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STRUCTURAL INTEGRITY AND PHYSICAL PROPERTIES OF PONDEROSA PINE OVER TIME AFTER DEATH BETWEEN VECTORS OF MORTALITY

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By

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Structural integrity and physical properties of ponderosa pine over time after death between vectors of mortality

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In an era of accelerated climate change, with persistent and increasing disturbance on our landscapes it is important to increase our knowledge of how these natural disturbances effect our lands. This study investigated the changes that take place in ponderosa pine (*Pinus ponderosa*) stems after death when killed by mountain pine beetle (*Dendroctonus ponderosae*) and by fire. Trees killed by mountain pine beetle as well as trees killed by fire were sampled and separated into two age classes, those dead 0-4 years and those dead 4+ years. Data was gathered on the modulus of rupture, modulus of elasticity, specific gravity, holocellulose to lignin ratio, and volumetric heat content for each age class and disturbance type. Analysis was conducted looking not only through time but also vertically through the stem profile. Looking vertically through the stem showed similar trends between beetle killed and fire killed trees in a lowering of the modulus of rupture, modulus of elasticity and specific gravity as height up the tree increases. Over all structural integrity of the stem in terms of modulus of rupture and modulus of elasticity is shown to be significantly different between disturbance types in the “young” age class (0-4 years dead) but not in the “old” age class (4+ years dead). This indicates an initial difference in the post disturbance environment influencing the decay of the stems, and suggests that this difference becomes mitigated as time since disturbance increases. Future studies in this area are needed to fully understand the driving factors behind these findings and the greater implications that mortality vector and disturbance have on the structural and physical properties of the trees left on the landscape.

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First, I would like to thank my advisor and friend Dr. Edwin Burke, for his constant encouragement and guidance throughout this endeavor. Few students have the opportunity to be taught by such a passionate and energetic professor, Ed's drive and devotion to his student's education is second to none and I count myself very fortunate to have been on the receiving end of his energies. Second, I am deeply grateful to my other committee members Dr. John Goodburn and Jim Reardon, for their guidance and patience as I stumbled my way through this project. Without their help, I would not have finished this degree.

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Contents

Introduction:

This project focuses on the changes in ponderosa pine (*Pinus ponderosa*) snags over time post mortem. Ponderosa pine is the dominant tree species on 27 million acres of forest across the western United States and is a component of the landscape on another 13.5 million acres (Graham & Jain, 2005). Ponderosa pine ranges widely across North America from Nebraska to the West Coast and from British Columbia to Mexico (Habeck, 1992). Of the large expanses of forestland in the intermountain west, vast swaths of lower and mid elevations are dominated by this robust and extensive species. In so being, many acres of our federally and state owned public lands across all agency managements fall under this forest cover type. A hardy species with good drought resistance, and thick ablative bark capable of offering protection from fire and insects, ponderosa can see significant mortality when adverse conditions align.

The intermountain west, which encompasses this study area in western Montana is a disturbance prone and driven ecosystem (Agee, 1993; Baker, 2009; Fiedler & Arno, 2015). Disturbance plays an ecologically significant role in the health and resilience of the landscape across all cover types. As a result of being a disturbance prone environment the landscape is dotted and in some cases covered with dead standing timber. Dead timber known as snags, are a crucial and commonly overlooked part of the ecological system (Brown, Reinhardt, & Kramer, 2003; Franklin et al., 1986). Snags provide nesting and denning habitat for birds and small mammals (Franklin et al., 1986; Mccieiland, Frisseli, Fischer, & Haivorson, 1979; Payer & Harrison, 2003) as well as habitat for a variety of invertebrates (Jia-bing, De-xin, Shi-jie, Mi, & Chang-jie, 2005). Due to the ecological importance of snags on cavity nesters (Evelyn L Bull, Parks, & Torgersen, 1997), previous work has been done to look at snag longevity (E.L Bull, 1983; Dahms WG, 1949; Scott, 1978), and useful duration of a snag as nesting habitat. Several studies have noted that a snags longevity is related to its size. Larger snags (greater diameter), are more likely to remain standing longer (E.L Bull, 1983; Dahms WG, 1949; Scott, 1978). This relationship between size and longevity was found to be the same for both trees killed by beetles and those killed in fire events (Keen, 1955). Longevity of snags not only impacts those insects and animals that live and nest in the snags structure but it also impacts the landscape when the fall. Course woody debris (CWD) is an important part of our forest ecosystems (Baker, 2009; Franklin et al., 1986). Natural successional trajectories, forest management and disturbances all influence the amount and distribution of CWD on the landscape.

Wildland fire is one of the most influential and largest scale disturbances that we see today. Fire has been present on the landscape since there has been fuel to consume (Agee, 1993; Pyne, 1982). Plant communities in the western united states have evolved with reoccurring fire and have become adapt in many and varying ways to cope with its presence (Fischer, W.C.; Bradley, 1987). Even with these adaptations there is still plenty of opportunity to see large scale mortality in our western forests. In the past century, there has been an increase in the acreage of forestland managed for varied uses, shifting national fire policies influencing the acreage allowed to burn, as well as a changing climate. Partially due to these factors we have seen a change in the duration, magnitude and intensity of wildland fires especially in the last few decades (Kasischke & Turetsky, 2006; Westerling, Hidalgo, Cayan, & Swetnam, 2006). When stand conditions promote crown fire, and high fire resonance time, the results can be crown scorch, high needle consumption, as well as root and stem damage. The interaction of such disturbance effects can lead to high mortality and a visual as well as ecological shift in the landscape (Kaufmann et al., 2008)

Although fire tends to capture our attention most rapidly, is not the only disturbance with large sweeping ecological impacts. Insect infestation and outbreaks can also exert influence over a landscapes successional trajectory, and ecological path. Along with other pests, ponderosa pine is a suitable host for mountain pine beetle (*Dendroctonus ponderosae*). A native species of bark beetle, *D. ponderosae* historically has been shown to preferentially select *P. contorta* (lodgepole pine) over ponderosa for its main food source. Recently though, mountain pine beetle has been shown through laboratory research and field sampling to be not only capable of crossing over to an alternate host under favorable conditions, but able to do so with no loss of vigor or fecundity (West, Briggs, Jacobi, & Negrón, 2016). These transitions and outbreaks in ponderosa pine are especially successful during times of moisture stress, injury from recent fire and stand overstocking resulting in low vigor and poor defensive capabilities (Neary, Ryan, & DeBano, 2005). Although a native species to the inland Northwest's forests and always present on the landscape in endemic levels, there have been several population upticks of mountain pine beetle resulting in large areas of dead pine forest. The last decade has seen the intermountain west of the United States and Canada in the midst of such an outbreak (Kurz et al., 2008). With wildland fire and bark beetle mortality more prevalent, managers must cope with an increased abundance of post disturbance landscapes. Standing dead timber, whether it is black and charred from a fire, or tuning from red to gray after a mountain pine beetle attack, is a factor that must be addressed and considered. Once a disturbance moves through a landscape the standing dead timber begins to change. Many factors can weigh into how long a snag stands. The density of the wood measured as specific gravity has been shown to change not only over time but also throughout the tree (Kotch, 1972; Lutes & Hardy, 2013). Specific gravity of wood as measured by ASTM standard D2395 (ASTM International, 2011) has been shown to decrease as the height up the tree increases in live trees but the rate of this change and how long the relationship remains post mortem has not been shown. Coupled with the specific gravity of the wood is the presence and abundance of decay within the snags. Decay fungi directly feed on and consume cellulose which is the main structural component of the wood (Forest Products Laboratory - USDA, 2010). The effects of decay on the structural integrity of wood can be significant long before there is a noticeable change in wood density (Curling, Clausen, Winandy, & Curling, 2001). The changing conditions of wood within the snags are the basis for many possible management concerns across the western United States.

