FIRE SCARRING PATTERNS IN SIERRA NEVADA WILDERNESS AREAS BURNED BY MULTIPLE WILDLAND FIRE USE FIRES

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ABSTRACT

Uncertainty associated with fire-scar reconstructions of historical fire occurrence has led to questioning both estimates of frequency derived from these methods and the inferences on fire regimes drawn from these estimates. Using information from multiple, naturally-occurring fires (referred to as wildland fire use (WFU) fires) in two Sierra Nevada wilderness areas, we identified forest structural, topographic, and fire characteristics influencing fire scarring in trees and conducted direct comparisons of fire-scar reconstructed fire extent and frequency to fire atlas-based estimates of fire extent and frequency. The most important factor influencing the probability of sampled *Pinus jeffreyi* trees scarring from WFU fires was the length of time since previous fire. When intervals between successive fires are short, probabilities of scarring were low. Tree basal area and aspect were also significant factors explaining observed pattern of tree scarring. In all WFU fires but one, the reconstructed extent of fires was substantially smaller than the fire atlas extent. As a result, fire-scar reconstructed estimates of fire rotation were much longer than fire atlas fire rotation. This information can provide some necessary insight in interpreting and accounting for uncertainty in fire-scar reconstructions for drier low- to mid-elevation forest types throughout the western United States.

Keywords: dendrochronology, dendrochronological reconstruction, fire ecology, fire history, fire management, fire regime, fire scar, prescribed natural fire, unrecorded fire problem

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INTRODUCTION

Throughout much of the drier, low- to mid-elevation forests in the western U.S., fires historically burned at intensities that often left mature trees unaffected or scarred by fire, but seldom killed (Schoennagel *et al.* 2004). Based on the records preserved in scarred trees, many researchers have reconstructed historical fire occurrence, and from these reconstructions inferred historical fire regime characteristics (fire frequency, seasonality, extent, and to a lesser degree intensity and severity) (e.g., Fulé *et al.* 1997, Brown *et al.* 1999, Swetnam *et al.* 1999, Taylor and Skinner 2003, Stephens and Collins 2004, Moody *et al.* 2006, Collins and Stephens 2007). In many cases, these inferences are intended to inform managers and policy makers of the historical or natural context of fire operating on the landscape. As a result, reconstructions of historical fire regimes are often used to inform management decisions to manipulate current forest structure and implement fire use. However, uncertainty associated with fire scar reconstructions has led to questioning both estimates of frequency derived from these methods and the inferences on fire regimes drawn from these estimates (Johnson and Gutsell 1994, Minnich *et al.* 2000, Baker and Ehle 2001, Baker 2006).

Minnich *et al.* (2000: 124) argued that fire-scar based methods of reconstructing fire occurrence “give undue importance to small fires and lead to inaccurate estimates of spatial fire intervals…” They contend that although these non-lethal fires are detected relatively frequently in the tree ring record, many of these fires are actually localized, low-intensity fires that have less of an impact on shaping forest structure. In fact, Minnich *et al.* (2000) argue it is the infrequent, larger and more intense surface fires that maintain forest structure in California’s unmanaged mixed-conifer forests. As a result, it is inferred that fire-scar based reconstructions overestimate the actual frequency of fires. Conversely, Baker and Ehle (2001) point out that unrecorded fires (i.e., fires that do not show up in the fire scar record) could lead to overestimation of the time between fires and the fire rotation (defined as the length of time necessary to burn a cumulative area equivalent to the size of the area of interest). Unrecorded fires could be a product of insufficient fuel accumulation or consumption near the base of trees, as well as loss of previous fire scars due to consumption by subsequent fires. Ultimately, it is not entirely clear how to account for the uncertainty in both of these processes leading to tree scarring over a landscape and the interpretation of individual fire scars across a landscape.

One way to begin to understand these uncertainties is to look at tree scarring patterns within known fire perimeters. This would allow for direct comparisons between reconstructed fire frequency and extent based on fire scars and actual fire frequency and extent. These comparisons could then be used to adjust or account for uncertainties in fire scar reconstructions of historical fire occurrence. However, a major limitation in conducting such comparisons is that few places exist in the western U.S. that have had multiple, overlapping fires that were mapped with reasonable accuracy (but see Rollins *et al.* 2001, Collins *et al.* 2007). Furthermore, in order to make reasonable connections between tree scarring patterns in historical fires and those in more recent fires, the areas with overlapping fires need to have forests that are relatively free of livestock impacts and be composed of large, old trees. The fires need to have burned under a wide range of weather- and fuel-moisture conditions, as opposed to either the moderate conditions associated with most management burns, or the extreme conditions associated with wildfires.

The few places in the western U.S. that have intact forests, minimal or no domestic livestock grazing over the last century, and have allowed multiple, naturally-occurring fires to burn relatively unimpeded are remote wilderness areas (Rollins *et al.* 2001, Collins and Stephens 2007). Illilouette Creek basin in Yosemite National Park and Sugarloaf Creek basin in Sequoia and Kings Canyon National Park are two such places. These basins provide a relatively unique opportunity to compare tree-scarring patterns to over 30 years of mapped wildland fire use (WFU) fires, spanning from 1973 to 2005. These fires were mapped by aerial surveys, global positioning system (GPS), or satellite imagery. We obtained the mapped fire perimeters and digital fire atlases (Morgan *et al.* 2001, Rollins *et al.* 2001) from fire management personnel in each park. In addition to the fire atlases, we used independently derived remotely sensed estimates of burn severity (Miller and Thode 2007) to verify the accuracy of the digital fire atlases and to characterize severity of WFU fires around collected fire scars (burn severity images were only available for WFU fires that occurred within the Illilouette Creek basin). To our knowledge there has been very little previous work that examines how tree-scarring patterns coincide with both digital fire atlases and burn severity imagery (but see Shapiro-Miller *et al*. in press). Here we present an analysis that aims to explain observed patterns of tree scarring along with comparisons between fire-scar reconstructed fire extent and fire rotation to that based on digital fire atlases. We intend for these results to advance the discussion on the uncertainties associated with fire-scar reconstructions of historical fire occurrence.

