Fire history of a naturally fragmented landscape in central Oregon

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Abstract: We examined the fire history of 11 forest isolates surrounded by lava flows (kipukas) in central Oregon to determine historical differences in fire regimes between kipukas and the surrounding forest, and the role of spatial and environmental variables in fire occurrence. Tree-ring analysis and statistical comparisons show that historical agency records underestimate the number of fires based on the incidence of fire scars. Fires occurred more frequently on kipukas, were typically smaller, and were predominantly lightning-initiated. Except for three widespread fires, fires on kipukas and in the surrounding forest were largely asynchronous. The mean fire-return interval (MFRI) in the surrounding forest decreased following Euro-American settlement and increased on the kipukas with spot-fire removal. This suggests either that forest management and fire exclusion in the surrounding forest decreased fire spread to the kipukas, or that most fires originated on the kipukas. MFRI correlates strongly with distance to the nearest kipuka and a distance-weighted isolation index. The number of fires correlates with elevation change and distance to the nearest kipuka. Fire in naturally fragmented landscapes is influenced by the spatial arrangement of patches, environmental conditions, and human activities. Reconstructing fire histories from forest isolates in the context of their mainland counterparts may have methodological advantages and theoretical implications for forested landscapes characterized by human-imposed insularity.

Introduction

Fire-history research generally focuses on the temporal and spatial patterns of fire in heterogeneous forested landscapes shaped by complex disturbance histories and environmental gradients (e.g., Veblen et al. 1994; Minnich and Chou 1997; Niklasson and Granstrom 2000; Howe and Baker 2003; Mouillot et al. 2003; Wallenius et al. 2004). This research includes a small subset of studies that explore fire within the context of forest isolates embedded in a nonvegetated landscape matrix (sensu Haila 2002). Following the well-developed theoretical context provided by island biogeographic theory (MacArthur and Wilson 1967; Lomolino 2000; Whittaker 2000), landscape ecology (Turner et al. 2001), and the disturbance concept (Pickett and White 1985), this body of research has investigated the fire history of isolates as it relates to species diversity (Watson 2002), ecosystem properties (Wardle et al. 1997; Wardle and...
Zackrisson 2005), carbon storage (Wardle et al. 2003), succession (Larocque et al. 2000), and plant evolution (Clarke 2002). Nonetheless, many questions regarding the initiation, spread, and ecological ramifications of fire in these ecosystems remain.

Few case studies compare the fire histories of forest isolates with those of their “mainland” counterparts and their results are often inconsistent with theoretical predictions. For example, landscape matrices consisting of inflammable (water) or sparse fuels (e.g., lava flows, avalanche paths, and peatland) would hypothetically inhibit the spread of fire from mainland to isolates by creating natural fuel breaks (Turner et al. 1989), resulting in lower fire frequencies among isolates. A small number of studies report lower fire frequencies in isolates relative to nearby mainland forests (Madany and West 1983; Grissino-Mayer and Swetnam 1995; Clarke 2002) and several indicate higher fire frequencies among isolates (Bergeron 1991; Murray et al. 1998; Fule et al. 2003). The role of other spatial and environmental factors, including isolate size, topographic relief, and climate variability, in isolate fire regimes is also poorly understood (Bergeron 1991; Fule et al. 2003).

Examining fire regimes among isolates further provides an opportunity to evaluate several assumptions regarding methodological issues inherent in fire-history research (e.g., Baker and Ehle 2001) and fire management (Turner et al. 1994). In many cases, isolates are significant locations for reconstructing fire histories because documented 20th-century fires can be used to test the completeness and sensitivity of fire-scar-based reconstructions. Moreover, isolates situated within a nonvegetated landscape matrix may provide one of the few opportunities to examine modern analogs of forest conditions prior to Euro-American settlement (Grissino-Mayer 1995; Fule et al. 2003). Finally, isolate–mainland ecosystems present an opportunity to reconstruct fire histories of forests that have experienced minimal changes to fuel loads and forest structure due to human activities such as grazing, logging, and fire suppression (Fule et al. 2003; Stephens et al. 2003; Westerling and Swetnam 2004).

This study investigates the fire history of 11 forest isolates (kipukas) and mainland (surrounding) forest in central Oregon to address several questions regarding the spatial and temporal nature of their respective fire regimes as well as some methodological implications of these differences. We specifically seek answers to the following questions: (i) How do the written record and fire-scar record compare? (ii) How do fire regimes (frequency and severity) differ between the kipukas and the surrounding forest during the pre- and post-Euro-American settlement periods? (iii) How do local environmental and spatial factors, including topography, isolate size, and degree of isolation, influence the occurrence of fire on the kipukas? (iv) How do the results of this study compare with those of other isolate–mainland fire-history studies?

