simulations for the mixed conifer type (M4N/G classes) as pictured by the Stand Visualization System (McGaughey 1997). The first column in Figure 9 is from 2006, the beginning year of the simulations; the second column is from 2026, halfway through the simulation. Remember that fires were only burned in 2006 – the 2026 stands are thus always the results of 20 years of undisturbed growth. The figure is organized with the average undisturbed plot in the top row, the average plot burned at high severity in the second row, the average plot burned at mixed severity fire in the third, and the average plot burned with low severity fire in the bottom row (Figure 9). Note the loss of canopy cover in the high severity burn, the loss of hardwoods in the high and mixed severity burns, and the high rate of snag and down log generation in the high and mixed severity burns as well (Figure 9).

DISCUSSION

It is impossible to say with certainty what future climates will look like in California. That said, there is nearly unanimous agreement that atmospheric CO_2 levels will more than double and temperatures will rise by at least a few degrees C by the end of the 21st century (Field et al. 1999, IPCC 2001). Most regional modeling efforts suggest that mean annual precipitation across California will remain similar to current values or increase (with strong regional differences), rain:snow ratios will increase, and the seasonality of precipitation in the state will become more pronounced (Gutowski et al. 2000, EPRI 2003, Hakkarinen and Smith 2003, Hayhoe et al. 2004). It is also impossible to say with certainty how climate change will impact the California fisher or its habitat. This is due to a number of factors, chief among them: (1) differing GCM predictions with respect to future precipitation patterns in California; (2) the broad spatial scale of current GCM and derivative models, which cannot properly model the relatively fine-grained topographic and forest structural landscapes that support fisher populations in California; and (3) a lack of information as to the likely direct impacts of climate change on fisher metabolism. As with climate, however, it appears we can make a few useful generalizations about the probable future state of fisher habitat in California.

Results of the EPRI modeling effort (EPRI 2003; Lenihan et al. 2003a,b) suggest that there may be important qualitative similarities in vegetation response to climate change in those parts of the Klamath Mountains and southern Sierra Nevada currently supporting fisher populations. For both areas, under both the HAD and PCM climate change scenarios, warming temperatures and increasing CO_2 are predicted to result in increased growth rates and – with the distribution of proportionally more precipitation in the winter (Miller et al. 2003a,b) – increased overall dominance of deeply-rooted woody lifeforms, especially trees (Lenihan et al. 2003a,b). In both areas, Lenihan et al. (2003a,b) also expect mixed evergreen forest to partially replace evergreen conifer forest, especially where precipitation increases are large. This is due to the positive impacts of warming and increased water availability on survival and competitiveness of broadleaf (especially deciduous) hardwoods vis-à-vis evergreen conifers (Woodward 1987, Lenihan et al. 2003a,b), which will probably be forced to migrate to higher elevations to track environmental conditions (Shafer et al. 2001). Under the wetter HAD scenario, mixed evergreen forest is also predicted to expand to lower elevations into area currently occupied by shrubland and mixed evergreen woodland (in this case, primarily canyon live oak, which tends to dominate south-facing canyon slopes under current climates). Hayhoe et al. (2004), basing their analysis on more detailed information on greenhouse gas emissions, also predicted a general statewide pattern of largescale shifts from evergreen conifer forest to mixed evergreen types. In the southern Sierra Nevada, the principal difference between the GCM scenarios in Lenihan et al. (2003a,b) is the high proportion of future landscape in grassland under the drier PCM model. This transition is caused by a decline in dormant season precipitation and an increase in frequency of fire, but primarily affects shrublands and areas of mixed evergreen woodland below the core range of fisher. Hayhoe et al. (2004) reported similar results under their dry future scenario.

Lenihan et al.'s (2003a,b) results can be compared to those of Miller and Urban (1999), who used a different model to predict forest and fire response to climate change in the southern Sierra Nevada. Like the EPRI effort, Miller and Urban (1999) examined responses to a variety of different climate change scenarios, but along an elevation gradient at the geographic coordinates of Sequoia National Park. Only the two lowest sites modeled (1800 and 2200 m) are found within elevations currently frequented by fisher. Miller and Urban's results are also from the period 500 to 800 years in the future, and are thus not directly comparable with the 100 year outputs from the EPRI project. Under all climate scenarios (excepting their highly unlikely "cooler and wetter" scenario), woody biomass decreased at both "low elevation" sites: at 1800 m, biomass ultimately decreased to nearly zero, and at 2200 m it decreased by an average of about 70% (Miller and Urban 1999). This biomass loss was accompanied by a shift in tree species composition at the two sites: at 1800 m, the modeled vegetation shifted from forest to grassland and shrubland, with a small remnant component of ponderosa pine, black oak and/or incense cedar, depending on the climate scenario. At 2200 m, species dominance shifted from white fir to incense cedar and ponderosa pine. Miller and Urban (1999) also found that fires were more frequent under future climate at all modeled elevations.

A number of previous studies have underlined the importance of hardwoods (especially large hardwoods) to California fisher resting and denning habitat (see, e.g., Carroll et al. 1999, Zielinski et al. 2004b). A study commissioned by the US Forest Service in California found that fisher presence in the Klamath region began to decrease when the conifer proportion of the tree canopy began to exceed 55% (Carroll 2005). The increase in mixed evergreen forest predicted for both the Klamath and southern Sierra Nevada by Lenihan et al. (2003a,b) suggests that *floristic* conditions for fisher survival may actually be enhanced by climate warming, as long as annual precipitation remains near or above current levels, and as long as direct temperature (or other) effects on the metabolisms of fisher and its prey do not force significant uphill movement. For example, stands currently dominated by white fir-ponderosa pine forest might transition in part to ponderosa pine-black oak, while Douglas fir-white fir forests (primarily in the Klamaths) might be partially replaced by Douglas fir-tanoak (Lenihan 2003a,b). In the case of Oregon white oak (*Quercus garryana*), a decrease in suitable habitat in the western Klamaths may be offset by enhanced climatic suitability in the Sierra Nevada (Shafer et al. 2001). Many researchers are expecting a future tendency toward more frequent fire throughout montane California (see below; Field et al. 1999, Miller and Urban 1999, Lenihan et al. 2003a,b). This may further benefit oaks (and other hardwoods) at the expense of conifers, as most oak tree species resprout after fire and require periodic disturbances to set back conifer competition (Abrams 1992, Chang 1996).

Although oak species and other hardwoods might benefit from warming temperatures and increased frequencies of fire in montane California, the impacts of future climate change on conifer species and overall forest structure may be less positive. There is abundant evidence that fisher habitat use is more strongly driven by forest physical structure than by tree species composition (Powell 1993, Zielinski et al. 2004a,b, 2006), but the fact remains that almost all fisher habitat in California is conifer-dominated. This is simply because the key structural features of fisher habitat (high tree canopy cover, high densities of snags and down logs, the presence of large cavity-forming trees, etc.) include elements that are best represented in late-seral forests, and late-seral forests in California are overwhelmingly dominated by conifer species. Note that it is not at all impossible for younger forests to provide the habitat attributes necessary for fisher occupancy (Powell 1993, Lewis and Stinson 1998). For example, many of the stands in which Zielinski et al. (2004a,b) found California fisher were mid-seral, but this is probably at least partly a result of the general lack of late-seral forests in the areas they sampled.

