Investigating Tree Mortality in the American Fire Footprint: Is California's Current Drought Affecting Post-Fire Mortality?

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ABSTRACT

I compared mortality rates pre- and post-fire, as well as pre- and post-drought between two study sites: the American Fire footprint in the American River Ranger District Forest and a controlled burn in Blodgett Forest. I created a model for mortality predictability using char, scorch and tree size as predictor variables with a logistic regression. After the fire, overall mortality rose by 4,063% for the American Fire footprint and 411% for Blodgett; a Chi-squared test yielded this to be a significant increase, indicating that fire has an effect on post-fire mortality. However, there was no strong statistical significance between the American Fire footprint post-fire mortality and Blodgett post-fire mortality, indicating that drought does not have an effect here. The best logistic regression for both study sites used char and DBH as predictor variables; however, the AF footprint model also used scorch. When controlling for tree size, the probability of mortality was much higher for the AF footprint than Blodgett, indicating that drought may actually have an effect on post-fire mortality. Realizing these discrepancies in mortality and mortality predictability between non-drought years and years with drought will be critical for future management regimens and conservation efforts.

KEYWORDS

Char, scorch, logistic model, disturbance ecology, Sierra Nevada

INTRODUCTION

Global weather and climate patterns have become more varied, with observable global temperature increases alongside increases in the frequency and duration of drought events and heat waves (Allen et al., 2010). California in particular has experienced a disruption in the state's historic water cycles, higher average temperatures, a geographical shift of plant species ranges, a lengthened fire season, and more intense fire years (Rodriguez and Alexeef, 2013). The current drought, beginning in 2011 and continuing today, has resulted in the second lowest average precipitation on record for any consecutive 3-year period (Seager et al., 2015) and has created favorable fire conditions. Historically, drier years in the northern Sierra Nevada have experienced more fires than wetter years (Taylor and Beaty, 2005). As these drier and hotter conditions become more frequent with climate change, fire frequency and fire severity will increase (Miller and Urban, 1999) (Mantgem et al., 2013). Increases in the mean fire intensity and mean area burned are already attributed to higher tree densities, a direct result of fire suppression (Miller and Urban, 1999).

Forests of the southwest United States are predicted to experience a decrease in forest growth rate and an increase in mortality rate as drought persists and temperatures rise (Williams et al., 2010). Forest structure has already undergone significant changes since fire suppression began in the 1860's, a management practice propelled by the increasing human population and the associated encroachment into the forest landscape. The era of fire suppression has resulted in an overall increase in tree density and vegetation, as well as increased fuel loads (Dolanc et al., 2014). Tree mortality is positively correlated to fire intensity and severity, as well as the magnitude of ecosystem responses such as topsoil loss, canopy cover loss, and conversion to non-forest environment (Fule et al., 2012). Thus, as California's fire regime changes, and higher intensity fires become increasingly common, tree mortality is expected to increase.

Although dynamics of forest structure and tree mortality in response to varying fire intensities, increasing temperature, and drought have been well-studied the immediate effects and interactions that California's current drought poses on tree mortality in recent fire footprints remains unknown. Char and scorch, two indicators of fire history, can be used to model tree mortality (Mantgem et al., 2013). Char, the height of the fire scar on the tree trunk, and scorch, the percent of crown damaged after a fire, are used primarily as indicators of fire severity. With drought as an additional stressor, it is unclear how, if at all, the likelihood of mortality at particular levels of char and scorch will change. Moreover, forest scientists and managers are largely unclear on how a drought of such intensity will influence tree mortalities, both overall and by species, particularly within recent fires in the Sierra Nevada.

In this study, I examined the effect of drought on tree mortality after the American Fire (AF), a wildfire in the Sierra Nevada of California. I determine if (a) species' and overall mortality trends are similar across study sites; and (b) if char and scorch are predictive of post-fire tree mortality; and (c) drought affects tree mortality, particularly in post-fire situations. I expect to find a common level of tree mortality in both study sites (i.e. scenarios without drought), and increases in tree mortalities in scenarios with drought, in both fire and no-fire scenarios. I also expect to find a positive effect on mortality by increasing fire severity. I incorporate data from Blodgett Forest Research Station to serve as a comparison site.

METHODS

Study System Description

I studied the American Fire footprint in the American River Ranger District within the Tahoe National Forest, Placer County in the central Sierra Nevada, CA. The American Fire (AF) occurred 3 years ago, and is the most recent fire in the area. It burned through 11,105 hectares on August 10-20, 2013, near Foresthill, CA, at an elevation of 3980-6907 feet. The dominant species of vegetation that characterize this system include *Abies concolor* (ABCO), *Abies magnifica* (ABMA), *Pinus ponderosa* (PIPO), *Pinus jeffreyi* (PIJE), *Pinus contorta* (PICO), *Pinus lambertiana* (PILA), *Calocedrus decurrens* (CADE), *Pseudotsuga menziesii* (PSME), *Lithocarpus desiflorus* (LIDE), and *Quercus kelloggii* (QUKE). This area has a history of mechanical thinning and fuel reduction (i.e. mastication, pile burning) to reduce fire risk and small tree density and retain large fire-resistant trees (Jones, 2008). Part of the forest burned in the American Fire was included in the Sierra Nevada Adaptive Management Study, a long-term collaborative project between the University of California, the University of Minnesota, U.S. Forest Service, the California Resources Agency, U.S. Fish & Wildlife Service and the Public; this project looks at forest and wildlife health as a result of different forest vegetation treatments.

To compare American Fire footprint mortality to a similar forest with an active fire management program, I used data from Blodgett Forest Research Station, located about 13 miles south of the AF footprint. Blodgett has similar environmental conditions and species composition to the forest of the AF footprint. Blodgett has varying management plans, including mechanical thinning, prescribed burns, and livestock grazing. The plots used for this study are part of an uneven-aged compartment, which most recently experienced a fire (controlled burn) in 2009, before the current drought.