Materials and methods

Study area

Our 1100 ha study site is located near the Lava Cast Forest Natural Area (LCF) in Newberry National Volcanic Monument (NNVM) in the Deschutes National Forest (Fig. 1). This area is dominated by three mid-Holocene lava flows dating to 6380 years before present (YBP), 5960 YBP, and 5800 YBP (Peterson and Groh 1969) that surround and isolate 12 older, forested cinder cone deposits (kipukas). These kipukas range in size from 0.4 to 113 ha and in elevation from 1590 to 1820 m. Hoffman Island (Fig. 1) was selectively logged from 1930 to 1960; the other kipukas remain in near-pristine condition except for a small number of stumps and logs cut during recent fire-suppression activities on three of them (K7, K9, and K10; Fig. 1). The forest surrounding the lava flows has been selectively logged and clear-cut since the 1930s, creating a patchy mosaic of clearcuts and second- and third-growth stands of ponderosa pine (Pinus ponderosa Dougl. ex P. & C. Laws.) and lodgepole pine (Pinus contorta Dougl. ex Loud.).

The kipukas are covered by forest stands that vary in species composition. Ponderosa pine dominates most south-facing slopes and the edges of the kipukas, while lodgepole pine dominates large, relatively level areas of the kipukas. A white fir – grand fir (Abies concolor (Gord. & Glend.) Lindl. – Abies grandis (Dougl.) Lindl.) hybrid dominates north-facing slopes and interior stands. Western white pine (Pinus monticola Dougl.) occurs infrequently along the margins of some kipukas and north-facing slopes. Common understory species include wax currant (Ribes cereum Dougl.), snowbrush (Ceanothus velutinus Dougl. ex Hook.), antelope bitterbrush (Purshia tridentata (Pursh) DC.), greenleaf manzanita (Arctostaphylos patula Greene), spurred lupine (Lupinus argenteus var. laxiflorus (Dougl. ex Lindl.) Dorn), white-vein wintergreen (Pyrola picta Sm.), and green rabbitbrush (Chrysothamnus viscidiflorus (Hook.) Nutt.).

The study area is located in the rain shadow of the Oregon Cascades and experiences a semi-arid climate with average annual precipitation ≅300 mm and average temperatures ranging from 0 °C in January to 17.3 °C in July as averaged over 1971–2000 (Oregon Climate Service 2005). Kipuka soils are weakly developed (A and C horizons) Andisols developed in Mazama-age (~6800 YBP) pumice and ash. Soil depth varies locally depending on pre-eruption topography (Geitgey 1992). In general, the pumice soils of central Oregon have a low bulk density and low thermal conductivity and are nutrient-limited (Youngberg and Dyrness 1965; Cochran et al. 1967), but they can have a high moisture-holding capacity if the pumice vesicles and pore spaces are small (Youngberg and Dyrness 1965; Geitgey 1992). These conditions may influence the distribution of ponderosa pine and lodgepole pine, enabling the latter to dominate areas with deep pumice deposits (Franklin and Dyrness 1988).

The area surrounding the caldera at NNVM has been spiritually important to the Molalla and Northern Paiute tribes (USDA Forest Service 1994). Both tribes used fire to improve forage for game and plant production and helped shape local plant communities (Sutton 2000). Euro-American settlement began in the 1860s following the establishment of the Santiam Wagon Road linking the Willamette Valley in western Oregon to central Oregon in 1864 and the Huntington Road connecting the Columbia River in north-central Oregon to the Klamath Reservation in 1867. Prineville, Sisters, Bend, and La Pine were the major settlements at the turn of the 20th century and were supported by timber-extraction and ranching activities (Hatton 1977, 1986, 1996; Deschutes...
Fig. 1. The study area within the Lava Cast Forest Natural Area in Newberry National Volcanic Monument, Deschutes National Forest, central Oregon. The kipukas included in this study are identified as K1–K11. The study boundaries are roughly defined by the locations of fire-scar samples. Contour lines are at 10 m intervals.
Fire records for the Deschutes National Forest date to 1908, the year the forest was established (McCauley 1993; USDA Forest Service 2001). Fire suppression was initiated as early as 1908 and fire lookout stations were established beginning in 1913 (McCauley 1993; USDA Forest Service 2001). Motorized equipment and roads improved fire-suppression efforts by the 1920s. Mechanization, including the use of pumper trucks, bulldozers, and chainsaws, was common by the 1950s and was followed by aerial support provided by air tankers and infrared radar in the 1960s (McCauley 1993).

**Fire-history reconstruction**

We constructed our fire history using USDA Forest Service historical records (McCauley 1993; USDA Forest Service 2001; USDA Forest Service 2004) and tree-ring evidence collected from fire-scarred trees. Historical records document fires in the study area from 1908 to the present. Fire data include date, name of fire, acreage, and township and range for 1908–1979 and date, latitude and longitude, ignition source, acreage, and township and range for 1980–2001. Our dendroecological fire record was developed from partial cross sections of fire-scarred trees, snags, and logs.