METHODS

Study Area

Illilouette Creek and Sugarloaf Creek basins are within designated wilderness areas in the south-central and southern Sierra Nevada, respectively (Figure 1). Each basin is over 15,000 ha with elevations ranging from 1,400 m to nearly 3,000 m on the surrounding ridges. The climate is Mediterranean with cool, moist winters, and warm, generally dry summers. Between the two basins, average January minimum temperatures range from -2 °C to -5 °C, while average July maximum temperatures range from 24 °C to 32 °C (averages based on observations from Yosemite and Sequoia and Kings Canyon national parks between 1948 and 2006). Precipitation varies with elevation and is predominantly snow, with annual averages near 100 cm in both areas. The forests in Illilouette Creek and Sugarloaf Creek basins are dominated by Jeffrey pine (*Pinus jeffreyi*), red fir (*Abies magnifica*), white fir (*Abies concolor*), lodgepole pine (*Pinus contorta*) (nomenclature follows Hickman 1993), and are interspersed with meadows and shrublands.

Within each basin we designated an approximately 500 ha study area to collect fire-scarred samples along with information on stand structure, fuels, and species composition (Figure 1). The locations of these study areas were chosen to optimally capture the range of area burned at different frequencies by WFU fires. In other words, within each basin we wanted a continuous study area in which part of the area had not been burned by WFU fires, part was burned by one WFU fire, part by two WFU fires, and so on up to four WFU fires for Illilouette basin and three for the Sugarloaf basin. We used the digital fire atlases to designate these study areas. We stratified these study areas by burn frequency (0 to 4 burns) then established a 200 m grid for stand structure sample plot locations. In Sugarloaf we had to use a 100 m grid for the zero-burn frequency stratum because very little unburned area existed. Our goal was to sample a minimum of five plots in each burn frequency stratum, and augment that as time and area permitted. In larger strata we sampled up to nine plots. In 2002, we sampled 63 0.05 ha circular plots between study areas, 24 in Illilouette and 39 in Sugarloaf. In each plot we identified tree species, measured tree heights and diameters, and measured canopy cover.

Dendrochronological Fire Reconstruction

We opportunistically collected cross-sectional slabs from 73 fire-scarred trees, snags, and downed logs between the two study areas in 2005. Recent research has shown that opportunistic or "targeted" sampling of fire-scarred trees to reconstruct historical fire occurrence yields results very similar to either random or systematic sampling (Van Horne and Fulé 2006). We cut and removed slabs from trees within approximately 70 m of plot center exhibiting visual evidence of multiple

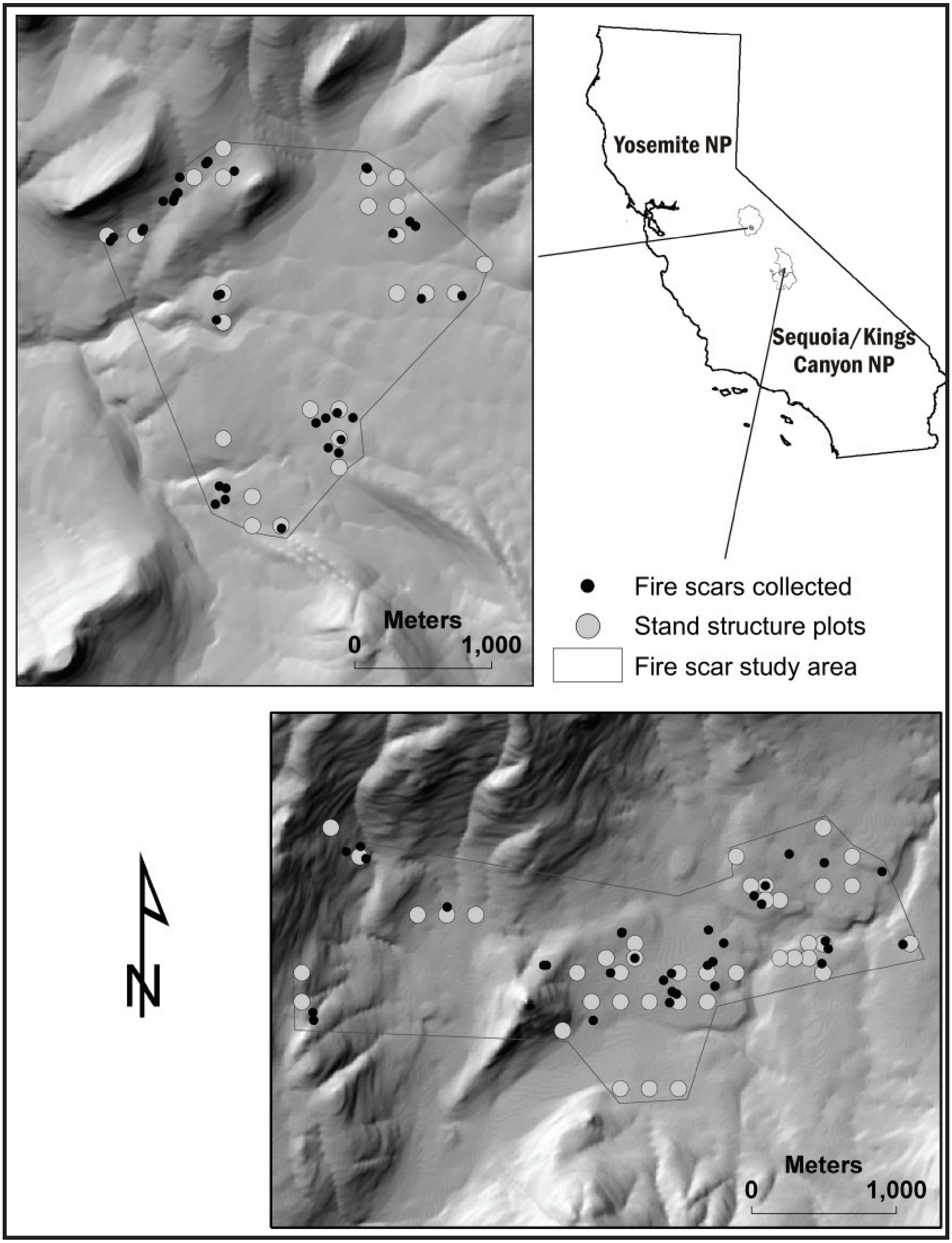

Figure 1. Fire scar and plot locations in Illilouette Creek basin (upper) and the Sugarloaf Creek basin (lower), California, USA.