Data Collection Methods

To collect mortality data, I used existing plots and tagged trees to compare vigor classes over a wide range of years. The American Fire footprint plots have been monitored by Professor John Battles and Professor Scott Stephens and their field teams (University of California, Berkeley) since 2004. Each plot is anchored on a 500 meter by 500 meter grid, with some randomly densified subsets lying on a 250 meter by 250 meter grid. In July-August 2015, I sampled 164 plots within the AF fire boundary (Figure 1), including 16 control plots outside the fire boundary. Additionally, I acquired tree and vigor data collected in 2007-2008, 2013 (before the fire), and 2014 of the same plots.

In the field I found each plot using maps, a compass, and a Garmin GPS. I located and re-marked each plot center with rebar and a plot tag, and drew out 3 transects to a radius of 12.6 meters each. Within each plot, I measured the species, diameter at breast height (DBH), vigor class, total height (meters), and height (meters) to live crown of each overstory tree (i.e. a tree with DBH greater than or equal to 19.5 cm). I used standard field measuring tapes, hypsometers (a triangulating device which determines heights or distances), and DBH tapes to measure transects, heights, and DBH of trees, respectively. I tried to measure each tree that had been measured in the prior years; if finding a tree was particularly difficult, I spent up to 10 minutes searching for a tag and the tree, with a metal detector if needed. If still unfound, I recorded it as missing and assigned it a vigor class of 7, 8, 9, 10, or 0. (Table 1, Appendix). Char and scorch were most recently measured in 2014 by another field team and these measurements were not redone in 2015, since fire damage would not have changed. Char was measured as a height along the trunk of the tree (from the ground), and scorch was measured as a height along the crown of the tree (from the base of the crown) and as a percentage scorched (of the full crown).

Data for Blodgett Forest was made available to me by John Battles and the Blodgett Forest Research Station. These measurements, including DBH, height, and vigor class, were taken on the same plots in 2003 and 2009 (before the controlled burn), as well as in 2010 and 2014 (after the controlled burn). A total of 55 plots were sampled before the controlled burn. Post-fire data was provided for 18 of those plots; control (i.e. post-2009, was not burned) data was provided for 17 plots.

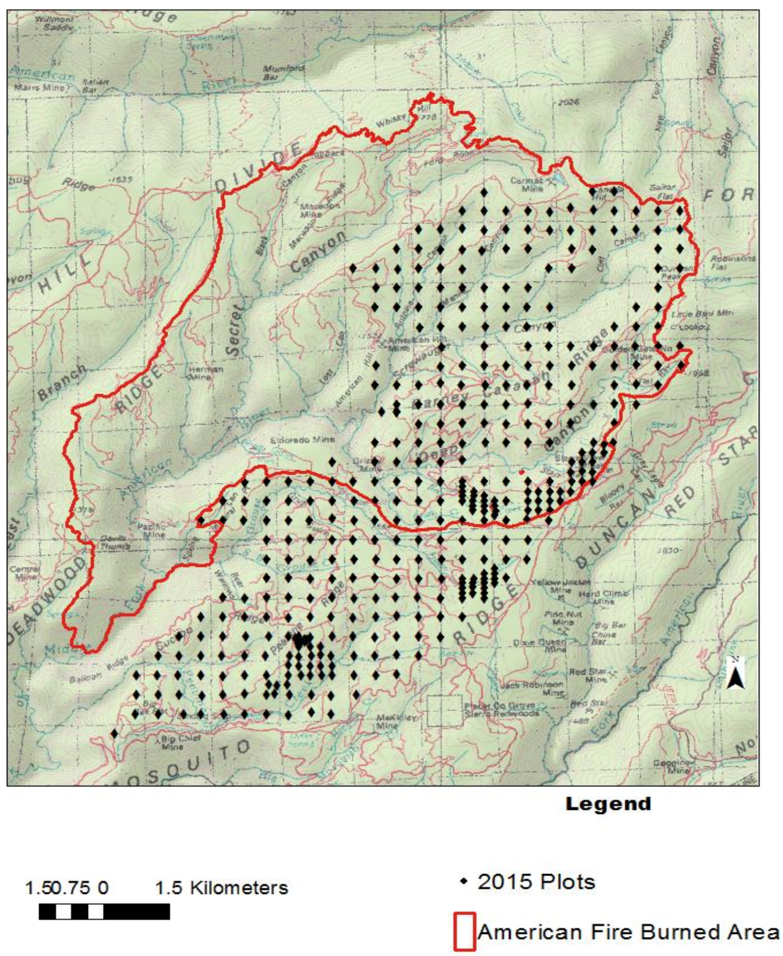

Figure 1. American Fire footprint with SNAMP plots, Tahoe National Forest, CA

Data Analysis Methods

Mortality Rate

To calculate American Fire footprint mortalities I compared the number of total remaining live trees between each year interval. I excluded a 2013-2014 comparison because this interval was the year in which the American Fire burned, and would have portrayed the number of trees which did not survive the fire; this number would not reflect post-fire mortality in any way. I coded each dead tree as a "1," and each live tree as a "0." I excluded missing trees, "new" trees (i.e. trees that grew to the 19.5 cm DBH requirement in a later year, when previously they had been too small to be recorded as an over-story tree), and plots that had no data for some census year. I used the function $m=\ln(N_1 / N_0)/t$ (Sheil et al., 1995) to calculate the actual mortality rate (m), where N_1 is the number of remaining live trees in the most recent sample year, N_0 is the number of live trees in the original sample year, and *t* is years between sample years. I found the overall annual mortality rate, as well as the mortality rates for each species. To calculate Blodgett mortalities I followed the same steps. I excluded a 2009-2010 comparison because this was the year in which the controlled burn occurred. To determine if there was a significant increase in mortality rates between two census years and/or environmental condition (i.e. fire, drought), I performed a Fisher X^2 test. For this statistical test, I had to exclude the species that had an "expected value" of 0 because this yielded an infinite answer, and was not useful to my analysis.

Linear Regression

I converted each measurement of char height to a percentage value, by comparing char height to the total height: (char ht. / total ht.)*100. I did not do this to the scorch data, since measurements were already in percent form. To see if a relationship between fire damage severity (i.e. char and scorch) and mortality exists, I calculated the total percent of trees that died across every increment of 10% of fire damage. I graphed these death rates on the y-axis and char or scorch level (in increments of 10%) on the x-axis to see any trends the data may exhibit. I used a linear regression and R^2 value to determine goodness-of-fit.