The combination of warmer climate with higher CO_2 fertilization will likely cause more frequent and more extensive fires throughout western North America (Price and Rind 1994, Flannigan et al. 2000); fire responds rapidly to changes in climate and will likely overshadow the direct effects of climate change on tree species distributions and migrations (Flannigan et al. 2000, Dale et al. 2001). A temporal pattern of climate-driven increases in fire activity is already apparent in the western United States (Westerling et al. 2006), and modeling studies specific to California expect increased fire activity to persist and possibly accelerate under most future climate scenarios, due to increased growth of fuels under higher CO_2 (and in some cases precipitation), decreased fuel moistures from warmer dry season temperatures, and possibly increased thundercell activity (Price and Rind 1994, Miller and Urban 1999, Lenihan et al. 2003a,b; Westerling and Bryant 2006). Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species compositions (Lenihan et al. 2003a,b), and will likely reduce the size and extent of late-successional refugia (USFS and BLM 1994, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for the types of habitat favored by fisher in California.

A key question is to what extent future fire regimes in montane California will be characterized by either more or less severe fire than is currently (or was historically) the case. Fire regimes are driven principally by the effects of weather/climate and fuel type and availability (Bond and van Wilgen 1996). 60 to 70 years of effective fire suppression in the American West have led to fuel-rich conditions that are conducive to intense forest fires that remove significant amounts of biomass (McKelvey et al. 1996, Arno and Fiedler 2005), and most future climate modeling predicts climatic conditions that will likely exacerbate these conditions. Basing their analysis on two GCMs under the conditions of doubled atmospheric CO_2 and increased annual precipitation, Flannigan et al. (2000) predicted that mean fire severity in California (measured by mean seasonal difficulty of control) would increase by about 10% averaged across the state. Vegetation growth models that incorporate rising atmospheric CO_2 show an expansion of woody vegetation on many western landscapes (e.g., Lenihan et al. 2003a,b), which could feedback into increased fuel biomass and connectivity and more intense (and thus more severe) fires. Use of paleoecological analogies also suggests that parts of the Pacific Northwest (including the Klamath Mountains) could experience more severe fire conditions under warmer, more CO_2-rich climates (Whitlock et al. 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for Sierra Nevada forests (e.g. Swetnam 1993, Miller and Urban 1999), but if fuels grow more rapidly *and* dry more rapidly – as is predicted under many future climate scenarios – then both severity and frequency may increase. Lenihan et al's (2003a,b) results for fire intensity (Figure 5) predict that 1/3 or more of the southern Sierra landscape may see mean fire intensities increase over current conditions by the end of the century. Up to ¼ of the Klamaths may see a similar increase if precipitation increases, but fire intensity decreases (and frequency increases) under the PCM warm-dry scenario, largely because of the replacement of evergreen forest by hardwoods, open woodlands, and shrub- and grass-dominated systems (Lenihan et al. 2003a,b), vegetation types that are not generally frequented by fisher.

If future fires in forests occupied by fisher are indeed more intense on average, then we can expect the severity of fire effects to increase as well. Based on the FFE-FVS modeling (Figures 7-9), it appears that increased frequencies of mixed and high severity fire in dense, mid- to late-seral stands of firs and mixed conifer species are likely to significantly reduce overstory cover and the density of large trees, two of the factors most closely correlated with fisher presence in California forests (Powell 1993, Zielinski 2004a,b). High severity, stand-replacing fire can render forest habitat unusable by fisher for many decades (Lewis and Stinson 1998). Decreases in overhead cover can lead to, among other things, increased drying effects from sun and wind in the dry season, and increased snow deposition in the wet season, which could seriously limit fisher mobility (Krohn et al. 1997) or force their restriction to smaller remnant patches of dense forest (where overhead canopy cover intercepts high proportions of snowfall; Weir 1995). Note that this tendency could be offset by decreasing snow-water ratios in future precipitation, depending on the elevation (Miller et al. 2003a,b). Loss of cover could also result in increased fisher losses from predation. Larger adult fisher are apparently rarely predated, but the probability of successful capture of fisher by predators such as raptors, bobcats, and mountain lions is thought to markedly increase in areas with low cover and simplified forest structure (Buck et al. 1994, Powell and Zielinski 1994, Truex et al. 1998; D. MacFarlane, pers. comm.). Decreases in large tree density could have negative effects on both denning and resting behavior of fisher, as fisher in California strongly prefer cavities in large, old trees (apparently to minimize the effects of summer heat and dryness; Zielinski 2004b). As the FFE-FVS modeling underlined, the effect of forest fire is generally to increase snags and the amount of down woody debris; fire also aids in the creation of tree cavities, especially where severities are low or patchy in effect. However, if frequencies of mixed and high severity fire increase as climates warm, there may well be a negative net effect on the amount and distribution of surface woody debris over the long term (USFWS 2006). Overall, probably the most significant outcome of potential losses in canopy cover and/or surface woody debris would be changes or reductions in the densities of fisher prey. California fishers are generalist predators (Powell 1993, Zielinski et al. 1999), hence they may be able to accommodate a certain amount of prey-base change. However, given that prey availability is a major driving factor in fisher distribution (Powell 1993, Powell and Zielinski 1994), it may be that the local survival of fisher is driven more by direct and indirect effects of changing climates on other small mammals and birds than by effects on the fisher itself.

Although I have focused on indirect effects of climate change on fisher, there will undoubtedly be significant direct effects as well. The distribution of any species is driven by multiple, interacting factors, but direct metabolic relationships with the physical environment usually form the foundation for a species' range (Krebs 1994, Brown and Lomolino 1998). It seems highly likely that the California fisher, which is fur-bearing and primarily restricted to cooler microhabitats (north-facing slopes, canyons) within its range, will be forced to move to cooler climes as temperatures rise. Simple use of lapse rates (which average 3.6°/1000 feet [6.5°/1000 m]; Luetgens and Tarbuck 1982) suggests that "optimal" temperatures for fisher habitat will move upslope 500-1000 feet (150-300 m) over the next century. Often temperature extremes are more important than means in driving species distributions – Hayhoe et al. (2004) found that the probability of extreme heat events in California will undergo a marked increase as temperatures rise. Under the future climate scenarios they assessed, the "heatwave season" in California increased by 5 to 13 weeks in length, depending on location. In the Los Angeles Basin, about

100 miles (160 km) south of the southern end of the Sierra fisher population area, Hayhoe et al. (2004) estimated that there would be 22 more days of maximum temperatures greater than 90°F (32°C) by the year 2100. There will certainly be direct effects of increasing temperature on fisher prey as well, but these will operate in different ways on different species and the aggregate outcome on the fisher prey base is difficult to predict. There will also likely be temperature effects on fisher habitat use *within* its range, wherever it may be. For example, Weir et al. (2004) found that air temperature was a fey factor in determining what resting structure was chosen by fisher: coarse woody debris was most often used under very cold temperatures, while "witches brooms" and branches were chosen more often under warmer conditions. There seem certain to be various, complicated interactions between these sorts of responses and future climates and disturbance regimes.

