

Post-fire Response of Coast Redwood One Year After the Mendocino Lightning Complex Fires

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Abstract

Coast redwood (*Sequoia sempervirens*) forests have undergone significant changes over the past century and are now in state more conducive for wildfires. Because fires have been uncommon in redwood forests over the past 80 years, managers have limited data to make decisions about the post-fire environment. In June 2008, a series of lightning storms moved through northern California igniting numerous fires throughout the redwood region of Mendocino County. Here, we collected fire-injury data on 1024 redwood trees on commercial timberlands three months after the fire and quantified mortality and biological responses one year later. Although over half the sampled trees had at least 90 percent of their crowns scorched, only 18.2 percent were completely top-killed after one year; and 87.7 percent of this mortality was confined to trees less than 20.3 cm in diameter. Over 80 percent of the trees regenerated leaves and shoots from axillary buds, and a similar percentage resprouted basally. Logistic regression modeling indicated that diameter at breast height (DBH), cambium kill, and percent crown scorch were significant predictors of tree mortality. These results indicate that although small redwoods are predicted to have the highest mortality, their ability to resprout may obviate the need for replanting in areas where redwood is dominant. The management implications for the larger surviving trees are less clear and require further long-term study to examine delayed mortality, growth rates, and wood quality.

Key words: basal sprouting, fire injury, mortality, redwood, Sequoia, wildfire

Introduction

The fire ecology of coast redwood (*Sequoia sempervirens*) continues to be an area of active inquiry. Over the past century, timber harvesting, fire suppression, and human encroachment have substantially altered the environmental context of coast redwood (Sawyer et al. 2000, Scanlon 2007). A major concern in many western forests is that increased woody debris, along with younger and denser forests, and a drier regional climate will lead to higher fire frequency and more catastrophic wildfires (Stephens et al. 2009). Conditions within many redwood forests throughout the region have changed substantially in recent decades and are now reaching states more conducive for wildfires.

Historically, large wildfires have been uncommon in coast redwood forests because of reduced ignitions and suppression policies of the past 80 years (Scanlon 2007). The lack of fire in redwood forests has resulted in a significant information gap regarding the effects fire on this species. Currently, managers have limited data to make decisions about harvest in the post-fire environment (Finney and Martin 1993, Ramage et al. 2010). In fact, there are no quantitative data on fire injury

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characteristics and the post-fire response of coast redwood on second- and third-growth commercial forestlands.

On 20 and 21 June 2008, a series of lightning storms moved through Mendocino County during a second-year of drought igniting 129 fires and burning 22,193 ha (54,817 ac) over a four-week period in what became known as the Mendocino Lightning Complex (MLC). Approximately, 42.3 percent of the burned area encompassed a single forest landowner. This unprecedented event provided an opportunity to examine the relationship between fire-injury characteristics and the response of redwood on forestlands over a 5-year period.

We present preliminary results on the response of coast redwood 1 year after the MLC fires. Specifically, our objectives were to: 1) quantify the biological response; 2) model fire-injury characteristics and tree mortality; and 3) use these data to develop future management guidelines.

Methods

Study area

Sampling sites were located in the North Coast physiographic province of Mendocino County, California and consisted of second- and third-growth coast redwood forests owned and managed by Mendocino Redwood Company for commercial timber production. These forestlands are primarily dominated by coast redwood, Douglas-fir (*Pseudotsuga menziesii*), and tanoak (*Notholithocarpus densiflorus*), and a small percentage of other hardwood and conifer species.

Sampling

During September 2008 we established permanent plots across four separate fire areas of the MLC. Within each fire we selected plot locations from fire severity maps based on landscape-level crown scorch indices obtained from satellite imagery. Plots (17.8 m (0.1 ha) radius) were installed until ~250 redwood trees ≥ 9.9 cm (3.9 in) diameter at breast height (DBH) were measured for each fire. Adjustments to the plot centers were made to maximize the number of redwood trees in each plot and cover a range of tree sizes and crown scorch percentages. In each plot trees were painted and tagged to facilitate monitoring in subsequent years.