Logistic Regression

To create a model for tree mortality in both study sites, I performed a binary logistic regression using the splines, RcmdrMisc, car, and sandwich packages in the R program (Ryan and Reinhardt, 1988)(Hood et al. 2007)(R Core Team, 2015). I input life status (i.e. dead or alive, "1" or "0") as the dependent variable and DBH, % char, and/or % scorch as the independent variables. I ran 4 generalized linear models using the binomial/logit function for each study site using different combinations of independent variables: DBH only, DBH and % charred, DBH and % scorched, and DBH, % charred and % scorched. To compare models for each study site, I examined the AIC (Akaike information criterion) values (Greenwood and Weisberg, 2008), which express the amount of information lost in the respective model, as a function of goodness-of-fit and the number of parameters used. The lowest AIC value marks the best model.

Once I identified the best model for the respective study site, I plugged in increasing dependent variable values into the equation, controlling for tree size using the mean DBH (cm) to calculate the probability of mortality at each point. Because the model is in logit form (i.e. the inverse of the sigmoidal logistic function), I transformed the best-model's mortality probability values using the inverse logit function in R using the splines, RcmdrMisc, car, and sandwich packages (R Core Team, 2015). I then graphed the resulting logistic regression curve for both study sites side-by-side to visualize any discrepancy.

RESULTS

Mortality Rate Analysis

American Fire footprint

The largest increases in mortality rates after the 2013 fire occurred for PIPO, PSME, and CADE. The mortality rate (% per year) increased for those species by 26,487%, 13,111%, and 9,205%, respectively. The mortality rate for firs rose from 0.0092 (%/yr) to 0.2745 (%/yr), an increase of 2,884%; that of pines rose from 0.0058 (%/yr) to 0.4044 (%/yr), an increase of 16,872% (Table 2). The difference between post-fire species mortality rates and pre-fire species mortality rates yielded a chi-square sum of 223.5, which rejected the null hypothesis with a 99% confidence interval.

The largest increases in mortality rates for the unburned control plots occurred for PSME and PILA, which increased by 209% and 124%, respectively. Fir mortality rate rose by about 130%, and that of pines by about 106%. PIPO exhibited no change in mortality, and CADE had a decrease in mortality rate. The difference between post-2013 species mortality rates and pre-2013 species mortality rates yielded a chi-square sum of 0.306, and failed to reject the null hypothesis. The difference between post-fire species mortality rates and post-2013 control (i.e. the unburned plots) species mortality rates yielded a chi-square sum of 2.6; this rejects the null at only a 70% confidence interval.

Table 2. American Fire footprint/American River Forest Mortality Rates

Species	Pre-Fire Mort. Rate AF Burn (% per year)	Post-Fire Mort. Rate AF Burn (% per year)	Change in Mort. AF Burn	Pre-2013 Mort. Rate AF Control (% per year)	Post-2013 Mort. Rate AF Control (% per year)	Change in Mort. AF Control
ABCO	0.0122	0.2290	+1777%	0.0653	0.1386	+112%
ABMA	0.0072	0.3001	+4068%	0	0.1335	n/a
CADE	0.0038	0.3536	+9205%	0.0809	0	-100%
PIJE	0	0	n/a	n/a	n/a	n/a
PILA	0.0075	0.4160	+5447%	0.0271	0.0606	+124%
PIPO	0.0015	0.3988	+26487%	0	0	+0%
PSME	0.0027	0.3567	+13111%	0.0196	0.0606	+209%
QUKE	0	0.0392	n/a	n/a	n/a	n/a
LIDE	n/a	n/a	n/a	n/a	n/a	n/a

FIR	0.0092	0.2745	+2884%	0.0548	0.1258	+130%
PINE	0.0058	0.4044	+6872%	0.0170	0.0351	+106%
OVERALL	0.0075	0.3122	+4063%	0.0492	0.1000	+103%

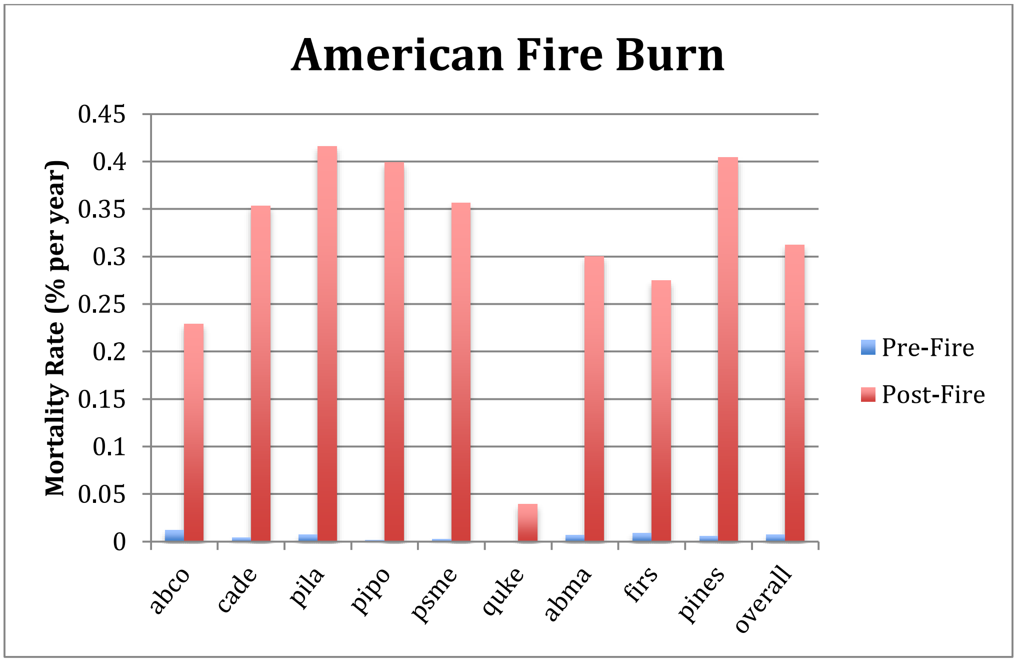

Figure 1a. Burn Mortality Rates by Species between 2007 & 2015. Between the first time interval (2007-2013) and the second time interval (2014-2015) mortality rates for all species have increased.

