FACTORS CONTRIBUTING TO LEGACY HARDWOOD MORTALITY FOLLOWING PRESCRIBED FIRE

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ABSTRACT

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Interruption of Indigenous stewardship has resulted in hardwood decline along what is now known as the middle Klamath River in northern California related to adverse effects to Tribal food sovereignty and community wellbeing. The survivors of a "legacy" of Indigenous stewardship are highly valued by the Karuk and neighboring Tribes for a myriad of culturally beneficial ecological associations and sources of traditional staple foods. Prescribed fire, following a century of fire exclusion, has resulted in unanticipated mortality of legacy tanoak (*Notholithocarpus densiflorus*), California black oak (*Quercus kelloggii*), and madrone (*Arbutus menziesii*), warranting further investigation. In order to better understand factors contributing to legacy hardwood mortality following prescribed fire, we characterized pre-fire basal fuels and conducted a post-fire mortality inventory for all three species.

For the fuels characterization, we measured litter and duff depth, woody fuels and fine root density around the base of 166 hardwood trees ranging in diameter at breast height [dbh] from 25 to 176 cm (median 51 cm dbh) across six sites in Karuk Aboriginal Territory. Transects accounted for distance from tree base (0-3 m) and direction in relation to the slope (up, down, left, and right facing upslope). Using linear mixed effects models, we determined that fuel depths under the tree crown were 41% and 42% greater than in canopy gaps for litter and duff, respectively. Distance and direction from the tree bole were the best predictive variables for fuel depth and loading. Fuels were largely slope-influenced, with uphill accumulations and downslope fuel “shadows” immediately next to the bole. Tree-level litter and duff depth were negatively related with Douglas-fir (*Pseudotsuga menziesii*) competition and tree dbh, and positively related with slope. Root density was highly correlated with duff depth, with fine and coarse roots (<5 mm) in 94% of duff samples. Legacy hardwood fuel and root densities were less than previous studies around conifers in the region, but comparable to mixed hardwood-conifer stands in previous studies. High basal fuel accumulation may warrant basal fuels remediation prior to prescribed fire.

For the post-fire mortality inventory, we estimated mortality in six prescribed fire sites (burned 2017-2019) using four to six fixed area transects (1000 m^2), and were compared to six representative unburned sites. Legacy hardwood size ranged from 25 to 186 cm diameter at breast height [dbh] (median 39 cm dbh). An estimated 43% of all sampled hardwood trees and 63% of the dead trees had pre-existing fire scars. Generalized mixed effects linear modeling was used for analysis. Stand-scale mortality rates were greater in prescribed burned areas (18%) than controls (13%), but not statistically significant ($P = 0.735$), and were comparable to observed rates of mortality in the region. Tree-scale mortality due to treatment varied among species ($P < 0.0001$), where black oaks died at the highest rates and were sensitive to prescribed fire (29% prescribed fire, 13% control). In contrast, tanoak had the same mortality rate between treatments (9% for prescribed fire and control; $P < 0.0001$). The most informative model predicting mortality

was scar width/dbh ratio and species ($P < 0.0001$), primarily driven by the presence of large pre-existing fire scars among madrones. This metric may account for remaining structural wood, and the likelihood of structural failure, although more research is needed.

These results provide important insights into the factors related to undesired legacy hardwood mortality following prescribed fire with implications into possible mitigation efforts that warrant further Indigenous-led investigation and restoration. This study additionally expands post-fire mortality and fuel accumulation research to western hardwood species of cultural importance to the Karuk and neighboring tribes in the region.

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Lastly, thank you to the legacy hardwoods who persist and continue to give despite years of neglect. Thank you for hosting us at your feet. May you receive the care that people have for you and thrive for generations to come.

TABLE OF CONTENTS

ABSTRACT ii
ACKNOWLEDGEMENTS v
TABLE OF CONTENTS viii
LIST OF TABLES x
LIST OF FIGURES xii
LIST OF APPENDICES xv
chapter 1. legacy hardwood fuels and root characterization 1
Abstract 1
Introduction 3
Materials and Methods 7
Study Site 7
Field Methods 7
Data Analysis 11
Results 13
Depth-to-Load Relationships 13
Within-tree spatial fuels variation 15
Root density 20
Among-tree fuels and root variation 22
Discussion 28
Depth-to-load relationships 28
Within-tree fuel spatial variation 29
Root density 32
Among-tree fuel spatial variation 33
Management implications 35
Literature Cited 37
chapter 2. prescribed fire legacy hardwood mortality inventory 45
Abstract 45
Introduction 47

Materials and Methods ... 52
Study Site ... 52
Field Methods ... 54
Data Analysis ... 56
Karuk Tribe and Manager Engagement and Review ... 58
Results ... 60
Stand scale legacy hardwood tree mortality ... 61
Tree-scale legacy hardwood tree mortality ... 63
Discussion ... 68
Literature Cited ... 74
APPENDICES ... 87
Chapter 1. Legacy hardwood fuels and root characterization ... 87
Appendix A. Fuels transect position in relation to the slope ... 87
Chapter 2: Prescribed fire legacy hardwood mortality inventory ... 88
Appendix B. Tree mortality and decay classes. ... 88
Appendix C. Effect of tree size on mortality ... 89
Appendix D. Effect of percent scar char on mortality. ... 90
Appendix E. Generalized linear mixed effects models for mortality. ... 91

LIST OF TABLES

Table 1. Study sites characteristics and tree sample size by species. Elevation range and mean values with range in parentheses are shown by site.................................... 8

Table 2. Linear regression results between fuel depth (cm) and load (Mg/ha) by tree species where the equation was forced through a y-intercept of zero: load=0+b_1 * depth; b_1 = slope coefficient, s.e.= standard error, R^2 = adjusted proportion of variation explained by the model with penalties for number of predictors added. 14

Table 3. Best models for within-tree fuel variation (fuel sample scale) for litter and duff depths (cm); litter, duff, 1-hr, 10-hr, and 100-hr fuel loading (Mg/ha). All models were linear mixed effects models with transect, tree, and site as nested random effects. P-values were estimated by comparing the model to the null model using anova. For litter load and duff density, the null models were most. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model. 18

Table 4. Mean depth (cm), loading (Mg/ha), and density (kg/m^3) for each fuel component by species within 3 m of the tree base. Sample size (n) for litter and duff depth was 1303 and loading was 545; woody fuel loading was 1040 and density was 427....................... 18

Table 5. Duff depth to root mass equations for each species separately and all species combined, where the equation was forced through a y-intercept of zero: load=0+b_1 * depth; b_1 = slope coefficient, s.e.= standard error, R^2 = adjusted proportion of variation explained by the model with penalties for number of predictors added... 21

Table 6. The best models for among tree fuels variation due to tree-level factors. baPSME = basal area (m^2/ha) Douglas-fir (Pseudosuga menzeseii), dbh = diameter at breast height (1.37 m), cw_perp = crown width perpendicular to the widest crown width, cbh = crown base height (m), total ba = total basal area of all surrounding species (m). The best model for 10-hr fuel loading was the null model. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model. 23

Table 7. Sites sampled for legacy hardwood mortality with mean values and ranges in parentheses. Total hardwoods sampled includes 953 trees in prescribed burns and in controls.. 55

Table 8. Percent mortality (%) by site, treatment, and species.. 62

Table 9. Mean values for each factor for live and dead trees within prescribed burned sites, excluding unburnt controls. P-value estimates, standard error, and coefficient estimates are included for univariate models. Variation inflation factor (VIF) values provided for field-measured covariates as an indicator of multicollinearity.. 65

Table 10. The best five models predicting legacy hardwood mortality with tree-scale covariate combinations using the lowest AIC for selection. Dbh = diameter at breast height (m), scar w = scar width at the base or widest part (m), char = % char of scar surface using an ocular estimate. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model. Species included madrone, tanoak, and California black oak.... 66

Table E 1. Model runs for data excluded older decay classes (> 5, n = 923) for all treatments, sizes, species, and scar characteristics with mortality (dead/alive) as a response. AIC was utilized to select the best model, and p-values shown were either summarized using R, or estimated using anova against the null model. Dbh = diameter at breast height (m), scar ht = scar height (m), scar w = scar width at the base or widest part (m), scar d = scar depth measured from the opening to the back of the tree (m), scar volume = ((w x ht x d)/3), scar sa = (w x ht)/2, char = percent char of scar surface via ocular estimate (%), rot = percent rot of scar surface via ocular estimate (%). 91

LIST OF FIGURES

Figure 1. Arianna Skikos and Kunal Mehta conducting fuels transects in relation to the slope (up, down, left right) at five distances between 0 and 3 m from tree bole. Photo credit Heather Rickard……………………………………………………………………….. 9

Figure 2. Workflow for pre-fire fuels and roots characterization using linear mixed effects modeling……………………………………………………………………………… 12

Figure 3. Depth (cm) to load (Mg/ha) relationship for leaf litter and duff among hardwood trees in the lower montane region of Karuk Aboriginal Territory, Klamath Mountains Region, California………………………………………………………………………. 15

Figure 4. Average fuel depth (cm) for litter and duff under the first 3 m of the tree crown from tree base compared to depth in the nearest canopy gap……………………………. 16

Figure 5. Fuel depth (cm) across all four directions (up, down, left and right facing upslope looking at the tree), and fuel sample distance from the bole (0, 0.5, 1, 2, and 3 meters) for litter and duff……………………………………………………………………………. 19

Figure 6. Woody fuel loading with respect to distance, direction and species. Distance metrics describe fuel loading along variable length transects where 0 = 0 – 0.5 m, 0.5 = 0.5 – 1 m, 1 = 1 – 2 m, 2 = 2 – 3 m……………………………………………………….. 20

Figure 7. Root density (kg/ m3) where greater values are lighter shades of blue for all four directions (up, down, left, and right, facing upslope) and five distances from the tree base. ……………………………………………………………………………………………21

Figure 8. Root density (kg/ m3) in relation to distance and direction from tree bole facing upslope across all three species………………………………………………………. 22

Figure 9. The best linear model for mean litter depth superimposed on data observations for additive factors, basal area Douglas fir (m2/ha) and slope (%)……………………… 24

Figure 10. The best additive model for mean duff depth for among-tree factors: slope, basal area (BA) Douglas-fir, and diameter at breast height (dbh)…………………………….. 24

Figure 11. The best model for mean litter load where load decreased with increased perpendicular width of the crown (left) and increased with greater crown base heights (right)……………………………………………………………………………………. 25

Figure 12. The best mixed effects linear model for mean 1-hr fuel load was diameter at breast height (cm), where larger trees rendered lower 1-hr fuel loads………………….. 25

Figure 13. The best linear mixed effects model for 100-hr fuel load where 100-hr fuels increased with greater crown base height…………………………………………….. 26

Figure 14. The best linear mixed effects model for bulk density of duff (kg/m^3) for total basal area of all surrounding species of trees (m^2/ha)…………………………………… 26

Figure 15. The best linear mixed effects model for mean root density where root density decreased with greater perpendicular widths of crown (m)……………………………… 27

Figure 16. Canopy of legacy madrones and black oaks with high Douglas-fir encroachment. Photo credit Stormy Staats courtesy of the Karuk Tribe and MKWC…... 33

Figure 17. Cultural Practitioner displays tanoak acorns gathered from under a surviving legacy tanoak tree following prescribed fire. Photo credit Stormy Staats, courtesy of the Karuk Tribe and the Mid Klamath Watershed Council…………………………………. 48

Figure 18. Legacy madrone tree just days after prescribed burn during Klamath River TREX at one of the study sites. Photo credit Stormy Staats, courtesy of the Karuk Tribe and the Mid Klamath Watershed Council………………………………………………. 50

Figure 19. Workflow for observed tree-scale factors on legacy hardwood mortality using generalized linear mixed effect modeling (GLMM). Blue filled shapes denote processes conducted using R (R Development Core Team 2022)…………………………………. 58

Figure 20. The distribution of live and dead tree sizes for post-prescribed fire mortality measured by dbh in cm. Mean = 45 cm, median = 39 cm, and range of 25 to 187 cm (n = 953)…………………………………………………………………………………... 60

Figure 21. Count of legacy hardwood trees with and without pre-existing fire scars and mortality status (43% of living trees had scars compared to 63% of dead trees)……….. 61

Figure 22. Percent hardwood mortality between units receiving prescribed fire (17.8%) compared to the control (12.7%), summarized by unit. P-value = 0.735, standard error = 1.671. McFadden’s R^2 value = 0.15…………………………………………………….. 62

Figure 23. Scar width-to-dbh ratio is an association of the widest width of the scar and stem dbh. Field assistant Arianna Skikos here pictured taking field measurements of a legacy madrone at a study site in Orleans, CA. Photo credit Heather Rickard…………………. 64

Figure 24. Scar width/dbh ratio for living and dead trees for madrone, tanoak, and black oak……………………………………………………………………………………. 66

Figure 25. The most informative legacy tree mortality generalized mixed effects model was an additive model with scar width-to-dbh ratio and species. Dead trees are represented by the mortality value of 0, and living trees are represented by 1.............................. 67

Figure 26. Narrow structural wood remaining (2-7 cm) after prescribed fire on a dead broken legacy madrone. Photo credit Heather Rickard....................................... 70

LIST OF APPENDICES

Appendix A. Fuels transect position in relation to the slope…………………………… 87

Appendix B. Tree mortality and decay classes………………………………………..88

Appendix C. Effect of tree size on mortality…………………………………………… 89

Appendix D. Effect of percent scar char on mortality………………………………….. 90

Appendix E. Generalized linear mixed effects models for mortality……………………91

CHAPTER 1. LEGACY HARDWOOD FUELS AND ROOT CHARACTERIZATION

Abstract

The interruption of Indigenous stewardship has resulted in hardwood decline along what is now known as the middle Klamath River in northern California, causing adverse effects to tribal food sovereignty and community wellbeing. A century of fire exclusion has led to an unprecedented fuel loading around legacy hardwood trees, possibly contributing to tree damage and death following fire; however, characterization of fuel loading associated with legacy hardwoods has not been formally investigated. We quantified litter and duff depth, woody fuels and fine root density around the base of legacy tanoak (*Notholithocarpus densiflorus*), California black oak (*Quercus kelloggii*), and madrone (*Arbutus menziesii*). We sampled 166 hardwood trees ranging in diameter at breast height [dbh] from 25 to 176 cm across six sites in Karuk Aboriginal Territory, with a median size of 51 cm dbh. Transects captured within-tree fuel and root density variation with distance from tree base (0-3 m) and direction in relation to the slope (up, down, left, and right facing upslope). Among-tree variation in fuels were associated with tree-level competition (basal area surrounding trees), tree and crown dimensions, and topographic stand conditions. Using linear mixed effects models, we determined that fuel depths under the tree canopy were 41% and 42% greater than in canopy gaps for litter and duff, respectively. Distance and direction from the tree bole were the best predictive variables for fuel depth and loading and the inclusion of species was less informative. Fuel accumulation was largely slope-influenced, with the greatest amounts immediately next to the bole on the uphill side, and with a fuel “shadow” immediately next to the bole in the downslope direction. A slight mounding effect overall was visible for tanoak and madrone, and generally fuels were lighter immediately next to the bole and increased with distance, except for in the downhill direction, where fuels increased with distance within the first three meters. Tree-level litter and duff depth were negatively related with Douglas-fir (*Pseudotsuga menziesii*) competition and tree dbh, and positively related with slope. Root density was highly correlated with duff depth, and fine and coarse roots (<5 mm) were found in 94% of duff samples. Root density varied with direction, and was 58% greater in the uphill direction compared to downhill. Among trees, root density was negatively correlated with the perpendicular width of the tree crown. Results of this study indicate the presence of elevated basal fuel accumulations associated with legacy hardwoods in the region, and that these fuel characteristics vary spatially with tree and stand conditions. These findings suggest that basal fuel accumulations may be a contributing factor affecting legacy tree mortality following fire and could warrant remediation prior to broadcast burning.

Introduction

Indigenous peoples have managed oak woodlands in what is now referred to as Klamath Mountains since time immemorial with frequent low-intensity fire (Karuk Tribe 2019, Anderson 2018, van Wagtendonk et al. 2018). In Karuk Aboriginal Territory along the middle Klamath River corridor, fire practices are evidenced by continued stewardship, living traditional ecological knowledge (TEK), in the surviving legacy hardwood trees, and confirmed by fire scar and charcoal records (Skinner et al. 2018, Knight et al. 2020). Traditionally, tanoak (*Notholithocarpus densiflorus*) acorn groves are burned annually in the fall as part of a complex cultural tradition that prevents insect predation, reduced competition, and stimulated nutrient cycling for hardwoods (Anderson 2005, Peters 2010, Halpern et al. 2022). Annual maintenance fires reportedly improve tree yield and reduced pests (Schenck & Gifford 1952). The complex cultural tradition of broadcast burning in and around acorn groves prevents competition, insect predation and nutrient cycling (Schenck and Gifford 1952, Anderson 2005, Peters 2010, Halpern et al. 2022). Colonial invasion and ongoing settler colonialism have challenged and interrupted stewardship relationships with legacy hardwood groves, including fire exclusion as enforced by the Weeks Act of 1911 (Norgaard 2019, Vinyeta 2022).

A century of fire exclusion has changed fuel accumulation patterns around the base of valued legacy trees. Generally, ground fuel characteristics are influenced by dynamics of fuel deposition and decomposition, and have been found to vary by species (van Wagtendonk 1998, Banwell & Varner 2014). Greater stand densities observed since colonization may both contribute more fuels and also inhibit decomposition (Keane 2008). Fuel composition around the base of legacy conifers has been shown to accumulate in a mound-shape and generally decreases with distance from the bole, with duff as the dominant fuel component (Banwell & Varner 2014, DiMario et al. 2018). One study on legacy sugar pines in the Klamath Mountain region showed that larger trees rendered greater litter and duff loading (DiMario et al. 2018). However, the patterns of basal fuel accumulations in hardwood trees is largely unknown.