Climate change is likely to precipitate a number of complicated (and largely unpredictable) outcomes. I have focused in this contribution on more immediate effects of climate change, but it may be that these are swamped or negated by unexpected interactions. Currently, much research is being done on the synergies of natural disturbance in western North America. For example, the complex relationships between rising temperatures and drought, water stress, insect and disease occurrence, and fire appear already to be driving rapid ecosystem response to climate change in western forests (Dale et al. 2001, Breashears et al. 2004). Such feedback effects among multiple disturbances are thought to be behind recent large-scale shifts in geographic distribution of ponderosa pine and piñon pine in the Southwest and California (Allen and Breashears 1998; J. H. Thorne, pers. comm.). In many cases, insect- or disease-caused mortality among conifers may benefit fisher by creating resting, denning and foraging habitat, but large inputs of standing and down dead wood – such as during pine beetle epidemics – may feedback into higher hazard of stand-replacing fire as well, which could ultimately cause the loss of these same habitat structures (Shaffer and Laudenslayer 2006, USFWS 2006). The foundation for many of these synergistic "loops" appears to be water stress in trees, as it weakens tree vigor and can lead to higher incidences of fire-, insect-, disease- and pollution-caused mortality. Most GCMs predict lower snow:rain ratios, reduced winter snowpack, earlier snowmelt, and lower dry-season streamflows (IPCC 2001, Miller et al. 2003a,b; Stewart et al. 2004), not to mention higher growing season temperatures, which will drive increases in evaporative demand. Recent data show that changes in these variables are already occurring in the predicted direction (Mote 2003, Stewart et al. 2005)

Many authors have underlined the importance of microenvironment to fisher survival (e.g., Powell 1993, Powell and Zielinski 1994, Buck et al. 2004, Harrison et al. 2004, Weir et al. 2004). The climate modeling efforts reported on in this paper simply do not have the resolution to reliably predict impacts of climate change on local habitat variables. In the EPRI modeling effort (EPRI 2003;Lenihan et al. 2003a,b), the minimum grid size was 100 km^2, much finer resolution than any other comparable effort, but still much too coarse-grained to permit realistic assessments of direct or indirect impacts climate change on local habitat. Fishers are closely connected to topographic variables (slope complexity, aspect, distance from streams, etc.) and habitat variables (tree densities, down woody debris, etc.) that will require more refined modeling techniques, such as those used by Zielinski et al. (2004a,b) and those currently being undertaken by the US Forest Service and the Conservation Biology Institute in the southern Sierra Nevada (see http://www.consbio.org/cbi/projects/fisher). The next obvious step is to incorporate climatic change inputs into these sorts of habitat models. Forest growth and disturbance simulations can also provide insight into likely impacts of changing fire (and other disturbance) regimes on vegetation structure, but a direct functional link to GCM outputs is still lacking; work on such a link is presently underway (R. Neilson, pers. comm.). Hopefully such work can be accomplished soon - broad extrapolations of uncertain processes to uncertain effects will do little in the end to conserve species at the edge of extinction.

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FIGURE CAPTIONS

Figure 1. The approximate range of fisher in California. The two population areas are indicated.

Figure 2. Future projected trends in mean annual temperature and mean annual precipitation, averaged across California. Projections from two future climate scenarios: the Hadley Climate Center HADCM2 model ("HAD") and the National Center for Atmospheric Research's Parallel Climate Model ("PCM"). Redrawn from EPRI (2003).

Figure 3. Predicted seasonal changes in precipitation for the two fisher population areas in California, based on the mean of the period 2080-2099 compared to the mean of the period 1961-1990. Projections from the "HAD" and "PCM" future climate scenarios (see text). (A) = Klamath Mountains; (B) = southern Sierra Nevada. Data represent the percent of landscape within each population area experiencing a given change. Data from EPRI 2003.

Figure 4. Vegetation types, current (mean of period 1961-1990) versus predicted future (mean of period 2070-2099). Projections from the "HAD" and "PCM" future climate scenarios (see text). (A) = Klamath Mountains; (B) = southern Sierra Nevada. Data represent the percent of landscape within each vegetation type. Data from Lenihan 2003a.

Figure 5. Predicted changes in fire rotation interval (FRI) for the two fisher population areas in California, based on the mean of the period 2080-2099 compared to the mean of the period 1961-1990; negative change means that fire frequency has increased. Projections from the "HAD" and "PCM" future climate scenarios (see text). (A) = Klamath Mountains; (B) = southern Sierra Nevada. Data represent the percent of landscape within each population area experiencing a given change. Data from Lenihan 2003a.

Figure 6. Predicted changes in fire intensity for the two fisher population areas in California, based on the mean of the period 2080-2099 compared to the mean of the period 1961-1990; negative change means that fire intensity has dropped. Projections from the "HAD" and "PCM" future climate scenarios (see text). (A) = Klamath Mountains; (B) = southern Sierra Nevada. Data represent the percent of landscape within each population area experiencing a given change. Data from Lenihan 2003a.

Figure 7. Results of FFE-FVS forest growth and disturbance simulations for the mid- to late-seral mixed conifer vegetation type (M4N/G). (A) = number of large conifer trees ($\geq$30 inches dbh) per acre; (B) = canopy cover (%); (C) = numbers of hardwood trees ($\geq$6 inches dbh) per acre.

Figure 8. Results of FFE-FVS forest growth and disturbance simulations for the mid- to late-seral mixed conifer vegetation type (M4N/G). (A) = numbers of large snags ($\geq$30 inches dbh) per acre; (B) = tons per acre of down logs $\geq$ 12 inches diameter.

Figure 9. Results of FFE-FVS forest growth and disturbance simulations for the mid- to late-seral mixed conifer vegetation type (M4N/G). Graphic representation of stand conditions in 2006 and 2026 after subjection to fires of different severities in 2006.

Table 1. Vegetation types simulated by the MC1 dynamic ecosystem model. Table modified from Lenihan 2003a.