Tree and fire-injury measurements

We measured tree DBH with a diameter tape (at 1.37 m above ground); total tree height and pre-fire height-to-crown base (HTCB) with a hypsometer. Fire-injury metrics such as percent volume crown scorched (PVCS) were visually estimated using a double-observer method until calibration was within 5 to 10 percent of each other. Crown scorch height (CSHT), maximum char height (CHHTMX), and minimum char height (CHTHMN) were measured with a hypsometer. Bark char was assessed by dividing tree circumference into four quadrants based on cardinal directions and visually classifying char severity within the first 30 cm above ground. Each quadrant was given a score (0=none; 1=low; 2=moderate; 3=severe) and all quadrant scores were summed to provide an overall score ranging from 0 to 12. Cambium kill was assessed by dividing the base of the tree into quadrants (similar to the bark char assessment). In the center of each quadrant, a cordless drill (with a 1.9 cm wide bit)

was used to access the cambium below the bark to score (0=live; 1=dead). A cambium kill rating was calculated by summing all of the quadrant scores for an overall score ranging from 0 to 4.

Biological response measurements

During the fall of 2009 all fire plots were revisited to evaluate tree status (live or dead) and measure specific biological responses. Percentages of live and dead crown were measured visually, and the percentage of bole sprouting was measured as a proportion of total tree height. Bole sprouting was considered a distinct form of regeneration so it was separated from the live crown measurement, which was further divided into residual canopy (unburned) and regenerating canopy (limb sprouting). Basal sprouts were assigned to parent trees based on proximity, and the total number of sprouts was tallied and the tallest sprout in each group was measured with a height pole.

Statistical analysis

We calculated means and standard errors to illustrate measures of central tendency and variation, respectively. Most of the tree and fire-injury data deviated from the assumptions of parametric statistics, so we used the non-parametric Wilcoxon rank-sum test to compare means between groups.

We used logistic regression to develop a statistical model of tree mortality based on several combinations of tree and fire-injury variables (bole injury and crown scorch). Variables were evaluated for collinearity prior to inclusion in logistic regression models. Model fit was assessed using the χ^2 goodness-of-fit test and the discriminatory ability of each model was evaluated using the Receiver Operating Characteristic (ROC). All statistics were analyzed with the program Stata version 11.1 and statistical significance was set at $\alpha=0.05$.

Results

A total of 1024 trees were measured across a total of 29 plots (6 to 9 plots sampled per fire). Tree size distribution followed a reverse J-shape distribution, with over 72.8 percent of the trees occurring in the two smallest size classes, and the remaining trees distributed among the merchantable size classes (> 40.6 cm DBH) in descending order of increasing size. One year after the MLC fires, 187 redwood trees (18.2 percent of all trees measured) were observed to be dead (defined as a completely top-killed primary stem). All top-killed trees were in the two smallest size classes, 164 (87.7 percent) of which were in the smallest size class (9.9 to 20.3 cm DBH).

Comparisons of tree characteristics showed that live trees were, on average, nearly twice as large (in diameter and total height) as dead trees. Dead trees, on average, exhibited significantly higher levels of crown scorch, bole char proportion, bark charring, and cambium kill compared to live trees (*table 1*).

Crown regeneration for 837 live trees exhibited a pattern of increasing mean percentage of live crown and a decreasing mean percentage of bole sprouting in progressively larger size classes of trees (data not shown). Only 318 (37.9 percent) live trees exhibited sprouting on greater than 5 percent of the bole, usually confined

Table 1—Mean tree and fire injury characteristics for 1024 redwood trees sampled with standard errors and ranges shown.