We sampled the kipukas both systematically and opportunistically, by traversing each stand type on the kipukas and targeting fire-scarred trees, snags, and logs with multiple fire scars to maximize our coverage of each stand on the kipukas. We sampled the forest surrounding the kipukas by systematically collecting partial cross sections from fire-scarred material located within 200 m of the lava, opportunistically selecting material displaying multiple fire scars. In the surrounding forest we focused our sampling west and southwest of the kipukas to ensure that we obtained an adequate sample of those areas most likely to burn following the spread of fire from the surrounding forest onto the kipukas (Fig. 1). We chose not to sample the young, monotopic, and managed lodgepole pine stands northeast and southeast of the kipukas because of the low probability of finding fire scars pre-dating the last stand-replacing fire. The use of these procedures on the kipukas and in the surrounding forest allowed us to avoid oversampling (as required by NNVM resource management directives) while assembling a comprehensive fire-history sample.

We sampled each fire-scarred feature by removing a partial cross section following the procedures outlined by Arno and Sneck (1977). Our samples were almost exclusively ponderosa pine: only 8 of the 85 samples were lodgepole pine. Logging of large-diameter trees in the surrounding forest during the 1930s and the subsequent deterioration of scarred stumps and logs resulted in a sample disparity between the surrounding forest (27%) and the kipukas (73%). However, our sample sizes were sufficient to characterize the generally widespread nature of fires in the surrounding forest and demonstrate a general lack of coincident fire dates between the kipukas and the surrounding forest.

We prepared our partial cross sections using a power planer and sanding each cross section with 120- to 1000-grit sandpaper until cellular structure was clearly visible. Once the cross sections were surfaced, we used a variable-magnification binocular microscope to identify the annual ring containing the tip of each fire scar. Each cross section was then visually cross-dated following the procedures outlined in Stokes and Smiley (1968), using marker rings identified in a master tree-ring chronology for the study area (Pohl et al. 2002). Fire scars were assigned calendar years and the season of fire occurrence was determined based on the intra-annual position of the fire scar in the tree ring (Baisan and Swetnam 1990).

We examined fire seasonality by graphing the frequency distributions of five fire-scar positions (early earlywood, middle earlywood, late earlywood, latemarrow, and dormancy) noted for the study area, the kipukas, and the surrounding forest. Dormant-season fires were assigned to the end of the previous growing season (fall) based on the high regional frequency of late-summer and fall fires (McCauley 1993; USDA Forest Service 2001; USDA Forest Service 2004; also see Heyerdahl et al. 2001). We determined changes in seasonality by graphing a 25-year moving average of the percentages of growing-season and dormant-season scars over time (Grissino-Mayer and Swetnam 1995). These data were then entered into the fire-history software FHX2 (Grissino-Mayer 2001) for the construction of fire chronologies and our temporal and spatial analyses described below.

**Temporal analysis**

Our temporal analysis compares mean fire-return intervals (MFRI) and Weibull median intervals (WMI) for three chronologies representing (i) the entire study area (kipukas and surrounding forest), (ii) the kipukas, and (iii) the surrounding forest. Because fire-interval data are often skewed and are better fit by the Weibull distribution (Grissino-Mayer 1995), we used a Kolmogorov–Smirnov test for fit (in the FHX2 software) to ascertain which distribution best fit our data (Grissino-Mayer 2001). We defined the length of each chronology using a period of reliability (POR), defined as the portion of the chronology with a sample depth of ≥5 partial cross sections to ensure an accurate representation of fire activity (e.g., Grissino-Mayer 1995; Touchan and Swetnam 1995). We tested each chronology for temporal changes between the pre-Euro-American settlement (POR–1859) and the post-settlement (1860–2001) time periods. There were insufficient fires in the settlement time period (between the major fire in 1823 and the next fire in 1883) to perform statistical analyses to characterize the fire regime during that period. We note here that although differences in sample size and sampling area between the kipukas and the surrounding forest will affect fire-return intervals, this effect is mediated somewhat by using composited intervals.

We conducted our tests using all fire dates recorded in the chronology and a filtered sample limited to fire years when at least 10% of all sampled trees (with a raw sample size ≥22 trees) were scarred. The filtered sample de-emphasizes lightning scars and spot fires (Grissino-Mayer 1995). We also estimated the extent of fires by examining changes in the percentage of trees scarred between the time periods; we interpreted lower percentages as representing smaller fires and higher percentages as representing either a single large fire or several smaller fires occurring in the same year.
Spatial and environmental analysis

We examined the relationships among isolation, fire frequency, and fire synchrony by comparing fire regimes between the kipukas and the surrounding forest. This comparison assumes that intervening lava flows reduce the spread of fire between the kipukas and the surrounding forest and among the kipukas as indicated by (i) longer MFRIs on the kipukas relative to the surrounding forest and (ii) low fire synchrony between the kipukas and the surrounding forest. We also tested for synchrony among the kipukas based on the hypothesis that individual kipukas have unique fire regimes as a result of fragmentation. Synchrony was tested using a $\chi^2$ test of association for autocorrelated data and the Ochiai Index, which provides a measure of association between two time-series data sets (Grissino-Mayer 2001).