Vegetation type	Description	California examples
Alpine/subalpine forest	tundra, boreal forest	alpine meadows, lodgepole pine forest, whitebark pine forest
Evergreen conifer forest	maritime temperate conifer forest, continental temperate coniferous forest	coastal redwood forest, coastal closed-cone pine forest, mixed conifer forest, ponderosa pine forest
Mixed evergreen forest	warm temperate/subtropical mixed forest	Douglas-fir–tan oak forest, tan oak–madrone–oak forest, ponderosa pine–black oak forest
Mixed evergreen woodland	temperate mixed xeromorphic woodland, temperate conifer xeromorphic woodland	blue oak woodland, canyon live oak woodland, northern juniper woodland
Grassland	C_3 grassland, C_4 grassland	valley grassland, southern coastal grassland, desert grassland
Shrubland	mediterranean shrubland, temperate arid shrubland	chamise chaparral, southern coastal scrub, sagebrush steppe
Desert	subtropical arid shrubland	creosote brush scrub, saltbrush scrub, Joshua tree woodland

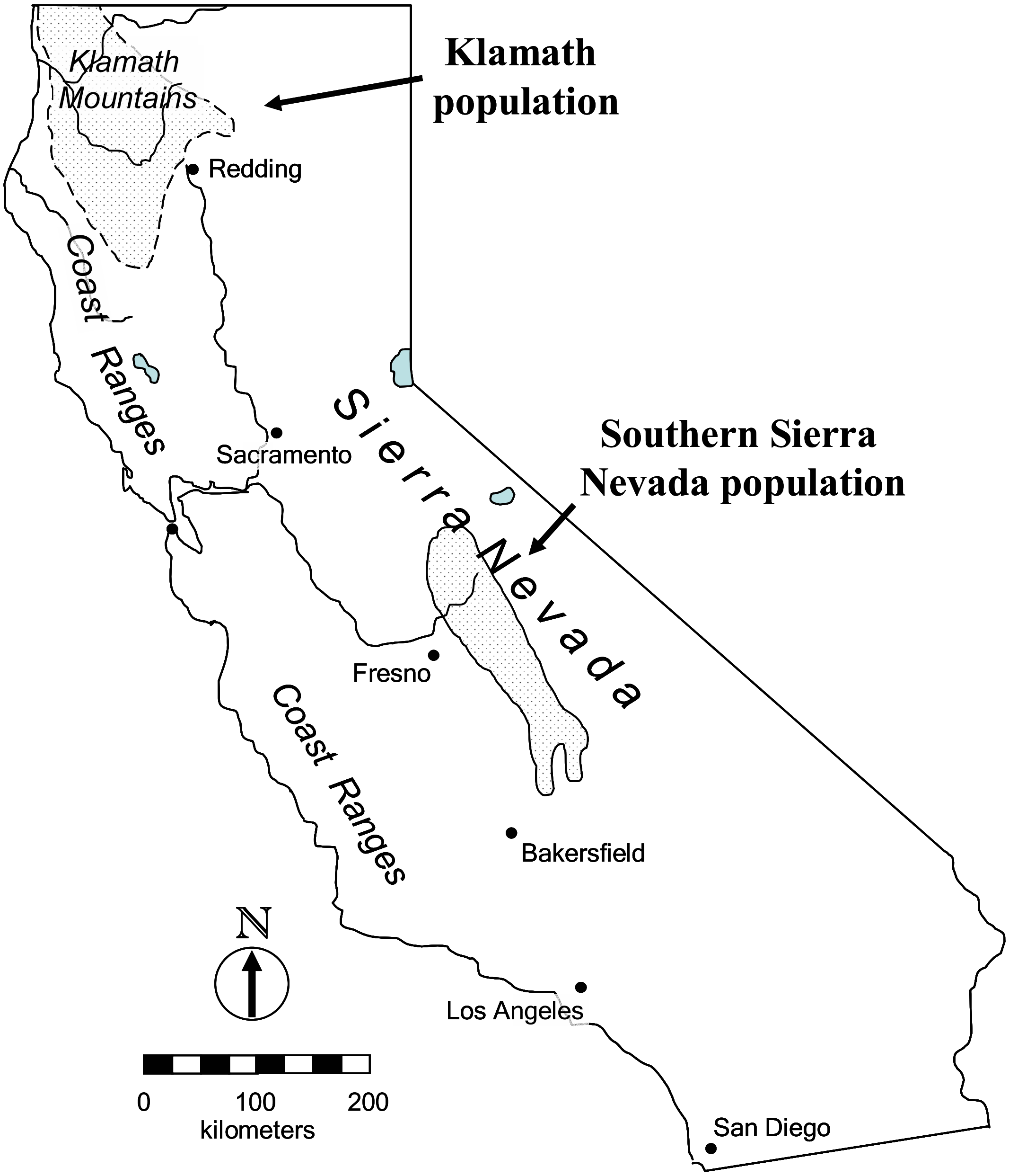

Klamath population
Klamath Mountains
Redding
Coast Ranges
Sacramento
Sierra Nevada
Southern Sierra Nevada population
Fresno
Coast Ranges
Bakersfield
N
Los Angeles
0
100
200
kilometers
San Diego

Figure 1

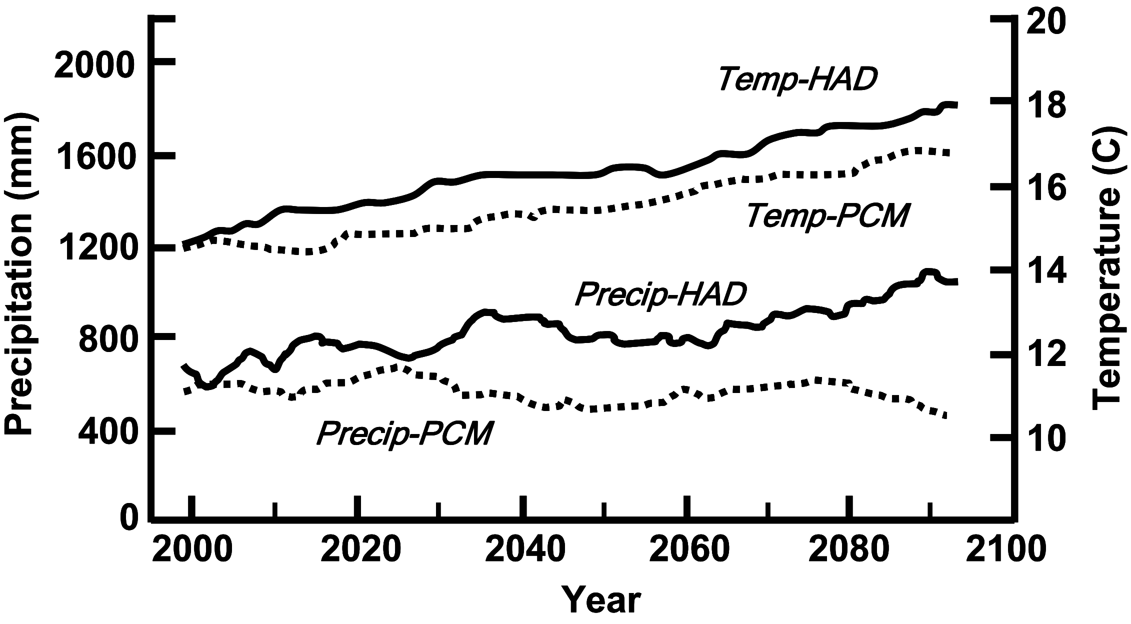

Temp-HAD
Temp-PCM
Precip-HAD
Precip-PCM
Precipitation (mm)
2000
1600
1200
800
400
0
Temperature (C)
20
18
16
14
12
10
2000
2020
2040
2060
2080
2100
Year