Previous studies demonstrate that patterns of basal fuel accumulation can impact post-fire tree mortality; however, prior research has almost exclusively focused on conifers. Elevated basal fuel accumulation following prolonged fire exclusion have been found across multiple conifer species (Swezy & Agee 1991, Banwell & Varner 2014, DiMario et al. 2018), that can contribute to mortality following prescribed burns. Cambium mortality has been found to increase with greater duff depth around the base of the tree (Ryan & Frandsen 1991). The higher bulk density of duff promotes prolonged smoldering at greater than lethal temperatures and duration (60°C for one minute) (Ryan & Frandsen 1991, Garlough and Keyes 2011) injuring or killing trees via partial (scarring) or complete cambial injury (death). Additionally, in the prolonged absence of fire, fine roots can establish in the accumulated duff (Swezy & Agee 1991). Fine root death in duff and lethal heating in the top mineral soil horizons can lead to loss of non-structural carbohydrates and reduced growth, reducing the overall resiliency of the tree to secondary stressors (Varner et al. 2005, Varner et al. 2009, Slack et al. 2016). Even under low-intensity fire, unprecedented amounts of fuels resulting from fire exclusion (Parsons & DeBenedetti

1979) has been linked to post-fire tree mortality (Swezy & Agee 1991, Stephens & Finny 2002, Varner et al. 2007), warranting further investigation in the role of fuel accumulations in post-fire tree mortality.

Duff accumulation at the tree base increases moisture-retaining substrate, which frequent fire would have prevented. Indeed, fine feeder roots (< 2 mm) have been found in duff mounds of legacy conifers (Swezy & Agee 1991, Varner et al. 2007, Bartley 2023). However, the spatial variation of fine and coarse root density is often highly variable and differs with distance from tree base (Olsthoorn et al. 1999) and between species (Büttner & Leuschner 1994). Greater root density has been observed with greater moisture (Kalisz et al. 1987). While roots have been found to decrease with stand-level competition (Finér et al. 2011, Namm & Berrill 2020), one study found that hardwood roots in Douglas-fir encroached stands were longer than hardwood roots in pure stands, perhaps due to the need to grow further for nutrients under greater competition (Hendriks & Bianchi 1995). Basal fuels and roots have not been characterized to date around the legacy hardwood species of interest to the Karuk Tribe (e.g. tanoak, black oak, and madrone) (Karuk Tribe 2019).

The goal of this research is to understand fuel accumulation patterns around the base of valued legacy hardwood trees in Karuk Aboriginal Territory, Klamath Mountain region of northern California. Research objectives include: 1) examining the effect of species on litter and duff depth-to-load relationships; 2) quantifying litter, duff, fine woody fuels (1-hr, 10-hr, 100-hr), and root density variation among species (tanoak, black oak, madrone) under the influence of the canopy and with distance and direction from the tree bole; and 3) evaluating the association of litter and duff depth and root density associated with tree- and site-level factors. Fuels characterization may inform restoration techniques and prescriptions to limit legacy hardwood tree damage and promote their continuance. Increasing our understanding of fire-induced legacy hardwood mortality is critical to support tribal resource objectives for current and future stewardship of woodland habitats.

Materials and Methods

Study Site

The study sites are located in central Karuk Aboriginal Territory near the town of Somes Bar in northern California. Study areas along the middle Klamath River corridor at low to moderate elevations (<600 m) were traditionally culturally burned at frequent intervals (ranging 1-7 years) prior to interruption of Indigenous stewardship and promotion of fire exclusion policies in the mid-19th century. The river corridor is well known for its steep slopes and complex topography, contributing to a wide variety of microclimates (Sherriff et al. 2022). The region is characterized by a Mediterranean climate with 130 cm average annual precipitation, falling predominately between November and April (Western Regional Climate Center 2019, Sherriff et al. 2022). January is the coldest month with an average minimum temperature of 1°C, and July is the hottest month with an average maximum temperature of 33°C (Western Regional Climate Center 2019). Climate change studies suggest a trend away from long-term averages, including increased annual temperatures and increased spring precipitation (Butz et al. 2015).

Field Methods

Five sites were opportunistically selected that contained a minimum of 5 trees ≥ 25 cm dbh of one or more of the species of interest (tanoak, black oak, and madrone; Table 1). These sites had no record of fire within the last 100 years, although had been recently hand thinned (stems <15 cm), pile-burned in preparation for prescribed fire. Surveys were conducted during the summer (June-August) of 2020 and 2021.

Table 1. Study sites characteristics and tree sample size (n) by species. Elevation range and mean values with range in parentheses are shown by site.

Site	Elevation Range (m)	Slope (%)	BA (m^2/ha)	Tanoak (n)	Madrone (n)	Black oak (n)
P2222	594-661	28 (10-56)	48 (16-68)	10	11	9
P2223	573-610	35 (0-67)	42 (22-56)	14	-	-
P2290	655-710	34 (2-71)	51 (16-70)	39	37	17
PPrivate	640-658	26 (7-42)	48 (36-66)	-	-	10
OCFR173	655-710	39 (10-60)	19 (12-28)	7	5	5

Selected legacy hardwood trees were tagged with a stainless-steel numbered tag, and their locations were recorded with a Garmin GXP GPS unit using Universal Transverse Mercator (UTM) projection and World Geodetic System (WGS) 84 datum. The tree dbh was measured with a diameter tape. Competition for each tree was estimated using a basal area factor prism (BAF 2) from the center point of each tree for all species. Slope (%) was estimated using a clinometer to capture microtopography focused on a 10 m radius from the tree. Crown width (m; widest part of crown and perpendicular to maximum crown width), total tree height (m), and crown base height (m) were all measured with a laser rangefinder. Crown volume (*cv*) was calculated by applying crown width and height measurements assuming an elliptical cylinder, where crown base height (*cbh*) was subtracted from tree height (*h*) for the crown height (*ch*), and multiplied by the radius of the maximum crown width (*cw_max*/2) by the radius of the crown width perpendicular to the maximum (*cw_perp*/2), and then multiplied by π.

Equation 1: $$cv = ch * \pi \left(\frac{cw\_max}{2}\right)\left(\frac{cw\_perp}{2}\right)$$

Figure 1. Arianna Skikos and Kunal Mehta conducting fuels transects in relation to the slope (up, down, left right) at five distances between 0 and 3 m from tree bole. Photo credit Heather Rickard.

Fuels were quantified along 3 m long planar intersect transects radiating from the tree base (Figure 1). For each tree, fuels were measured along transects in two of four possible directions (upslope, downslope, left, and right facing upslope) and the directions selected were alternated systematically across all sampled trees. Litter and duff depths (cm) were measured at 0, 0.5, 1, 2, and 3 m from the base. Fine woody fuels (1-hr, 10-hr, 100-hr) were tallied along each transect between each litter/duff sample (Brown 1974). Fuel loading (Mg/ha) was calculated using Equation 2, where woody fuel count was denoted as *n*, the midpoint of the diameter range (d^2) was 3.18 mm, 9.53 mm, and 2.54 cm for 1-, 10-

, and 100-hr fuels, respectively. Specific gravity (*s*) values for 1- and 10-hr fuels were 0.48, and 0.4 for 100-hr fuels, and the non-horizontal correction factor (*a*) was 1.13, as provided by Brown (1974). Transect length (*l*) varied from 0.5 m to 1 m, with distance from the bole for all three fuel size classes. The slope correction factor (*c*) was determined using Equation 3.

Equation 2: $$Fuel\ load\ (\frac{Mg}{ha})\ = \frac{(1.234*n*d^2*s*a*c)}{l}$$

Equation 3: $$c\ = \sqrt{(1-\left(\frac{(\%\ slope)^2}{100}\right))}$$

Two additional litter and duff depths were also measured in the nearest canopy gaps to each sampled tree (range = 3.0 to 93.0 m, mean = 14.9 m). In general, sites were highly encroached, and true canopy gaps were sometimes difficult to find, and often required extending well beyond the crown of the tree of interest. Care was taken not to disrupt fuel stratification using a small hand trowel, measuring depths with a ruler (cm) to leave fuels as found. The litter layer (O_i) is defined as the upper organic soil horizon containing recently deposited dead needles or leaves, bark, cones, and other non-woody organic material. Under the litter layer, the fermentation (O_e) and humus (O_a) layers were combined for duff measurements. After fuels measurements were completed, destructive fuel samples were collected in one of the two transects using a circular 15 cm diameter metal frame. Leaf litter and duff were each placed in separate bags and brought back to the Wildland Fire Lab at Cal Poly Humboldt in Arcata, California. In the lab, duff samples were placed into water to remove mineral soil from organic material, air-dried for one day in a greenhouse, and then placed in a drying oven at 105°C for 2-3 days. Fine and coarse roots (≤ 5 mm) in duff samples were removed and weighed separately from duff. Leaf litter with woody fuels was dried and weighed without washing. The root density was calculated for analysis by volume of duff (Equation 4).

Equation 4: $$root\ density\ \left(\frac{kg}{m^3}\right) = 1000 * \frac{mass\ roots\ (g)}{(duff\ depth\ (cm) * \pi * 7.5^2)}$$

<u>Data Analysis</u>

To address my first research objective to evaluate the effect of species on depth-to-load variation, I examined litter and duff depth-to-load relationships using linear regression in R (v4.2.1, R Core Development Team 2023) with depth as the independent variable and loading as the dependent variable. The linear equation was forced through the y-intercept of zero, and the slope and standard error was reported for all data by fuel component. I then filtered the data by species and used the same analysis to estimate slope and standard error. I evaluated the model via visual inspection, goodness of fit (R^2), and P-value.

For my second research objective, I tested the effect of species, distance, and direction on litter and duff depth and loading, root density, and woody fuel loading utilizing a linear mixed effect modeling approach. I used the *lme4* package (Bates et al. 2015) with transect nested in tree and site as the random effects (intercept only). The best model for each factor was selected using the lowest Akaike Information Criterion (AIC) value. If two models were within 2 AIC, the simpler model was selected. To determine the effect of canopy presence on litter and duff depth, I averaged canopy litter and duff depth from all measurements 0 – 3 m from the tree bole, and compared them to average measurements in canopy gaps. I then analyzed the effect of canopy on fuel depth using a linear mixed effects model with *lme4* package, and tree and site factors were assigned as random effects (intercepts only).

For the third research objective, I analyzed the impact of site- and tree-level factors such as slope, tree dbh, height, crown dimensions, tree-specific encroachment (basal area Douglas fir and other species) on mean tree litter and duff depth, root density, and woody fuel load. I utilized linear mixed effects models with site as a random effect (intercept only), and evaluated model performance using the AIC model selection approach mentioned previously.

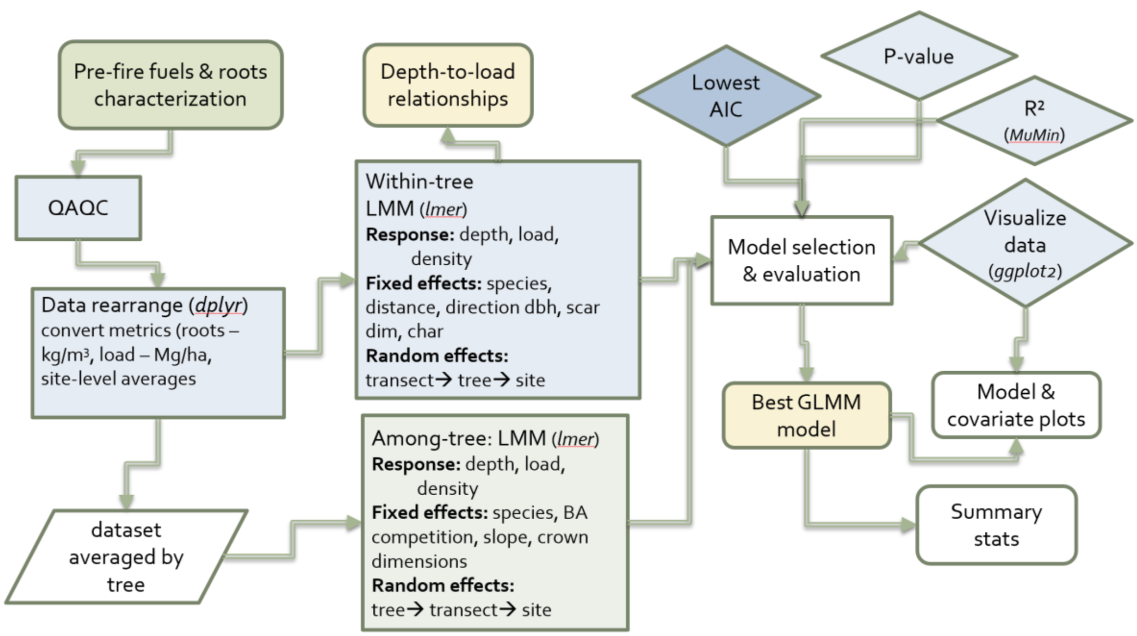

Figure 2. Workflow for pre-fire fuels and roots characterization using linear mixed effects modeling.

Results

Depth-to-Load Relationships

Field samples rendered 1514 fuel depth measurements from 166 hardwood trees ranging in size from 25 to 176 cm diameter at breast height (dbh), with a median size of 51 cm dbh. Litter and duff loading were analyzed from 545 destructive samples (Table 1). Six sites were selected where tree-centered slope ranged from 0 to 71% with basal area encroachment (all species) ranging from 12 to 70 m^2/ha.

Depth and load were positively and linearly correlated for both duff and litter, where deeper fuels were associated with greater loads (Table 2, Figure 3). When species was included as an additive factor, the duff model performed the same (AIC for both models was 5388 compared to 5644 for null model; $P < 0.0001$). The litter model performed worse (AIC was 5188 compared to 5185 without species and 5188 for the null model; $P = 0.137$) than models with depth and species included. The significance of this relationship differed between fuel components, where duff load was more positively correlated with depth than litter, and the depth-to-load (linear) model for litter was not significant for individual species (Table 2).

Table 2. Linear regression results between fuel depth (cm) and load (Mg/ha) by tree species where the equation was forced through a y-intercept of zero: load=0+b_1 * depth; b_1 = slope coefficient, s.e.= standard error, R^2 = adjusted proportion of variation explained by the model with penalties for number of predictors added.

Species	n	Fuel component	b_1 (s.e.)	P-value	R^2
Tanoak	219	Litter	1.52 (0.88)	0.085	0.014
		Duff	4.36 (0.49)	<0.0001	0.27
Madrone	151	Litter	0.67 (1.04)	0.522	0.0027
		Duff	6.09 (0.67)	<0.0001	0.35
Black oak	171	Litter	0.77 (0.74)	0.301	0.0063
		Duff	8.84 (0.66)	<0.0001	0.51
All species	541	Litter	1.17 (2.21)	0.0254	0.0092
		Duff	6.47 (0.36)	<0.00001	0.38

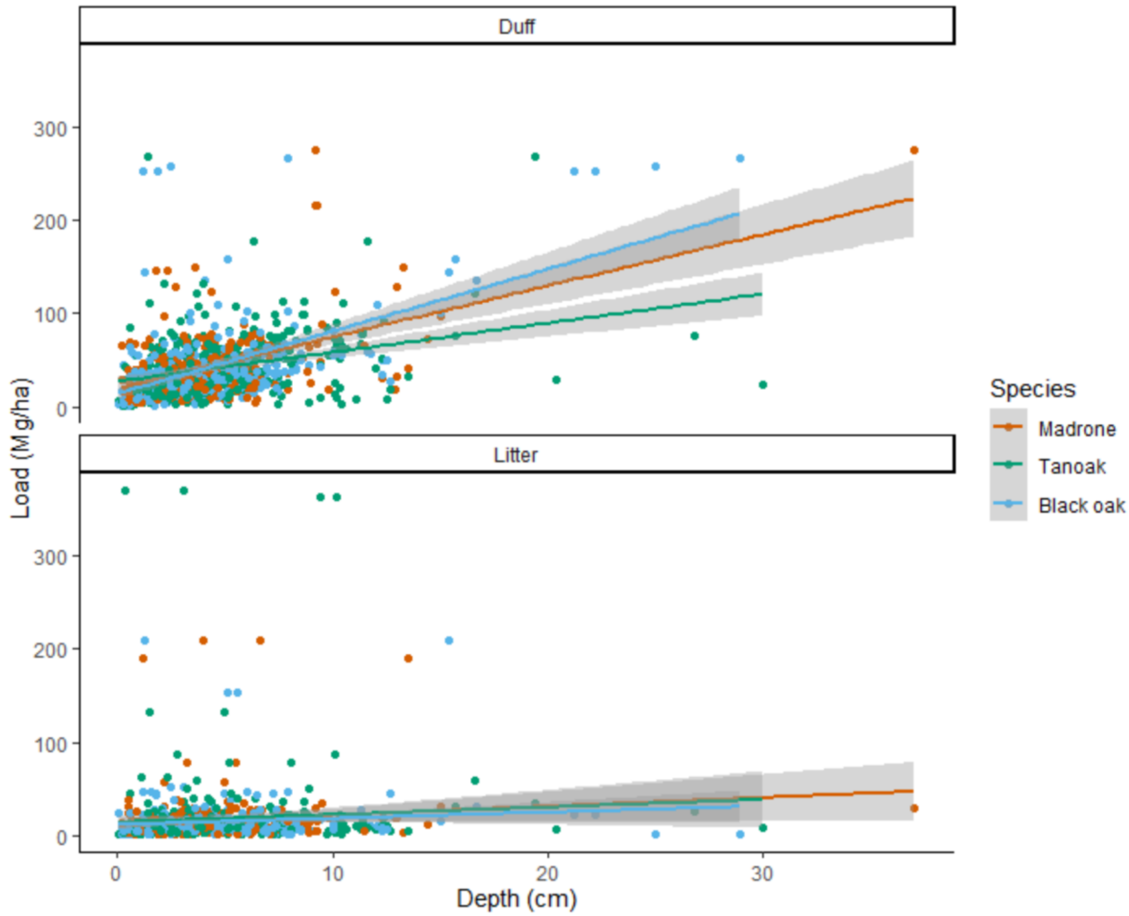

Figure 3. Depth (cm) to load (Mg/ha) relationship for leaf litter and duff among hardwood trees in the lower montane region of Karuk Aboriginal Territory, Klamath Mountains Region, California.

Within-tree spatial fuels variation

Fuels beneath the canopy were greater than canopy gaps for litter ($P < 0.0001$) and duff depth ($P < 0.0001$; Figure 4), but did not vary significantly by species ($P = 0.524$). The mean fuel depth beneath the canopy for litter and duff was 41% and 42% greater than in canopy gaps, respectively, with total mean fuel depth of 8.90 cm under the canopy compared to 6.35 cm in gaps. For litter, the average depth below the canopy was 3.53 cm compared to 2.60 cm in gaps; and duff depth under the canopy was 5.37 cm compared to 3.75 cm in gaps.