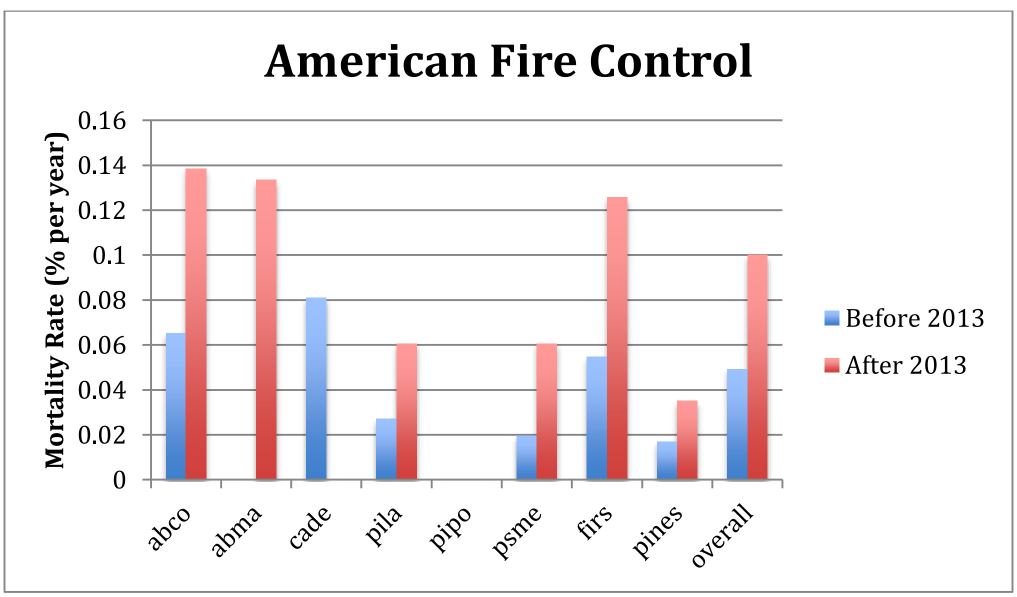

Figure 1b. Control Mortality Rates by Species between 2007 & 2015. Between the first time interval (2007-2013) and the second time interval (2014-2015) mortality rates for most species have increased. PIPO exhibited no mortality, while CADE exhibited a decreased in mortality rate.

Blodgett

The largest increases in mortality rates after the 2009 fire occurred for PIPO, ABCO, and CADE. Mortality increased for those species by 4179%, 518%, and 454%, respectively. The mortality rate for firs rose from 0.0378 (%/yr) to 0.1733 (%/yr), an increase of 358%; that of pines rose from 0.0193 (%/yr) to 0.3466 (%/yr), an increase of 1696% (Table 3). LIDE, PILA, and QUKE all exhibited a decrease in mortality rate. The difference between post-fire mortality rates and pre-fire mortality rates yielded a chi-square sum of 16.1, which rejects the null hypothesis with a 95% confidence interval.

The largest increases in mortality rates for the unburned control plots occurred for PIPO and QUKE, which increased by 901% and 262%, respectively. Fir mortality rates rose by about 101%, and that of pines by about 240%. LIDE and PILA exhibited a decrease in mortality rate. The difference between post-2009 species mortality rates at unburned plots and pre-fire (i.e. pre-2009) species mortality rates yielded a chi-square sum of 1.37, and failed to reject the null hypothesis. The difference between post-fire species mortality rates and post-2009 control (i.e. unburned plots) species mortality rates yielded a chi-square sum of 2.25, and failed to reject the null hypothesis.

Table 3. Blodgett Forest Mortality Rates

Species	Pre-Fire Mort. Rate Blodgett (% per year)	Post-Fire Mort. Rate Blodgett (% per year)	Change in Mort. Blodgett Burn	Post-2009 Mort. Rate Blodgett Control (% per year)	Change in Mort. Blodgett Control
ABCO	0.0358	0.2213	+518%	0.0644	+80%
ABMA	n/a	n/a	n/a	n/a	n/a
CADE	0.0338	0.1874	+454%	0.0442	+31%
LIDE	0.0542	0	-100%	0	-100%
PILA	0.0359	0	-100%	0.0308	-14%

PIPO	0.0081	0.3466	+4179%	0.0811	+901%
PSME	0.0375	0.1082	+189%	0.0921	+146%
QUKE	0.0590	0.0558	-5.4%	0.2136	+262%
FIR	0.0378	0.1733	+358%	0.0760	+101%
PINE	0.0193	0.3466	+1696%	0.0657	+240%
OVERALL	0.0358	0.1831	+411%	0.0660	+84%