Figure 2

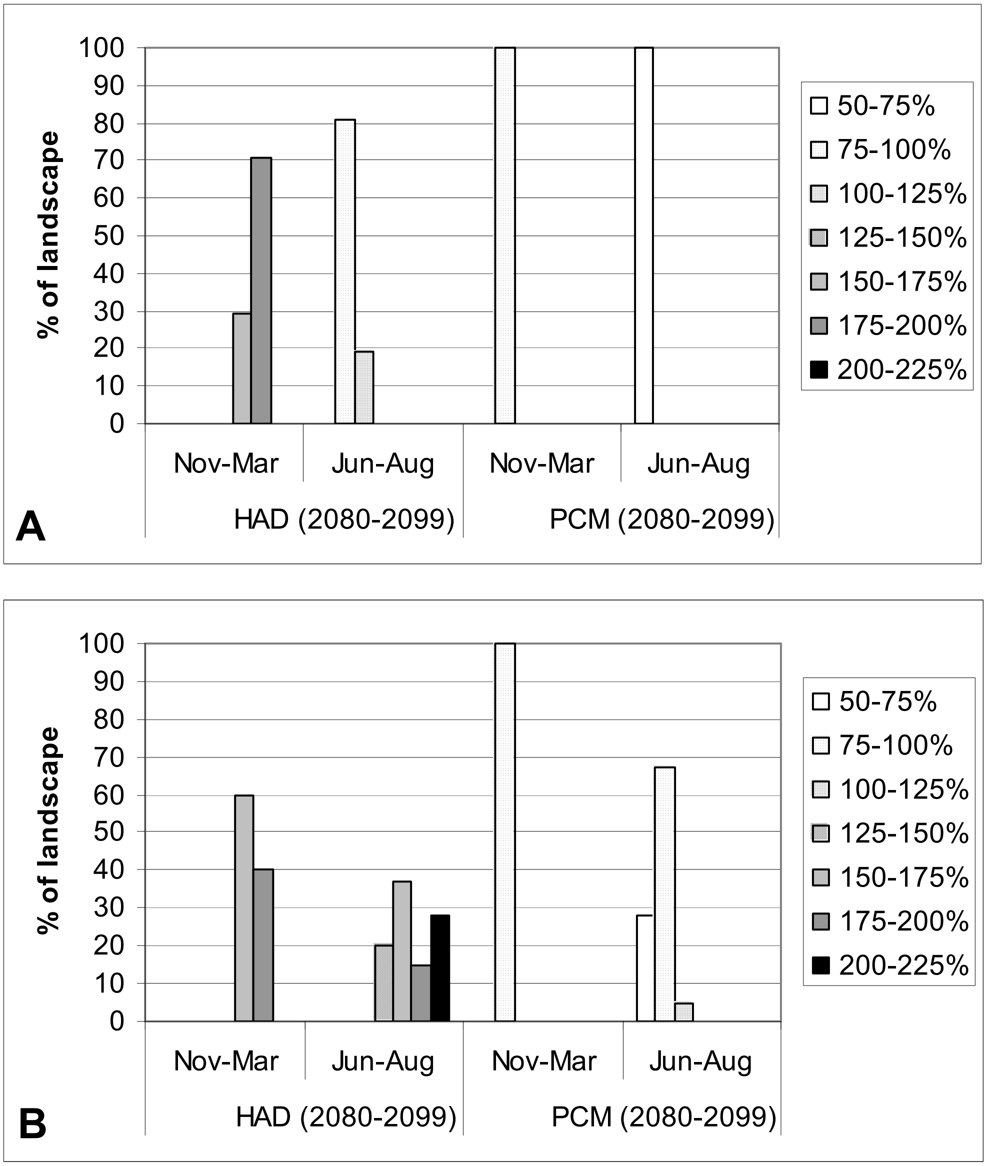

A
% of landscape
100
90
80
70
60
50
40
30
20
10
0
Nov-Mar
Jun-Aug
Nov-Mar
Jun-Aug
HAD (2080-2099)
PCM (2080-2099)
50-75%
75-100%
100-125%
125-150%
150-175%
175-200%
200-225%
B
% of landscape
100
90
80
70
60
50
40
30
20
10
0
Nov-Mar
Jun-Aug
Nov-Mar
Jun-Aug
HAD (2080-2099)
PCM (2080-2099)
50-75%
75-100%
100-125%
125-150%
150-175%
175-200%
200-225%

FIGURE 3

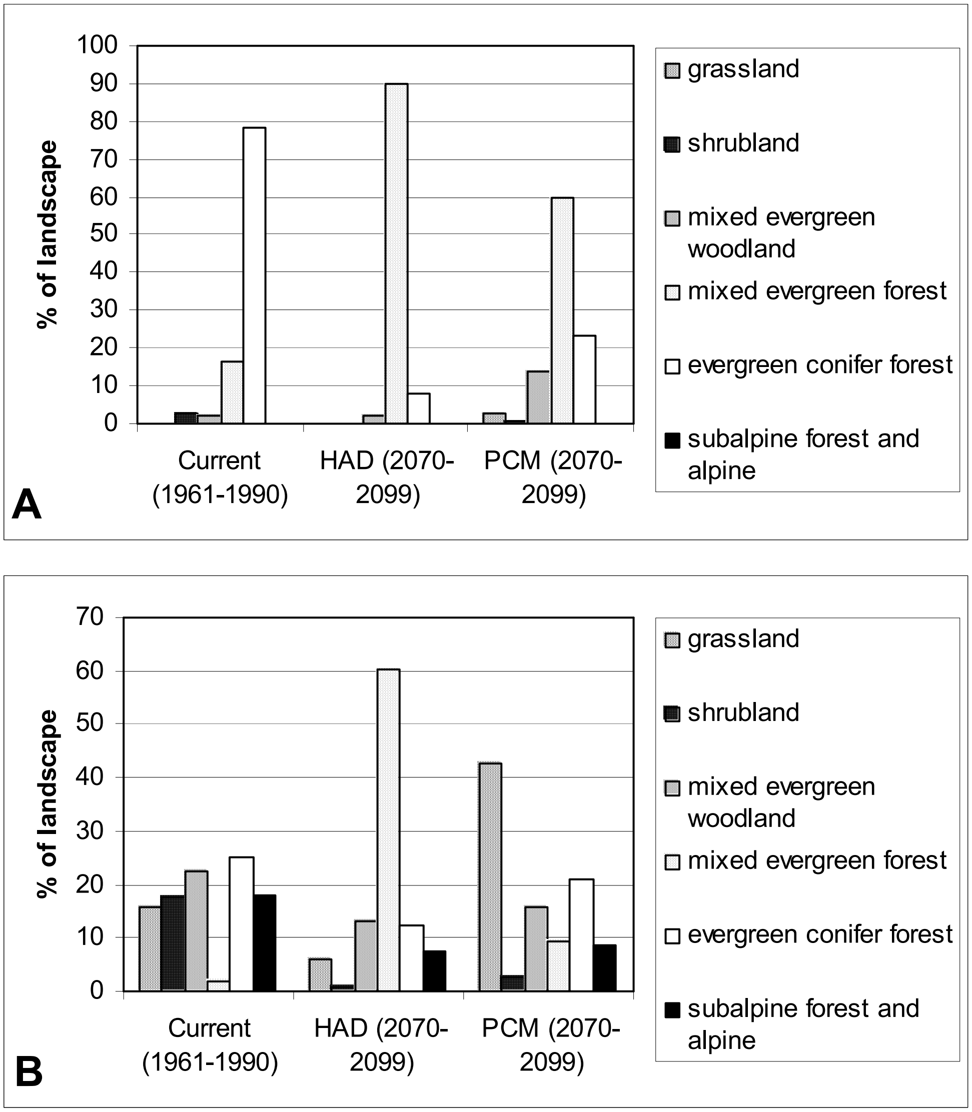

% of landscape
100
90
80
70
60
50
40
30
20
10
0
Current (1961-1990)
HAD (2070-2099)
PCM (2070-2099)
A
grassland
shrubland
mixed evergreen woodland
mixed evergreen forest
evergreen conifer forest
subalpine forest and alpine
% of landscape
70
60
50
40
30
20
10
0
Current (1961-1990)
HAD (2070-2099)
PCM (2070-2099)
B
grassland
shrubland
mixed evergreen woodland
mixed evergreen forest
evergreen conifer forest
subalpine forest and alpine