fire scars. While walking between plots, we also collected slabs from any tree we noticed with multiple fire scars. Sampling only multiple-scarred trees is an efficient method for detecting the maximum number of fire years with the least ecological damage and field and laboratory work (Brown and Wu 2005). We took GPS locations, with approximately 5 meter accuracy, for each fire-scarred tree we collected.

Fire-scarred slabs were sanded to a high polish, then cross-dated against a master chronology using standard dendrochronological techniques to assign calendar years to fire scars (specific methodology was as explained in Brown and Wu 2005). Except when confined by the fire scar study area boundary, we mapped the spatial extent of fires recorded by scars within our study area by constructing a convex hull polygon around trees (3 minimum) that recorded a particular fire (Bekker and Taylor 2001). While a complete census of all fire-scarred trees would be optimal for the most accurate reconstruction of fire extent, doing so would be infeasible due to the effort required and destructive nature of sampling fire scars. Our relatively complete spatial coverage across the Illilouette and Sugarloaf study areas (Figure 1) allows us to make reasonable assertions on tree scarring patterns.

Spatial Data

We obtained digital fire atlases (e.g., Rollins *et al.* 2001) for WFU fires that occurred between 1973 and 2005 from fire management staff at each park. Five WFU fires burned across the Illilouette study area and four across the Sugarloaf study area during the period (Figures 2 and 3). The fire atlases are a best approximation of actual burn perimeters, but do not provide information on the spatial heterogeneity of burning within fire areas (Morgan *et al.* 2001). We used satellite-based estimates of burn severity to characterize this heterogeneity within fires that occurred in the Illilouette Creek basin (Miller and Thode 2007). These estimates of burn severity also serve as independent checks verifying the reliability of the digital fire atlases. Based on visual inspection, there was a high degree of agreement in the extents and locations of fires between perimeters from digital fire atlases and burn severity estimates from the satellite imagery for the Illilouette Creek basin. As such, we submit that the fire atlases are reasonably accurate for our purposes of comparing and understanding uncertainty in fire-scar reconstructions. Burn severity images for fires that occurred prior to 1984 were derived using a relative version of the differenced Normalized Difference Vegetation Index (RNDVI) (Thode 2005). For fires that occurred in 1984 or later, we used a relative version differenced Normalized Burn Ratio (RdNBR), which improves the estimation of burn severity across multiple fires and vegetation types (Key and Benson 2005, Thode 2005, Miller and Thode 2007). Both RNDVI and RdNBR are continuous estimates of burn severity. RNDVI estimates were re-scaled so that the range matched that of the RdNBR estimates.

Using the GIS software package ArcGIS®, we extracted burn severity (for Illilouette study area only) and topographic (slope, aspect) information from pixels (30 m spatial resolution) immediately adjacent to each of the collected fire-scarred trees. Additionally, we compared fire-scar locations and reconstructed fire extent to the digital fire atlases (Figures 2 and 3). For each fire, we calculated the proportion of the study area burned based on the fire atlas and the fire-scar reconstructed extent. We identified the maximum possible fire-scar reconstructed extent using a convex hull polygon that we drew around the potential recorder fire-scarred trees within a given WFU fire perimeter (based on fire atlases). We identified potential recorder trees for a given

