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RESEARCH REPORT

CONDITION OF LIVE FIRE-SCARRED PONDEROSA PINE TWENTY-ONE YEARS AFTER REMOVING PARTIAL CROSS-SECTIONS

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ABSTRACT

Concern over the effects of removing fire-scarred partial cross-sections may limit sampling of live ponderosa pine to reconstruct fire history. We report mortality rates for ponderosa pine trees 20 to 21 years after removing fire-scarred partial cross-sections to reconstruct fire history. In 2015, following surveys every five years since 2000, we revisited 138 trees that were alive when we sectioned them in 1994/95 and 386 similarly sized, un-sectioned neighbor trees of the same species that were also alive in 1994/95. Between 1994/95 and 2015, a significantly greater proportion of sectioned than neighbor trees died, yielding average annual mortality rates of 3.3% *versus* 2.2%. However, many of the trees that died were likely killed by prescribed fires in 2002 and 2003 (64 sectioned plus neighbor trees). When we excluded these trees to assess the effect of fire-scar sampling rather than the effect of modern fires, the difference in proportion of dead trees was no longer significant and yielded average annual mortality rates of 2.1% *versus* 1.4% for sectioned and neighbor trees. We continue to suggest that sampling live, fire-scarred ponderosa pine trees remains a generally non-lethal method of obtaining information about historical fires that can supplement the information obtained from dead fire-scarred trees.

Keywords: Ponderosa pine, *Pinus ponderosa*, fire history, Oregon, partial cross-sections, fire scar, wounding, dendrochronology, tree rings, catface, tree mortality.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson; nomenclature from USDA NRCS[§]) is widely distributed in western North America and can survive repeated wounding by frequent, low-severity fires that lethally heat the vascular cambium around a portion of the stem circumference (Falk *et al*. 2011). Multi-century records of historical fire regimes can be reconstructed from these wounds, or fire scars, by removing a partial cross-section using a chain saw (Arno and Sneck 1977). Despite concern that this sampling may result in tree death, the long-term effect of removing fire-scarred partial cross-sections from live trees to reconstruct fire history is poorly documented (but see Cochrane and Daniels 2009; Rist *et al*. 2011).

In a previous study we reconstructed fire history by removing fire-scarred partial cross-sections from live and dead ponderosa pine trees in the dry mixed-conifer forests of the Blue Mountains of northeastern Oregon in 1994 and 1995 (Heyerdahl *et al.* 2001). These trees were sampled from 78 plots covering *ca.* 5000 ha. In 2000, we addressed concerns over the effects of removing partial cross-sections from live trees at two sites (Imnaha and Dugout) by re-locating 138 sectioned trees. To account for mortality unrelated to sectioning, we also located the three ponderosa pine trees of comparable diameter that were nearest each sectioned tree (mean distance 16 m, range 1–69 m;

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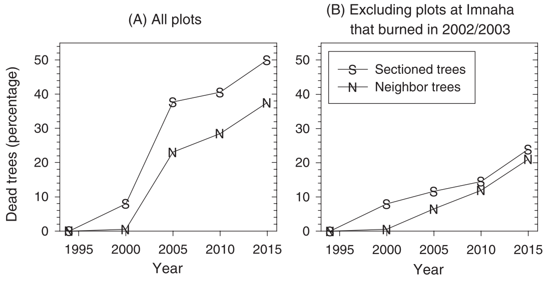

Figure 1. (A) History of tree mortality among 138 sectioned ponderosa pine trees and 386 similarly sized neighbor trees of the same species. All trees were alive in 1994/95 when we removed fire-scarred partial cross-sections from the sectioned trees (Heyerdahl and McKay 2001, 2008). (B) Many of the dead trees (64 trees) were likely killed by prescribed fires in 2002 and 2003. To focus on the effect of removing partial cross-sections rather than on the effect of modern fires, this panel includes only trees that were not in the plots burned during prescribed fires.