Variables ^a	Total Mean (n=1024)	Live Mean (n=837)	Dead Mean (n=187)
DBH (cm)	31.9 (0.68) 9.9-151.9	35.6 (0.78) 9.9-151.9	15.3 (0.35) ^b 9.9-33.8
TLHT (m)	19.5 (0.33) 3.7-55.5	21.4 (0.37) 4.6-55.5	11.1 (0.29) ^b 3.7-26.8
HTCB (m)	8.7 (0.22) 1.2-36.0	9.5 (0.23) 1.5-36.0	5.2 (0.19) ^b 1.2-18.6
CSHT (m)	14.1 (0.27) 0-48.2	14.9 (0.32) 0-48.2	10.8 (0.28) ^b 3.7-26.8
PRCS (%)	69.7 (1.15) 0-100	63.7 (1.31) 0-100	96.3 (0.85) ^b 10-100
CHHTMX (m)	5.5 (0.14) 0-28.0	5.7 (0.16) 0-28.0	4.8 (0.20) 0-19.8
CHHTMN (m)	2.8 (0.10) 0-27.1	2.7 (0.11) 0-27.1	3.1 (0.20) ^b 0-19.8
PRCHMX (%)	30.4 (0.64) 0-100	27.1 (0.61) 0-100	45.6 (1.83) ^b 0-100
BCR	8.5 (0.06) 0-12	8.3 (0.06) 0-12	9.4 (0.15) ^b 0-12
CKR	0.9 (0.04) 0-4	0.6 (0.04) 0-4	2.2 (0.11) ^b 0-4

^a DBH = diameter at breast height; TLHT = tree height; HTCB = Pre-fire height-to-crown base; CSHT = crown scorch height; PRCS = crown scorch; CHHTMX = maximum bole char height; CHHTMN = minimum bole char height; PRCHMX = bole char proportion; BCR = bark char rating; CKR = cambium kill rating

^b Significantly different from live trees (P<0.05)

to trees with a greater percentage of fire-injury, particularly those with dead tops and higher percentages of dead crowns. Mean percentage of limb sprouting increased with larger size classes indicating lower levels of canopy injury with increasing tree height.

Basal sprouting was associated with a total of 822 out of 1024 trees (80.2 percent). Sprouts were associated with 654 of 837 live trees (78.1 percent) and 168 of 187 dead trees (89.8 percent). Basal sprouting patterns showed significant differences in both sprout number and maximum sprout height between live and dead trees (*table 2*).

Logistic regression modeling yielded five significant models consisting of two- and three-variable combinations, all of which had excellent model fit and discriminatory ability in predicting live and dead trees based on fire-injury (*table 3*; ROC values ≥ 0.8). The best model contained DBH, PRCS, and CKR as significant predictors of mortality. Alternative models with different measures of bole damage (BCR and PRCHMX) were also significant, but ranked lower than the three-variable model with CKR. DBH was the single-most important variable in determining probability of mortality, followed by measures of bole damage, and PRCS.

Table 2—Mean maximum height and mean total number of basal sprouts by size class, live and dead trees. Standard errors () and ranges shown.

DBH Class (cm)	Live			Dead		
	Mean Max Height (m)	Mean No. of Sprouts	N	Mean Max Height (m)	Mean No. of Sprouts	N
9.9-20.3	0.96 (0.04) 0.10-3.00	5.3 (0.30) 1-28	228	1.31 (0.05) ^b 0.15-3.00	7.7 (0.47) ^b 1-40	151
20.3-40.6	0.97 (0.04) 0.05-3.30	5.8 (0.34) 1-30	234	1.39 (0.19) 0.30-3.00	6.1 (1.26) 1-20	17
40.6-60.9	0.94(0.05) 0.15-2.50	7.1 (0.63) 1-50	128	NA	NA	NA
60.9-81.2	0.99 (0.10) 0.15-2.50	5.2 (0.60) 1-16	43	NA	NA	NA
> 81.2	0.99 (0.13) 0.15-2.10	7.2 (1.00) 1-17	21	NA	NA	NA
All Size Classes	0.96 (0.02) 0.05-3.30	5.9 (0.21) 1-50	654	1.32 (0.05) ^b 0.15-3.00	7.6 (0.44) ^b 1-40	168

^b Significantly different from live trees (P<0.05)

Table 3—Top five mortality models for coast redwood one year post-fire. Model 1 is the best overall model.