This project seeks to understand the changes that occur within ponderosa pine snags over time in regards to their woods strength, lignin/cellulose content and heat content. Variables will also be compared between two vectors of mortality, fire and mountain pine beetle. An increased understanding of the properties of snags lends us the opportunity to better manage our forests post disturbance and can potentially give land managers insights into the future characteristics of the landscape. Knowing the rate of a snags strength loss, the changes in its holocellulose to lignin ratio and how this relates to heat content can inform us on the potential for wind throw, the likelihood for pulse loading of fuels, an areas capability for fostering flaming versus smoldering combustion and where to concentrate limited ground resources during and post disturbance as well as possible safety concerns for the public as they use their public lands.

Study Goals:

1) How does the structural integrity of a ponderosa pine snag change over time, and does this relationship differ between vectors of mortality?

The pattern of change and deterioration seen in ponderosa pine snags as they age is of particular interest to this study. The possibility of being able to describe the changes seen with a simple model is not only intriguing but an important part of improving land management strategies and resource allocation. As the snags that populate the landscape of post disturbance forests age and begin to deteriorate increasing amounts of fuel will eventually begin to enter these systems as course woody debris. Obtaining a general timeline of when these pulses of fuel are likely to become available for wildland fires is a valuable asset to managers on the ground.

This objective is to be investigated by developing a chronosequence to obtain samples from trees killed by both fire and mountain pine beetles from what will be considered “young” snags which are dead less than four years and “old” snags, those being dead more than four years.

2) Quantifying changes in heat content and lignin/cellulose content in ponderosa pine snags.

As with the aforementioned objective quantifying the changes in heat content (HC) and Holocellulose to lignin content has the potential to impact the wider land management field. The heat content of a material is a measure of the available energy that is available to be released upon sustained combustion. This measure changes as the material undergoes physical and chemical changes such as a snag does as it is exposed to moisture, insects, fungal decay and other factors. These factors, primarily those of decay are the driving forces in the change of the lignin and cellulose content which in return effects the HC.

Commonly used models do not take into consideration possible changes in heat content characteristics. A dead fuel of less than one year is considered to have the same heat content as a fuel dead 10 years (Rothermel, 1972). If there is a perceivable and definable change in the HC of these snags over time, then an amendment to current models could be produced after future inquiry.

Methods:

General Methods:

For this study two age classes of dead standing ponderosa pine were identified and employed to gather samples across the post-mortem spectrum. Four groups of snags and one group of green trees, as a control, were identified with each group consisting of five trees that met the desired conditions. In each of the age classes there were one group of beetle mortality and one group of fire mortality. The age classes are broken into "young" snags, trees being dead less than four years, and "old" snags as those dead more than four years. Four of the five groups sampled were situated on Lubrecht Experimental Forest at an elevation of 4,100- 4,700 feet (1,250-1,433 meters). Lubrecht Experimental Forest is located in the Rocky Mountains of western Montana, 35 miles north east of Missoula, Montana. The site of the lone off-Lubrecht Forest was from a stand 4.5 miles (7.2 kilometers) west of the other groups at the same elevation and aspect.

All sites and study trees were identified after consultation with the forest manager and land owners to confirm dates of fires and year of death by bark beetles. Trees were of the same approximate age and size, averaging 74.9 feet (22.8 meters) tall and 14.8 inches (37.6 centimeters) in diameter. Sample trees were selected after surveying selected areas and verifying cause of mortality for each tree. Cause of mortality was confirmed by visually inspecting the trees for the presence of pitch tubes, charring on the bark, and the presence and prevalence of blue stain. If a potential sample had multiple pitch tubes with evidence of mountain pine beetle larval galleries under the bark with prevalent blue staining in the wood, it was considered a confirmation of beetle mortality. Conversely if a potential sample tree was in an identified fire area and showed extensive charring of the bark, few to no pitch tubes, and minimal blue staining, the cause of mortality was classified as fire kill.

The trees were felled by hand with chainsaws. The felling cuts were placed as low on the stem as topography and safety allowed. Doing so allowed for as much distance between the first and second sections as possible. Five sections of four feet in length were delineated and removed from each of the trees felled. Sections were centered 3.3 feet (1 meter) above the felling cut and then at 20%, 40%, 60% and 80% of total stem height. The section closest to the ground was identified as section one, and numbering continued sequentially up the tree, Figure 1. Section one was centered at this set distance above the felling cut to minimize the effects of damage incurred to the stem during the felling process. On multiple occasions the fifth section (centered at 80% of total stem height) was unable to be sampled due to shattering upon impact with the ground or due to minimum diameter constraints. The sections were removed from the sites and taken to a portable Wood-Mizer sawmill located at Lubrecht Experimental Forest and cut into multiple flitches as depicted in Figure 2.

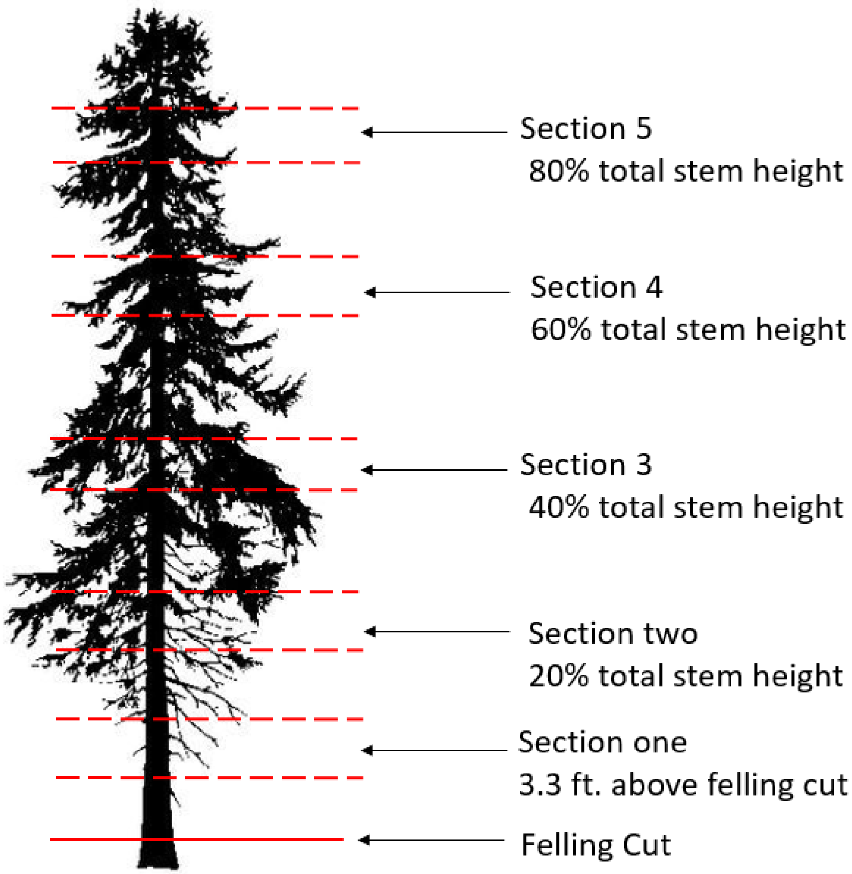

Figure 1: Depicts how sample trees are broken into sections

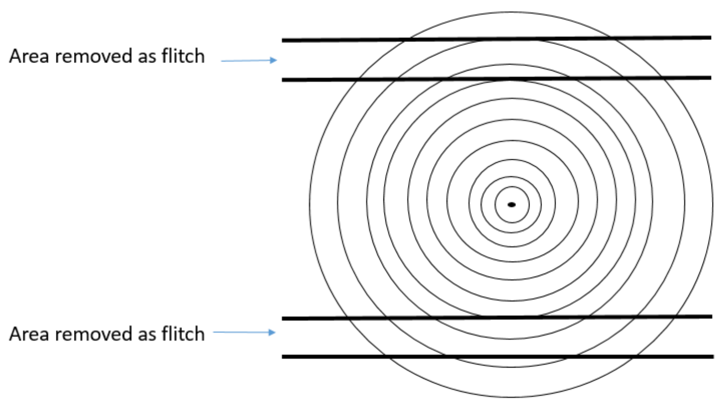

Figure 2: Each tree section was cut into several flitch sections to later have samples cut from it.