386 neighboring trees total; Heyerdahl and McKay 2001). As of 2005, a significantly larger fraction of the sectioned versus neighbor trees had died (Heyerdahl and McKay 2008). However, many of these trees died during two prescribed fires at Imnaha in 2002 and 2003 (36 sectioned trees), mostly because fire consumed enough of the fire-scarred cavity that the trees failed structurally (*e.g.* Fig. 1d in Heyerdahl and McKay 2008), an effect of modern fires that has been noted elsewhere (Gray and Blackwell 2008; Hood 2010; Larson *et al.* 2013). Catfaced trees died at a similar rate during these fires whether they were sectioned or not (Heyerdahl and McKay 2008). When we excluded all the trees from the plots that burned during the prescribed fires to focus on the effect of removing partial sections rather than on the effect of modern fire, the difference in the fraction of dead trees among the sectioned *versus* neighbor trees was not significant (Heyerdahl and McKay 2008). We suggested that mortality among sectioned trees was low in part because we removed relatively small sections, averaging 7 cm in vertical depth and only 8% of the tree's cross-sectional area, from large trees of a species with effective, resin-based defenses against insects and pathogens. We have since conducted two additional surveys - one in 2010 and another in 2015. Our objective is to report mortality rates for the sectioned trees and their neighbors over the past 20 to 21 years.

METHODS

In 2010 and 2015, we determined whether the sectioned and neighbor trees were alive or dead by the presence or absence of green needles. To assess whether dead *versus* surviving sectioned trees differed in diameter (mean diameter at breast height of 1.4 m (dbh)) or size of sample removed (mean cross-sectional area and mean vertical depth), we used non-paired, one-tailed t-tests, allowing for differences in variance.

We assessed whether sectioning led to more deaths among sectioned than neighbor trees using two methods. First, we tested for a difference in the proportion of these two groups that died (equivalent to a χ^2 test of homogeneity; Zar 1984), both including and excluding all trees in the plots burned by the prescribed fires at Imnaha (regardless of whether they died or not). Second, we compared the mortality rates of sectioned and neighbor trees in a simple survival analysis by fitting a mixed-effects Cox proportional hazard function to our census data (SURVIVAL library, Therneau 2015; R programming environment, R Core Team 2016). We included two binary terms as fixed effects: (a) whether or not trees were sectioned and (b) whether or not trees were in plots that burned in the prescribed fires. Site and plot-within-site were included as random effects.

We computed the average annual mortality rate as $1 - (N_t/N_0)^{1/t}$, where N_0 is the initial number of sectioned or neighbor trees, N_t is the number of those trees still alive in 2015, and t is the total number of years over which mortality was assessed (Sheil *et al.* 1995). We report the geometric mean of the mortality rates computed from trees originally sampled in 1994 *versus* 1995.

RESULTS

As of 2015, 50% of the sectioned trees had died (69/138 trees; Figure 1), many of them likely as a result of the prescribed fires at Imnaha (36 trees, Heyerdahl and McKay 2008). Of the 33 dead sectioned trees that were not killed by the prescribed fires, most were still standing (26 trees), had broken 0.5 to 7 m above sectioning height (4 trees), or had failed at the roots (2 trees). The remaining tree broke at the height of the sectioning wound, but likely did so as a consequence of a local fire

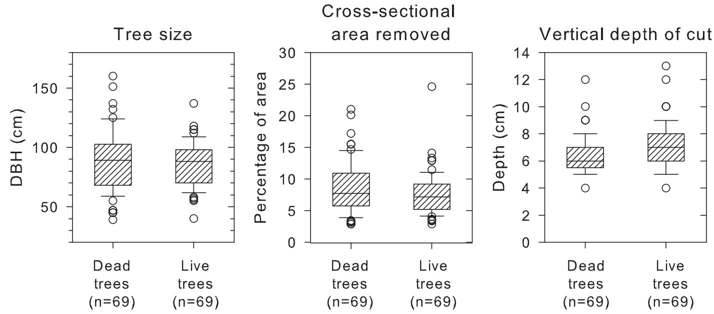

Figure 2. Characteristics of live *versus* dead sectioned trees. All 138 trees were alive in 1994/95 when fire-scarred partial cross-sections were removed from them. The boxes enclose the 25th to 75th percentiles and the whiskers enclose the 10th to 90th percentiles of the distribution of trees. The horizontal line across each box indicates the median and all values falling outside the 10th to 90th percentiles are shown as circles.