We employed Spearman’s rank correlation analysis to investigate the relationship between fire occurrence and spatial and environmental variables. All correlations were conducted using spatial and environmental variables from the 10 kipukas with fire-scar records. Using MFRIs and total number of fires on each kipuka as our dependent variables, we examined how kipuka area, perimeter, elevation change, distance from the surrounding forest, distance from the nearest kipuka, and total isolation value (TIV) influence the frequency and spread of fires across the study site. We used TIV indices to better analyze the role of isolation and fire, recognizing their potential to explain patterns on the landscape. Lacking previous analyses of this type we created three TIV indices specific to the landscape at LCF (cf. Hadley 1987). Our indices are variously weighted by area and (or) distance to neighboring kipukas and the surrounding forest to determine whether combinations of area and distance to neighboring kipukas influence the number of fires and MFRIs of an individual kipuka:
Table 2. Percentages of scarred trees in the study area, kipukas, and surrounding forest.

<table>
<thead>
<tr>
<th></th>
<th>Study area (n = 304)</th>
<th>Kipukas (n = 204)</th>
<th>Surrounding forest (n = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of fires scarring</td>
<td>≥10%</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>≥25%</td>
<td>3</td>
<td>4</td>
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<td>Year</td>
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<td></td>
<td>1918</td>
<td>58</td>
<td>1918</td>
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<td></td>
<td>1823</td>
<td>41</td>
<td>1823</td>
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<td></td>
<td>1740</td>
<td>48</td>
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<td>Major fires</td>
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<td>% of trees</td>
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<td></td>
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<tr>
<td>No. of trees</td>
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Note: Data represent fire years where ≥10% and ≥25% of the sampled trees alive during a given fire year were scarred. Major fires represent fire years where ≥25% of susceptible trees were burned; $n$ is the number of fire scars identified for each sampling unit.

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Fig. 3. A 25-year moving average of fire scars by season. Note that dormant-season scars appear after 1850 and cease after 1960.

Table 2.

<table>
<thead>
<tr>
<th></th>
<th>% of fires scarring</th>
<th>Major fires</th>
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<tr>
<td></td>
<td>≥10%</td>
<td>≥25%</td>
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<tr>
<td>Study area ($n = 304$)</td>
<td>14</td>
<td>3</td>
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<tr>
<td>Kipukas ($n = 204$)</td>
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<tr>
<td>Surrounding forest ($n = 100$)</td>
<td>36</td>
<td>17</td>
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</tbody>
</table>

Fig. 3. A 25-year moving average of fire scars by season. Note that dormant-season scars appear after 1850 and cease after 1960.

\[
TIV_1(K_i) = D(K_i, K_{n_1}) + F_i
\]

\[
TIV_2(K_i) = \left[ \sum_{j=1}^{5} A(K_{n_j}) \right] / D(K_i, K_{n_1}) + F_i
\]

\[
TIV_3(K_i) = \frac{1}{5} \left[ \sum_{j=1}^{5} A(K_{n_j}) \right] / D(K_i, K_{n_1}) + F_i
\]

where $F_i$ is the distance (in metres) from the surrounding forest to the $i$th kipuka ($K_i$), $A$ is the kipuka area (in hectares), $D$ is the distance (in metres) between kipukas, and $K_{n_1}, K_{n_2}, K_{n_3}, K_{n_4},$ and $K_{n_5}$ are the five nearest neighbors to $K_i$ in order of proximity.

Results

Fire-history reconstruction

We derived our fire history from 94 years of documented fire occurrence from USDA Forest Service fire atlas data and a 808-year fire-scar record. Historical fire records from the Deschutes National Forest document 25 fires in or within 2 km of the study area between 1908 and 2002 (McCauley 1993; USDA Forest Service 2001; USDA Forest Service 2004). Over 75% of these fires were small class A fires.
Comparison of kipukas and the surrounding forest

The MFRIs for the study area show little change between the pre-Euro-American settlement (5 years) and post-settlement (4 years) eras (Table 3, Fig. 2a). Removing spot fires and lightning scars from the analysis using a 10% filter increases the pre- to post-settlement MFRI from 19 years to 46 years ($p < 0.10$) (Table 3).