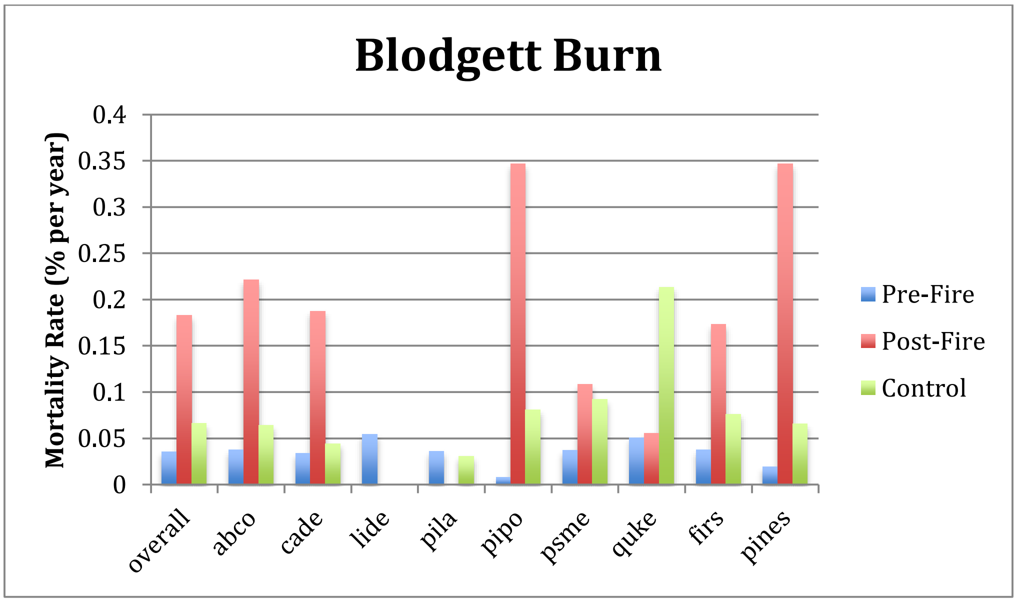

Figure 2. Control and Burn Mortality Rates by Species between 2003 & 2014. Most species exhibited an increase in mortality rate after the fire, except for LIDE and PILA, which had no mortality. PIPO (and pines) had a surprisingly high post-fire mortality rate. Most species also had increased mortality rates in the control, except for LIDE and PILA. Interestingly, the mortality rate for QUKE was highest in the control.

American Fire and Blodgett Burn

Mortality rates in the American Fire footprint increased much more than in the burned Blodgett plots after fire. However, the difference in species mortality rates was not statistically significant: the chi-square sum of the difference in post-fire mortality rates between the two sites was 0.84, and failed to reject the null hypothesis. The series of chi-square test results are summarized below in Table 4. Species mortality rate trends between census years slightly differed between study sites: PILA mortality increased in the American Fire footprint, but decreased in the burned plots of Blodgett. Additionally, mortality rates in the control plots of Blodgett for PILA and QUKE were higher than those of the post-fire plots, whereas in the

American Fire footprint, all species mortality rates for control plots were lower than in post-fire plots. However, the difference in mortality rates between control plots and pre-fire plots for both study sites was statistically insignificant.

Table 4. Chi-square test results

Expected Rate	Observed Rate	Degrees of Freedom	Chi-square sum	Rejects null? (y/n)
Pre-2013 AF Control	Post-2013 AF Control	3	0.306	No
Pre-Fire AF	Post-Fire AF	5	223.5	Yes, 99% CI
Post-2013 AF Control	Post-Fire AF	2	2.6	Yes, 70% CI
Pre-2013 AF Control	Pre-Fire AF	2	0.14	No
Pre-Fire Blodgett	Post-Fire Blodgett	7	16.1	Yes, 95% CI
Post-2009 Blodgett Control	Post-Fire Blodgett	6	2.25	No
Pre-Fire Blodgett	Post-2009 Blodgett Control	6	1.37	No
Post-Fire Blodgett	Post-Fire AF	4	0.84	No
Pre-Fire Blodgett	Pre-Fire AF	4	0.16	No

Regression Analysis

Linear Regression

When graphing the overall percentage of deceased trees against increasing char range, I found that there was a fairly strong positive relationship between the percentage of tree charred and mortality. The R^2 for the American Fire data was 0.875, and that of the Blodgett burn was about 0.855 (Figure 3). The percent of deceased trees was higher for lesser amounts of char in the American Fire footprint than the Blodgett burn.

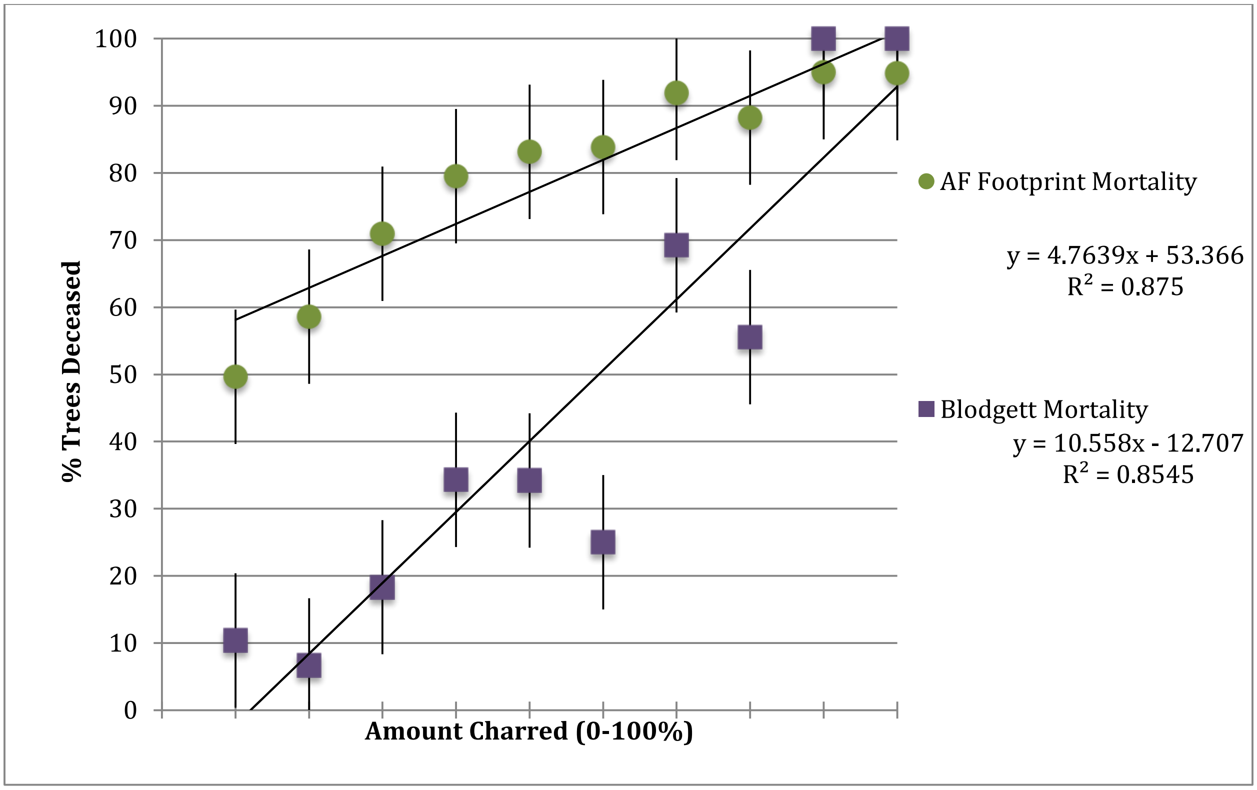

Figure 3. Linear regression of mortality as a result of char amount in AF and Blodgett. Amount charred is shown in increments of 10%. Each point represents the percent of dead trees with a char amount within the respective interval (i.e. 0-10%, 11-20%). There is a pretty strong positive correlation between these two variables.