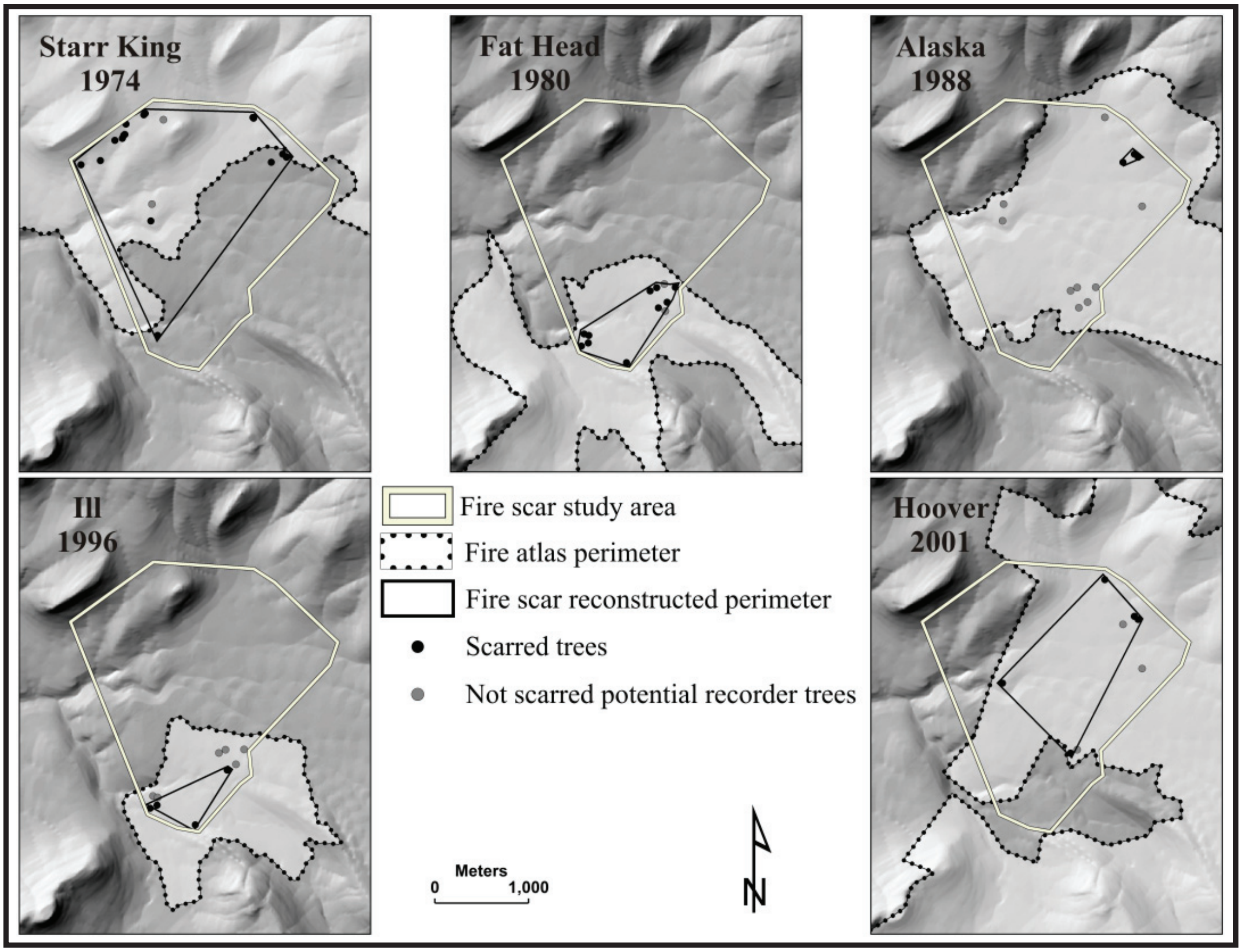

Figure 2. Tree scarring patterns and perimeters for the five WFU fires that burned in Illilouette Creek basin fire scar study area.

fire event as those that: 1) had open wounds with prior evidence of fire (which all of the fire-scarred slabs we collected had), 2) had a death date later than the given WFU fire, and 3) were located within a given fire perimeter. Fires were recorded by trees outside of the fire atlas perimeters of three of the nine WFU fires (Figures 2 and 3). These trees were included in the analysis described in the following section. We also used digital fire atlases to derive values for the time since the last fire for each potential recorder tree within a given WFU fire perimeter. In cases where the previous fire predated the WFU period (1973 to present), we used the date of the most recent pre-WFU fire identified in the tree rings for each particular fire-scarred cross-sections. For example, estimates for the time since the last fire from potential recorder trees ranged from 73 years to 139 years, depending on the length of time between the WFU fire and the next earliest fire recorded in the tree ring.

Data Analyses

We used categorical tree and logistic regression analysis as complementary techniques to explain the observed patterns of fire scarring from WFU fires across the Illilouette and Sugarloaf study areas. In both analyses, we used the same set of predictor variables that could affect whether or not a tree scars in a given fire: dominant forest type, basal area (each based on plot-level