The fire history of the kipukas (Table 3, Fig. 2b) includes a slight decrease in the pre- to post-settlement era MFRIs (from 7 to 6 years). When filtered, MFRI increases over the entire time period, and it also increases across the pre- to post-settlement time periods from 19 to 46 years ($p < 0.05$). The surrounding-forest MFRI decreases from 12 to 7 years between the pre- and post-settlement period when all fire scars are considered ($p < 0.10$) (Table 3, Fig. 2c). Filtered MFRIs for the surrounding forest do not differ significantly between pre-settlement and settlement periods. Mean percentages of scarred trees (MPS) between the pre- and post-settlement periods for the study area, kipukas, and surrounding forest fire histories are significantly lower ($p < 0.05$) in the post-settlement era (Table 3).

Historical MFRIs for the kipukas were shorter than those of the surrounding forest over the entire chronology (6 vs. 9 years; $p < 0.05$) and during the pre-settlement period (6 vs. 12 years; $p < 0.05$) (Table 4). MFRIs for both the kipukas and the surrounding forest increased over time and were similar during the post-settlement period. Filtered MFRIs show no significant difference between the kipukas and surrounding forest over the entire chronology and during the post-settlement period. MPS was lower on the kipukas than in the surrounding forest for the entire chronology (11% vs. 25%; $p < 0.05$) and the pre-settlement period (13% vs. 40%; $p < 0.05$) (Table 4). During the post-settlement period, MPS decreased.

Chi-square tests and the Ochiai Index show that the fire regimes in the kipukas and surrounding forest are asynchronous, or statistically independent ($p < 0.05$), for all fire years and for the filtered fire years. Only 16 of 92 scars were found in common between the kipukas and surrounding forest when all fire scars dated between 1600 and 2001 were considered; the 10% and 25% filtered histories yielded 4 of 24 and 2 of 15 scars in common, respectively. Comparisons of synchrony between pairs of kipukas indicate that in spite of the three landscape-scale fires, each kipuka possesses a unique fire history. The three widespread fires of 1740, 1823, and 1918 burned the kipukas and the surrounding forest at ~80-year intervals (Figs. 2 and 4).

Spatial and environmental factors

Autocorrelation among our spatial and environmental variables resulted in generally high correlations between our independent (MFRI) and dependent (total number of trees scarred) variables (Table 5). Distance to the nearest kipuka correlated most strongly with MFRI ($S = 0.799$, $p = 0.01$), followed closely by our area-weighted isolation index TIV1 ($S = 0.782$, $p = 0.01$). The remaining isolation indices (TIV2 and TIV3) are weakly correlated with MFRI, suggest-

**Note:** MFRI comparisons are based on (i) all fire years and (ii) a filtered sample where ≥10% of the sampled trees and a minimum of 2 trees were scarred. MPS is the number of scarred partial cross sections as a percentage of the total trees alive at each fire year, averaged over each time period. Incomplete fire-return intervals were included to allow statistical testing of modern fire regimes. The period of reliability (POR) for the surrounding forest during the pre-settlement era is 1600–1859 ($p < 0.10$; **, $p < 0.05$; significant differences were determined using Student’s $t$ test).

<table>
<thead>
<tr>
<th>Study area</th>
<th>Pre-settlement era (1458–1859)</th>
<th>Post-settlement era (1860–2001)</th>
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</thead>
<tbody>
<tr>
<td><strong>Sample</strong></td>
<td><strong>MFRI</strong></td>
<td><strong>MPS</strong></td>
</tr>
<tr>
<td>All</td>
<td>5</td>
<td>13**</td>
</tr>
<tr>
<td>Filtered</td>
<td>19*</td>
<td>—</td>
</tr>
<tr>
<td>Kipukas</td>
<td>7</td>
<td>15**</td>
</tr>
<tr>
<td>Filtered</td>
<td>19**</td>
<td>—</td>
</tr>
<tr>
<td>Surrounding forest</td>
<td>12*</td>
<td>40**</td>
</tr>
<tr>
<td>Filtered</td>
<td>30</td>
<td>—</td>
</tr>
</tbody>
</table>

(<0.25 acre; 1 acre = 0.405 ha), most of which were lightning-caused (McCauley 1993; USDA Forest Service 2001; USDA Forest Service 2004). Our fire-scar record was reconstructed from 85 cross-dated partial cross sections: 63 for the kipukas and 22 for the surrounding forest (Table 1). The composite fire record includes 304 fire scars representing 98 different fire events for the study area between AD 1458 and 2001 (Fig. 2a). The POR for the entire study area and the kipukas is 1458–2001; the POR for the surrounding forest is 1600–2001 (Fig. 2b). The reconstructed fire history for the kipukas is based on 204 scars representing 72 fire events between AD 1458 and 2001 (Fig. 2b). MFRI and WMI for the kipukas over the POR (1458–2001) are 7 and 5 years, respectively. The Weibull distribution better fit the interval data (probability > $d = 0.18$).