Model Rank	Intercept	DBH	PRCS	CKR	BCR	PRCHMX	ROC
1	-1.5039	-0.1698	0.0305	0.5425	-	-	0.912
2	-4.4398	-0.1989	0.0427	-	0.3541	-	0.909
3	-1.9276	-0.1743	0.0349	-	-	0.0253	0.904
4	1.2200	-0.1786	-	0.6690	-	-	0.902
5	-1.8892	-0.1797	0.0454	-	-	-	0.893

Probability of mortality for the most significantly burned trees (PRCS ≥ 80 , CKR =4) was high (>0.7) for trees 13.0 cm (5.11 in) DBH or less (*fig. 1*). As DBH increases, probability of mortality declines, nearly reaching zero (survival probability of 1) for trees with a DBH of 46.0 cm (18 in). We did not observe any mortality in trees greater than 33.8 cm (13.3 in) DBH.

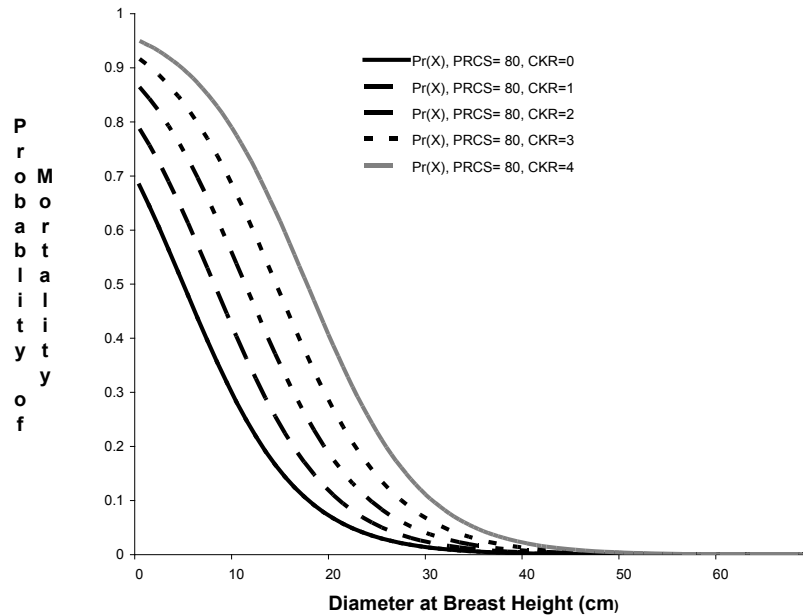


Figure 1—Probability of mortality based on DBH for trees with 80 percent crown scorch (PRCS) at all levels of cambium kill (CKR).

Discussion

The ability of coast redwood to resist fire and other disturbances has been documented in several observational accounts (Abbot 1987, Fritz 1932). Our study is the first to provide quantitative measures of fire-injury and biological response of second- and third-growth redwoods, and possibly, for one of the largest wildfire complexes (by area burned) in the redwood region in over 70 years (Scanlon 2007). Our initial concern regarding the MLC fires was that a landscape comprised of young coast redwood combined with moderate to severe fires might result in significant mortality of merchantable size classes (> 40.6 cm), with even greater concerns about decreases in growth and development of defects.

Mortality of merchantable sized trees was not observed in any of the plots one year following the MLC fires. Mortality was confined to the two smallest size classes, which is not surprising given that fire typically moves from the ground up and tends to impact smaller trees. Finney and Martin (1993) also observed mortality in the same size classes but for prescribed fires of differing intensities. Interestingly, they did not observe any mortality in trees larger than 32.4 cm (12.7 in) DBH, which was close to our maximum mortality size of 33.8 cm (13.3 in) DBH. However, a substantial portion of their sampling distribution included trees < 9.9 cm DBH whereas ours did not (Finney, pers. comm.). This sampling difference is an important distinction because mortality of trees < 9.9 cm DBH was disproportionate compared to larger DBH trees in their study. Although we did not directly measure trees this small, > 90 percent of these trees were observed dead in all plot-level tallies across our study sites.

Coast redwood exhibited both resistance and system resilience to fire across all plots. Despite having sustained significant crown and bole injuries, nearly 75 percent

of the trees ≤ 40.6 cm (16 in) DBH were still alive and were regenerating new crowns from epicormic sprouts. The incidence and extent of bole sprouting was greater in small trees because the original crown and dormant buds along their limbs were severely damaged or killed. Higher levels of limb sprouting were also seen in larger trees whose buds were located sufficiently above convective heat currents to avoid lethal temperatures. Basal sprouting occurred around all size classes of trees and was most vigorous around dead trees. Thus, already established redwood stands that experience significant fire, including those comprised of juvenile-sized trees, are likely to maintain site dominance into the future without the need for replanting. Furthermore, coppicing severely damaged young trees may further enhance sprout development and regeneration time.