FIGURE 4

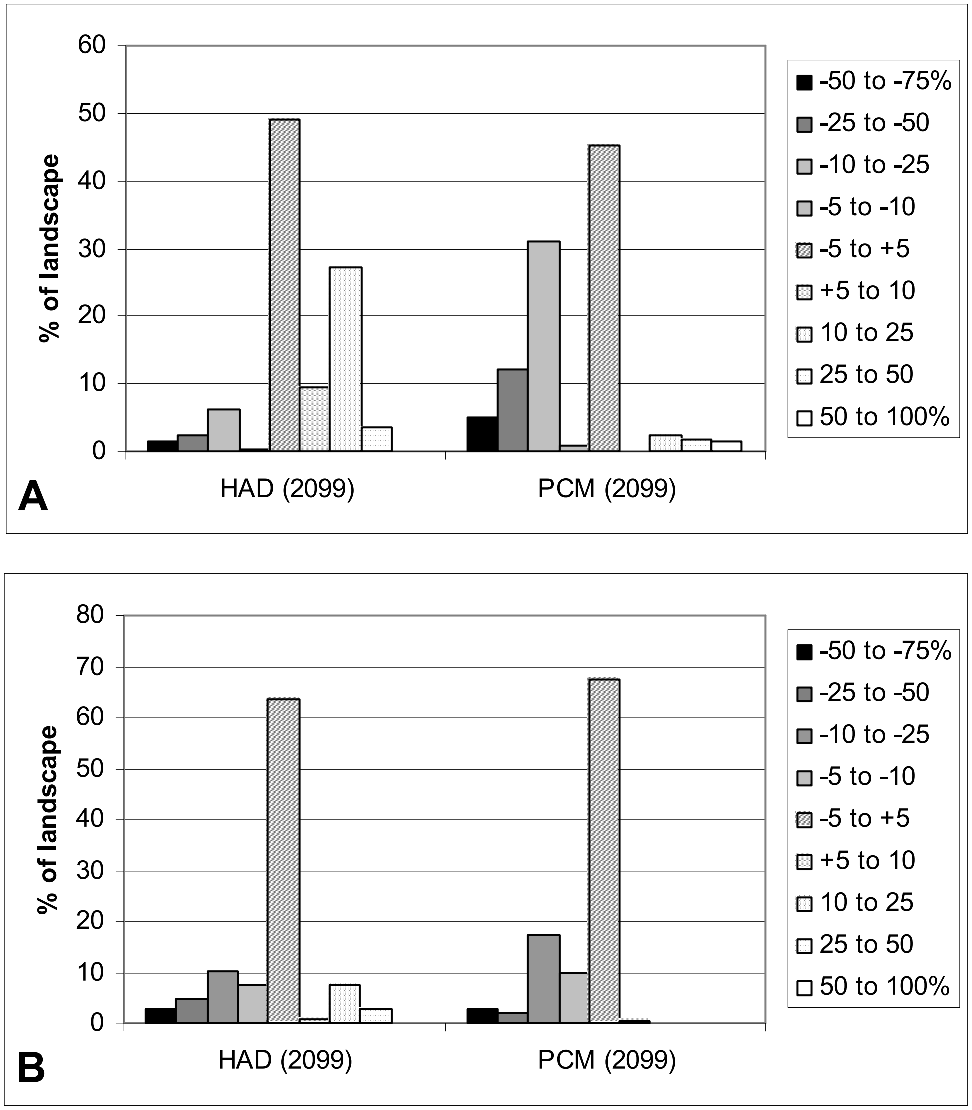

A
% of landscape
0
10
20
30
40
50
60
HAD (2099)
PCM (2099)
-50 to -75%
-25 to -50
-10 to -25
-5 to -10
-5 to +5
+5 to 10
10 to 25
25 to 50
50 to 100%
B
% of landscape
0
10
20
30
40
50
60
70
80
HAD (2099)
PCM (2099)
-50 to -75%
-25 to -50
-10 to -25
-5 to -10
-5 to +5
+5 to 10
10 to 25
25 to 50
50 to 100%