The reconstructed fire history for the kipukas is based on 204 scars representing 72 fire events between AD 1458 and 2001 (Fig. 2b). MFRI and WMI for the kipukas over the POR (1458–2001) are 7 and 5 years, respectively. The Weibull distribution better fit the interval data (probability > $d = 0.53$). The cross sections collected from the surrounding forest recorded 100 scars representing 42 fire events between AD 1611 and 2001 (Fig. 2c). MFRI and WMI over the POR (1600–2001) are 9 and 8 years, respectively. As in the other analyses the Weibull distribution better fit the interval data (probability > $d = 0.33$). The lower WMI in each chronology indicates a fire-frequency distribution slightly skewed toward more frequent fires.

We were able to assign 68% of the fire scars ($n = 208$) identified for the study area to season. Eighty-one percent of these occurred during the growing season (75% in the earlywood, 6% in the latewood) and 19% in the dormant period. The most notable change in fire seasonality occurred between 1880 and 1950 as a shift toward dormant-season fires (Fig. 3). In other periods, minor variations in timing of the fire season occurred; these seasonal shifts were consistent across the kipukas and the surrounding forest.
ing that kipuka area is less important than distance to the neighboring kipuka and the surrounding forest.

Our second dependent variable, the total number of fires on each kipuka, is strongly correlated with elevation change ($r = 0.832, p = 0.01$) and distance to the nearest kipuka ($r = -0.813, p = 0.01$) (Table 5). Both distance to the nearest kipuka and elevation change are highly correlated with kipuka area and kipuka perimeter.

Maps depicting sampled fire-scar locations (Figs. 4a–4c) show a wide range of burn patterns across the study site. Fire-scar evidence of the major fire in 1918 is found in both the surrounding forest and on the larger kipukas (Fig. 4a). Scar locations show that this fire burned on several of the smaller kipukas but less in the northern and eastern portions of the study area. We found a similar pattern with the major fires in 1740 and 1823. Other fires were generally restricted to the surrounding forest (Fig. 4b) or to individual kipukas (Fig. 4c). The smallest kipuka (K1, ~0.4 ha) in our study lacked fire-scar evidence for all fire dates, including the 1883 fire, which burned both in the surrounding forest to the west and on Hoffman Island to the east (Fig. 4b).

**Discussion**

**Methodological considerations in the reconstruction of the kipukas’ fire history**

The fire regime at LCF is characterized by frequent small fires interspersed with widespread fires. MFRIIs fall within the 3- to 42-year range reported for other ponderosa pine forests east of the Oregon Cascades (Weaver 1959; Soeriaatmadja 1966; McNeil and Zobel 1980; Bork 1984; Agee 1993). The longer post-settlement-era MFRI is similar to trends noted in nearly all fire-history and stand-structure studies of western ponderosa pine forests (e.g., Weaver 1959, 1961; Cooper 1960; Covington and Moore 1994). Our fire-scar data identify 16 fire years that are absent from the USDA Forest Service records, suggesting that the written record underestimates the number of fires in the study area during the post-settlement (fire suppression) period. In the absence of any temporal or spatial patterns in the unrecorded fires we assume that the omissions result from general record-keeping issues rather than the isolation of the kipukas. This suggests that developing an independent fire-scar record will help to confirm the accuracy of historical records when they are used as the primary data source for fire-history reconstructions. The combined use of historical documentation and fire-scar data appears necessary to increase the precision of recent fire histories in our study area and has been shown to be useful in other areas (Fule et al. 2003).

Unlike values for other locations in Oregon (e.g., Teensma 1987; Morrison and Swanson 1990; Hadley 1999; Heyerdahl et al. 2001), our unfiltered MFRI for the entire study area shows no evidence of a shift toward fewer fires in the post-settlement period. This weak demarcation between pre- and post-settlement fire periods reflects a combination of factors, including (i) differences in fire scar sample depths between the kipukas and surrounding forest, (ii) a comparatively weak post-settlement human influence on the local fire regime, and (iii) the prevalence of lightning-caused fires during both periods. Differences in the number of fire-scar samples between the kipukas ($n = 63$) and the surrounding forest ($n = 22$) introduces a potential sampling bias, skewing the fire-return interval for the study area toward the shorter kipuka MFRI. Some of this discrepancy may be due to the larger number of recorder trees found on the kipukas, a result of their protection from timber harvesting by their relative isolation and limited access. The fewer samples from the surrounding forest reflect the fact that few recorder trees, snags, and logs remain uncut following timber harvesting near less accessible edges of the lava flows. This lower sample number may also imply the disappearance of trees as a result of more intense burning in the surrounding forest. The comparatively late Euro-American settlement of central Oregon also may have contributed to similar pre- and post-settlement fire regimes by delaying the effects of human intervention by 40–50 years compared with that occurring in the Blue Mountains (Langston 1995) and western Cascades (Hadley 1999). Although much of the forest landscape surrounding the study area has been logged, these activities began in the 1930s.