at Dugout rather than structural failure caused by the sectioning wound; much of the bole was consumed before the stem broke, similar to the trees that were felled by the prescribed fires at Imnaha (*e.g.* Figure 1d in Heyerdahl and McKay 2008). We found no significant difference in the diameter of sectioned trees that died *versus* those that survived ($p = 0.2618$, Figure 2). Nor was there a significant difference in the size of the partial cross-sections we removed (cross-sectional area, $p = 0.0541$; vertical depth, $p = 0.0312$). The wounds appear little changed since the time of sectioning (Figure 3). As of 2015, 38% of the neighbor trees had died (145/386 trees, Figure 1), many of them likely as a result of the prescribed fires at Imnaha (67 trees, Heyerdahl and McKay 2008).

In assessing whether sectioning led to more deaths of sectioned trees than of neighbor trees, our two methods yielded similar results. First, significantly more sectioned than neighbor trees have died (69/138 *versus* 145/386; $p = 0.0108$), but this difference was not significant when we excluded trees in the plots that burned during the prescribed fires at Imnaha (30/89 sectioned *versus* 70/255 neighbor trees; $p = 0.2630$). Second, survival analysis indicated that sectioning did not significantly increase the rate of tree mortality, regardless of whether or not the plots burned. In unburned plots, the difference in the mortality rates of sectioned versus unsectioned trees was not statistically significant ($p = 0.1260$). Further, the interaction term between sectioning and burning was not significant ($p = 0.2339$), suggesting that sectioned and unsectioned trees had similar mortality rates in the burned plots. However, the mortality rate of the trees in the burned plots was significantly ($p < 0.0001$) and substantially (247%) higher than the mortality rate of trees in unburned plots.

Figure 3. The sectioning wounds are remarkably unchanged after 21 years. Typical condition in 2010 and 2015 of a wound resulting from the removal of a partial cross-section in 1994. This tree was alive in 2015. The condition of this particular wound in 2000 and 2005 was shown in Figure 5a of Heyerdahl and McKay (2001) and Figure 1b in Heyerdahl and McKay (2008), respectively.

From 1994/95 to 2015, sectioned trees died at an average annual rate of 3.3% *versus* 2.2% for neighbor trees. The rates were lower for both groups when we excluded all the trees in the plots burned by the prescribed fires at Imnaha: 2.1% *versus* 1.4%.

DISCUSSION

Our results suggest that removing a small, fire-scarred partial cross-section from a live ponderosa pine tree does not often lead to the tree's death, at least in the first few decades after sampling. The annual mortality rate among the old ponderosa pine trees we have been following in the Blue Mountains is consistent with annual mortality rates of large trees of the same species documented in the 1990s and 2000s elsewhere in the Northwest (van Mantgem *et al*. 2009; Clyatt *et al*. 2016; Reilly and Spies 2016). The rate of mortality at Dugout and Imnaha has increased recently, similar to increasing rates of mortality that have been attributed to drought across western North America (van Mantgem *et al*. 2009) and elsewhere (Allen *et al*. 2010). At our sites, nearly as many trees died in the 5 years between 2010 and 2015 as died in the previous 15 years (47 *versus* 53 trees), exclusive of the trees killed by the prescribed fires at Imnaha.

There is evidence from other studies that removing large sections from *Pinus* can lead to stem breakage. Both Cochrane and Daniels (2008) and Rist *et al*. (2011) suggest that boles are more likely to break at the sectioning wound if more than 25% of the tree's cross-sectional area is removed. The partial sections we removed averaged 8% of the tree's cross-sectional area (range 3 to 25%). Of these, the one tree to break at the sectioning wound only did so after fire consumed much of the catface. We continue to suggest that removing small, fire-scarred partial cross-sections from ponderosa pine trees remains an important and generally non-lethal method of obtaining information about historical fires that can supplement the information obtained from dead fire-scarred trees.

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