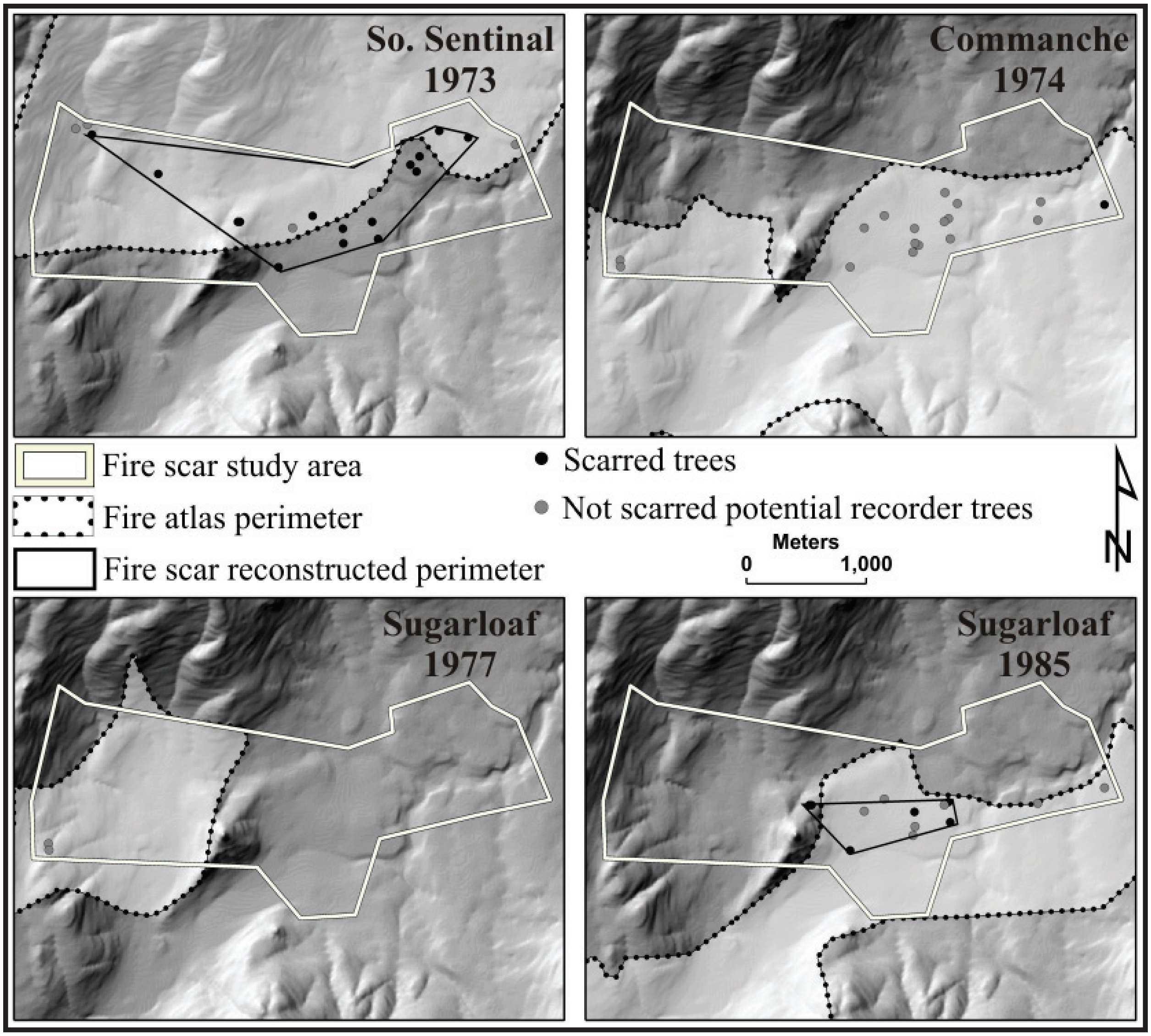

Figure 3. Tree scarring patterns and perimeters for the four WFU fires that burned in Sugarloaf Creek basin fire scar study area.

data), slope, aspect, time since previous fire, and burn severity (for Illilouette study area only). We used the categorical tree analysis to identify potential threshold values for variables explaining scarring patterns, and logistic regression to more directly assess the strength of both individual predictor variables and the model as a whole. We treated each potential recorder tree for a given fire event as an independent observation. We believe this assumption is reasonable, even given that a single fire-scarred tree could have been a potential recorder in multiple WFU fires, because each fire event involves a distinct combination of the predictor variables: burn severity and time since previous fire. Furthermore, fuel accumulation leading up to each fire and fuel consumption during each fire is most likely different for each tree in a given fire event and for the same tree in different fire events. Spatial autocorrelation is another concern for violation of the independence assumption. However, based on spatial modeling of Sierra Nevada forests (Miller and Urban 1999), plots that are more than 15 m apart can be reasonably assumed independent from one another. In our study, potential recorder trees in a given WFU fire meet this criterion.

We ran the categorical tree and logistic regression analyses in the statistical software packages R (http://www.r-project.org) and SAS®, respectively. The categorical tree, which was run using the RPART function in R, is constructed by repeatedly splitting the data into increasingly homogenous groups based on the response variable: not-scarred potential recorder tree (0) or fire-scarred tree (1). Each split is based on a simple rule for a given predictor variable (≥ or <), which minimizes the sum of squares within the resulting groups. The number of splits was determined using the one-standard error rule on the cross-validated relative error (Breiman *et al.* 1984, De'ath 2002). The rule for each split identifies the value or level of a given predictor variable at which the response, which was probability of scarring, changes substantially. For logistic regression, we used a stepwise model selection method ($\alpha = 0.1$) with the same set of predictor variables mentioned previously. None of the predictor variables exhibited any co-linearity with other variables. We used a goodness of fit test to evaluate the adequacy of the logistic regression model (Hosmer and Lemesow 2000).

RESULTS

Based on our identification of potential recorder trees, the total number of observations used in the statistical models explaining patterns of tree scarring in these WFU fires was 117. Because burn severity data were only available for Illilouette fires, we initially ran logistic regression and categorical tree analyses on the Illilouette data alone. Neither initial statistical model identified burn severity as a significant predictor variable explaining observed patterns of tree scarring. Based on these findings we combined the Illilouette and Sugarloaf observations into a single dataset to run each model so that we could extend our scope of inference ($n = 117$).

Both statistical methods yielded adequate models explaining tree scaring from WFU fires across the Illilouette and Sugarloaf study areas (logistic regression area under ROC curve = 0.78, categorical tree explained 33% of the total sum of squares) (Figure 4). By far, the most important variable in both models was time since previous fire (logistic regression maximum likelihood estimate = 0.018, $P = 0.0002$). Based on actual observations and logistic regression results, the probability of a tree scarring from a given WFU fire increased as the time since previous fire increased (Figures 4A and 4B). The categorical tree analysis resulted in a similar relationship, indicating that the probability of scarring was extremely low (0.04) if the time since previous fire was less than nine years (Figure 4C). The logistic regression analysis also identified aspect as a significant explanatory variable that influenced tree scarring ($P = 0.05$). Modeled probabilities of scarring were highest on south-facing aspects (maximum likelihood estimate = 0.801), and lowest on east-facing aspects (maximum likelihood estimate = -0.583) (Figure 4B). The categorical tree analysis did not identify aspect as an important predictor variable. Rather, basal area was important, with higher tree basal area (≥ 36.2 m^2 ha^{-1}) leading to increased probability of scarring (0.81) (Figure 4C).

Comparisons between reconstructed fire extent using fire scars and fire extent based on fire atlases revealed highly variable agreement in the fire scar reconstruction (Figures 2, 3, and 5). Reconstructed fire extent was closest to the atlas fire extent for the first WFU fire in both study areas (1974 in Illilouette, 1973 in Sugarloaf). However, extensive fires in 1988 for the Illilouette study area and in 1974 for the Sugarloaf study area were only detected at a very small spatial extent using