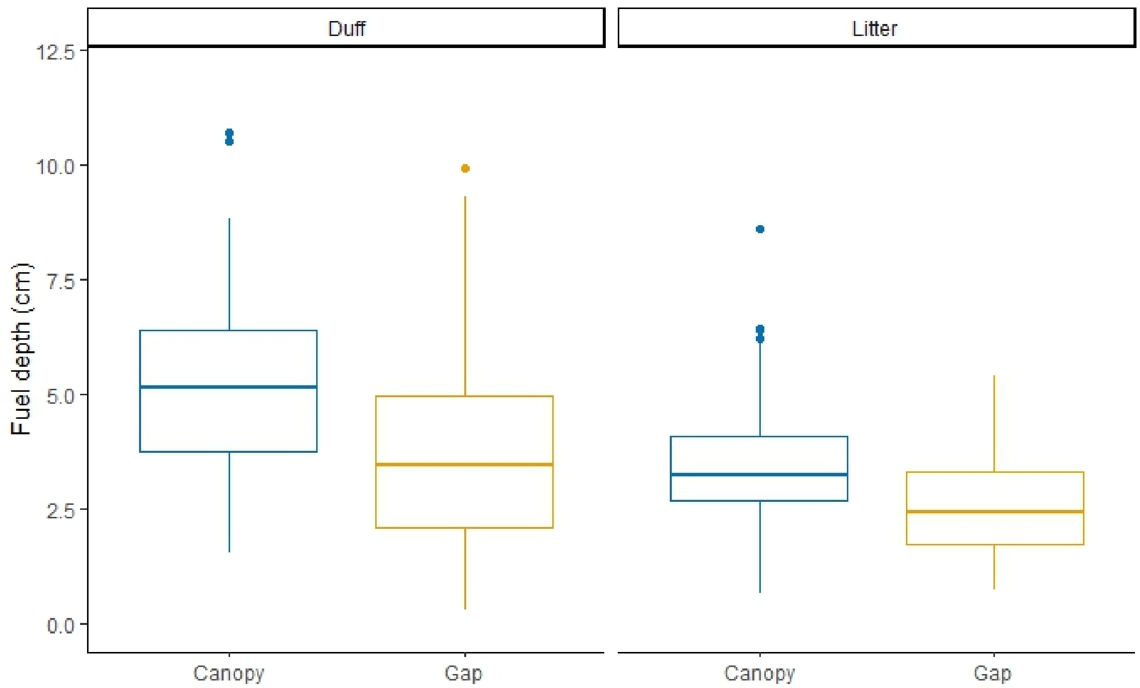

Figure 4. Average fuel depth (cm) for litter and duff under the first 3 m of the tree crown from tree base compared to depth in the nearest canopy gap.

Within-tree fine fuel variation was primarily associated with distance and direction from the tree bole (Table 3). Litter depth was best described by distance (P = 0.00015), where in all directions litter increased 35% from the base to 3 m. For duff depth, an interactive model with distance and direction was most explanatory (P < 0.00001), where in the downhill direction, depth increased 41% from the tree base to 3 m, but decreased 27% from the base to 3 m in the uphill direction (Figure 5). Candidate models for litter loading (n = 545) were not more descriptive than the null model. Duff loading was best predicted by an interaction between distance and direction ($P = 0.0017$) in a similar slope-influenced pattern as duff depth.

Fine woody fuel loading (1-100 hr) was primarily described by distance and direction (Table 3, Figure 6). One-hour fuels showed a 72% increase from the base to 3 m in the downslope direction, and an 8% decrease along the upslope transect for all species combined, although madrone lacked the uphill 1-hr fuel accumulation at the base compared to tanoak and black oak (Figure 6). The best model for ten-hour fuels was an interactive model with distance and direction ($P = 0.00034$) where fuels increased 98% from the base to 3 m downslope compared to 15% along the upslope transect. The best model for 100-hr fuel load included direction only ($P = 0.000188$), in which the upslope transect was 108% greater than the downslope transect (5.25 cm upslope, 2.58 cm downslope).

Table 3. Best models for within-tree fuel variation (fuel sample scale) for litter and duff depths (cm); litter, duff, 1-hr, 10-hr, and 100-hr fuel loading (Mg/ha). All models were linear mixed effects models with transect, tree, and site as nested random effects. P-values were estimated by comparing the model to the null model using anova. For litter load and duff density, the null models were most. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model.

Fuel metric	Model factors and interactions	Sample size (n)	R^2M	R^2C	P-value
litter depth	distance*direction	1303	0.020	0.291	0.00011
duff depth	distance*direction	1303	0.0270	0.272	<0.0001
litter load	null	545	0	0.0177	0.00311
duff load	direction*distance	545	0.0270	0.272	0.0017
1-hr load	species*distance*direction	1040	0.0515	0.584	<0.0001
10-hr load	direction*distance	1040	0.0258	0.257	0.00034
100-hr load	direction	1040	0.0191	0.103	0.00019
litter density	null	427	0	0.054	<0.0001
duff density	null	427	0	0	0.245
root density	direction	427	0.0500	0.127	<0.0001

Table 4. Mean depth (cm), loading (Mg/ha), and density (kg/m3) for each fuel component by species within 3 m of the tree base. Sample size (n) for litter and duff depth was 1303 and loading was 545; woody fuel loading was 1040 and density was 427.

	Depth		Load					Density		
Species	**Litter**	**Duff**	**Litter**	**Duff**	**1-hr**	**10-hr**	**100-hr**	**Litter**	**Duff**	**Roots**
Tanoak	3.59	5.43	16.36	42.83	2.85	4.91	4.93	759.97	86.33	1.44
Madrone	3.44	4.84	17.62	45.98	2.88	3.88	5.2	591.38	91.51	1.45
Black oak	3.77	5.81	14.59	52.95	3.06	4.71	7.02	514.73	84.35	1.18
All species	3.45	5.76	16.36	43.61	2.84	4.46	5.62	633.98	87.06	1.36

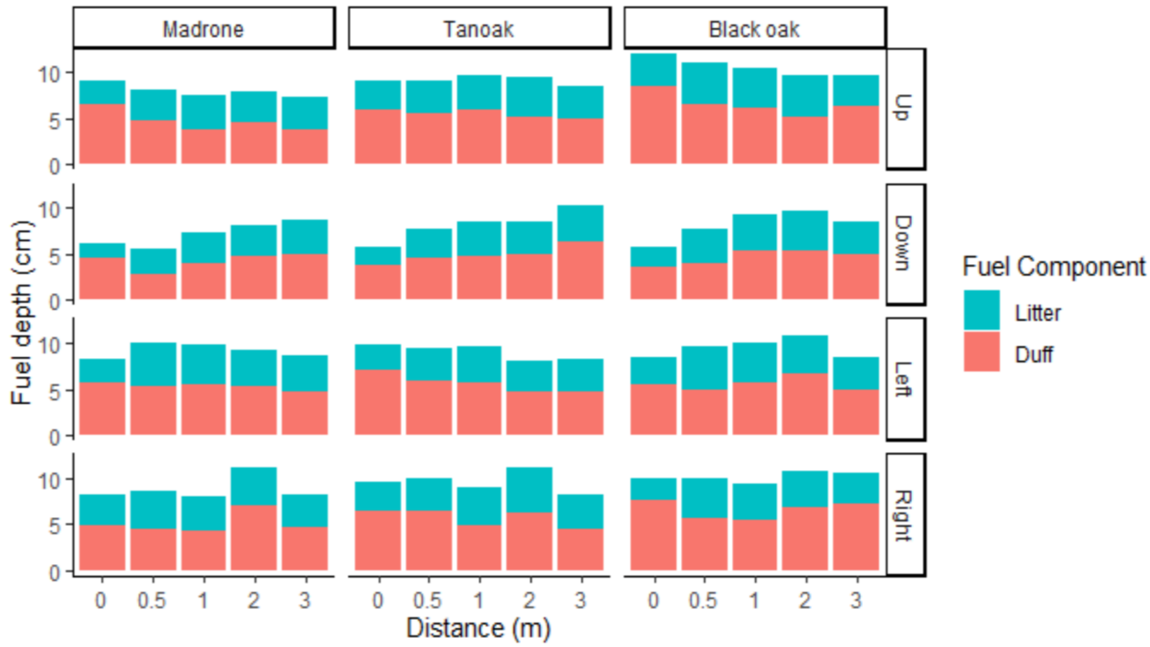

Figure 5. Fuel depth (cm) across all four directions (up, down, left and right facing upslope looking at the tree), and fuel sample distance from the bole (0, 0.5, 1, 2, and 3 meters) for litter and duff.

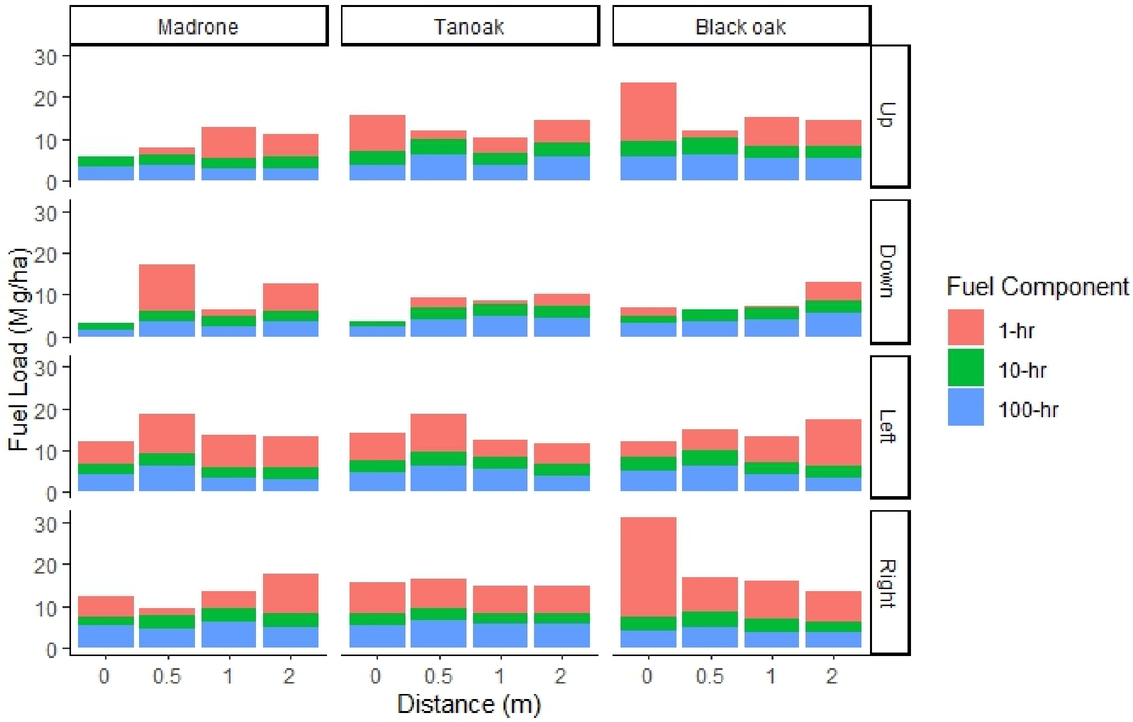

Figure 6. Woody fuel loading with respect to distance, direction and species. Distance metrics describe fuel loading along variable length transects where 0 = 0 – 0.5 m, 0.5 = 0.5 – 1 m, 1 = 1 – 2 m, 2 = 2 – 3 m.

<u>Root density</u>

Roots were found in 94% of duff samples, where root mass increased with duff depth ($P < 0.0001$, Table 5) and root density ranged from 0.0199 to 3.99 kg/m^3. The spatial distribution of root density was best described by direction ($P < 0.0001$) in relation to slope, where root density was 58% greater on the uphill side of the tree compared to the downhill transects. However, the additive model of direction and distance performed just as well as the direction only model ($P < 0.0001$), where roots increased just beyond the base of the tree to 0.5 m in all directions. A distinct root shadow within 1 m of the base in the downhill direction was 43% less than the average for the other tree directions within the same distance (Figure 7). The addition of species as a factor was not more informative than models including direction and distance.

Table 5. Duff depth to root mass equations for each species separately and all species combined, where the equation was forced through a y-intercept of zero: load=0+b_1 * depth; b_1 = slope coefficient, s.e.= standard error, R^2 = adjusted proportion of variation explained by the model with penalties for number of predictors added.

Species	n (samples)	b_1 (s.e.)	P-value	R^2
Tanoak	172	0.24 (0.035)	<0.0001	0.286
Madrone	114	0.42 (0.029)	<0.0001	0.653
Black oak	141	0.21 (0.019)	<0.0001	0.464
All species	427	0.27 (0.015)	<0.0001	0.431

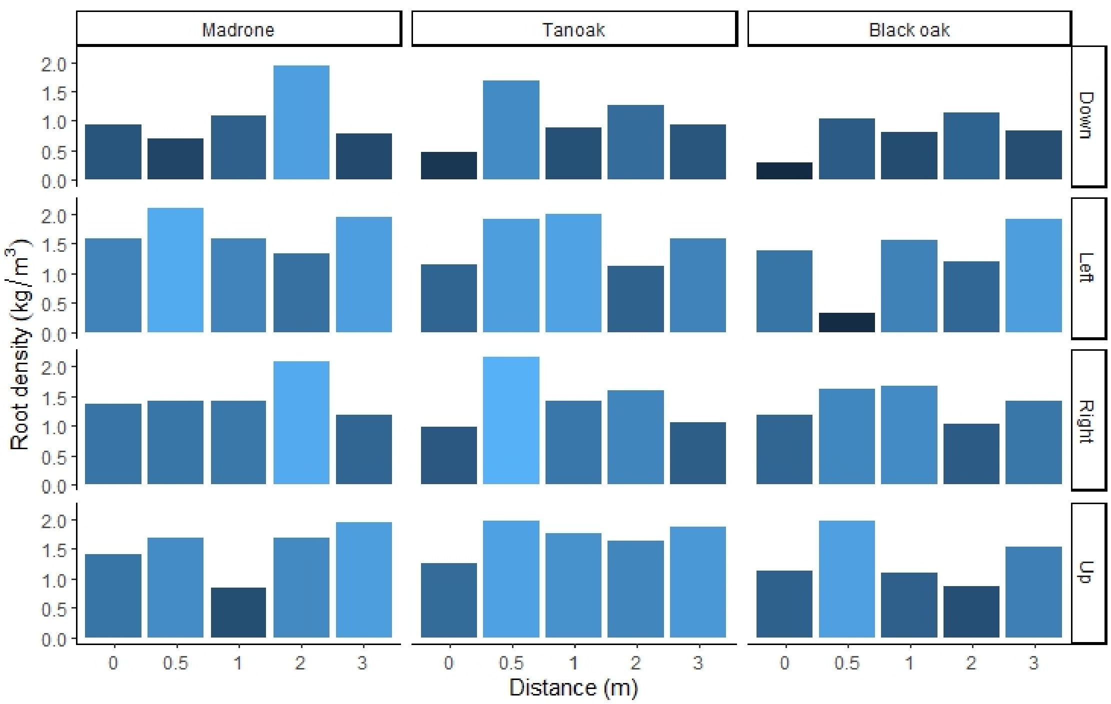

Figure 7. Root density (kg/ m3) where greater values are lighter shades of blue for all four directions (up, down, left, and right, facing upslope) and five distances from the tree base.

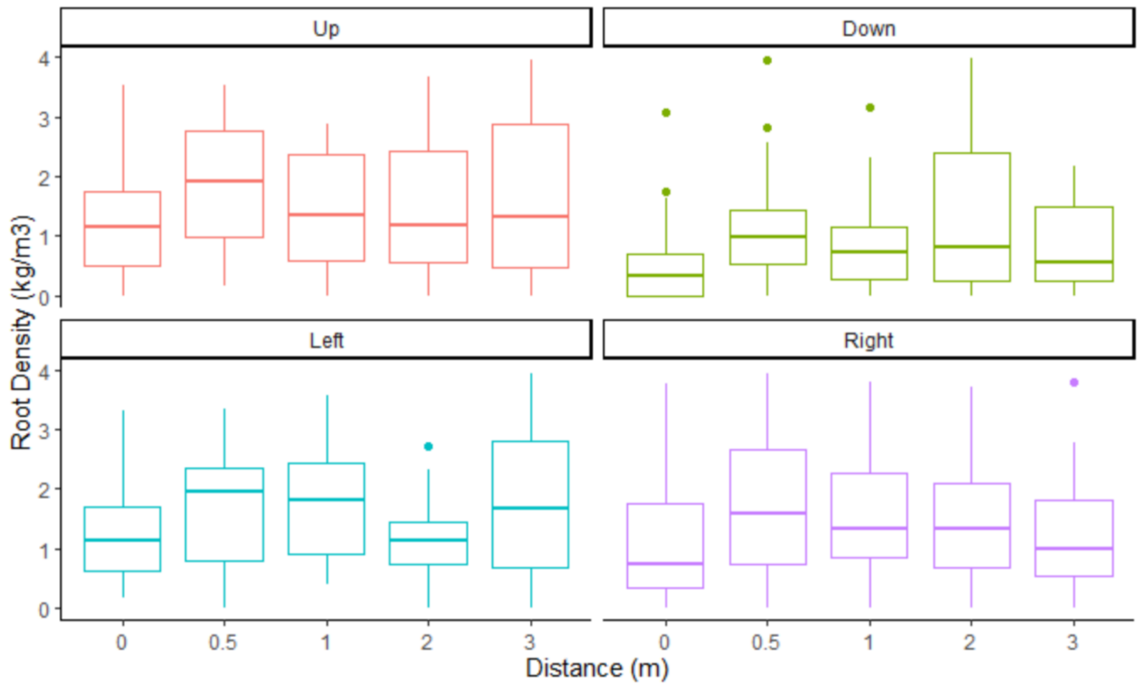

Figure 8. Root density (kg/ m3) in relation to distance and direction from tree bole facing upslope across all three species.