The sampling bias, however, may well be superficial. Filtering our fire record appears to (i) remove the effect of dissimilar sample sizes and sampling areas (i.e., the larger number of recorder trees on the kipukas) between the kipukas and the surrounding forest, and (ii) clarify the influ-

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**Table 4. Spatial comparison of mean fire-return interval (MFRI) and mean percentage of trees scarred (MPS) values between the kipukas and the surrounding forest during the pre- and post-settlement eras.**

<table>
<thead>
<tr>
<th>Fire era</th>
<th>Sample</th>
<th>MFRI (years)</th>
<th>MPS (%)</th>
<th>Surrounding</th>
<th>Kipukas</th>
<th>Forest</th>
<th>Surrounding</th>
<th>Kipukas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire chronology (1600–2001)</td>
<td>All</td>
<td><strong>6</strong></td>
<td><strong>9</strong></td>
<td><strong>11</strong></td>
<td><strong>25</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Filtered</td>
<td>22</td>
<td>30</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-settlement (1600–1859)</td>
<td>All</td>
<td><strong>6</strong></td>
<td><strong>12</strong></td>
<td><strong>13</strong></td>
<td><strong>40</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Filtered</td>
<td>19*</td>
<td>30*</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-settlement (1859–2001)</td>
<td>All</td>
<td>6</td>
<td>6</td>
<td>7*</td>
<td>10*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Filtered</td>
<td>41</td>
<td>39</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** MFRI comparisons are based on (i) all fire years and (ii) a filter where ≥10% of the sampled trees and a minimum of 2 trees were scarred during the respective eras. MPS is the number of scarred partial cross sections as a percentage of the total trees alive at each fire year, averaged over each time period. Incomplete fire-return intervals were included to allow statistical testing of modern fire regimes. The dates in parentheses denote the POR for each era (*, $p \leq 0.10$; **, $p \leq 0.05$; significant differences were determined using Student’s $t$ test.

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ence of lightning-ignited spot fires. We note a clearer distinction between pre- and post-settlement fire regimes on the kipukas: removing spot fires via the filter reveals a shift to a longer MFRI post settlement. This suggests that post-settlement management and fire-suppression activities in the surrounding forest effectively decreased the spread of fire from the surrounding forest to the kipukas, and reveals human influence on the fire regime that is not apparent from the unfiltered record. This is corroborated by the surrounding-forest filtered MFRI, where spot fires increase in importance post settlement. It also suggests that the spot fires originated on the kipukas as a result of lighting ignitions.

Isolate–mainland comparisons

Contrary to our initial assumptions, we found both a greater number of fires and higher fire frequencies on the kipukas and asynchrony between fires on the kipukas and in the surrounding forest. We attribute these findings to local spatial and environmental variables (kipuka area and elevation change) that appear to be critical drivers of isolate fire regimes. Regional and hemispheric drivers of fire may also be important.

We interpret the strong correlation between the total number of fires on the kipukas and elevation change as an indirect measure of lightning ignitions, particularly on larger, more topographically diverse kipukas. Convection storms, lightning activity, and lightning ignitions are frequent in central and eastern Oregon (Bork 1984; Rorig and Ferguson 1999) and are locally reinforced topographically by intense surface heating and the convection of unstable air superheated by the underlying lava flows (cf. Schroeder and Buck 1970). These results are similar to those reported by Bergeron (1991), who attributes higher fire frequencies on islands relative to mainland lakeshore landscapes to lightning ignitions at higher elevations. Wardle et al. (1997), working on an archipelago in the Swedish boreal forest, also found that larger islands burned more often than smaller ones as the result of a higher number of lightning ignitions. Lightning is also cited as a possible ignition source generating the more frequent fires observed on geographic islands in Grand Canyon National Park, Arizona, USA (Fule et al. 2003).

The dominance of growing-season fires at LCF also supports the important role of topography and lightning ignitions. Growing-season fires also occur at Lava Beds National Monument in northeastern California, which is similar to LCF in elevation, climate, and geology (Miller et al. 2003). However, most other Pacific Northwest fire-history reconstructions show that fires occur mostly during the dormant season and are influenced by a variety of factors including southerly aspect (Beatty and Taylor 2001; Heyerdahl et al. 2001), low elevation (Bekker and Taylor 2001), regional climate variation (Norman and Taylor 2003), and early-season Native American ignitions (Norman and Taylor 2003). The dominance of growing-season fires at LCF may be related to factors that include the prevalence of steep south- to west-facing slopes that contribute to earlier snowmelt and drying of fuels. The short growing season (mid-May through early August) (Taylor and Hannan 1999) also overlaps the period with the highest probability of con-
vection storms and lightning ignitions in the Pacific Northwest (Rorig and Ferguson 1999).