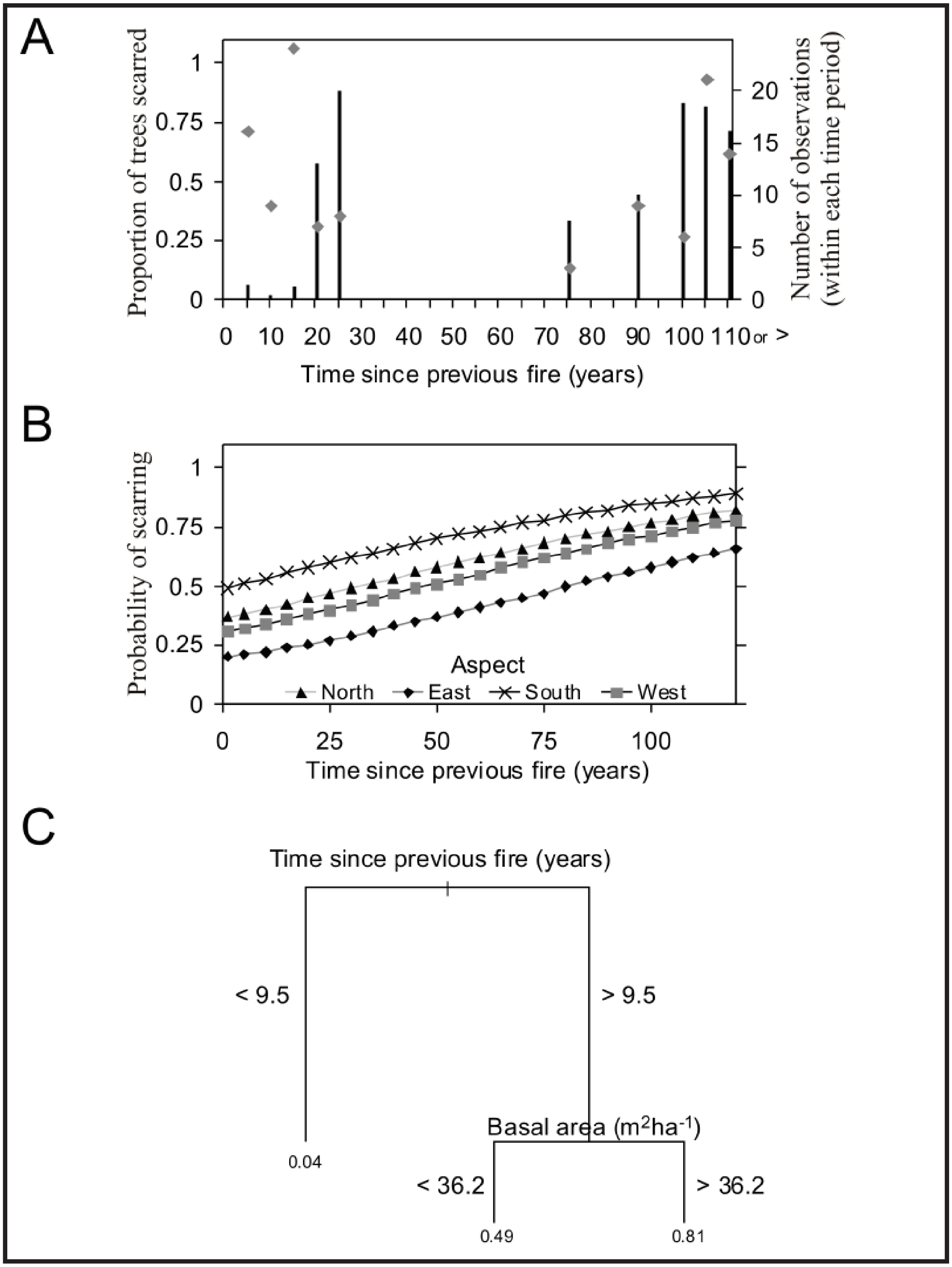

Figure 4. (A) Actual proportion of trees scarred for 5-year time since previous fire periods (vertical bars) and number of observations within each period (gray diamonds). (B) Modeled probabilities of tree scarring for the four cardinal aspects using logistic regression. (C) Categorical tree break points explaining the influence of both time since previous fire and basal area on tree scarring patterns in wildland fire use fires. The vertical depth of each split is proportional to the variation explained. The number below each terminal node in the categorical tree is the probability of scarring from WFU fires for that group.