Among-tree fuels and root variation

Average fuel depth, loading, and root and duff density were described by crown dimensions, competition by Douglas-fir, tree size, and topography. An additive model with Douglas-fir basal area and slope described mean litter depth ($P = 0.000335$), where litter depth decreased with greater Douglas-fir encroachment and increased with slope (Figure 9). An additive model with Douglas-fir basal area, slope, and dbh was the best model for mean duff depth ($P < 0.0001$; Figure 10). For mean duff load, the most descriptive single factor was dbh ($P = 0.0124$), where larger trees were surrounded with overall lower duff load (Figure 11). Crown width perpendicular to the widest measurement was the most descriptive factor for both mean litter loading ($P = 0.0807$) and mean root density ($P = 0.0230$) (Table 6, Figure 11, Figure 15). Mean woody fuel loading appeared to be more influenced by tree and crown dimensions, where dbh was the best model for 1-hr fuel loading (P = 0.0395), and larger trees had lower fine fuel loading. The null model was best for 10-hr fuels, although the secondary model was total basal area of surrounding trees of all species (P = 0.16). Crown base height best described 100-hr fuel loading (P = 0.0604) and had a positive relationship, where greater fuel loading was associated with greater crown base height. Bulk density of duff was best described by the basal area of all species of surrounding trees (P = 0.0735).

Table 6. The best models for among-tree fuels variation due to tree-level factors. baPSME = basal area (m^2/ha) Douglas-fir, dbh = diameter at breast height (1.37 m), cw_perp = crown width perpendicular to the widest crown width, cbh = crown base height (m), total ba = total basal area of all surrounding species (m). The best model for 10-hr fuel loading was the null model. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model.

Fuel metric (mean)	Model factors and interactions	Sample size (n)	R^2M	R^2C	P-value
litter depth	baPSME+slope	117	0.101	0.101	<0.0001
duff depth	baPSME+dbh+slope	117	0.0596	0.0596	0.000335
litter load	cw_perp	115	0.0132	0.0132	0.0807
duff load	cbh	115	0.00783	0.00783	0.250
1-hr load	dbh	114	0.0264	0.312	0.0395
10-hr load	null	114	0	0	<0.0001
100-hr load	cbh	114	0.0307	0.0307	0.0604
duff density	total ba	115	0.0472	0.0472	0.0735
root density	cw_perp	115	0.0372	0.194	0.0230

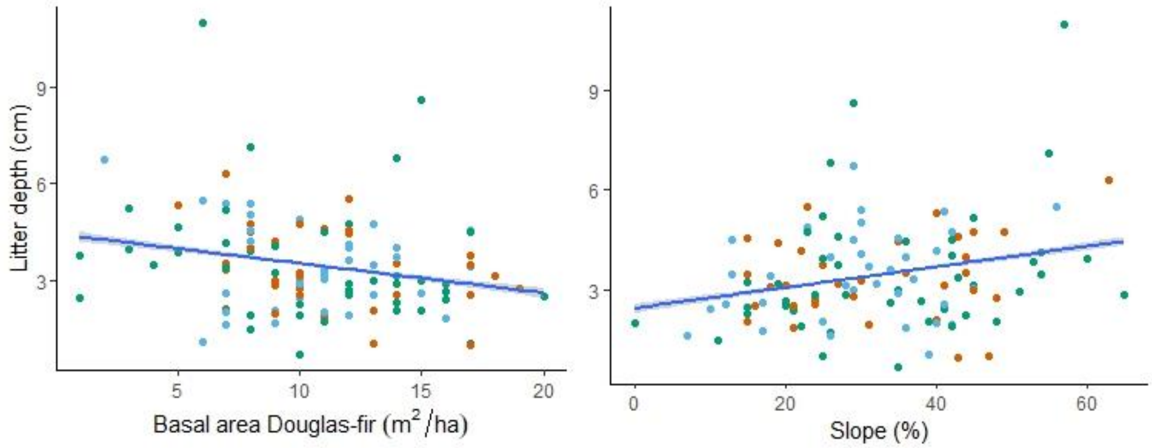

Figure 9. The best linear model for mean litter depth superimposed on data observations for additive factors, basal area Douglas fir (m2/ha) and slope (%).

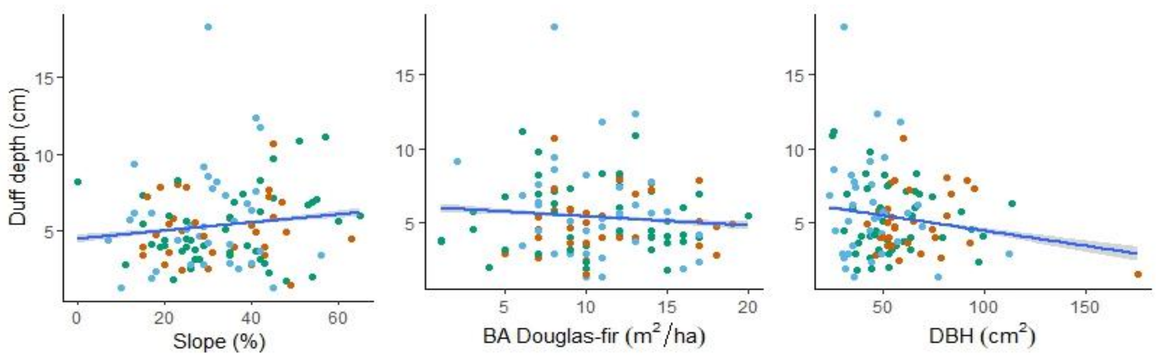

Figure 10. The best additive model for mean duff depth for among-tree factors: slope, basal area (BA) Douglas-fir, and diameter at breast height (dbh).

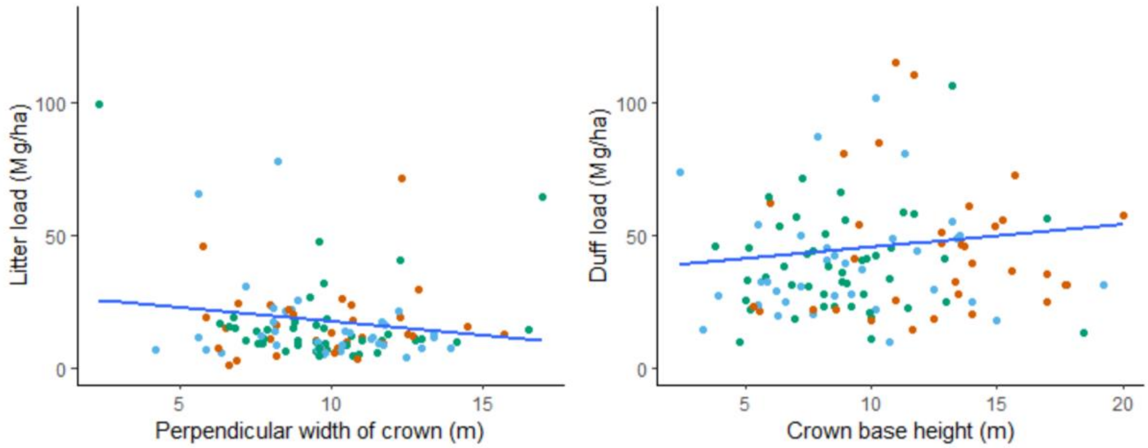

Figure 11. The best model for mean litter load where load decreased with increased perpendicular width of the crown (left) and increased with greater crown base heights (right).

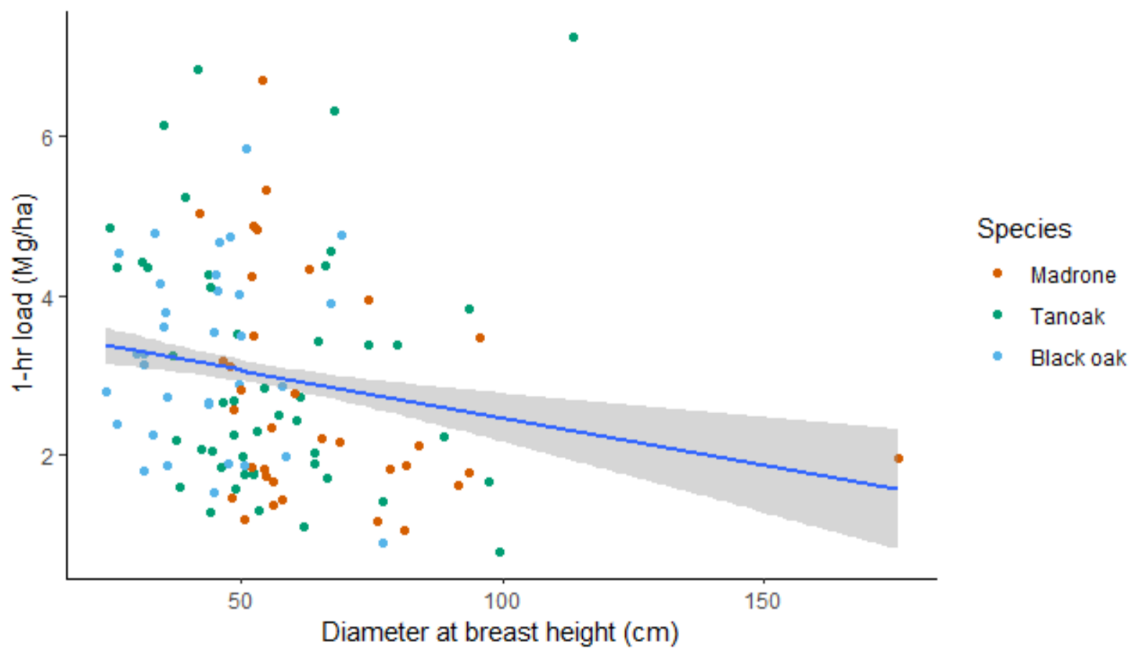

Figure 12. The best mixed effects linear model for mean 1-hr fuel load was diameter at breast height (cm), where larger trees rendered lower 1-hr fuel loads.

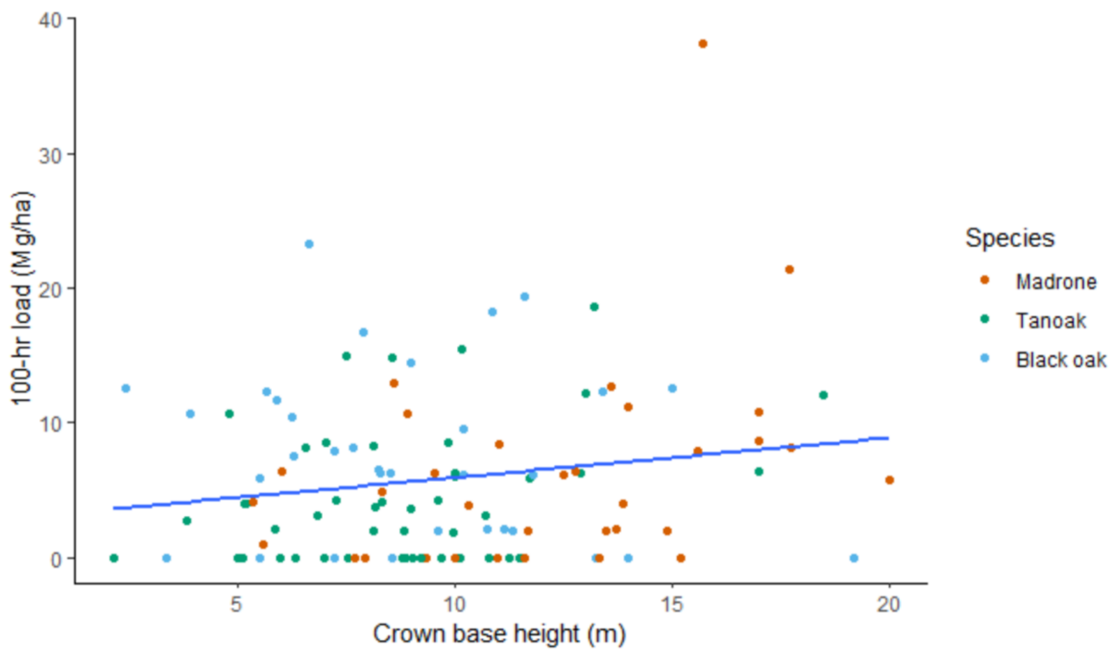

Figure 13. The best linear mixed effects model for 100-hr fuel load where 100-hr fuels increased with greater crown base height.

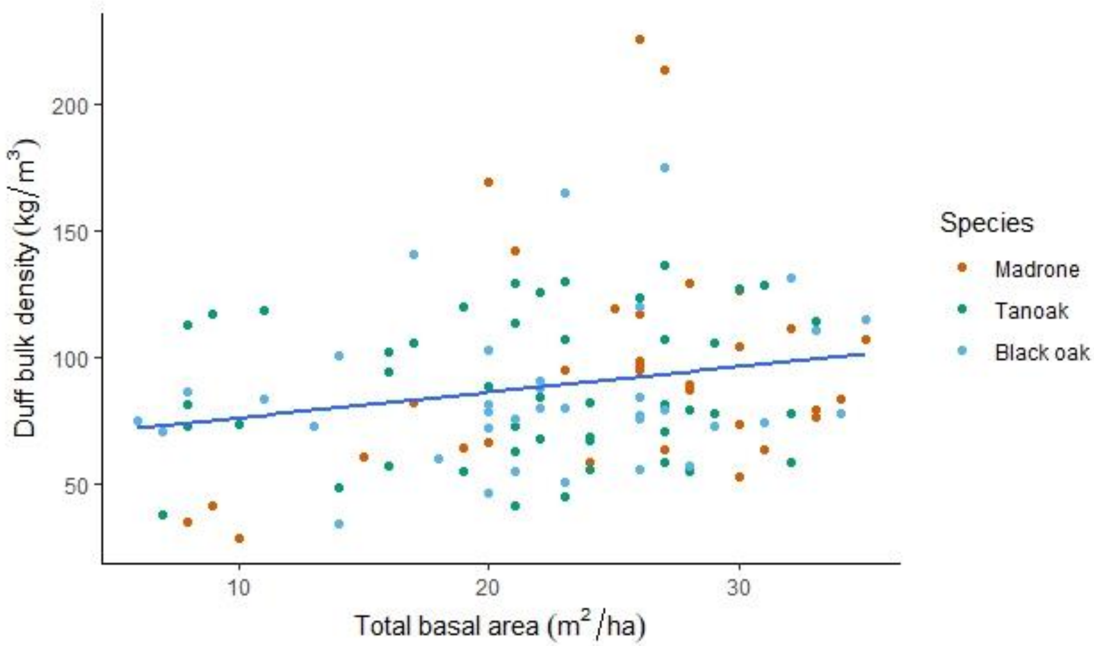

Figure 14. The best linear mixed effects model for bulk density of duff (kg/m^3) for total basal area of all surrounding species of trees (m^2/ha).

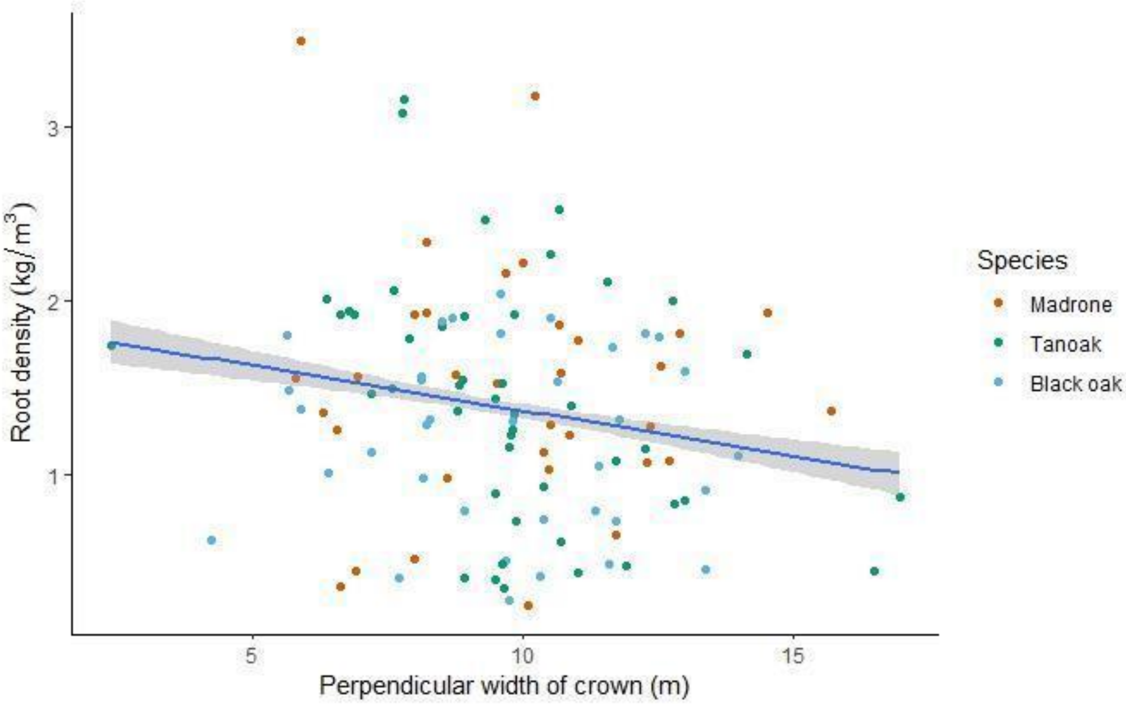

Figure 15. The best linear mixed effects model for mean root density where root density decreased with greater perpendicular widths of crown (m).

Discussion

This study broadens fuels science beyond conifers of commercial importance to include hardwood tree species of Indigenous cultural interest with the intention of assisting tribal managers to mitigate post-fire legacy hardwood mortality. While basal fuel mounding has been documented and informed mitigation efforts for legacy conifer species (e.g., Hood 2007, DiMario et al. 2018), this is the first analysis to characterize fuels surrounding legacy hardwoods. These findings suggest that fuels around legacy hardwood trees vary spatially at the tree scale with distance from the bole in relation to the slope position, and that tree and site-level factors related to management and topography contribute to accumulation patterns in the region.

Depth-to-load relationships

Positive depth-to-load relationships were strongest for duff, also supported by previous research (vanWagtendonk 1998, DiMario et al. 2018). Importantly, relationships varied among species, where black oak displayed the largest coefficient and variance explained ($b_1 = 8.84$, $R^2 = 0.51$, $P < 0.0001$), followed by madrone ($b_1 = 6.09$, $R^2 = 0.35$, $P < 0.0001$), and then tanoak ($b_1 = 4.36$, $R^2 = 0.27$, $P < 0.0001$); (Table 2). Further, it should be noted that models including species were not as informative compared to the simpler depth-only model for duff or litter loading. Compared to previous research on 19 conifer species (mean duff $b_1 = 1.750$, $R^2 = 0.881$; van Wagtendonk et al. 1998), our combined data for three hardwood species produced a 270% steeper relationship for duff (mean duff $b_1 = 6.47$, $R^2 = 0.38$, $P < 0.0001$). This potentially suggests greater bulk densities for hardwood species compared to conifer species. The variance explained for our models was relatively low, however, suggesting other unaccounted for factors are important. Poor model performance for litter depth-to-load may be due to the inclusion of woody fuels in some litter samples.