FIGURE 5

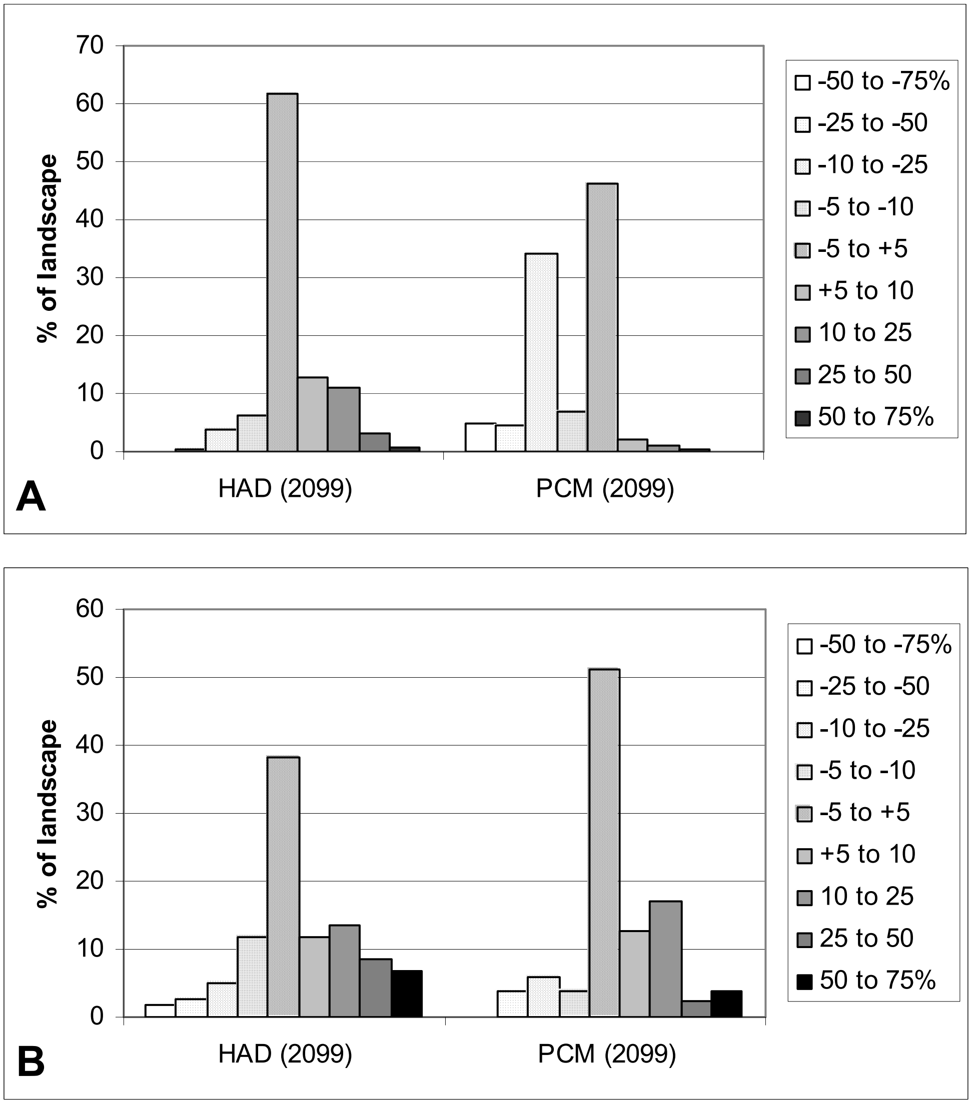

70
60
50
40
30
20
10
0
% of landscape
HAD (2099)
PCM (2099)
A
-50 to -75%
-25 to -50
-10 to -25
-5 to -10
-5 to +5
+5 to 10
10 to 25
25 to 50
50 to 75%
60
50
40
30
20
10
0
% of landscape
HAD (2099)
PCM (2099)
B
-50 to -75%
-25 to -50
-10 to -25
-5 to -10
-5 to +5
+5 to 10
10 to 25
25 to 50
50 to 75%

FIGURE 6

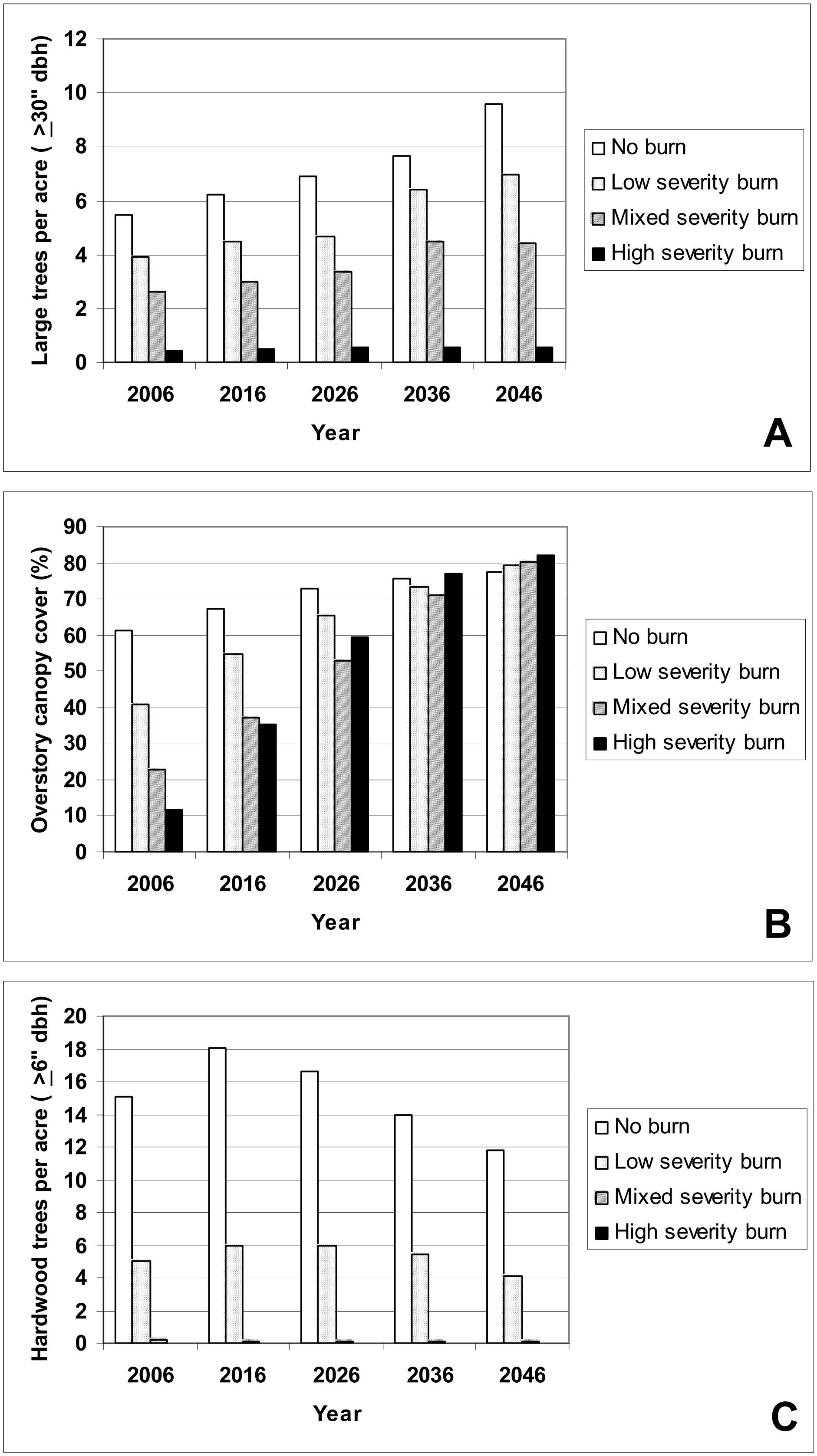

Large trees per acre (>30" dbh)
12
10
8
6
4
2
0
2006
2016
2026
2036
2046
Year
□ No burn
□ Low severity burn
▨ Mixed severity burn
■ High severity burn
A
Overstory canopy cover (%)
90
80
70
60
50
40
30
20
10
0
2006
2016
2026
2036
2046
Year
□ No burn
□ Low severity burn
▨ Mixed severity burn
■ High severity burn
B
Hardwood trees per acre (>6" dbh)
20
18
16
14
12
10
8
6
4
2
0
2006
2016
2026
2036
2046
Year
□ No burn
□ Low severity burn
▨ Mixed severity burn
■ High severity burn
C