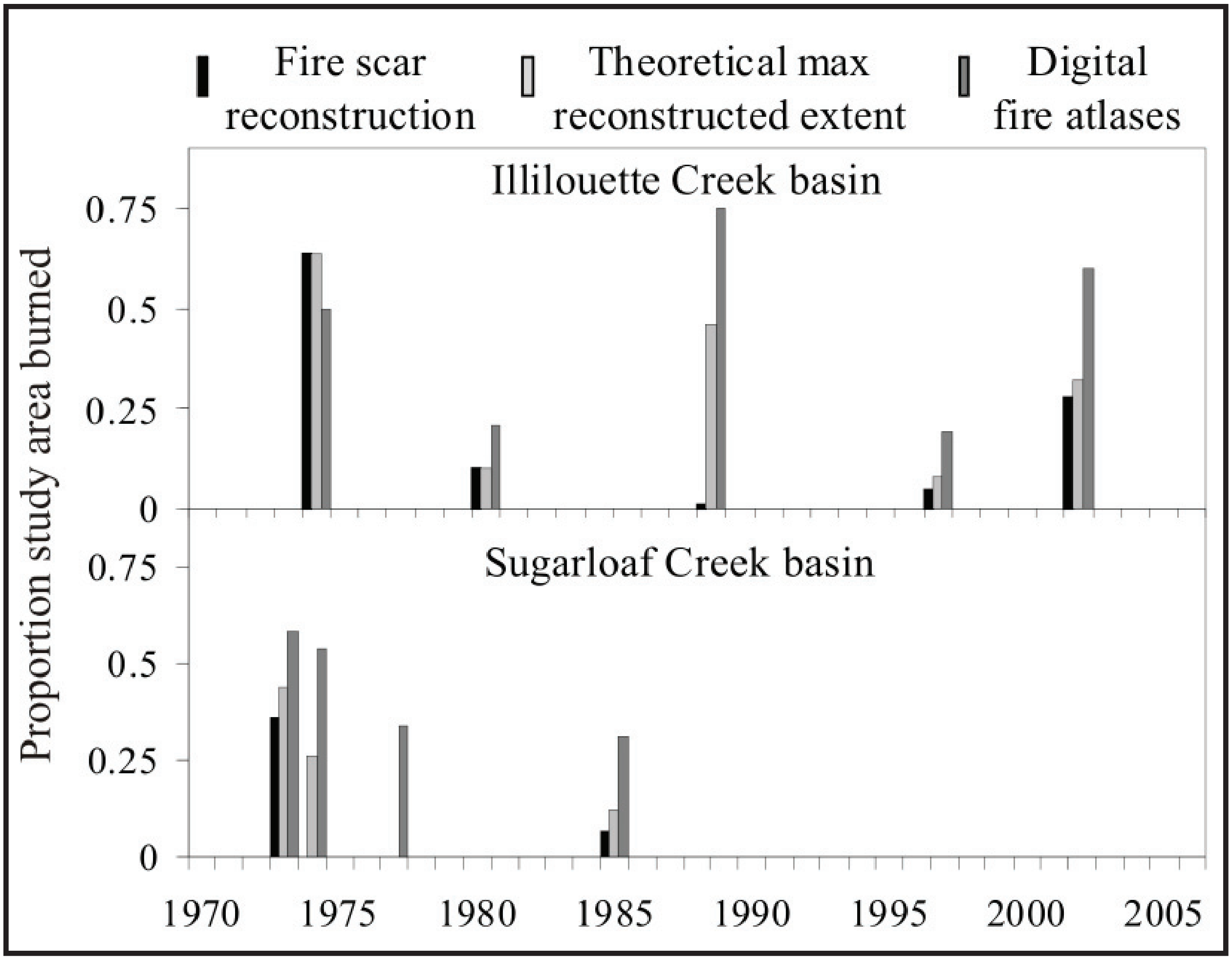

Figure 5. Comparisons of fire extent based on: recorded fire scars (black bars), all potential recorders (light gray bars), and fire atlases (dark gray bars).

fire scars (Figures 2, 3, and 5). With the exception of those two major discrepancies (1988 in Illilouette and 1974 in Sugarloaf), the reconstructed extent was fairly close to the theoretical maximum reconstructed extent based on potential recorder trees (Figure 5). As a result of the underestimated fire extent based on fire-scars, the reconstructed fire rotation (defined as the length of time necessary to burn a cumulative area equivalent to the size of the study area) was longer than the digital atlas fire rotation, calculated using fire atlases (Figure 6). In the Sugarloaf study area, the reconstructed fire rotation, using fire scars, was four times the length of the digital atlas fire rotation.

DISCUSSION

Patterns of Tree Scarring

It is worth noting that each of the fire-scarred cross-sections we collected had open cavities, which were most likely created by fires that occurred long before the WFU fires burned in either the Illilouette or Sugarloaf study areas (Collins and Stephens 2007). Because the potential for scarring from fire increases when trees have open cavities, our inferences on the probability of scarring from fire are limited to scars formed following an initial injury. The identification of time since previous fire as a strong predictor variable in both statistical

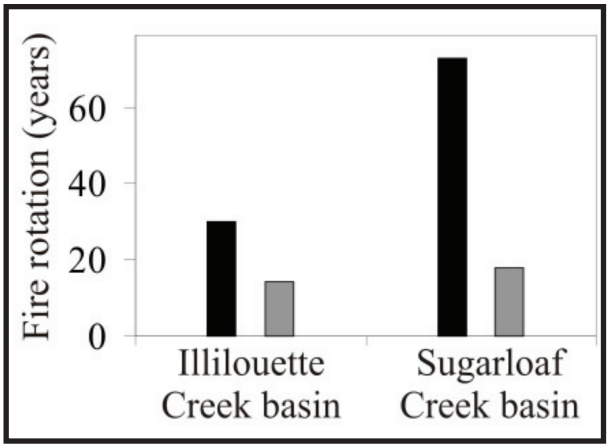

Figure 6. Fire rotation estimates based on the fire scar reconstruction (black bars) and digital fire atlases (gray bars) are calculated from the beginning of the WFU period (1973) to the year fire scarred samples were collected (2005).

models explaining the presence or absence of a fire scar has important implications for interpreting fire-scar reconstructions of historical fire. Time since previous fire can be viewed as a proxy for fuel accumulation (van Wagtendonk 1985, Collins *et al.* 2007). This suggests that fire-scar formation is at least partially dependent on fuel accumulation. The logistic regression model predicts that as time since previous fire exceeds 80 years, which is approximately the length of the fire exclusion period in Illilouette and Sugarloaf (Collins and Stephens 2007), probabilities of a tree scarring are above 50 % for all aspects (Figure 4B). In fact, the probability of a tree scarring on a south-facing slope at the same length of time since previous fire (80 years) is 80 %. Therefore, fuel accumulation during the uncharacteristically long fire-free interval caused by fire exclusion in these Sierra Nevada wilderness areas may have led to much higher percentages of trees scarred from the first WFU fire in each area than might otherwise be observed historically.

Although the idea of tree scarring being dependent on fuel accumulation is not completely novel, it does suggest a mechanism responsible for the absence of fire evidence in the tree-ring record. At much shorter periods since the previous fire, probability of scarring from these WFU fires is much lower (Figures 4A and 4B). The extremely low probability of scarring when the time since previous fire is under nine years, based on the categorical tree analysis, clearly demonstrates that overlapping fires occurring at fairly short intervals did not scar many trees in these study areas (Figure 4C). This finding suggests that fuel accumulation is important in contributing to the 'unrecorded fire problem' discussed by Baker and Ehle (2001). This emphasizes a major limitation of historical fire reconstructions based on fire scars where intervals between successive, overlapping fires are short. In areas where these types of fires are common, fire-scar derived fire frequencies will likely underestimate true fire frequency. However, the degree of underestimation will likely depend on the scale and intensity of fire-scar sampling, as well as fuel accumulation rates within a given forest type or stand. In forest types where fine fuels accumulate rapidly following fire, scarring may occur more readily, thus lessening the degree of underestimation.