Our logistic regression modeling supports previous observations that tree size (DBH) and different measures of fire injury are important factors in predicting mortality of coast redwood (Finney and Martin 1993, Ramage et al. 2010). Based on our best model, trees exceeding 46 cm DBH are predicted to have nearly 100 percent survival probability regardless of fire injury. However, as tree DBH becomes progressively smaller, fire injury becomes a more important determinant of survival probability. This concurs with plot-level bole survival data recently published by Ramage et al. (2010) for second- and old-growth redwood stands. Mortality models for prescribed fire also illustrate a similar effect of DBH on survival probability (Finney and Martin 1993).

The utility of the cambium kill metric in mortality models following wildfire has been reported by others but not for coast redwood (Hood et al. 2007). Measures of cambium kill significantly improved mortality predictions for trees ≤ 20.3 cm DBH with high levels of crown scorch. However, assessing cambium is labor intensive so alternative measures of bole injury (BCSUM and PRCHMX) may be preferable for field application. Previous research has shown that cambial damage is associated with fuel loading and fire behavior immediately surrounding individual trees (Ryan and Frandsen 1991). Although we did not have any pre-fire fuels data for our plots, we hypothesize that cambial damage was not only influenced by accumulated litter and woody debris, but also by the clumped distribution of regenerating trees surrounding remnant parent stumps that continued to burn and emit radiant heat long after the fire passed through. This latter hypothesis is supported by our observation, as well as others in the redwood region (Finney and Martin 1993), that many of the stump-facing sides of coppice-generated trees proximal to burned stumps had severely burned bark and dead cambium.

Although PVCS was significant in the model, its ability to improve prediction was not as significant as CKR and other measures of bole damage. The ability of coast redwood to readily resprout from aerial buds may explain the lesser importance of this variable when compared to mortality models developed for other non-sprouting tree species. Nonetheless, PVCS along with measures of bole injury are important metrics of fire severity as they may capture physical and behavioral aspects of the fire that are spatially distinct and driven by multiple factors such as fuel loading, topography, adjacent vegetation, and weather conditions.

The high regenerative capacity of coast redwood to wildfire is problematic for modeling mortality. First, categorizing responses into discrete groups (dead or alive) potentially results in significant loss of information that might be better represented along a continuum. For example, 40.7 percent of live trees (341 of 837) had dead

crowns of 50 percent or greater and varying amounts of cambium mortality, yet were grouped with live trees having significantly less or no damage. Such trees, if retained to grow for several decades, may exhibit reduced growth rates, have poor wood quality, and many defects. Uncertainty regarding the long-term effects of wildfire on redwood highlights a need to better define what characteristics constitute damage because using the likelihood of mortality as a standard for harvest may be inappropriate for this species.

Conclusions

Redwood exhibited considerable resistance and resilience to wildfire even on a landscape that has been significantly altered by over a century of commercial timber harvesting and several decades of fire exclusion. Overall, the fires of 2008 were an admonition that conditions conducive for wildfire exist on many landscapes throughout the redwood region. While many of the fires on our forestlands caused significant damage to young stands of redwood and other more fire-sensitive conifer species, at least 50 percent of the fires had minimal impact on the forests as they behaved like a prescribed fire. Given the state of our forests, this observation underscores the importance of reintroducing fire as a tool to reduce wildfire risk in many areas on large forested landscapes within the redwood region. Although our understanding of the short-term responses of coast redwood to wildfire fire is greatly enhanced by this research, further study is necessary to test many of our assumptions how wildfire affects coast redwood over a longer period of time. Annual monitoring of our permanent plots in these fire areas will continue into the future and is necessary to answer questions regarding delayed mortality, reduced growth rates, increased pathogen susceptibility, wood quality, and generation time for wildlife habitat.

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