Within-tree fuel spatial variation

Combined litter and duff depth was 40% greater under the canopy within the first 3 m of the tree bole (8.90 cm) compared to canopy gaps (6.35 cm). Average within-tree litter and duff depth for hardwoods was 9.21 cm, which is less than the 11 to 14 cm range of fuel depths observed under sugar pines (*Pinus lambertiana*) in the Klamath region (DiMario et al. 2018), and significantly greater than observations on conifers in the Sierra Nevada, with an average of 0.68 cm litter and 4.61 cm duff depth (van Wagtendonk et al. 1998).

Among fuel types, duff was the most significant contributor to the fuel bed compared to litter and woody fuels, especially at the uphill base of the tree. Duff bulk density for sugar pine (54.16 - 80.72 kg/m^3; DiMario et al. 2018) as well as Jeffrey pine (*Pinus jeffreyi*) (69.5 kg/m^3) and white fir (*Abies concolor*) (66.1 kg/m^3; Banwell & Varner 2014) in the Lake Tahoe Basin were less than our findings overall (84.35 – 91.51 kg/m^3). van Wagtendonk et al. (1998) found a wider range among conifers (34.86 -981.82 kg/m^3) and a much greater overall mean of 177.37 kg/m^3, closer to the average duff bulk density of 131 kg/m^3 observed for sugar pine and Jeffrey pine in the Sierra Nevada (Bartley 2023). Duff accumulations at the base of conifer species can contribute to bole cambium damage during low intensity fire due to lethal heating during long duration smoldering fires (Ryan

& Frandsen 1991, Swezy & Agee 1991, Stephens & Finney 2002, Varner et al. 2007). Further examination is needed to relate duff accumulation impacts to hardwood tree species damage following prescribed fire.

Previous research has documented changes in basal tree fuels in relation to distance from tree. In our study, litter followed the trend of decreasing fuels with distance from the tree, where depth decreased 35% from the base to 3 m. In similarly dense mixed stands, a comparable 30% decrease with distance from 0.5 m to 2 m and 50% within 5 m of the tree base was observed for Jeffrey pine and white fir (Banwell & Varner 2014). This contrasts with a more dramatic decrease with distance from the bole in open sugar pine (*Pinus lambertiana*) stands (95% decrease of fermentation layer); (DiMario et al. 2018). In the Sierra, a 67% reduction with distance (Hille & Stephens 2005) was very similar to 65% decrease in duff depth between 30 and 210 cm from tree base also in mixed stands for ponderosa pines (Ryan & Frandsen 1991).

While previous studies have established that within-tree fuels vary with distance from tree bole, we provide the first known evidence that direction in relation to slope is also important. Results from this study confirm observed trends of fuel accumulation on the uphill base of the tree with a fuel shadow just below the tree on the downhill side. We found that duff decreased 27% in the upslope direction within 3 m and increased 41% downhill direction. Uphill base accumulation may be due simply to gravity on a slope, where falling fuels slide or roll once hitting the forest floor before stopping on a stabilizing feature, such as a tree, log, rock, or berm. In contrast, the trunk may consequently shield the downhill base of the tree from falling or sliding fuels. In addition to initial fuel deposition, sidehill trails utilized by animals and people are observed to occur on the uphill side of especially large legacy hardwood trees, and foot traffic of all kinds may further combine and compress fallen ground fuels to the tree bole. Findings suggest that in areas with substantive slope, direction in addition to distance may be important to consider in future research and management efforts.

Compared to previous studies on legacy conifer trees (Banwell & Varner 2014, DiMario et al. 2018), fuel mounding on legacy hardwood trees was somewhat present, but not as pronounced. Species variations in leaf morphology (Stephens et al. 2004), chemistry (McClaugherty 1985), and increased hardwood litter contributions to overall decomposition (Masuda et al. 2022) could explain the shallower and irregular mounding observed in the legacy hardwoods of this study compared to conifers in previous studies. Fine root presence and associated mycorrhizal fungi may accelerate litter decomposition (Lang et al. 2021). Crown characteristics and structure could also be responsible for mounding differences between conifers and hardwoods (Fry et al. 2018). Apically dominant, cone-like conifer crowns may concentrate fuels at the tree base, whereas hardwood trees typically have more of an open and horizontally branching crown (Niemiec et al. 1995). Legacy hardwoods have also experienced crown reduction and damage due to encroachment (Cocking et al. 2017). This may reduce the degree to which legacy hardwoods contribute to their own basal fuels.

Fuel depths, loading, and densities did not vary significantly between legacy hardwood species. While some studies have found species differences (van Wagtendonk et al. 1998, Stephens et al. 2004, DiMario et al. 2018, Bartley et al. 2023), others (Banwell

& Varner 2014, Bartley et al. 2023) did not find strong species trends. Similar to forest stands studied in Lake Tahoe Basin (Banwell & Varner 2014), the areas we studied were dense mixed species stands (BA/ha 28-60 m^2/ha and 19-51 m^2/ha, respectively) with substantial contributions of fuels from surrounding species. This differs from the pure stands that van Wagtendonk et al. (1998) and Stephens et al. (2004) sampled, where fuel deposition might more easily be correlated to individual trees. It is possible that the effect of individual hardwood species in this study may be dulled by the deposition of Douglas-fir in these highly encroached stands, which was the most abundant tree, accounting for 26% of total basal area of encroachment.

Root density

Fine and coarse roots were found in the majority of duff samples, and were highly correlated with duff depth as observed in previous research (Swezy & Agee 1991). Roots were greatest in uphill duff accumulations, and first increased, then decreased with distance from tree bole in a slight mounding pattern, comparable to Olsthoorn's (1999) observations in Douglas-fir stands. Bartley (2023) found lower densities (0.386 kg/m^3) compared to our findings (1.36 kg/m^3) in the organic (O) horizon, possibly due to different moisture levels and climate factors, although I should note that they excluded coarse roots (2-5 mm) from analysis. Among-tree root density variation was negatively associated with larger canopy widths perpendicular to the widest length. Bartley (2023) found a weak but opposite relationship between crown health (leaf area index) and increased fine roots, suggesting variation and complexity of fine roots due to overstory health and composition. Reduced hardwood canopy with increased roots aligns with Vogt et al.'s (1987) findings of greater fine roots in lower productivity sites, with greater contributions from hardwood roots following canopy closure by Douglas-fir without increased angiosperm contributions to the canopy. Contributing to uncertainty, we did not separate fine (0-2 mm) from coarse (2-5 mm) roots, nor did we positively identify root species. The vulnerability of these important feeder roots to damage and consumption during fire (Swezy & Agee 1991) is another possible factor contributing to legacy hardwood mortality that warrants deeper examination.

Figure 16. Canopy of legacy madrones and black oaks with high Douglas-fir encroachment. Photo credit Stormy Staats courtesy of the Karuk Tribe and MKWC.

Among-tree fuel spatial variation

Douglas-fir encroachment was negatively correlated with mean tree litter and duff depth, suggesting greater fuel density. Indeed, duff bulk density had a positive relationship with encroachment (total basal area, m^2/ha), where more encroached trees experienced greater bulk densities. Douglas-fir has small evergreen needles, contributing to limited, shallower and more compact leaf and duff layers (van Wagtendonk et al. 2010). Douglas-fir has some of the highest observed bulk density among conifer species (981.83 kg/m^3; van Wagtendonk 1998). Increased bulk density has been shown to increase the residence time of fire and bole damage (Ryan and Frandsen 1991, Varner et al. 2009), and may be considered a possible contributing factor to legacy hardwood mortality and damage (Hood et al. 2018). This increased litter and duff density could also diminish the positive role of fire in hardwood groves because it is often harder to ignite under prescribed fire conditions. It would additionally be interesting to attempt a similar fuels characterization around pure stands of legacy hardwoods compared to these highly encroached mixed conifer stands.

We found that duff depth and 1-hr fuels were greater under smaller hardwood trees, counter to previous research that associated larger duff depth with larger trees (DiMario et al. 2018). One interpretation for smaller dbh and greater fuel depth is that the smaller, typically younger trees established more recently in available canopy openings where they may have greater, but limited light and more vigorous crowns and leaf deposition. Compared to legacy trees that have crowns often extended well beyond the bole, younger tree crowns were often fuller, more vertical, and positioned directly above the tree bole. We did not account for solar radiation at the stand or tree level, which could potentially inform the presence of smaller trees, and hardwood tree deposition.

Greater among-tree fuel depth on steeper slopes points to the micro-topographic importance of tree position on the slope, which is counter to our expectations. Variance inflation factor (VIF) and correlation tests did not suggest collinearity between slope and other among-tree site and tree factors. Previous research has observed greater fuels on flatter slopes among conifers (Bartley 2023), presumably where fuels would accumulate directly under the tree crown. On a slope, fuels may slide downslope due to gravity and disturbance, and clump along side-hill trails, often on the uphill base of older trees. Future research on hardwood basal fuels may account for slope, fuel catching features (such as trees and trails), tree lean and associated position of the hardwood tree crown in relation to the tree bole, in order to better understand fuel accumulation dynamics.

Management implications

High amounts of duff depth, loading, and density surrounding the base of legacy hardwood trees could be contributing to post-fire tree mortality (Swezy & Agee 1991, Stephens & Finny 2002, Varner et al. 2007). Basal duff depths and high duff loading may warrant manual duff reduction prior to prescribed fire, although it should be noted that remediation efforts have been met with varied success (Swezy & Agee 1991, Noonan-Wright 2010, Nemens et al. 2019). Fuel accumulation trends suggest that targeting fuels on the uphill side of the tree may focus overall tree fuel reduction. Additionally, fine roots in duff may be mitigated by prescribed burning under higher duff moistures (Varner et al. 2007). Increased bulk density with greater encroachment confirms a need to reduce Douglas-fir competition from around legacy hardwood trees to restore traditional fire regimes. Harwood litter deposition may burn quickly and more often (Engber & Varner 2012) without substantially heating or damaging roots or bole cambium compared to the much less flammable Douglas-fir litter deposition. Nevertheless, management techniques should be considered within the complex social context of the problem for greater likelihood of success and as a matter of environmental justice.

High rates of fuel accumulation and Douglas-fir encroachment are direct results of the interruption of Karuk peoples' relationship with hardwood groves by the settler state (Vinyeta 2021). Solutions for restoration should be understood within the socio-political context of land dispossession and criminalization of Indigenous stewardship that has created the problem (Marks-Block & Tripp 2021) if they are going to be meaningful and lasting. In the relatively short time that the USDA Forest Service has asserted management authority over Karuk lands, a complete reversal of management paradigms and experimentation has had cascading negative socio-ecological impacts (Karuk Tribe 2019, Vinyeta 2021), with legacy hardwood tree neglect arguably one of them. Karuk ceremonial leader, Leaf Hillman, explains considerations for legacy hardwood restoration moving forward:

> *The Forest Service can't just take our traditional knowledge [use of fire] and apply it themselves to these trees because they don't believe in the spiritual dimensions of management. Leaving out spirituality and severing people-plant-animal relationships has resulted in grave neglect. They need us to do the applying with care and understanding of the importance of reciprocity with these trees as spirit beings* (pers. comm., July 22, 2023).

Leaf and other Karuk Cultural Practitioners understand that the interrelationships between people, plants and animals should be centered in management, and not merely reduced to fuel reduction objectives.

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CHAPTER 2. PRESCRIBED FIRE LEGACY HARDWOOD MORTALITY INVENTORY

Abstract

Interruption of Indigenous stewardship has resulted in hardwood decline along what is now known as the middle Klamath River in northern California, related to adverse effects to Tribal food sovereignty and community wellbeing. Limited groves of hardwood trees have persisted, despite colonial management regimes in favor of timber species. These survivors of a "legacy" of Indigenous stewardship are highly valued by the Karuk and neighboring Tribes for a myriad of culturally beneficial ecological associations and sources of traditional staple foods. Prescribed fire following over a century of fire exclusion has resulted in recent unanticipated mortality of legacy hardwood trees, warranting the need to better understand and prevent legacy hardwood mortality. I quantified post-fire legacy hardwood mortality with tree and site characteristics in prescribed burn areas for tanoak (*Notholithocarpus densiflorus*), California black oak (*Quercus kelloggii*), and madrone (*Arbutus menziesii*) using a generalized linear mixed effects (GLMM) model analysis. Post-fire legacy hardwood mortality was estimated in six burn units (burned 2017-2019) using four to six fixed area transects (1000 m^2), and were compared to six representative unburned units. Legacy hardwood size ranged from 25 to 186 cm diameter at breast height [dbh], with a median size of 39 cm dbh. An estimated 43% of all trees and 63% of dead trees had pre-existing fire scars. Stand-scale mortality rates were greater in prescribed burned areas (18%) than controls (13%), but were not statistically significant ($P = 0.735$) and were comparable to observed rates of mortality in the region. Tree-scale

mortality due to treatment varied among species ($P < 0.0001$), where black oaks died at the highest rates and were the most sensitive to prescribed fire (29% prescribed fire, 13% control). In contrast, tanoak had the same mortality rate between treatments (9% for prescribed fire and control; $P < 0.0001$). Tree scale analysis using generalized mixed effects modeling suggests that an additive model including scar width/dbh ratio and species ($P < 0.0001$) were the strongest predictors of hardwood tree mortality, primarily driven by the presence of large pre-existing fire scars among madrones. These results provide important insights into the factors related to undesired legacy hardwood mortality following prescribed fire with implications into possible mitigation efforts that warrant further Indigenous-led investigation to retain legacy trees.

Introduction

Indigenous peoples have managed oak woodlands in lower montane regions of what is now referred to as the Klamath Mountains since time immemorial with frequent low-intensity fire (Anderson 2018, van Wagtendonk et al. 2018). The application of frequent fire is evidenced by traditional knowledge and surviving legacy trees, and confirmed by fire scar and charcoal records (Skinner et al. 2018, Knight et al. 2020). For the Karuk and other California tribes, hardwood trees have multidimensional cultural importance for food sovereignty and community wellbeing (Karuk Tribe 2019, Norgaard 2019, Sowerwine et al. 2019). Surviving trees from a historical legacy of Indigenous stewardship are especially revered, and for good reason: a legacy tanoak (preferred acorn and traditional staple food in the region) has been estimated to produce up to 450 kg of acorns annually, while a mature tree 30-40 years old will produce an average of 57 kg per year (Baumhoff 1963, Bowcutt 2015). Klamath River Jack explained the importance of annual burning in acorn groves in his 1916 letter to the Forest Service: “Indian burn every year just same, so keep all ground clean, no bark, no dead leaf, no old wood on ground, no old wood on brush, so no bug can stay to eat leaf and no worm can stay to eat berry and acorn. Not much on ground to make hot fire so never hurt big trees, where fire burn. Now White Man never burn; he pass law to stop all fire in forest and wild pasture” (Jack 1916).

Figure 17. Cultural Practitioner displays tanoak acorns gathered from under a surviving legacy tanoak tree following prescribed fire. Photo credit Stormy Staats, courtesy of the Karuk Tribe and the Mid Klamath Watershed Council.

Fire exclusion enforced by the Weeks Act of 1911, aligned with state-sanctioned genocide, ongoing settler colonialism, and the imposition of resource-extraction land management paradigms on Karuk lands and people (Norgaard 2019, Vinyeta 2022) has resulted in a complete restructuring of forests in favor of conifers and a reduction in the human use of fire from the ecosystem (Knight et al. 2020). This socio-ecological shift has had numerous ongoing adverse effects on Karuk food sovereignty and community wellbeing (Norgaard 2004, Halpern 2016), and is inextricably linked to threatened ecological integrity of an exceptionally biodiverse landscape (Whitakker 1960, Wallace 1983, Norgaard 2020, Skinner et al. 2018).

Hardwoods have been under-valued in the capitalist socio-economic management system imposed on Karuk lands since colonization (Rossier & Tripp 2019, Norgaard 2020). The destruction of traditional foods including acorn trees has been documented as a strategy of Indigenous genocide and forced assimilation (Madley 2016, Streamer 2018).

Often considered “valueless species” in colonial forestry regimes, hardwoods have been subject to removal, herbicide application, and replacement by timber species via planting and fire suppression (Bowcutt 2015, Vinyeta 2022). After more than 100 years of management by the USDA Forest Service, forests in the region have densified to include three times more trees now than in the 1880s, with Douglas-fir (*Pseudotsuga menziesii*) as the primary culprit (Knight et al. 2020). During this time, the estimated presence of oaks in the region has decreased by half. For the purpose of this investigation, surviving older and larger trees that have persisted from a legacy of Indigenous management and subsequent colonial forestry regimes are hereby referred to as “legacy trees”.

The Karuk Tribe has made significant gains toward revitalizing fire practices on Karuk land through collaborative stewardship (Oliver 2019, Marks-Block & Tripp 2021). Examples include the Klamath River and Karuk Women’s+ Prescribed Fire Training Exchanges (TREX), which have hosted broadcast burning events since 2014 until the present. Contrary to cultural objectives to benefit traditional foods, fibers and medicines; some prescribed burns on Karuk lands during TREX burns have resulted in undesired legacy hardwood tree mortality following even low intensity fire (Tripp 2015). While post-fire tree mortality is an important ecological process (Franklin et al. 1987), the rate of hardwood tree mortality is elevated due to climate change and fire suppression conditions and Karuk managers would prefer if mortality was mostly limited to encroaching Douglas-firs (Karuk Tribe 2010, Karuk Tribe 2019, Harling & Tripp 2014). The Tribe and partners are seeking to understand the phenomenon of legacy hardwood tree death under low to moderate prescribed fire intensity to preserve their cultural heritage in the remaining legacy hardwood oaks and madrones.

Altered fire regimes can cause undesired post-fire mortality due to a number of co-occurring direct and indirect factors (Hood et al. 2018). Post-fire tree mortality has been associated with characteristics relevant to fire-adaptation in trees, including bark thickness (Jackson et al. 1999), litter flammability, crown structure, and crown base height (Hood et al. 2018). Mortality has also been linked to fire severity and damage metrics, such as, post-fire bole char and scorch height/volume (Van Wagner 1973, Thies et al 2008). Although mortality has been directly associated with fire severity, high fuel accumulations under low intensity fire have been associated with tree death (Swezy & Agee 1991, Stephens & Finny 2002).