The two variables of secondary importance in the two statistical models can both be interpreted as affecting fuel availability and fuel quantity (Figure 4B and 4C). The noticeably higher probabilities of scarring from WFU fires on south-facing aspects are most likely due to generally warmer and drier conditions that exist on south-facing slopes (Taylor and Skinner 1998). These conditions are caused by higher solar insolation on south-facing slopes, and can lead to greater fuel consumption and heat output in fires, relative to north- and east-facing aspects (Beaty and Taylor 2001, Stephens 2001, Skinner *et al.* 2006). The higher probability of scarring in stands with greater basal area may also be related to greater fuel availability, and consequently greater fuel consumption. Greater basal area is generally associated with larger trees, which generally have larger crowns, thus contributing to greater quantity and continuity of fine fuels to the forest floor (Skinner *et al.* 2005). Greater continuity of fine fuel promotes fire spread into areas of higher tree basal area, and the greater quantity leads to greater consumption and heat output (van Wagtendonk *et al.* 1998, Skinner *et al.* 2005, Ritchie *et al.* 2007). Increased heat output from fires, especially near the base of trees where fine fuels tend to accumulate, increases the probability of partial cambium mortality, and thus fire-scar formation (Gill 1974, McBride and Laven 1976).

Fire Scar - Fire Atlas Comparison

The high degree of agreement between fire-scar reconstructed extent and digital atlas extent for the first WFU fires in each study area (1974 in Illilouette, Figure 2; 1973 in Sugarloaf, Figure 3) is likely attributed to more uniform burning as a result of greater fuel accumulation during the fire exclusion period (Collins and Stephens 2007). The higher fire-scar reconstructed extent (relative to the atlas extent) for the 1974 Starr King fire in the Illilouette study area is a product of the convex hull polygons we created around recording fire scars, which tends to over simplify the more complex fire perimeters (Figure 2). For all fires except the first WFU fire in Illilouette, fire-scar reconstructed extent and the theoretical maximum reconstructed extent were less than the digital atlas fire extent (Figure 5). This is not surprising given both the stochastic nature of fire scar formation, and that our fire scar collection was based primarily on gridded plots within strata developed to optimize sampling areas of different burn frequencies, rather than collection intended to maximize area within WFU fire perimeters. What is more surprising is that some fires are completely missed (1977 in Sugarloaf) in the fire-scar record, or only detected at small spatial scales (1974 in Sugarloaf, 1988 in Illilouette). It is very plausible that without the knowledge of fires obtained from fire atlases and burn severity images, several fires between the two study areas would be interpreted as localized in extent, when in fact they were relatively large. Baker and Ehle (2001) refer to fires detected in the tree-ring records at small spatial extents as creating the "small fire problem." Minnich *et al.* (2000) made a similar claim, stating that fire scar reconstructions "give undue importance to small fires." Both of these studies suggest that fires detected at small spatial scales in the tree-ring record inflate estimates of fire frequency. We have shown that in fact, the opposite is true, at least for the Sierra Nevada Jeffrey pine mixed forests that we studied. The estimates of fire rotation based on fire-scar reconstructions are much longer than those based on the digital atlases (Figure 6).

Although it is clear that there is error in the fire-scar reconstructions of fire frequency, it appears that the error is in the direction of what Baker and Ehle (2001) refer to as the "unrecorded fire problem." The discrepancies between fire rotation estimates based on fire scars and the digital-atlas based fire rotation demonstrate the impact of this "unrecorded fire problem." This problem is not only due to the fires that are missed or only recorded at small spatial extents, it is also due to insufficient sampling. For all but one of the WFU fires in these two study areas, the theoretical maximum extent derived from convex hull polygons was well below digital-atlas fire extent (Figure 5). This means that even if these WFU fires scarred all the potential recorder trees, fire-scar reconstructed estimates of fire rotation would still be longer than the atlas-based rotation. It is necessary to state that our comparisons are imperfect because the fire perimeters mapped in the digital atlases are most likely approximate (Morgan *et al.* 2001), and indeed we found several trees outside fire perimeters that recorded fires (Figures 2 and 3). Despite the potential inaccuracies in mapping, we submit that the relatively recent nature of the fires analyzed between the two study areas

(1973 to 2005) and along with the agreement between independent satellite-based estimates of burn severity for fires that occurred within the Illilouette Creek basin, suggest that the atlases we use are reasonable estimates of actual fire extents and locations. Therefore, we infer that in order to capture a more accurate extent of each of these fires using fire-scar reconstructions we would need much more spatially intensive sampling throughout each study area. However, our findings indicating relatively low probabilities of scarring when times between successive fires was short suggests that some fires will likely be recorded at small spatial scales or missed entirely in potential recorder trees. Furthermore, the fire-scar record may simply not exist at all locations on the landscape.

Given the inconsistency in the differences between reconstructed fire rotation (1973 to 2005) and the digital atlas rotation for the Illilouette (atlas: 14.3; fire scar: 30.1) and the Sugarloaf (atlas: 18.0; fire scar: 72.9) study areas, we do not believe proposing a calibration or correction factor is prudent (*sensu* Baker and Ehle 2001, Baker 2006). This is especially so given that the correction factors proposed in these studies would result in an even greater underestimation. Rather, we intend for this study to serve as an initial step in attempting to meaningfully understand uncertainty in fire-scar based reconstructions. Using information from multiple, naturally occurring fires, we identify forest structure, topographic, and fire characteristics influencing fire scarring in trees, as well as provide direct comparisons of fire-scar reconstructed extent and frequency to fire atlas-based estimates of extent and frequency. While the WFU fires we studied may not closely resemble historical fire due to differences in climate or effects of fire exclusion, we believe that these WFU fires represent as close to natural burning conditions as any place in the western U.S. (Collins *et al.* 2007, Collins and Stephens 2007). As such, we believe that these results are applicable towards interpreting and accounting for uncertainty in fire-scar reconstructions of historical fire occurrence in similar forest types. It is not clear how widely applicable these results are across other forest types and regions; similar studies in different forest types and regions should be done to see if similar patterns occur.

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