A similar, but much weaker, trend appeared when I plotted the overall percentage of deceased trees against increasing percentage of tree scorched. The R^2 value for the American Fire data and Blodgett burn data was about 0.012 and 0.581, respectively; for the American Fire only, the amount of scorch was basically not predictive of the amount of deceased trees (Figure 4). The percent of deceased trees was higher for lesser amounts of scorch in the American Fire footprint than the Blodgett burn, similar to the linear regression for char.

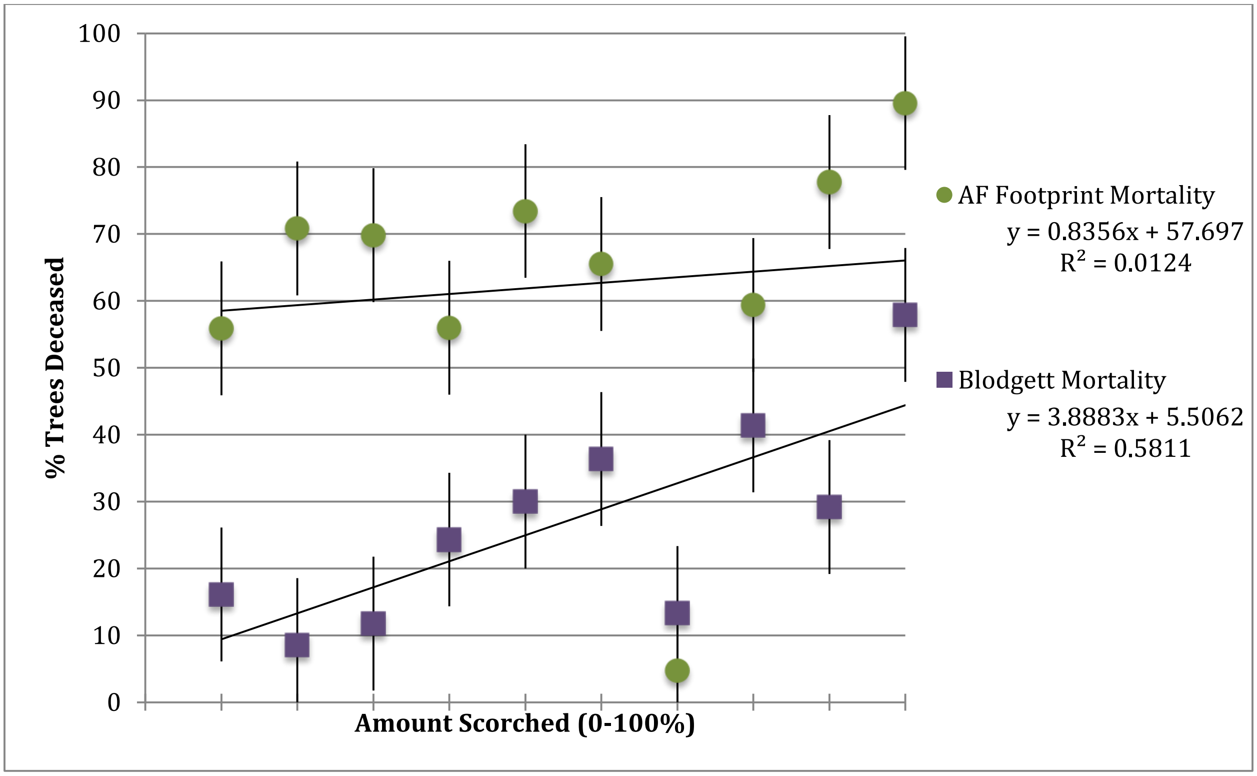

Figure 4. Linear regression of mortality as a result of scorch amount in AF and Blodgett. Amount scorched is shown in increments of 10%. Each point represents the percent of dead trees with a scorch amount within the respective interval (i.e. 0-10%, 11-20%). There is a stronger positive correlation for the Blodgett burn site, and essentially no correlation for the American Fire footprint site.

Logistic Regression

The best model for the American Fire footprint incorporated all three variables: DBH, percent char, and percent scorch; it had an AIC of 1263.568 (Table 5a). This model had the equation:

$$\text{Probability of mortality} = 0.02847(\%\ char) - 10^{-4.15889}(DBH) + 0.004735(\%\ scorch) - 0.01345,$$

where % char and % scorch are given as a value between 0 and 100, and DBH is in centimeters. Both the char variable and the scorch variable were statistically significant with p-values <0.05; DBH was not a statistically significant variable, with a p-value of 0.981. (DBH was actually not a statistically significant variable in any of the American Fire models, except for model #1).

Table 5a. American Fire AIC Results for Probability of Mortality Model

Model	Variables	AIC

1	DBH	1436.272
2	DBH, % Char	1266.049
3	DBH, % Scorch	1331.933
4	DBH, % Char, % Scorch	**1263.568**

The best model for the Blodgett burn incorporated only two variables: DBH and percent char; the AIC value was 641.4980 (Table 5b). This model had the equation:

Probability of mortality = 0.04402(% char) – 0.04896(DBH) – 1.03779,

where % char is given as a value between 0 and 100, and DBH is in centimeters. Both variables were statistically significant, with p-values <0.05.

Table 5b. Blodgett AIC Results for Probability of Mortality Model

Model	Variables	AIC
1	DBH	748.6011
2	DBH, % Char	**641.4980**
3	DBH, % Scorch	741.0632
4	DBH, % Char, % Scorch	643.4317

The graphed logistic (i.e. inverse-logit) models showed higher levels of mortality probability than that of the Blodgett burn at a given level of fire damage, when controlled for tree size using the Blodgett median DBH of 29.464 cm, and the American Fire footprint median DBH of 30.8 (Figure 5).