Figure 18. Legacy madrone tree just days after prescribed burn during Klamath River TREX at one of the study sites. Photo credit Stormy Staats, courtesy of the Karuk Tribe and the Mid Klamath Watershed Council.

One possible mechanism of legacy tree vulnerability to fire may be the presence of sometimes extensive, pre-existing fire scars and cavities. Hardwoods and other trees respond to fire-caused stem injury through woundwood formation and compartmentalization to limit further damage and decay (Smith & Sutherland 2001). Legacy hardwoods are known for persisting many years with large scars or hollowed out cavities, thereby providing wildlife habitat (Mazurek & Zielinski 2004). Despite adaptations, Karuk fire practitioner Bill Tripp has pointed out that excessive accumulation of rot on scar surfaces and cavity fuel build-up may render legacy hardwoods vulnerable to even low intensity fire (2015). Post-wildfire mortality was recently correlated with fire scar presence on legacy giant sequoias (*Sequoiadendron giganteum*); (Shive et al. 2022). Kinkead et al. (2017) found that hardwood trees that died following prescribed fire had scars that were six times larger than surviving trees, but research directly examining this mode of mortality has not received adequate attention.

Scarred legacy trees experiencing excessive competition due to the prolonged absence of fire may exacerbate tree vulnerability. Competition from shade-tolerant, fire-intolerant conifers such as Douglas-fir and other conifers has caused significant stress on legacy hardwoods, contributing to their lack of resiliency to fire. Pre-fire growth variability caused by climatic variations and/or competition, has been linked to post-fire tree mortality (van Mantgem et al. 2003, Kane & Kolb 2014). Conifer encroachment occurs in phases of establishment to overtopping within 100-150 years, after which hardwood mortality is often observed (Hunter & Barbour 2001, Cocking et al. 2012, Cocking et al. 2014, Cocking et al. 2017). While Douglas-fir are relatively fire-intolerant at juvenile stages (Engber &

Varner 2012), they can become fire resistant with maturity and thicker bark (Hood et al. 2018). Consequently, low severity fire in mixed mature stands has a negligible effect on mature Douglas-fir, while further weakening hardwoods (Cocking et al. 2012). The more mesic conditions created by conifer encroachment (Kane 2021), may indeed increase the speed of rot on cavity surfaces (Boddy 2001), a suspected factor in tree death. While previous research on fire-related tree death may help to explain legacy hardwood mortality, current knowledge is largely biased towards conifers with limited attention given to the hardwood species in the Klamath region.

This project was intended for the benefit of Tribes and cooperating agencies to protect their highly valued living cultural resources. I hypothesized that legacy hardwood scar basal scar presence and size were significantly correlated with mortality. I have focused my analysis on addressing the following objectives: 1) quantify legacy tree mortality at the stand scale in previously prescribed burned areas; and 2) determine the role of fire scar cavity and other tree level factors associated with legacy hardwood mortality. Information from this study will provide a clearer understanding of legacy hardwood mortality trends following prescribed fire in the region that can inform adaptive management strategies to retain these culturally valuable trees.

Materials and Methods

Study Site

This research was centered in Karuk Aboriginal Territory near the northern California town of Orleans. Study areas along the middle Klamath River corridor at moderate elevations (<600 m) were historically culturally burned at frequent intervals prior to settler colonial invasion, the genocide of peoples and cultures, and fire suppression policies interrupted Indigenous stewardship in the mid-19th century. The river corridor is well known for its steep slopes and complex topography, contributing to a wide variety of microclimates (Sherriff et al. 2022). The region is characterized by a Mediterranean climate with 130 cm average annual precipitation, falling predominantly between November and April (Western Regional Climate Center 2019, Sherriff et al. 2022). January is the coldest month with an average minimum temperature of 1°C, and July is the hottest month with an average maximum temperature of 33°C (Western Regional Climate Center 2019). Climate change studies suggest a trend away from long-term averages, including increased annual temperatures and precipitation variability (Butz et al. 2015).

Historically, the lower elevation sites close to the river and villages were dominated by hardwood trees such as tanoak, California black oak, Pacific madrone, and Oregon white oak (*Quercus garryana*), with scattered conifers such as ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), and Douglas-fir (Skinner et al. 2018, Knight et al. 2020). Currently most historic hardwood groves in the region are in advanced stages of encroachment by Douglas-fir (Karuk Tribe 2019). Surface to substratum soils to which trees of interest are adapted are predominantly reddish-brown gravelly clay and silt loam owing to serpentinized metamorphic parent material (Foster & Lang 1982).

Field Methods

My field crew and I conducted the post-fire inventory in six prescribed fire burn units burned in the fall 2017 and 2019. Prescribed fire sites had no record of fire since fire suppression policies. Prior to broadcast burning, sites were treated with manual fuels reduction (stems <6 inches) and pile burning to varying degrees, often only within 50’ of the perimeter. During prescribed burns, prescription parameters for weather ranged 10-29° C for temperature, <1.6 kph sustained winds, 25-89% relative humidity, and 7-15% moisture for 10-hr and 6-12% for fine dead fuels. Fire behavior parameters included an allowable range of flame lengths (0.3 – 3.4 m) and rates of spread (10 – 1891 m/hr) with a combination of heading, backing and flanking firing techniques. Study sites contained a minimum density of 50 legacy hardwoods per hectare of all three species, and depending on the size of the unit, we established between four and six 10 m × 100 m fixed-area transects to represent unit variation. Since the size limit for legacy hardwood trees is not well understood, all hardwood trees 25 cm diameter at breast height (dbh 1.37 m) or larger were included to capture the impact of fire on a broad range of tree ages and sizes. To account for background mortality rates, an equal amount of control unburned units were sampled either directly proximal to each burned unit or in comparable stands (similar density, slope, aspect, size distribution of legacy hardwoods, and competition).

Table 7. Sites sampled for legacy hardwood mortality with mean values and ranges in parentheses. Total hardwoods sampled includes 953 trees in prescribed burns and in controls.

Sites	Size (ha)	Elevation range (m)	Year burned	Aspect	Slope (%)	Basal area (m^2/ha)	Trees sampled (n)
Bacon Flat	14	326-411	2017	SW	22 (5-35)	32 (8-48)	212
White Oak	4	323-349	2017	S	12 (6-15)	12 (0-24)	105
Pearson	6	213-302	2017	W	33 (19-50)	4 (0-32)	95
Bull Pine	6	561-637	2019	S	15 (0-43)	40 (24-62)	202
Lacy	11	613-747	2019	SE	29 (12-74)	28 (4-66)	185
Szabo	4	181-271	2019	ENE	48 (35-57)	18 (12-24)	154

Transects were drawn onto unit maps before entering the field and distributed to capture variation in elevation, aspect, tree species and density. We inventoried all hardwoods >25 cm dbh within the transect area, where tree species, size (dbh), basal scar characteristics and mortality status was coded following Thomas et al. (1979). All topkilled trees were classified as dead, regardless of resprouts, because the legacy tree growth form is the subject of this study rather than genetic individuals. These codes outlined seven statuses, in which four were most common: alive and thriving (1), alive and declining (2), topkilled with some fine branches and intact bark (3), topkilled with no fine branches and loosening bark (4) (Appendix A). The basal fire scar and cavities were characterized by measuring the scar height (ground to top), maximum basal width, and horizontal depth from the outer bark of the tree to the back of the cavity. Field scar metrics were used to estimate scar size in several secondary scar metrics. Estimated scar metrics include width to dbh ratio (width/dbh), surface area (assuming a triangle shape, (height x width)/2), and volume (assuming a pyramid shape, (height x width x depth)/3). An ocular estimate of percent scar surface rot and char was quantified in increments of 5% to characterize the observed complexity of a scar's vulnerability to and impact from fire. Often cavity surfaces had extensive and complex layers of both exposed rotten wood as well as blackened charred surface from historic or recent prescribed fires, so cumulative surface rot and char estimations together sometimes totaled more than 100%.

Data Analysis

Dead trees at later stages of decay were recorded in the field, but analysis was limited to recently dead trees with bark still on or just starting to separate (status three and four, Appendix A) because the intention for this study was to understand mortality related to prescribed fire within the past five years. Trees at later stages of decay (>4) were excluded (n = 30) leaving a total of 953 trees for analysis. Thriving (1) and surviving (2) were combined as living (n = 811 or 85%), and dead with fine branches and bark intact (3) and dead with bark loosening (4) were combined as recently dead trees (n = 142 or 15%).

In order to quantify legacy hardwood mortality at the stand scale, I summarized percent mortality by transect and site, and analyzed the effects of site-level factors on percent mortality using generalized linear models (glm). I conducted univariate and multivariate analyses of site level factors, including mean basal area (m^2/ha), mean slope (%), treatment (prescribed fire, control), site, and species. Models were evaluated using Akaike's Information Criterion (AIC) model selection, where the model with the lowest AIC and the fewest number of parameters were selected as the most parsimonious (Burnham and Anderson 1998). Models were compared to null models. Model fit for the glm was estimated using McFadden's pseudo-R^2 (McFadden 1974). I additionally estimated mortality at the tree scale by summarizing percent mortality by treatment and species. I evaluated the strength of treatment and species using a generalized mixed effects model (glmm) with a binomial distribution using the *lmer* package in R (R Development Core Team 2022). Random effects structure included transect nested within site, with treatment and species as fixed predictor variables affecting mortality as a binary response (dead, alive).

To determine the role of fire scar cavity and other tree level factors associated with hardwood tree mortality status (dead, alive), I used a glmm approach (Figure 19). Random effects structure included transect nested within site. Fixed predictor variables included species, tree size (dbh, cm), scar size (height, width, depth (cm), volume (m^3), surface area (m^2)), scar width/dbh ratio, and % char and % rot of the scar surface. A total of 21 models with different combinations of tree-scale factors with 34 different variable combinations were conducted for a total of 435 model runs. Model selection was determined based on AIC. The goodness of fit of the top mixed effects models was estimated for theoretical marginal and conditional R^2 values using the MuMin Package (Nakagawa 2017), and P-value was estimated by conducting analysis of variance (anova) of the model against the null model in R (R Development Core Team 2022).

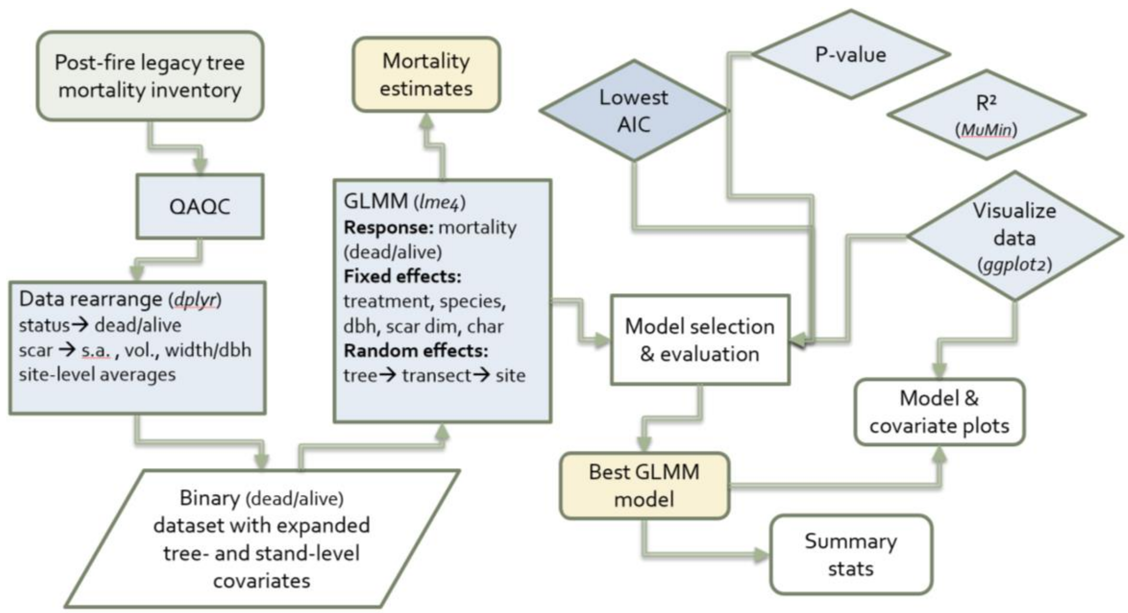

Figure 19. Workflow for observed tree-scale factors on legacy hardwood mortality using generalized linear mixed effect modeling (GLMM). Blue filled shapes denote processes conducted using R (R Development Core Team 2022).

Karuk Tribe and Manager Engagement and Review

This project was conceptualized, implemented and evaluated in close coordination with the Karuk Tribe DNR and partnering agencies. This research was heavily informed and motivated by my pre-existing relationships and work in the area. I have lived on Karuk lands since 2010 and have been employed by the Tribe since 2015 (until present). I have participated in prescribed fire on behalf of the Tribe since 2014, assisting with most of the burns in this study as a fire effects monitor (FEMO), and saw first-hand the impacts to legacy hardwoods. I additionally participated in collaborative meetings as a Karuk Tribe employee prior to taking on this research position, during which we identified the need to understand and prevent legacy hardwood mortality.

As a graduate student researcher, I followed the Karuk Tribe's Practicing Píkyav Policy for Collaborative Projects and Research Initiatives. This process is designed to respect Tribal knowledge sovereignty, reduce impacts on Karuk eco-cultural resources and people, and foster mutual reciprocity with researchers. I developed and presented a Practicing Píkyav Proposal for Karuk Resources Advisory Board (KRAB) advice and approval, and consulted with my designated Practicing Píkyav Committee during all subsequent stages of research. Changes in research questions and direction were co-determined during a Píkyav Field Institute - WKRP Workshop with Karuk DNR employees and partners halfway through the project. Cultural Practitioners were given honorariums for their contributions, and I donated to the Karuk Fund for Eco-cultural Revitalization as an active acknowledgement of Karuk stewardship prior to each research presentation outside the community. Additionally, I collaborated with DNR's K-12 Environmental Education Division, as both a graduate student and Karuk Tribe employee, to share my inquiry process and findings about legacy hardwood mortality with Karuk youth. We co-led legacy-hardwood-themed field trips for elementary school students and I contributed to the Karuk Nanu'ávaha ("our food") Curriculum.

Results

I sampled a total of 953 trees that ranged in size from 25 cm to 182 cm dbh, with a mean dbh of 45 cm and a median dbh of 39 cm (Figure 20). The majority of trees were in smaller dbh sizes. The sites had an average density of 175 hardwood trees/ha within the sampled size range. A relatively large proportion of total trees (43%) had pre-existing fire scars including madrones (60%), and black oaks (30%), tanoaks (23%; Figure 21). A larger proportion (63%) of total dead trees had pre-existing fire scars with 82% of madrones, 50% of black oaks, and 32% of tanoaks. (Figure 21). Fire scars were observed across the full range of tree sizes, suggesting the possibility that even the smallest trees could be survivors from a legacy of Indigenous stewardship.

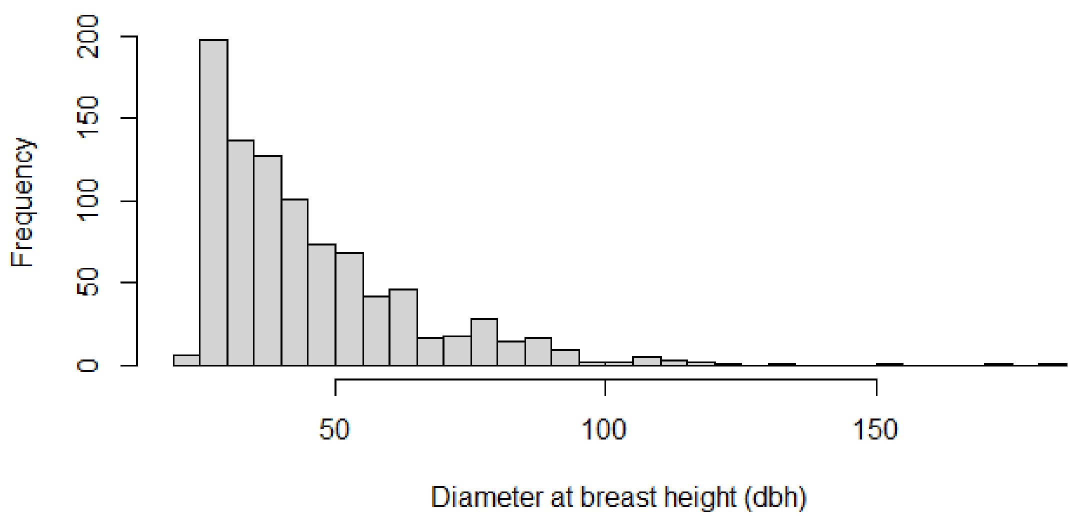

Figure 20. The distribution of live and dead tree sizes for post-prescribed fire mortality measured by dbh in cm. Mean = 45 cm, median = 39 cm, and range of 25 to 187 cm (n = 953).

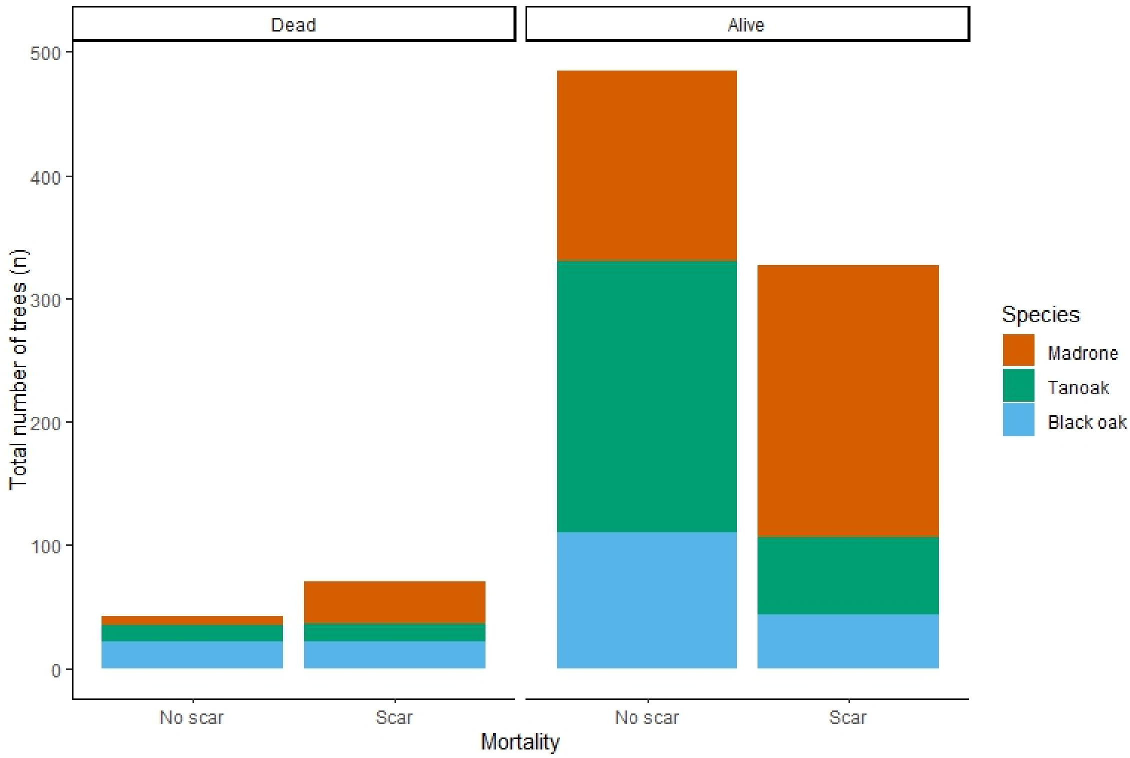

Figure 21. Count of legacy hardwood trees with and without pre-existing fire scars and mortality status (43% of living trees had scars compared to 63% of dead trees).