Flitches were comprised of two sawed planes and two “live” edges. Once transported to the Wood Sciences Laboratory at the University of Montana Missoula, flitches were cut into multiple 1”x1”x16” samples on which all future testing would be performed Figure 3. While the sample sticks were being cut from the flitches, knots were avoided and the grain of the wood was kept as straight as possible. All other natural variations within the samples such as rot, and insect galleries were not actively avoided. This was done to encompass the true nature and variation seen in the snags as they age.

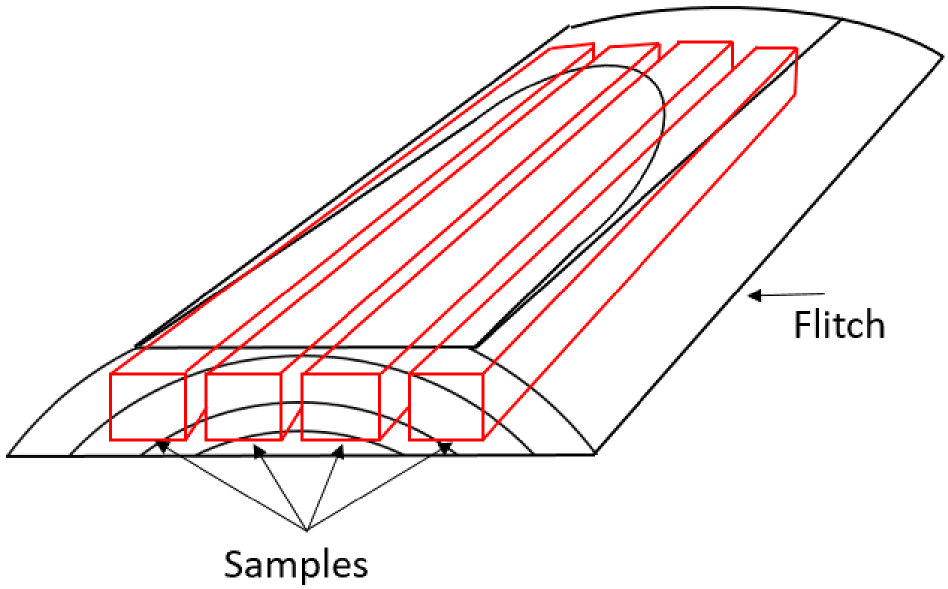

Figure 3: Multiple 1 inch x 1 inch x 16 inch long samples are cut from flitches.

Static Bending Testing

A 60,000-pound capacity Tinius Olsen universal testing machine was used for strength and stiffness testing. Test procedures followed American Society for Testing and Materials (ASTM) Standard Test Methods for Small Clear Specimens of Timber ASTM D143-11 (ASTM International, 2014). Three replicate test specimens (sticks) within each sample section were tested in static bending. The number of tests performed ranged from 120 to 138 depending on the group, and resulted in a total of 388 tests total, Table 1 . Several of the tops of the snags broke into sections too short to yield test sticks of the required length minimum of 16 inches. Breakage during felling due to the small diameter, advanced decay and boring-insect damage were the primary causes of the shattering of this smallest diameter-stem section.

Structural Testing Sample Marix			
Snag Class	**Mortality Code**	**Sample Type**	**Number of Tests**
Young	1	Beetle/Fire	130
Old	2	Beetle/Fire	138
Control	3	Green/Dried	120
Total			**388**

Table 1: Experimental design matrix for structural testing.

The modulus of rupture or MoR shown in

Where:

MoR= modulus of rupture

P= maximum load on sample (lbf)

b= width of sample (in)

h= depth of sample (in)

L= span of beam between reaction points

Equation 1 was calculated and used in the comparison of structural testing to mitigate the influence of variations in height and depth between samples (ASTM D-2555). A modulus of elasticity or MoE, Equation 2, was also calculated for each sample using data gathered from structural testing (ASTM D-2555). Moisture content, Equation 3 (ASTM D-4442), and specific gravity, Equation 4 (ASTM D-2395) were both measured for each sample after structural testing was conducted.

$$\mathrm{MoR} = \frac{3PL}{2bh^2}$$

Where:

MoR= modulus of rupture

P= maximum load on sample (lbf)

b= width of sample (in)

h= depth of sample (in)

L= span of beam between reaction points

Equation 1: Measure of the samples strength at point of failure

$$MoE = \frac{P'L^3}{4bh^3\Delta}$$

Where:

MoE= modulus of elasticity

P’= load at proportional limit (lbs)

b= width of beam

h= depth of beam

L= span of beam between reaction points

Δ= deflection of beam at proportional limit

Equation 2: Measure of sample

$$MC\% = \left(\frac{W-OD}{OD}\right)*100$$

Where:

MC%= moisture content percent

W= wet weight

OD= oven dry weight

Equation 3: Gravimetric moisture content

$$SG = \frac{V}{OD}$$

Where:

SG= specific gravity

V= volume

OD= oven dry weight

Equation 4: V=volume (g) and OD = oven dry weight (g)

Wood Scientists' past work to define the mean, variability and 95% exclusion limit values for North American commercial wood species has produced accepted standard values for the MoR and MoE for many native species. The standard sources for these green clear wood is ASTM standard D2555 also published in the Wood Handbook (Forest Products Laboratory - USDA, 2010). It is standard for these laboratory-test derived values to be reported in the undried condition (green) as well as at 12% moisture content. Most the samples tested had moisture contents well below the standard 12% testing and reporting convention. To correct for the difference in moisture content the reference MoR and MoE standards were adjusted using Equation 5 (Forest Products Laboratory - USDA, 2010)

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{\left(\frac{12-M}{M_p-12}\right)}$$

Where:

P= property at desired moisture content

P_{12}= property at 12% moisture content

P_g= property at green wood of species

M= desired moisture content

M_p= 25 (standard value from Wood Handbook)

Equation 5. As stated in the text MoR and MoE are conventionally reported at a moisture content of 12%. The samples collected in this study averaged only 7.5% moisture content and thus a correction based on moisture had to be done. This equation allows for the change of MoR and MoE based on moisture.

With this equation the MoR and MoE for all groups other than the green control can be more accurately compared to the ASTM standards for MoR and MoE of ponderosa pine. Figure 4 depicts the relationship between moisture content and both the Modulus of Rupture and the Modulus of Elasticity, as described in Equation 5. As moisture content increases, there is a clear and dramatic decrease in the MoR and the MoE. It is because of this well-defined and documented relationship that adjustment of these numbers is required before attempting comparative analysis of materials of the same species with different moisture contents.