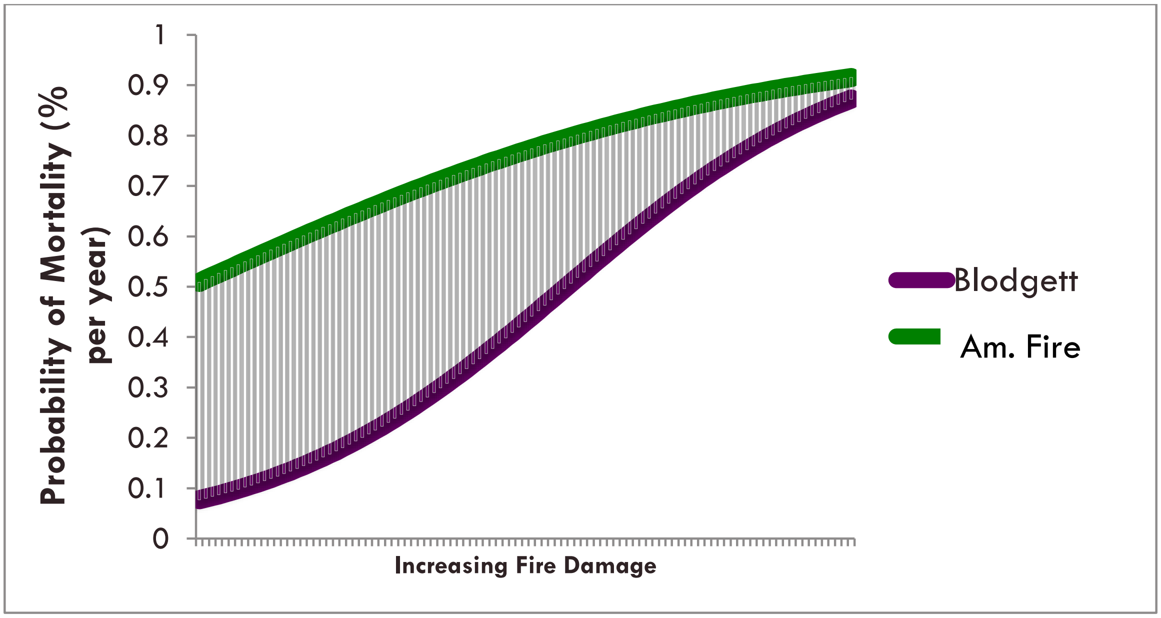

Figure 5. Logit model for AF footprint and Blodgett mortality probability. The probability of mortality as a result of increasing fire damage is higher in the AF footprint than for Blodgett, particularly at lesser levels of fire damage. The shaded area between the curves emphasizes the difference in probability of mortality between the two study sites.

DISCUSSION

The species and overall mortality rates, particularly before fire and drought, were fairly similar between the American Fire footprint (burn and control plots) and Blodgett (burn and control plots). Post-fire mortality rates increased at both sites, which I found to be adequately predicted by char (as well as scorch in the AF footprint); this difference in model structure brings into question the significance and usefulness of scorch as a variable. The best logistic models for both study sites reflected an increased incidence of mortality and mortality probability in the drought-affected American Fire footprint. Though the difference between sites' post-fire mortality rates is not quite statistically significant, discrepancies between the sites' logistic models, as well as observed mortality patterns in other forests, suggests that drought possibly has had an effect on post-fire tree mortality in the AF footprint. Future monitoring will provide more insight on this sites' post-fire mortality dynamics. To preserve forest health, thinning, prescribed burns, and more accurate modeling become crucial.

Tree mortality trends

Species and overall mortality rates increased after fire for both study sites (despite a few exceptions at Blodgett forest). In general, post-fire mortality rates in the American Fire footprint were higher, and increased much more from the pre-fire mortality rates, than those in Blodgett. The increases in mortality rates for both sites were statistically significant, indicating that fire increased trees' vulnerability (Regelbrugge et al., 1992). There were a few instances of decreases in mortality rates, particularly in the control plots of both study sites and the burned plots of Blodgett; perhaps these particular individuals survived the fire with minimal damage, and/or were especially resilient to environmental stress. PIPO had one of the highest values of, and largest increases in, mortality rate, in both the American Fire footprint and Blodgett. Pines are known for being drought- and fire-tolerant (Collins et al. 2014), which makes PIPO's observed high mortality puzzling. Collins et al.'s 2014 model projected Blodgett's PIPO mortality to be markedly higher than any other species', despite very low observed mortality. This aligns well with the trends I observed in the American Fire footprint and Blodgett today.

There was no statistical significance for the differences between either AF control plots across all years, or between AF control and non-control plots before the fire. This lack of statistical significance indicates that mortality rates were fairly similar before the American fire and in unburned areas after the fire. The exact same test results and trends occurred for the burn in Blodgett. The chi-square test also showed that there was no statistical significance for the differences in mortality rates at the Blodgett site and the American Fire site before the fire; this indicates that mortality rates were fairly similar across sites before the current drought.

Five damage as predictors of tree mortality

By first plotting the American Fire footprint and Blodgett mortality data against measures of char or scorch, I was able to confirm that a relationship existed between the amount of a tree's fire damage and the amount of tree mortality. There was a clear positive linear relationship between the percent of tree charred and mortality for both the American Fire footprint and Blodgett. This relationship was much less apparent for measures of scorch, however. At Blodgett, there was a weak positive linear relationship between the percent of tree scorched and mortality, and virtually no linear relationship in the AF footprint. (Two of the points on the scorch graph are unusually low, which may indicate an inconsistency in the data or an unexplained phenomenon, as it occurred for both study sites at the same interval.) The cause of this difference in trends is unclear. Tree mortality can be caused by a reduction in xylem conductivity alone (i.e. char/stem damage), without any crown injury (Michaletz et al. 2012); perhaps in my case char is impairing trees' functions more than scorch. Despite these varying relationship strengths, visualizing these patterns in the raw data still illustrated the fact that char and scorch are predictive of mortality, for fire increases a survivor trees' vulnerability (Regelbrugge et al. 1992).