FIGURE 7

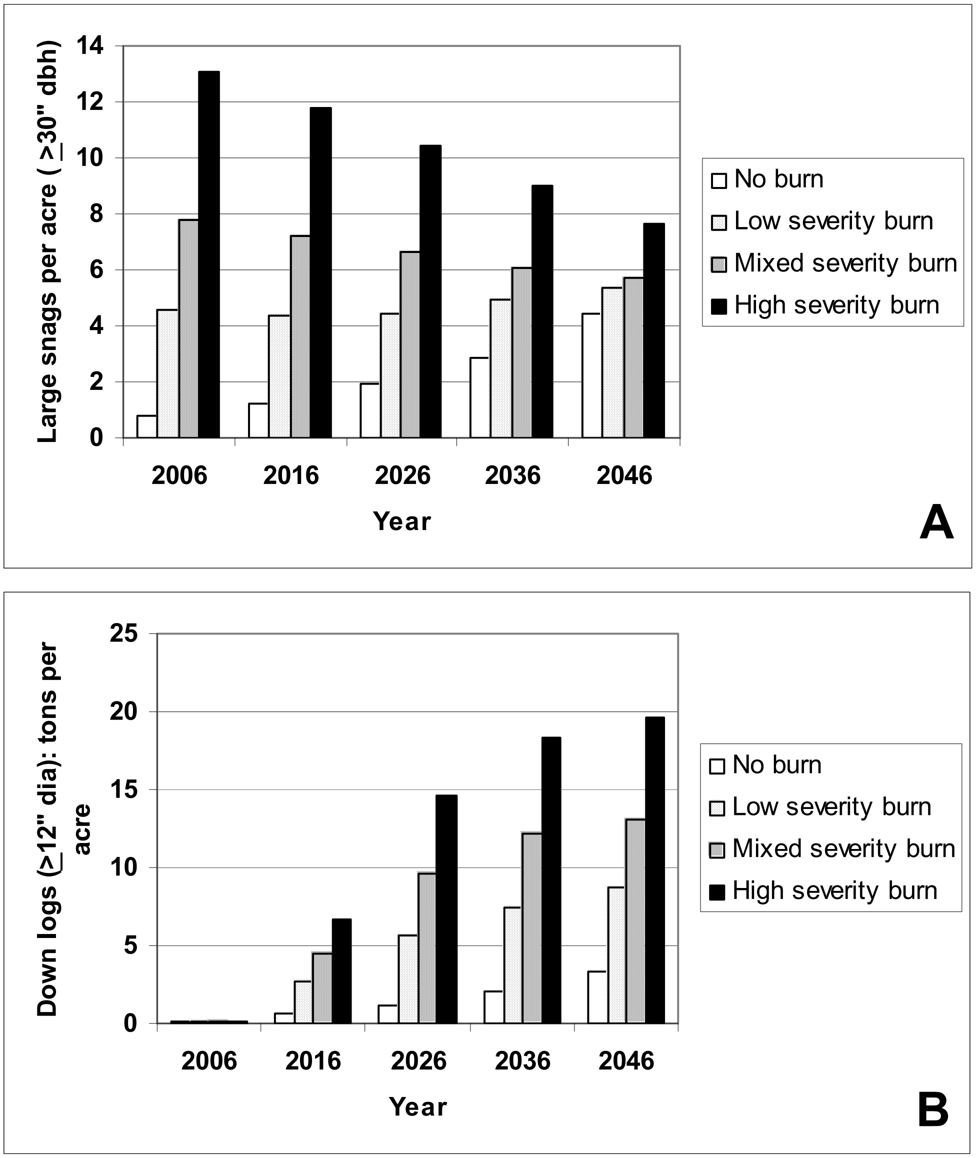
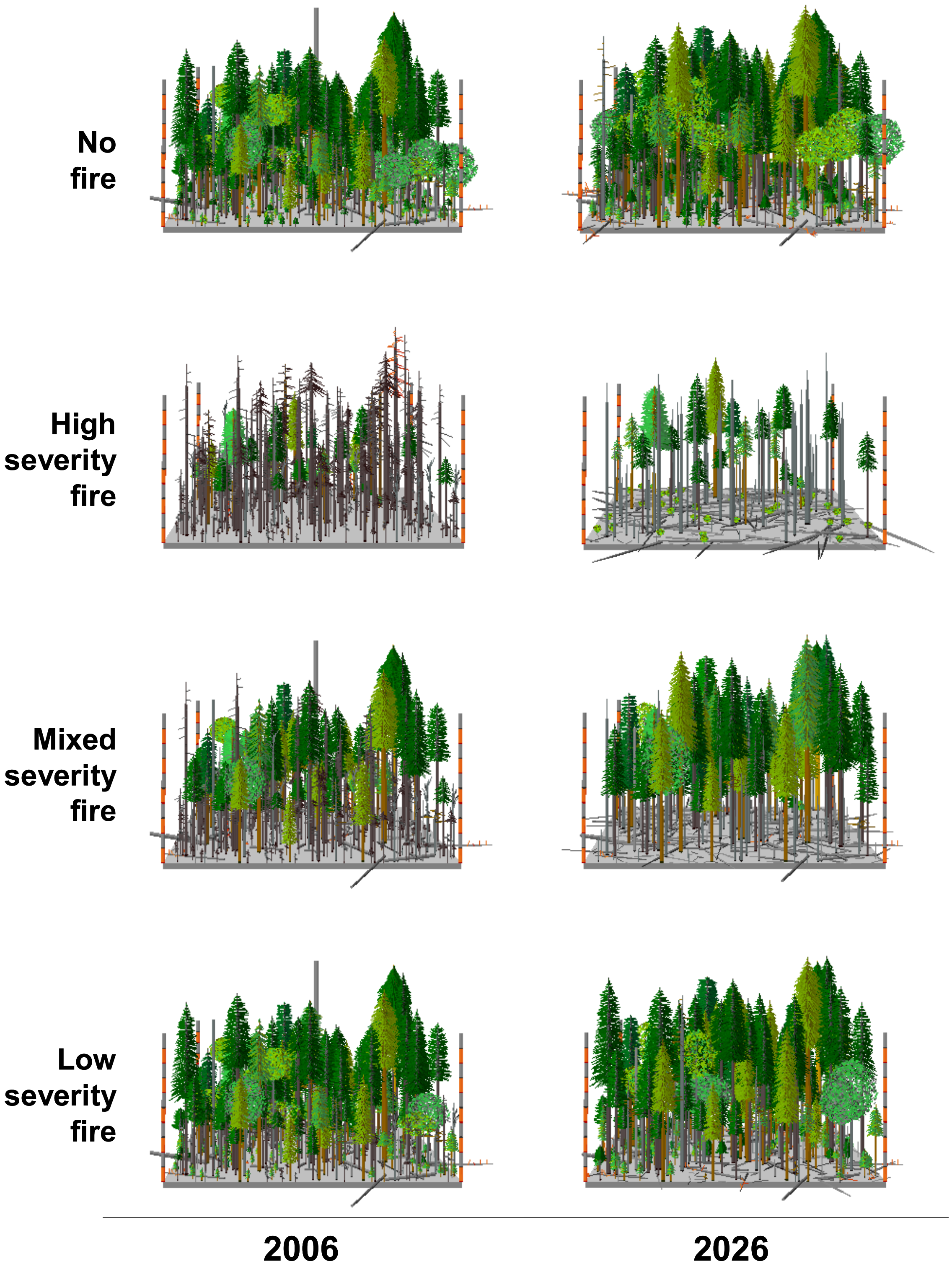


FIGURE 8


No fire
High severity fire
Mixed severity fire
Low severity fire
2006
2026