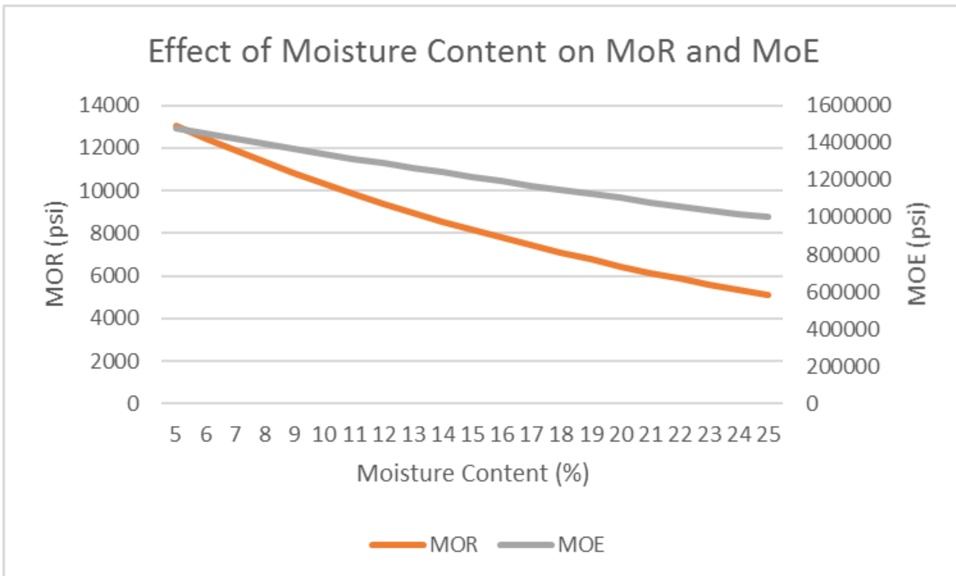

Figure 4: This figure shows the relationship between both the MoR and the MoE as described by the Equation 5. 12% moisture content is the standard at which dry wood numbers are reported, but in this study moisture contents averaged closer to 7%.

Heat Content and Lignin/Cellulose Testing

Samples were ground using a Wiley Mill in preparation for testing in an adiabatic bomb calorimeter by which the heat content for each sample was computed. A 0.5mm screen was used in the grinding process insuring a consistent final product. Wood samples from all the sticks within a tree-height section were aggregated during the grinding process, allowing tree-height sections within the tree to remain separate. Thus, strength-tested wood from each height level within each tree was evaluated for heat content.

Heat Content Sample Marix			
Years Dead	**Mortality Code**	**Sample Type**	**Number of Tests**
Young	1	Beetle/Fire	93
Old	2	Beetle/Fire	96
Control	3	Green/Dried	43
Total			**232**

Table 2: Heat content sample matrix showing number of samples tested from each of the mortality groups and age classes. A total of 232 test were conducted among all groups.

Heat content of the samples were measured using standard bomb calorimetry lab techniques (ASTM D5865-13). Table 2 shows the heat content sample matrix. 232 tests were conducted on the samples with a minimum of two replicates per sample. If the calculated net heat content (see Equation 3) for both replicates was within 10% of each other no further replicates were performed. If the tests differed by more than 10%, then a third replicate was tested. This protocol allows for efficiency in testing as well as accuracy and redundancy in measurements.

$$J = \left[\frac{(\Delta T * 2402) - (C * 4495.02)}{S}\right] * 4.184$$

where:

J= joules

ΔT= change in temperature (c)

C= capsule weight

S= sample weight

Equation 6: Net energy produced from test

Using Equation 7, which is a modified version of an equation published by White (White, 1987), we were able to take the results of the calorimeter testing after running them through Equation 6 and quantify the amount of holocellulose and lignin in each sample.

$$C = \frac{HC - 24}{7.3}$$

Where:

C= cellulose percent

HC= observed heat content (MJ/Kg)

24= heat content of lignin (MJ/Kg)

Equation 7: Equation for determining the percentage of cellulose in sample

The equation is modified in the form that we used a weighted ratio of cellulose to hemicellulose with slightly different values form those used in White's paper. White used a heating value of 18 MJ/Kg to define cellulose, but after consulting other sources that cite the heating value of cellulose lower around the 16 MJ/kg mark and hemicellulose as low as 15 MJ/Kg it was decided that a weighted value of 16MJ/Kg for cellulose and 15 MJ/Kg for hemicellulose at a ratio of 70/30 would be used for these calculations (Petterson, 1983). Giving an overall heating value of 15.7 MJ/Kg for holocellulose.

Lignin percentage of the sample was derived by simply taking one minus the cellulose percentage (White 1987), from Equation 7, see Equation 8.

Equation 8 Lignin Content

$$L = 1 - C$$

Where:

L=lignin percentage

C= cellulose percentage

Equation 8: Percentage of lignin in sample

The volumetric heat content of the samples was calculated by multiplying the specific gravity of the sample by the samples corresponding heat content. This calculation gives a measure of the heat content of based up on its density on a volume scale Equation 9.

Equation 9 Volumetric Heat Content

VHC=SG*HC

Where:

VHC= Volumetric Heat Content

SG= Specific Gravity

HC= Heat Content

Equation 9 Calculation for volumetric heat content of a sample. This calculation of potential or stored energy is based upon the samples density and volume.

Results

Moisture Content

Static bending tests for the control group were carried out on both green samples and a set of samples dried to more closely match the average moisture content of the non-control trees. Table 3 shows the samples segregated by group and assigned a moisture code for easier identification. As shown, sampled trees across all age groups, as well as the dry control group, all had very low moisture contents. None had a mean that exceeded 9.6%, and the overall mean for groups 1 and 2, was 7.3%. The variability within groups 1-3 was also low with standard deviations within individual groups ranging from a low of 0.49% in the Old snag group, to a high of 1.65% in the dry control group. This is shown graphically in Figure 5 as well.

Moisture Content			
Group	**Moisture Code**	**Mean**	**SD**
Young	1	6.7	1.28
Old	2	7.8	0.49
Dry Control	3	9.6	1.65
Green Control	4	39.9	27.42

Table 3: Table showing the mean and standard deviation of moisture contents for all age classes as well as the dry and green control groups. It is worth noting how small of a standard deviation groups 1-2 have.

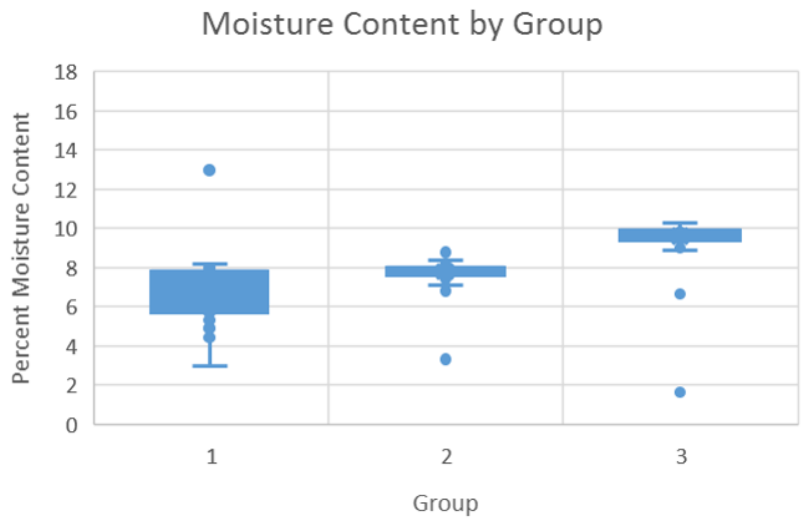

Figure 5: Moisture content distributions for moisture groups 1-3 from Table 3. These distributions are very tight with minimal deviation from the mean as also indicated in Table 3.

As depicted in Table 3 and Figure 6, the green control group was not only significantly higher in moisture content, but also had much higher variation within the group.