It is difficult to explain why the AF footprint's best logistic model incorporated all three variables, whereas the Blodgett burn's best logistic model incorporated only two, especially in light of the fact that the linear regression for % scorch and % deceased trees in the AF footprint showed a negligible correlation between these two variables, as opposed to the slightly stronger correlation seen for the Blodgett burn. Additionally, the statistical insignificance of the DBH variable in all of the AF footprint models is ambiguous (except for model #1, where DBH was the only variable). Lastly, the AIC values of the 2nd best model for both study sites were very close to those of the 1st best model; the values were only off by a value of about 2 or 3. This brings into question the effect of the scorch variable: taking it out of the AF footprint model, or adding it into the Blodgett model, does not seem to change the AIC too much. Furthermore, the Blodgett model's scorch variable was statistically insignificant when char and DBH were also variables. Perhaps this means that scorch is not as strong determinant of mortality probability as char in this system. However, the scorch variable has been found to be statistically significant in other Sierra Nevada species mortality probability models (Hood et al. 2007), so maybe there is some merit to including this variable. A more definite conclusion can be reached with a larger sample size.

Nonetheless, when both study sites' best models are graphed side by side (Fig. 5), the discrepancy in mortality trends between the American Fire footprint and Blodgett burn becomes apparent. The probability of mortality increased with increasing fire severity at both study sites, which is a general trend that has been observed in other post-fire sites, such as the Stanislaus Fire Complex in 1987 (Regelbrugge et al. 1992). At high levels of fire damage, the probability of mortality becomes quite similar; eventually the two curves converge to 1 (i.e. 100% probability of mortality). This pattern is not unexpected, since at large levels of fire damage a tree will have a much more difficult time performing processes necessary for survival (i.e. water uptake through the xylem, photosynthesis) (Regelbrugge et al., 1992)(Michaletz et al., 2012). At lesser levels of fire damage, however, the probability of mortality was much higher for the American Fire footprint than for the Blodgett burn. Because these two models are reflections of the true data, this divergence signifies a more intense post-fire mortality dynamic (i.e. more deaths) in the drought-affected AF footprint than the pre-drought burn in Blodgett; trees appear to be more vulnerable in the former site than the latter.

Effect of drought on tree mortality

The difference in mortality probability between the two logistic models exemplifies the likely effect drought has had on post-fire tree survivorship in the American Fire footprint when compared to Blodgett's controlled burn. The inclusion of the scorch variable in the American Fire footprint model, and its absence from the Blodgett model, might suggest that drought also affects post-fire mortality modeling (though whether it is a useful variable is uncertain in this study). Despite the seemingly obvious implications of the difference in logistic models, the chi-square test between the two sites' post-fire mortality rates rejected the null hypothesis at a confidence interval of only 70%. This is not a strong indication of statistical significance, and alludes to the conclusion that drought did not increase post-fire mortality in the American Fire footprint. In many cases, drought has been attributed to increased tree mortality (across the globe, as a result of climate change), particularly because it impairs xylem activity and makes trees more susceptible to insects and disease (Allen et al. 2010) (van Mantgem et al. 2013). Increased mortality from the compounded effects of fire and drought have been observed in other forests such as the Amazon, explained as a "co-effect" dynamic in other forest systems (Brando et al. 2014). With this in mind, it might be that this particular chi-square test result signifies a possible drought effect, which can be made more explicit if the drought persists and/or with a larger dataset.

Limitations and Future Directions

Comparing mortality rates between two different locations always poses some challenges. Differences in biogeochemical and physical surroundings such as soil type, presence of competitors, slope, and watershed dynamics may all influence the vulnerability of an individual tree or a population (Weaver & Clements, 1938), and thus affects the strength of comparison between the American Fire footprint and Blodgett forest. Additionally, increased competition resulting from higher forest density and basal area may be a confounding variable, particularly since this dynamic is common in some old forests in the western U.S. (van Mantgem et al, 522). My study did not look at how char and scorch affects probability of mortality on a species level; partitioning the analysis in this way might result in very different logistic models. It is possible that Blodgett plots were slightly affected by the first couple years of drought, since the last census year was 2014 (3 years after the official beginning of the drought). Lastly, American Fire footprint post-fire mortality rates where only calculated using 2 census years; undoubtedly subsequent data collection will allow for a more robust post-fire analysis.

Future monitoring of these plots will reveal more information on forest response to drought and fire stress. A larger sample size over a wider variety of Sierra Nevada environments, perhaps from other University of California and Forest Service research forests, might strengthen comparisons and models. Another possible level of analysis could include a comprehensive record of regional fire history, which may uncover trends specific to fire frequency interval. Comparisons to forests outside of the Sierra Nevada range would be of interest, and may contribute to knowledge on how climate change affects survival dynamics across the United States.

Management Implications

Knowledge concerning how forest mortalities are affected in drought can ground conservation efforts and serve as a rationale to update forest planning and management, such as mechanical thinning programs and prescribed burns, which are designed to decrease fuel loads and reduce fire risk. Since post-fire mortality is likely higher in areas affected by drought, increased fuel load reduction will be much more crucial in quelling the possibility of wildfires and/or restoring a natural fire regime (Fule et al. 2012). Prescribed burns can be better planned with updated tree physiological models (i.e. response to fire injury) reflecting drought conditions, so as to minimize unwanted tree deaths (Butler and Dickinson, 2010). Timber harvesting companies can be able to make better judgments on which trees to cut, particularly in salvage logging operations, using knowledge on large environmental stressors (i.e. drought) present in the forest and char and scorch as visible metrics.

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APPENDIX

Table 1. Vigor classes as assigned in the field, and respective code for analysis, with criteria for assignment

Vigor Class	Code	Criteria
1, 2, or 3	0	Clearly alive, with at least some alive leaves/branches (green vegetation); crown may be fully present or partially missing
4, 5, or 6	1	Clearly dead, with either leaves/needles still present or gone; no green vegetation in crown; trunk may be broken
0, 7, 8, 9, or 10	Excluded from analysis	Missing tree; tag may be missing, and/or tree may not be found, no best guess