Stand scale legacy hardwood tree mortality

At the stand scale, the mean mortality rate in prescribed fire sites was 17.8% compared to 12.7% in unburned controls, although treatment was not statistically significant (P = 0.735, standard error = 1.671, McFadden's R^2 value = 0.150). The null model was favored in all cases compared to glm models that included combinations of and interactions between basal area, slope, site, species, and treatment.

Table 8. Percent mortality (%) by site, treatment, and species.

Site	Treatment	Madrone	Tanoak	Black oak	Total
Bacon Flat	Prescribed fire	23	12	4	25
	Control	5	3	0	3
Bull Pine	Prescribed fire	7	0	59	20
	Control	8	1	11	6
Lacy	Prescribed fire	9	6	19	12
	Control	0	2	2	14
Pearson	Prescribed fire	17	0	19	13
	Control	17	0	25	17
Szabo	Prescribed fire	18	15	25	19
	Control	19	45	20	27
White Oak	Prescribed fire	17	-	26	21
	Control	0	-	0	0

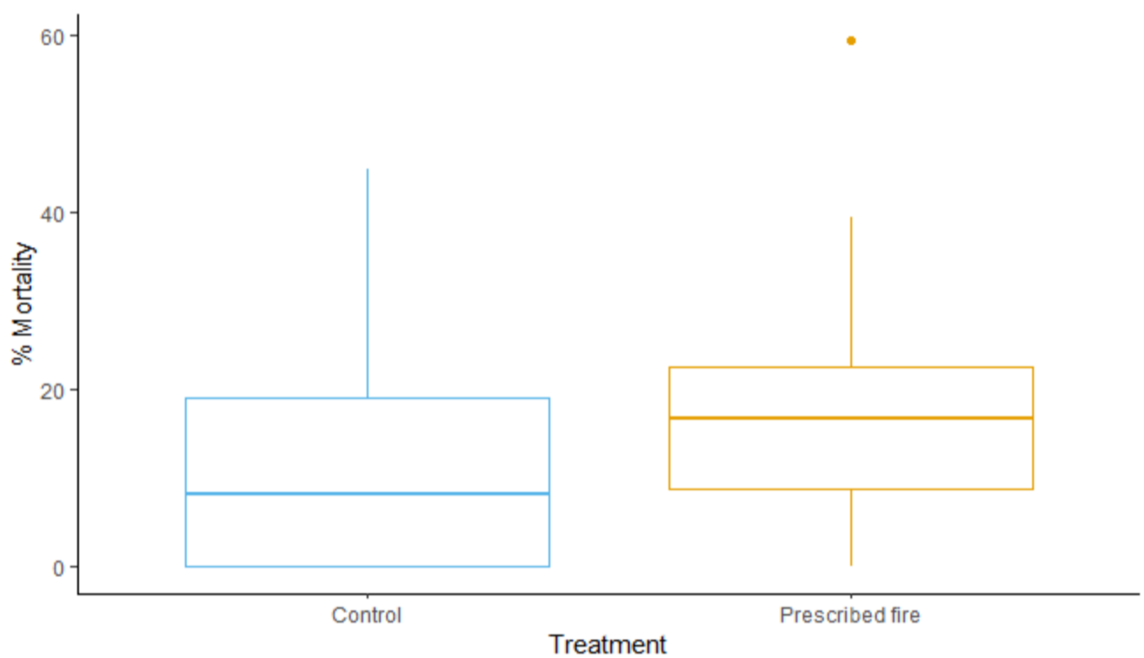

Figure 22. Percent hardwood mortality between units receiving prescribed fire (17.8%) compared to the control (12.7%), summarized by unit. P-value = 0.735, standard error = 1.671. McFadden's R^2 value = 0.15.

<u>Tree-scale legacy hardwood tree mortality</u>

At the tree scale, mortality in prescribed burned areas was twice as much as in unburned controls, with a rate of 16% in prescribed fire sites compared to 8% in controls ($P = 0.0061$). Mortality rates due to treatment varied among species ($P < 0.0001$). Black oaks died at the highest rates (29% prescribed fire, 13% control), followed by madrone (14% prescribed fire, 6 % control), and tanoak (9% prescribed fire, 9% control) ($P < 0.0001$).

The most informative glmm predicting tree mortality was an additive model with scar width-to-dbh ratio and species (P-value < 0.0001) (

Table 9). This varied among species, where dead madrone scar/dbh ratios were 98% larger than living trees and the only species that was statistically significant ($P < 0.0001$). Dead tanoaks averaged a larger discrepancy between live and dead trees with 144% larger scar/dbh ratios in dead trees ($P = 0.170$). Dead black oaks had 69% larger scar ratios than living trees ($P = 0.158$), but was not statistically significant.

Figure 23. Scar width-to-dbh ratio is an association of the widest width of the scar and stem dbh. Field assistant Arianna Skikos here pictured taking field measurements of a legacy madrone at a study site in Orleans, CA. Photo credit Heather Rickard.

Table 9. Mean values for each factor for live and dead trees within prescribed burned sites, excluding unburnt controls. P-value estimates, standard error, and coefficient estimates are included for univariate models. Variation inflation factor (VIF) values provided for field-measured covariates as an indicator of multicollinearity.

Covariate	Species	Live	Dead	P-value	Standard error	Coefficient	VIF
scar width (cm)	madrone	24.99	42.00	0.007	0.007	-0.019	
	tanoak	4.53	10.00	0.242	0.016	-0.019	
	black oak	11.57	22.72	0.025	0.010	-0.021	
	total	15.36	28.29	0.0003	0.005	-0.017	2.17
dbh (cm)	madrone	52.91	43.78	0.003	0.017	0.051	
	tanoak	40.18	40.99	0.925	0.024	-0.002	
	black oak	40.03	47.69	<0.0001	0.003	-0.031	
	total	45.98	45.04	0.361	0.008	0.007	1.32
scar char (%)	madrone	31.54	59.14	<0.0001	0.003	-0.013	
	tanoak	5.55	17.50	0.080	0.012	-0.020	
	black oak	18.38	47.97	0.002	0.006	-0.018	
	total	20.11	47.40	<0.0001	0.003	-0.014	2.18
scar depth (cm)	madrone	25.42	28.21	0.895	0.006	-0.001	
	tanoak	6.680	17.75	0.858	0.013	-0.023	
	black oak	12.92	27.47	0.014	0.010	-0.024	
	total	16.56	26.16	0.022	0.004	-0.009	1.99
scar height (cm)	madrone	57.01	168.48	0.079	0.001	-0.001	
	tanoak	11.52	76.00	0.017	0.004	-0.008	
	black oak	38.61	65.72	0.246	0.002	-0.003	
	total	37.96	108.23	0.033	0.001	-0.002	1.21
scar width/ dbh ratio	madrone	0.49	0.97	0.0003	0.326	-1.175	
	tanoak	0.09	0.21	0.170	0.847	-1.161	
	black oak	0.29	0.49	0.158	0.423	-0.597	
	total	0.31	0.61	<0.0001	0.216	-0.848	--
scar surface area (m^2)	madrone	0.12	0.59	0.027	0.364	-0.806	
	tanoak	0.01	0.15	0.071	2.934	-5.292	
	black oak	0.10	0.13	0.502	0.779	-0.522	
	total	0.08	0.31	0.012	0.352	-0.887	--
scar volume (m^3)	madrone	0.05	0.21	<0.000	0.004	-0.928	
	tanoak	0.01	0.06	0.071	3.927	-7.098	
	black oak	0.03	0.04	0.457	2.392	-1.781	
	total	0.03	0.11	0.073	0.557	-0.999	--

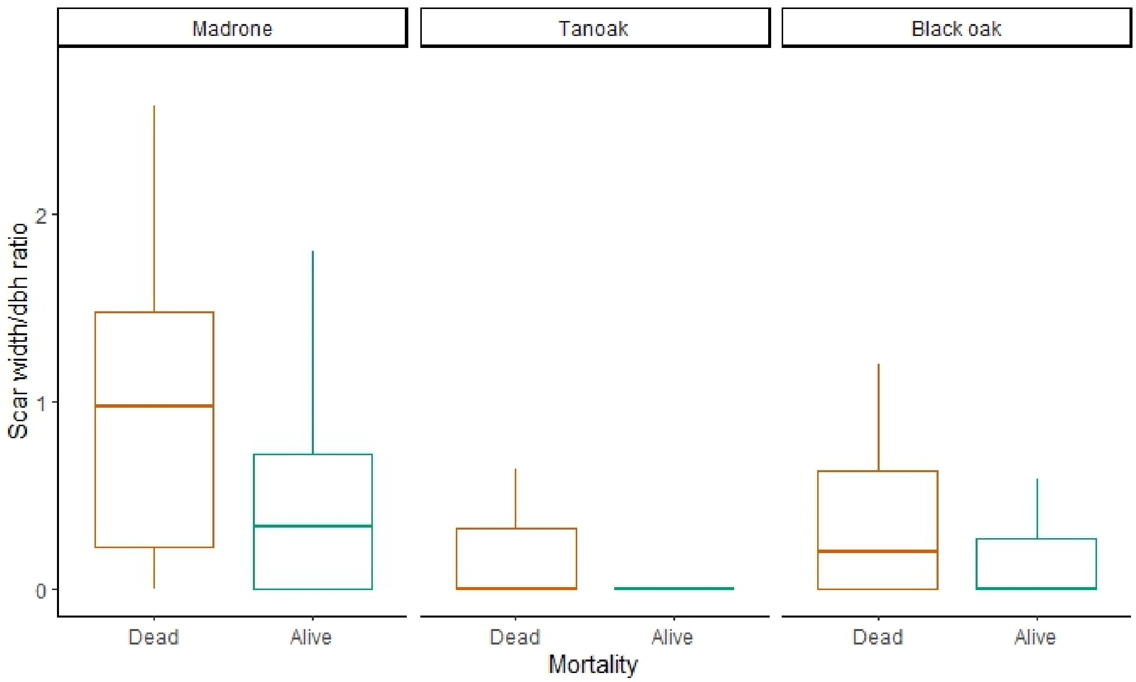

Figure 24. Scar width/dbh ratio for living and dead trees for madrone, tanoak, and black oak.

Table 10. The best five models predicting legacy hardwood mortality with tree-scale covariate combinations using the lowest AIC for selection. Dbh = diameter at breast height (m), scar w = scar width at the base or widest part (m), char = % char of scar surface using an ocular estimate. R^2M = marginal R^2, including only fixed effects, and R^2C = conditional R^2 for the entire model. Species included madrone, tanoak, and California black oak.

Covariates & model equations	AIC	R^2M	R^2C	P-value
scar w/dbh + species	365.44	0.14	0.32	<0.0001
scar w/dbh + dbh + species	365.57	0.15	0.33	<0.0001
scar w + species	366.97	0.14	0.30	<0.0001
scar w/dbh + char	375.81	0.09	0.21	<0.0001
char	376.13	0.08	0.19	<0.0001

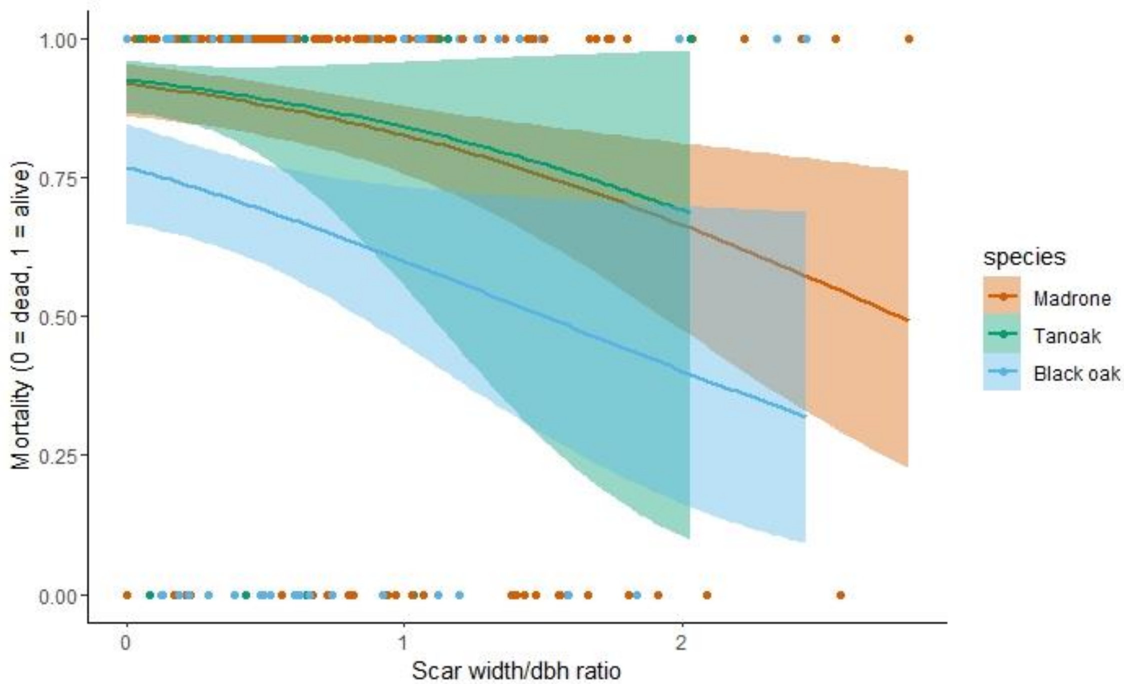

Figure 25. The most informative legacy tree mortality generalized mixed effects model was an additive model with scar width-to-dbh ratio and species. Dead trees are represented by the mortality value of 0, and living trees are represented by 1.

Discussion

This is the first study of its kind to quantify prescribed fire impacts on western legacy hardwoods. My findings describe factors contributing to post-fire legacy hardwood mortality trends in a region where Karuk Tribe-led collaborative stewardship efforts focus on their survival. I found elevated mortality rates in recently prescribed burned sites compared to long-unburned controls, but the trends varied among species. At the stand scale, hardwood mortality rates due to treatment, species and other factors were not significant (n = 6 sites), but had slightly higher mortality (18% prescribed fire, 13% control). Mortality rates at the tree-scale had more statistical significance and power (n = 923), with more than twice the rate of mortality observed in trees that experienced prescribed fire (16%) compared to long unburned trees (6%). Mortality rates at unburnt control sites were less than estimates of tree mortality for conifers in the region, ranging between 15% and 18% during this time period (Lemmo 2022). Both tree- and stand-level prescribed fire mortality estimates are comparable to the >10 % die-off events observed following drought or other disturbances (Mueller-Dombois 1983, Anderegg et al. 2013). To my knowledge, mortality of hardwood species in the Klamath Mountain region has not yet been accounted for in regional drought and tree mortality assessments.

Surprisingly, comparisons of basal area competition at the stand-scale was not found to be a contributing factor to mortality rates, though it was not accounted for at the tree-scale in this study. Stand densification has been associated with higher rates of tree mortality in conifers (Gleason et al. 2017, DeSiervo et al. 2018), and reduced post-fire survival (Botequim et al. 2017). Oak tree mortality has been associated with long-term environmental stressors and growth decline (Pederson 1998). Further research is needed on the effect of Douglas-fir competition on legacy hardwood death following prescribed fire.

At the tree-scale, my findings suggest that the most vulnerable legacy hardwood trees are those with larger pre-existing fire scars in proportion to their dbh. While this trend was observable across species, it was strongest for madrones that also had the highest rate of preexisting fire scars and the largest scar width/dbh ratios. Kinkead et al. (2017) found that among hardwood trees in the Ozarks that died following prescribed fire, dead trees had scars six times larger than surviving trees. Two previous studies focused on giant sequoia did not find that pre-existing fire scars had any relationship to prescribed fire mortality (Lambert & Stohlgren 1988, Haase & Sackett, 1998). However, recent research on the same species under wildfire conditions found scarred trees had a 2.4 times greater likelihood of post-fire mortality (Shive et al. 2022). In our study, width was the most informative of all scar size metrics. One reason is that greater width describes a larger opening for surface fire to enter the cavity from the ground. The mechanisms of scar size and tree mortality are still uncertain, though fire scars have been shown to weaken the hydraulic efficiency of trees (Bär et al. 2018, Partelli-Feltrin et al. 2021). Xylem damage may be an indirect mechanism of post-fire mortality causing delayed tree decline (Hood et al. 2018, Michaletz 2018). While fire scar size appears to be important, the scar size: tree stem ratio may be more informative.

Structural stem failure due to cavity hollowing during fire was observed anecdotally, although it was not a measurement of post-fire mortality in this research.

Cannon et al. (2015) found that tree instability under high winds in Georgia was associated with larger preexisting fire scars (more commonly in hardwoods) and used a fire scar index (proportion of scarred trunk circumference x scar height (m)) in his analysis. Fire scar size in relation to stem size may account for remaining structural wood in the tree stem to support the tree, sometimes notably narrow (Figure 26).

Figure 26. Narrow structural wood remaining (2-7 cm) after prescribed fire on a dead broken legacy madrone. Photo credit Heather Rickard.