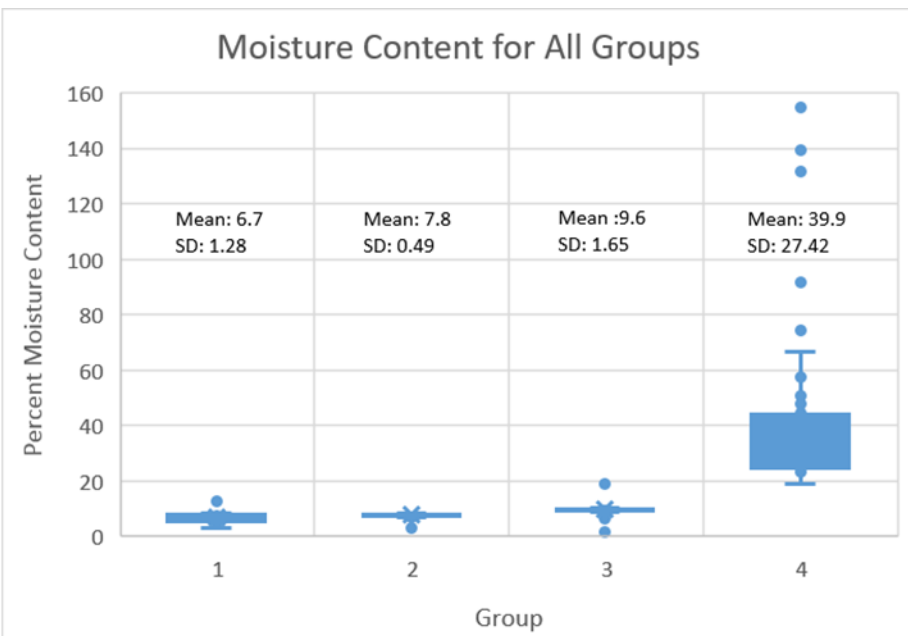

Figure 6: Here we see the distinct difference between groups 1,2 and 3 from group 4. It was expected that group 4 (green control) would have a much higher average moisture content and standard deviation.

Specific Gravity

Sample test sticks used in the MoR and MoE testing, were sampled for determination of gravimetric dry basis moisture content and oven-dry volume/oven-dry weight specific gravity.

Using a two-wan ANOVA to analyze the significance of disturbance, age and the interaction of the two on specific gravity showed that only the Age factor reported any significance Table 4.

Specific Gravity ANOVA Output Table	
Factors	P-value
Disturbance	0.072
Age	0.013*
Disturbance*Age	0.388

Table 4 Output table for the two-way ANOVA used to analyze the governing factors on the specific gravity of the samples. Note: P-values delineated with (*) are considered significant.

Since age was found to be the only significant factor influencing specific gravity, subsequent analysis of specific gravity was based upon this factor. Figure 7 shows the distribution of the specific gravities of the mechanical testing sample sticks by age group.

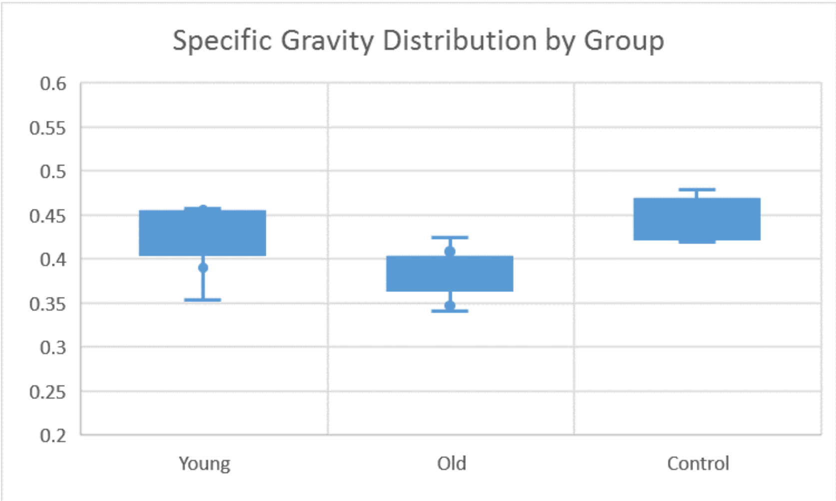

Figure 7: Specific gravity distribution of samples as separated by age group. Note the depressed specific gravity of the "old" age class. This can be an indication of decay within the wood.

Although there is obvious overlap between the groups, comparative analysis using t-tests, shows significant differences. Statistical analysis shows no difference between the means of the Young snag group and the Control group, where p= 0.698, but both of those groups differed from the Old snag group with p-values of $1.7E^{-12}$ and $2.4E^{-11}$ respectively.

Figure 8 shows specific gravity separated not only by age class, but also the cause of mortality, and section within the tree (vertical position in the tree Figure 1). As shown by Kotch in his publication on southern yellow pine in 1972 there is a negative relationship between height in a tree and specific gravity. Here we can see this trend shown nicely when we view the specific gravity of the Control group as profiled vertically through the tree. The other four groups also show signs of this relationship although they deviate from the slope of the control line. This deviation from the control is most notable for both the Old Beetle and Fire groups. This again shows the effect that age since death plays as a factor on specific gravity.

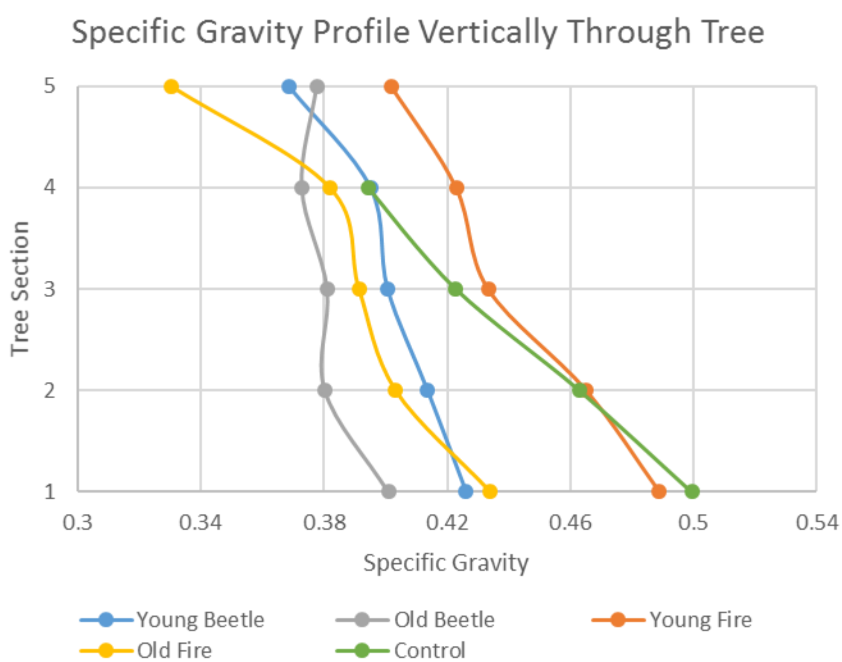

Figure 8: Mean specific gravity by age, mortality type and section within the tree. Seen here is the relationship between specific gravity and height in the stem. Across all mortality groups and age classes there is a trend for specific gravity to decrease as height up the tree increases.

Modulus of Rupture

Static bending tests for modulus of rupture determination were done for all sample groups in the study. Tests for the control group were carried out on both green samples as well as samples dried to match the moisture content of the snag samples. As shown in Figure 9, the green control samples closely mimic the results found to be standard for green ponderosa pine as reported in the ASTM standards and the Wood Handbook. The mean observed green control MoR differs from the literature reported MoR by only 4.43%.