The asynchrony of fire regimes between the surrounding forest and the kipukas, and among the kipukas themselves, indicates that the intervening lava is an effective but not absolute barrier to the spread of fire across the local landscape. While most fires are restricted to individual kipukas or to the surrounding forest, a few have successfully spread across most of the fragmented landscape. Such independence of fire from landscape heterogeneity has been observed elsewhere (Turner et al. 1989; Bergeron 1991; Bessie and Johnson 1995; Hellberg et al. 2004). In the case of LCF, we assume that the probability of spot fires decreases with distance from large kipukas and the surrounding forest and that their timing and frequency are related to fire severity, local wind conditions, and relative humidity.

The shift to dormant-season fires between 1880 and 1950 appears to be consistent with recovery following the more widespread 1823 and 1918 fires and the coincident 80- to 90-year periods of low fire activity and fuel accumulation during stand recovery. Logging in the years following the 1918 fire would also slow fuel accumulation. These local drivers of fire likely interact with regional and hemispheric processes to generate the fire regime (Heyerdahl et al. 2001). The shift described above may also correspond to a negative phase of the Pacific Decadal Oscillation from 1830 to 1920 described by Pohl et al. (2002). However, because the role of tropical and North Pacific teleconnections in central Oregon is weak (Pohl et al. 2002), further investigation into the specific climate controls on intra-annual timing of fire and its impacts on vegetation is warranted.

It is worth examining briefly the three studies that show the opposite results to ours: lower fire frequencies on isolates. In the case of ponderosa pine forests at El Malpais National Monument in New Mexico (Grissino-Mayer and Swetnam 1995), the authors propose that the longer fire-return intervals on two small kipukas reflect the influence of a nearby forest. This low-density forest with patchy fuels has a long fire-return interval and is the source of fire for the kipukas. Synchrony of fire histories between the kipukas and this nearby forest suggests, interestingly, that the intervening lava flow is not a barrier to fire spread between forest and kipukas. So topographic, edaphic, and spatial considerations drive the lower fire frequencies. Rocky outcrops in a matrix of open eucalypt forest in Australia are assumed to experience less frequent and intense fire because of the physical barrier presented by the rocky substrate (Clarke 2002). Fire intervals are not explicitly derived in Clarke’s (2002) study, but are developed from the differences among plant fire-response traits. Here again, topographic, edaphic, and spatial factors are significant. Finally, fuel discontinuity appears to be responsible for the longer fire-return interval on an isolated mesa in Utah (Madany and West 1983). These studies and the other research presented here indicate that the factors governing fire frequencies on isolates (whether longer or shorter than their mainland counterparts), such as topography, human activities, soil type, size of isolate, distance to mainland, and a variety of biophysical variables, are similar and all are critical. This suggests that fire frequencies on isolates cannot be predicted simply on the basis of area or distance; rather, they result from a more complex combination of factors that may act to drive them in either direction.

**Conclusions**

Our study demonstrates the value of reconstructing the fire history of forest isolates in the context of their mainland counterparts. By doing so, we have shown that isolate fire
scars may provide a more robust record of small fires than that noted in the historical fire records and can reduce many of the problems typically associated with the limited temporal overlap between historical agency fire records and fire-scar records. We also find that fire histories reconstructed from isolates and their mainland counterparts create their own challenges. Most notably, the biophysical conditions characterizing forest isolates may only approximate those of the surrounding forest. This may create a new set of calibration issues for reconstructing fire history, including how topography, environmental conditions created by the surrounding matrix, and human activities in the surrounding forests influence the probability and spread of fire. Specifically, it may be difficult to control for the indirect effects of logging and fire-exclusion and -suppression activities in the surrounding forest, particularly as these activities reduce the data available for fire-history reconstruction. More generally, researchers should not assume a straightforward relationship between fire occurrence on isolates and the mainland. Developing a more robust theoretical context for the initiation and propagation of disturbance among isolates is critical as forested landscapes become increasingly characterized by human-imposed insularity.

Acknowledgements

J. Chase, M. Christensen, H. Huntley, D. Praza, K. Hrinkevich, K. Pohl, and S. Stanton provided field and laboratory assistance. We thank B. Johnson, the Sub-Regional Fire Planner with the USDA Forest Service Fort Rock – Bend Ranger District Office, for access to fire-history and GIS records for the study area. K. Pohl, S. Stanton, M. Weber, E. Heyerdahl, J. Riser II, and G. Dean provided insightful comments on earlier drafts of the manuscript. Maps and GIS databases were ably manipulated by E. Arabas. This research was supported by funding from the Mary Stuart Rogers Foundation, the Murdock Charitable Trust, the Willamette University Science Collaborative Research Program, the Atkinson Foundation, and a Portland State University faculty research grant.

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