The best single variable that described mortality in this study was percent scar surface char. If we entertain char as a proxy for recent fire entry into the tree cavity, this would suggest that basal fuels remediation treatments (involving removal of leaf litter, duff and woody fuels from around the tree base) could be a temporary protective measure. Removing leaf litter, duff, and woody fuels within one meter from the bole has been shown to limit damage to the cambium and crown following prescribed fire (Hood et al. 2007, Kolb et al. 2007, Fowler et al. 2010). However, studies that assessed the effectiveness of fuel removal treatments on legacy conifer survival following fire did not determine that raked trees fared significantly better than un-raked trees (Swezy & Agee 1991). I am not aware of other research evaluating the effectiveness of fuel removal around the hardwoods included in this study. One recent study did not find a direct association between remediation and post-fire mortality on Oregon white oak (Nemens et al. 2019). Anecdotally, managers in the Klamath region have observed that ground fuel removal around the base of legacy hardwoods and from within the cavity interior may prevent surface fires from reaching the bole of the tree, thereby preventing ignition of the often rotten and receptive cavity surface. Remediation could prevent tree death in the short-term, although it should be noted that the flammable rotten scar surface would not be protected from flying firebrands, longer flame lengths, or canopy scorch under prescribed or wildfire conditions where much higher rates of mortality would be predicted (Hood et al. 2018, Shive et al. 2022).

While presence and size of the basal scar may be an influential factor, these findings should not be misinterpreted to suggest that pre-existing fire scars are killing legacy hardwood trees. These trees are adapted to live hundreds of years with open scars and hollowed out cavities that provide important habitat for threatened wildlife species (Mazurek & Zielinski 2004, Remm & Lõhmus 2011). Basal scars are an inevitable, and perhaps desired, impact of low severity fire, where fire often eddies on the down-wind and upslope side of the tree (Smith & Sutherland 1999). Regular low-intensity broadcast burning that was traditionally conducted would have left the surface of these scars charred, strengthening the exposed surface. Char is not only resistant to burning and heat generation that could injure the cambium or consume stem wood during subsequent fires; but it is also resistant to rot, preventing further decay of the heartwood by insects and microorganisms (Southam & Ehrlich 1943).

Despite the potential relationship of structural failure, cavity presence and fire, these trees stand for many years with limited structural stem wood. This may in part be due to the inherent mechanical wood strength of the species studied (Niemiec et al. 1995). Research also suggests that scar formation by frequent fire could provide the tree additional strength due to woundwood "ribs" (locally wide growth rings at the edge of the scar), which help distribute the weight of the tree on the stem (Mattheck 1998, Smith & Sutherland 2006). It is possible that under frequent fire conditions, scarred trees may have even greater stability. In the absence of fire and increased fuels and rot build-up in the cavity, wood consumption by fire may cause the stem to reach a breaking point sooner.

Fire exclusion policies have left these trees and their scar surfaces especially vulnerable to fire, and fire may indeed be a solution under restored Indigenous leadership. Safe and careful use of fire on the interior of the cavity could remove pests, and prevent tree death by reducing highly flammable rotten fuels on surfaces of living trees. Legacy hardwood stewards may consider tree-focused cavity restoration under cooler or wetter conditions than the prescribed burns studied. The revitalization and continuance of traditional fire tending practices with innovative restoration techniques may support the persistence of legacy hardwood trees and intergenerational cultural continuity for Indigenous gatherers who have tended to them. A sentiment shared by other Cultural Practitioners, Leaf Hillman describes the importance of enabling restored relationships between Indigenous people, places and living cultural resources:

> *These trees are spirit people, and just like us, they need to feel like they have a purpose and a reason to exist. In my own experience, I've seen that when plants are visited and used, they respond positively. Tending to the relationship strengthens the tree, and strengthens its relationship with other spirit beings, like animals and people too* (Leaf Hillman, pers. comm., 7/22/23).

I would argue that this research confirms the perspective that the source of legacy hardwood mortality rates is directly related to their neglect by the settler colonial state that has interfered with previously existing reciprocal relationships between Indigenous people and their places. The findings of this data may be useful to tribal stewards to focus protection efforts on surviving legacy hardwood trees for generations to come.

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APPENDICES

Chapter 1. Legacy hardwood fuels and root characterization

Appendix A. Fuels transect position in relation to the slope

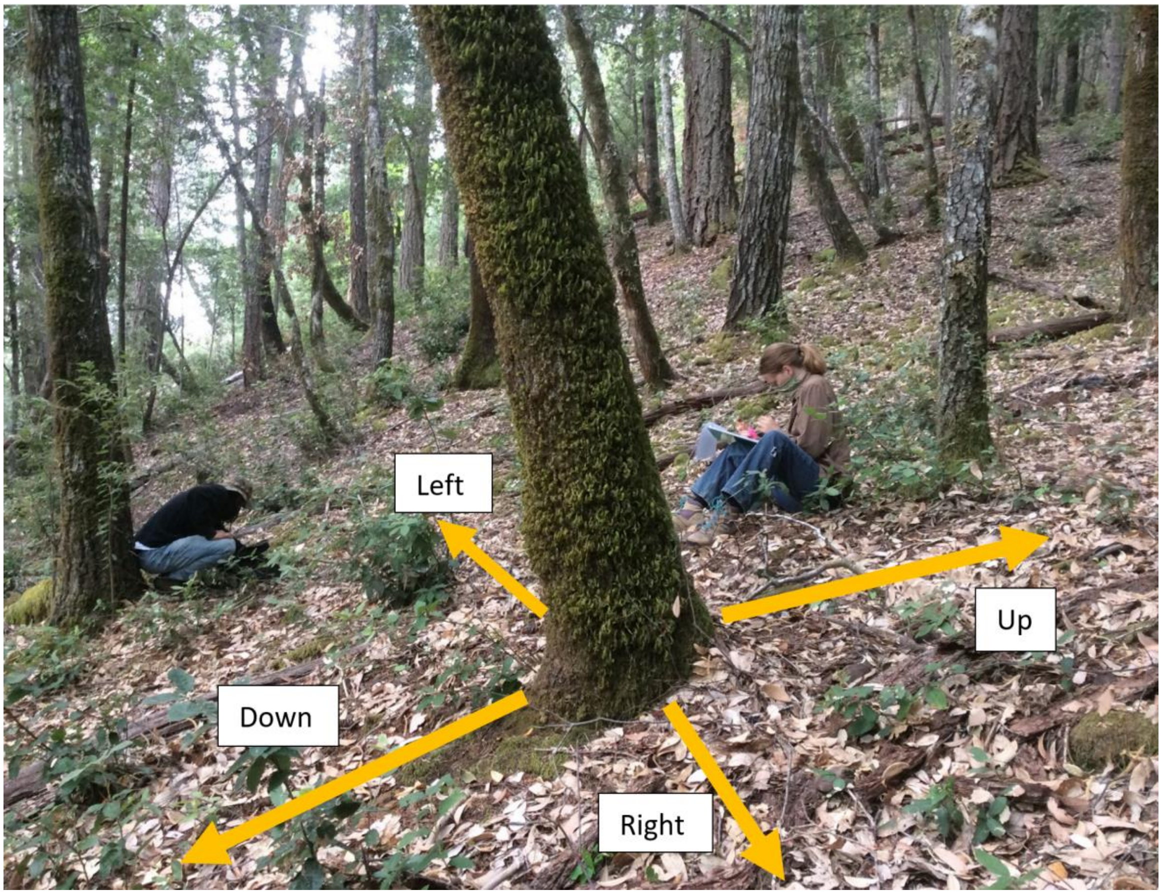

Figure A 1. Fuel transect directions (up, down, left, and right) around a black oak where some accumulation of fuels is somewhat visible at the uphill side of the bole and a fuel shadow without leaf litter is visible on the downhill side. Field assistants Chris and Grace here pictured.

Chapter 2: Prescribed fire legacy hardwood mortality inventory

Appendix B. Tree mortality and decay classes.

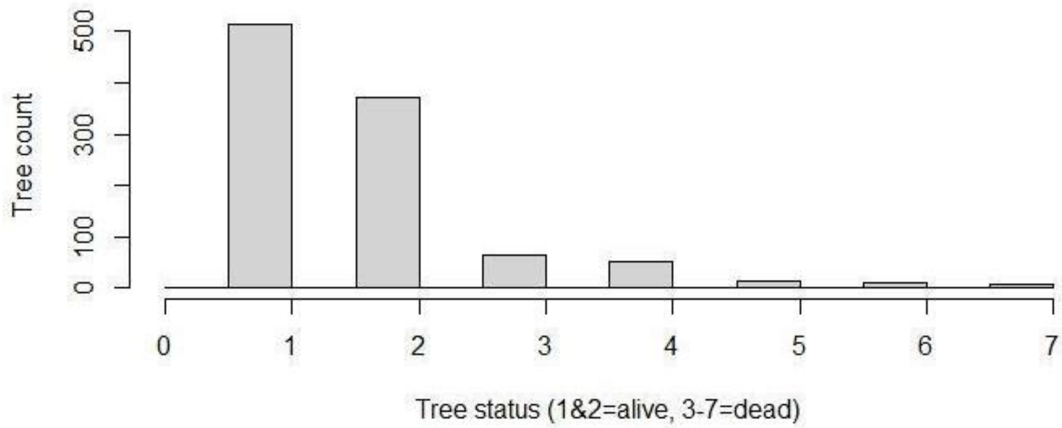

Figure B 1. Histogram of tree count by tree mortality status for all trees. Status 1 and 2 were grouped as living, status 3 and 4 grouped as dead, and decay classes beyond 4 were excluded from analysis.

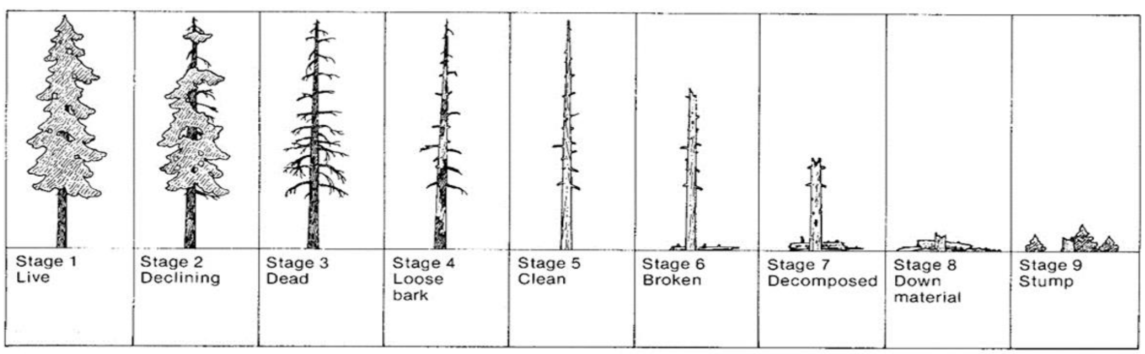

Figure B 2. Snag classification by Thomas et al. (1979) for Pacific Northwest wildlife habitat trees referenced to classify tree mortality for this study.

Appendix C. Effect of tree size on mortality

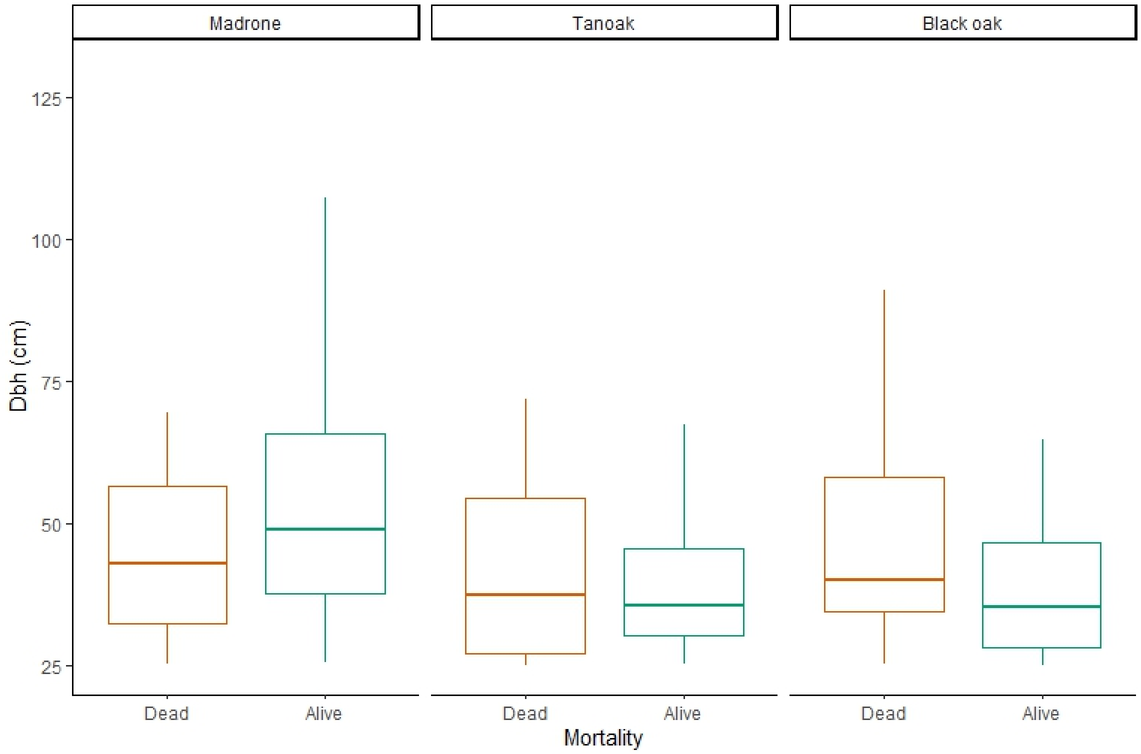

Figure C 1. Mortality by tree size (dbh) and species in prescribed burned areas only. For the additive generalized mixed effects model including both dbh and species, P-value = 0.00773, conditional R^2 = 0.164.

Appendix D. Effect of percent scar char on mortality.

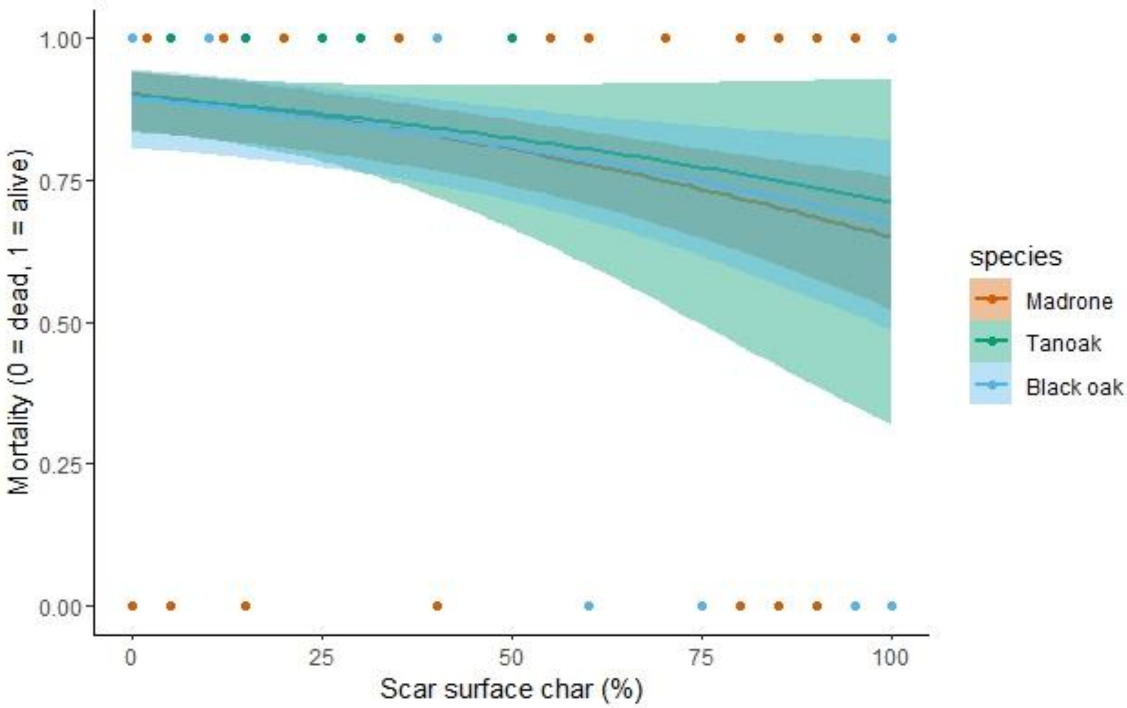

Figure D 1. Effect of percent scar surface char on mortality using a generalized linear mixed effects model with prescribed fire data subset. Figure shows the negative relationship between percent char and mortality, where the more charred the surface was for all three species, the more likely the tree would die (P-value < 0.0001, conditional $R^2 = 0.192$).

Appendix E. Generalized linear mixed effects models for mortality.

Table 11. Model runs for data excluded older decay classes (> 5, n = 923) for all treatments, sizes, species, and scar characteristics with mortality (dead/alive) as a response. AIC was utilized to select the best model, and p-values shown were either summarized using R, or estimated using anova against the null model. Dbh = diameter at breast height (m), scar ht = scar height (m), scar w = scar width at the base or widest part (m), scar d = scar depth measured from the opening to the back of the tree (m), scar volume = ((w x ht x d)/3), scar sa = (w x ht)/2, char = percent char of scar surface via ocular estimate (%), rot = percent rot of scar surface via ocular estimate (%).

Model	Covariates & model equations	AIC	P-value
1	species	644.1036	<0.001
2	treatment	659.7705	0.00534
3	dbh	667.2078	0.773
4	scar ht	654.5713	0.00248
5	scar w	646.4539	<0.001
6	scar d	656.9575	<0.001
7	scar vol	661.6212	0.0281
8	dbh + scarw	645.9289	<0.001
9	dbh * scarw	646.2086	<0.001
10	scarw/dbh	644.0684	<0.001
11	(scarw/dbh) + dbh	646.0673	<0.001
12	(scarw/dbh) + dbh + species	620.0049	<0.001
13	scarw + species	619.9995	<0.001
14	dbh + species	645.7503	<0.001
15	dbh + tx + species	641.0585	<0.001
16	dbh + tx * species	641.0585	<0.001
17	(scarw/dbh) + species	618.6125	<0.001
18	scar sa	654.2063	<0.001
19	char	636.0202	<0.001
20	rot	665.6499	0.184
21	scarw/dbh + char	632.7567	<0.001