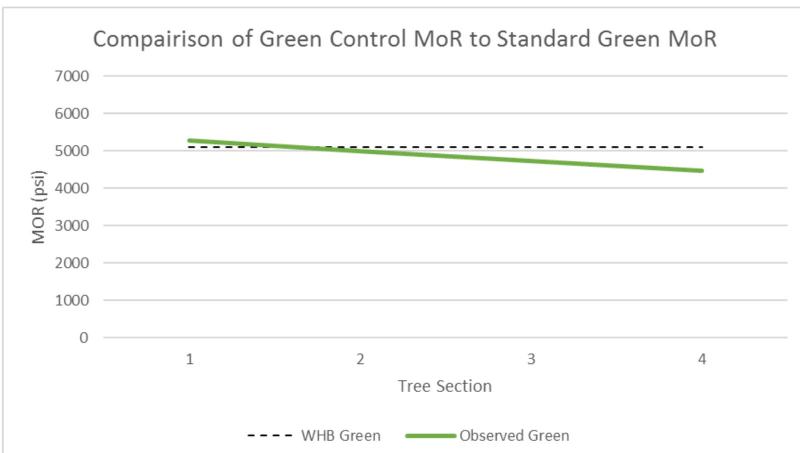

Figure 9: This figure shows both the observed green control MoR for the samples tested and the standard MoR for green ponderosa pine as determined by the ASTM standards and the USDA's Wood Handbook. Although the observed data shows an average deviation of 4.43% from the standard measure, this is not considered a significant difference.

The dry control MoR tests showed more deviation from those reported in the Wood Handbook, deviating by 22.44%. After the difference in moisture content was accounted for, and the published MoR corrected from 12% moisture content, to 7% moisture content using Equation 5, the dried control samples closely fit the published data. Deviating by only 3.22%, Table 4.

Group MoR Averages and Differences			
Group	**Averages (psi)**	**12%**	**7%**
Young Beetle	7717.66	-17.90	-35.10
Old Beetle	7528.14	-19.91	-36.70
Young Fire	11147.41	18.59	-6.26
Old Fire	6850.38	-27.12	-42.40
Dry Control	11509.28	22.44	-3.22

Table 5: MoR averages by group as well as percent difference from published mean MoR from the Wood Handbook (12%) and the moisture content corrected mean MoR (7%).

Table 4 depicts the average MoR by group, and the percent deviation of each group from the MoR standard. As can be seen above, the Young Beetle group has an average MoR of 77717.66psi (534.84 MPa) This average is 17.9% lower than the published standard for ponderosa pine at 12% moisture content. This difference in MoR is further accentuated once the standard is corrected for the lower moisture content at which this testing occurred. Correcting for moisture increased the difference in observed MoR to 35.1% below the expected value from a clear straight grained sample of ponderosa pine at 7% moisture content. The Young Fire group although also having a lower average MoR than suggested by the literature, only differed by 6.26% from the adjusted MoR. Both the Old Fire, and the Old Beetle groups average MoRs are well below the moisture corrected standard. These being 42.40% and 36.70% below the corrected standard respectively.

T-tests were conducted and a significance value of 0.05 used on the Modulus of Rupture data to determine statistical difference. Comparisons were done between mortality vectors and within vectors between groups. All groups were also compared against the dry control group as a test of deviation from the expected.

Significance of Difference Between MoR Groups					
	Old Beetle	Young Fire	Old Fire	Total Fire	Dry Control
Young Beetle	0.7295	0.0034	0.4910		0.0001
Old Beetle		0.0002	0.7938		
Total Beetle				0.5496	2.6E-05
Old Fire		0.0002			
Dry Control	2.7E-06	0.1948	3.9E-06	0.0004	

Table 6: Corresponding p-values are reported for each of the T-tests run on the MoR data set. A 0.05 significance level was used when determining statistical difference.

As Table 5 shows, no significant difference in MoR was found between the Young and Old beetle groups, as a calculated p-value was 0.7295. Both the Young and Old Beetle groups showed differences from the dry control group with p-values well below the 0.05 significance threshold of 0.0001 and $2.7E^{-06}$. When the entire beetle-killed group is compared collectively to the dry control group, a significant difference is found with a calculated p-value of $2.6E^{-05}$. Unlike the beetle group, the MoRs for the Young and Old fire groups showed a difference between themselves with a p=0.0002. Unlike with the beetle mortality groups the Young fire group showed no significant difference from the control group with a p-value of 0.1948. Like the beetle mortality group, the fire group collectively showed a significant separation from the control group as well. Although the Young beetle and fire groups differed significantly in their observed MoRs, these being 7717.66 and 11147.41 psi respectively, as well as showing significant difference when a t-test was applied, p=0.0034, it is worth noting that the Old beetle and fire groups showed no significant difference, with MoRs of 7,528 psi (51.9MPa), and 6850 psi (47.23 MPa) respectively, and a p-value of 0.7938.

The previous findings would suggest that although initially there is a difference between the MoR results based upon disturbance type, but that the difference no longer exists by the second age class. To more clearly show this, a two-way ANOVA was run. The results from the ANOVA are depicted below in Table 7, Figure 10 and Figure 11. In Table 7 we see that

Disturbance does not show significance with a p-value of 0.096. Age does show significance as does the Disturbance*Age interaction term with p equaling 0.011 and 0.040 respectively.

Modulous of Rupture ANOVA Output Table	
Factors	P-Value
Disturbance	0.096
Age	0.011*
Disturbance*Age	0.040*

Table 7 Output table for two-way ANOVA run on the MoR data. Here we see corresponding P-values for the various factors tested. Note: P-values delineated with (*) are significant.

In the graphic depicting the least squares means for Age in Figure 10 there is clear separation of the two points indicating potential significance as verified by the p-value in Table 7. Also in Figure 10 the least squares means for Disturbance are plotted and they show much less separation between the points and almost no separation between the error bars. This conversely would indicate low if any significance, and again this is shown by a nonsignificant p-value in Table 7 of 0.096.

Figure 10 Least squares means of Age and Disturbance as produced using SYSTAT© for the MoR data. In this figure, we see evidence of the Age term showing significance whereas the Disturbance term shows none.

Figure 11 displays the least squares means for both disturbance types and how they change between age classes. The difference in MoR seen between Beetle kill and Fire killed trees that is evident in the Young trees disappears as we transition to the Old age class.

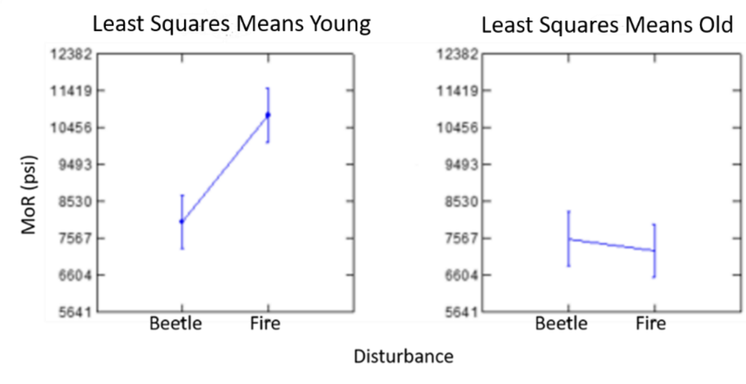

Figure 11 Least squares means as produced using SYSTAT© plotted form the ANOVA run on the MoR data. Any difference shown in the MoR between disturbance type in the young age class all but disappears by the time the old age class is sampled.

A downward trend in MoR as height up the bowl increases is seen for all groups as shown in Figure 12. Three of the mortality and age groups display a noticeable increase in MoR from section one (closest to the ground) to section two (centered at 20% of stem height, Figure 1). Above this height in the tree, the downward trend in MoR proceeds for sections three, four and five.

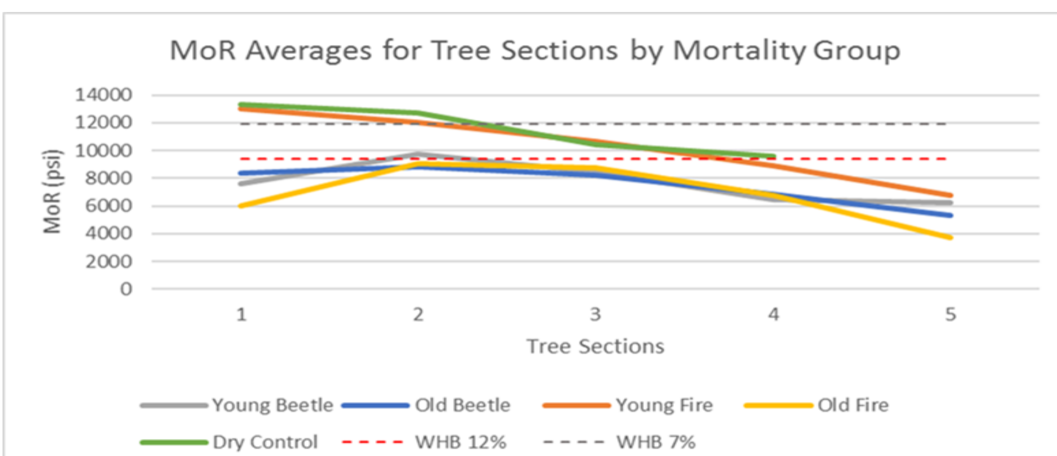

Figure 12: Changes in MoR over the length of the stem for each of the mortality groups and age classes. For all groups, there is an overall loss in MoR as height up the stem increases. All groups other than the Control and Young Fire group saw an increase from section one to section two then a fall in MoR through the remaining sections.

These increases in the MoR from the first to second sections of the tree occur in both the Young and Old Beetle killed groups as well as in the Old Fire mortality group. For these groups, there is a 27.61, 6.19, and 50.67% increase in MoR between the first and second sections respectively, Table 8.

Percent Change In MoR Between Tree Sections				
Group	**1-2**	**2-3**	**3-4**	**4-5**
Young Beetle	27.61	-14.77	-31.01	-3.54
Old Beetle	6.19	-7.32	-20.41	-28.28
Young Fire	-7.32	-13.01	-19.52	*
Old Fire	50.67	-3.92	-29.23	-82.69

Table 8: Percent change in MoR between tree sections. Note missing data delineated by an (*) are due to lack of samples caused by damage from the felling process.

Modulus of Elasticity

The modulus of elasticity (MoE) was also calculated for each of the samples using the data collected from the static bending tests that produced the observed MoR. As with the MoR, a moisture correction was done on the standard MoE reported in the ASTM standards and the Wood Handbook to account for the lower moisture content of our samples. This correction was done for all samples except for the comparison of the green control to the green standard as these moisture contents were already comparable. The MoE for the green control samples deviated from the standard MoE for ponderosa pine by 9.54%. The green control MoE and the standard number published in the Wood Handbook are 904,586 psi (6236.9 KPa) and 1,000,000 psi

(6894.8 KPa) respectively. From the Wood Handbook we are given an average MoE for ponderosa pine (dried to 12% moisture) of 1,290,000 psi (8894.2 KPa) (Forest Products Laboratory - USDA, 2010), in Table 9 we see the average MoE for each group and how they compare to the number from the Wood Handbook at 12% moisture and that number adjusted to 7%. It is with this number that the dried control group as well as the other groups are compared against. The dried control group very closely matched the adjusted MoE, only deviating by 0.93%.

Group MoE Averages and Differences			
Group	**Averages (psi)**	**12% diff**	**7% diff**
Young Beetle	893689.97	-30.72	-37.19
Old Beetle	1113316.57	-13.70	-21.75
Young Fire	1299783.44	0.76	-8.64
Old Fire	1075186.95	-16.65	-24.43
Dry Control	1436006.79	11.32	0.93

Table 9:Differences between observed group MoE and standard MoE from the Wood Handbook (12%) as well as the difference between the observed group MoE and moisture adjusted MoE (7%).

Similar trends were observed with the MoE as were with the MoR when the groups are separated and their means compared to the adjusted MoE. The Young Beetle group showed an MoE 37.19% lower than the adjusted MoE. The Young Fire group falls 8.19% below the same measure. The Old Beetle and Fire groups show a higher reduction in MoE than the Young Fire group but less than the Young Beetle group deviating from the adjusted MoE by 21.75% and 24.43% of the adjusted MoE respectively.

Inter and intra mortality group comparison was done again using t-test analysis as it was for the MoR comparison. The results of the t-tests are shown in Table 10. There is a significant difference found when the Young Beetle group is compared to the Old Beetle group with p-values for these tests calculated at 0.0073 and 0.0004 respectively. In the Fire mortality group the Young and Old groups showed statistical difference during comparison with a p-value of 0.0184. As with the MoR, Young Beetle and Young Fire groups showed significant differences in MoE as well. When compared against each other a p-value of $6.9E^{-06}$ was shown. Interestingly as well, when the Old groups of each mortality type were compared against each other, there again was no difference shown, p= 0.7960. The Beetle and Fire groups show differences with the test statistic falling right at the significance level of 0.05 with a p-value of 0.0532. When all groups were compared against the dry control, all were found to be significantly different from it except the Young Fire group with a p=0.2698

Significance of Difference Between MoE Groups					
	Old Beetle	Young Fire	Old Fire	Total Fire	Dry Control
Young Beetle	0.0073	6.9E-06	0.0093		4.2E-07
Old Beetle		0.0049	0.7960		
Total Beetle				0.0532	0.0002
Old Fire		0.0184			
Dry Control	0.0002	0.2698	0.0009	0.0110	

Table 10: Reported P-values for MoE mortality and age groups.

A two-way ANOVA was also run on this data and the results are displayed in Table 11, Figure 13 and Figure 14. In Table 11 we see that the Disturbance factor shows significance with a calculated p-value of 0.004 as does the interaction term of Disturbance*Age also with a p-value of 0.004. Age is not found to be significant as it has a p-value that is far larger than the 0.05 significance level, this being 0.968. These finding correspond with the p-values found in Table 10 above where there is mild significance of difference found between the Total Beetle group and the Total Fire group suggesting that Disturbance is a significant factor.

Modulous of Elastisity ANOVA Output Table	
Factors	P-Value
Disturbance	0.004*
Age	0.968
Disturbance*Age	0.004*

*Table 11 ANOVA output table for MoE data. Both the Disturbance and Disturbance*Age interaction term showed significance with p-values below the 0.05 significance level. Age did not show significance. Note: P-values delineated with (*) are significant.*

Looking at a graphical depiction of the least squared means for both the Age and Disturbance terms in the ANOVA it is clear that Age shows no significance at the 0.05 level. The least squared means for Age were 1,115,989 psi (7694.47 MPa) for the Young age class and 1,113,479 psi (7677.17 MPa) for the Old age class. There is almost complete overlap shown in the error bars as well. The Disturbance term shows clear significance with least squares means being 1008147psi (6950.93 MPa) for the Young age class and 1221322 psi (8420.72 MPa) for the Old age class. The high separation between the two plotted points reinforces the level of significance seen in Table 11 with a p-value of 0.004.

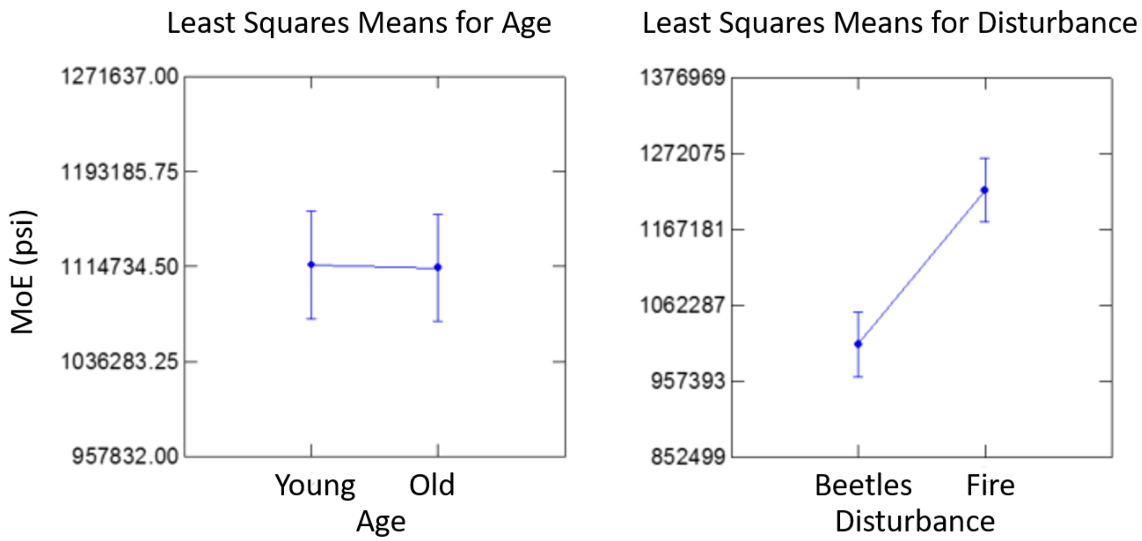

Figure 13 Least Squares Means of Age and Disturbance for the MoE data as produced using SYSTAT©. In this figure, we see evidence of the Age term showing no significance as there is no

separation of the plotted pints and almost complete overlap. The Disturbance term does show evidence of significance with good separation between plotted points and no overlap of the error bars.

As previously seen in the same plots for the MoR data, Figure 14 illustrates the change that occurs over time within the mortality or disturbance types. Initially in the Young age class there is a distinct difference between the Beetle mortality group and the Fire mortality group with the Fire group having a much higher MoE. As we change to the Old age class there is a profound drop in the represented value for the Fire mortality group, to the point that it is almost equal to the value for the Beetle mortality group.

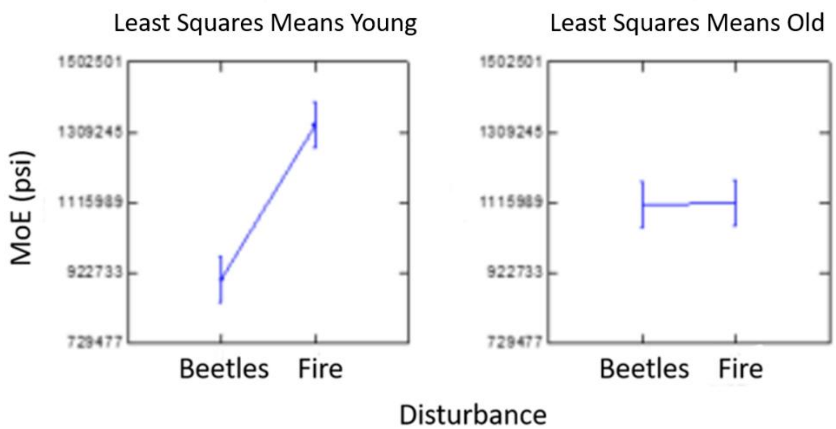

Figure 14 Least squares means of disturbance by age class for the MoE data set as produced using SYSTAT©. As before, the difference in values seen between disturbance types in the Young age class is no longer maintained in the Old age class.

The trends for MoE between sample groups as well as vertically through the tree are not as clear as those for the MoR but there are general similarities. Figure 15 illustrates trends seen vertically through the tree in relation to the MoE value. In general, there is a loss of MoE across all both mortality types and age groups. The Young Beetle group does show a lower MoE value for section one than it does for any of the other sections but the trend of decreasing MoE as section increases holds true starting with section two of that group.

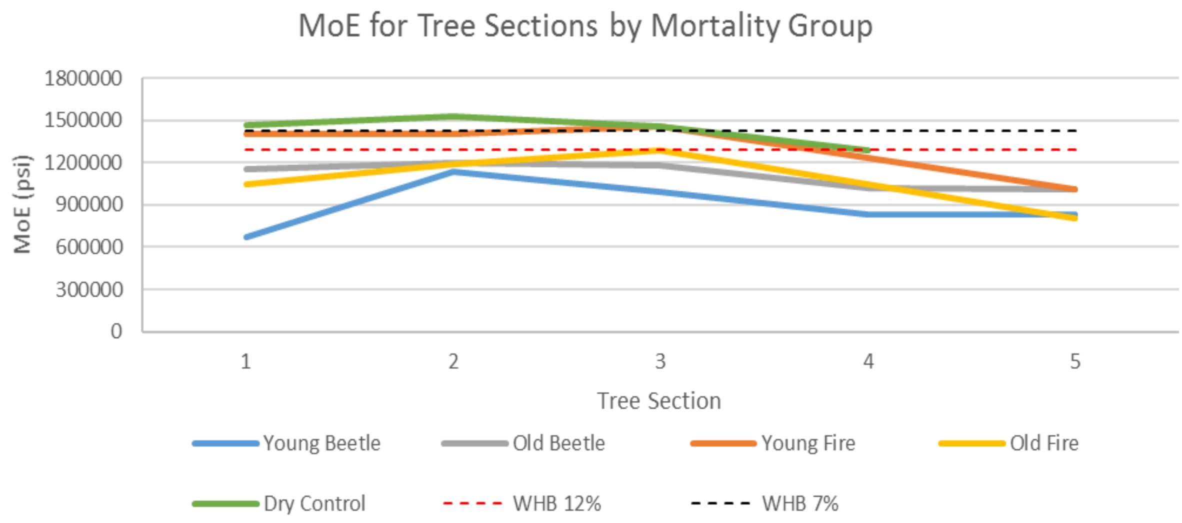

Figure 15: MoE averages by mortality group as going vertically through the tree. Refer to Figure 1 for section specifics. We see similar trends as with the MoR and the specific gravity. There is a tendency for the MoE to decrease as height up the stem increases. We also see the values for most groups well below what is expected from the Wood Handbook.

An increase in MoE between section 1 and 2 was observed for all groups except Young Fire as is shown in Table 12. As with the MoR, the Young Fire group did not see an increase between sections 1 and 2, in fact a negligible decrease of 0.05% was seen between these sections. As height up the tree progresses (moving from section 1 through section5) the Old Beetle group showed continued although variable loss. Both Fire mortality groups show an increase in MoE from section 2 to section 3, but then show the expected decrease starting in section 4 and continuing to section 5.

Percent Change In MOE Between Sections				
Group	**1-2**	**2-3**	**3-4**	**4-5**
Young Beetle	69.15	-12.58	-16.43	-0.24
Old Beetle	3.70	-1.28	-14.12	-0.28
Young Fire	-0.05	3.83	-15.50	-17.89
Old Fire	13.99	7.85	-18.70	-23.34

Table 12: Mean percent MOE change between sections

Holocellulose to Lignin Ratio

The heat content of the samples was calculated using adiabatic bomb calorimetry. This testing resulted in a heating value for each sample measured. Using White's equations (Equation 7 and 8) this heating value was converted into the percentage of holocellulose and lignin within the sample. These percentages were then converted into a ratio representing the percentage of holocellulose to lignin. The mean ratio values for each group are shown in Table 13 and Figure 16 shows the holocellulose to lignin ratios for each group separated by section within the tree.

Mean Holocellulose to Lignin Ratio by Group	
Young Beetle	1.04
Old Beetle	1.49
Young Fire	1.85
Old Fire	2.26
Control	1.48

Table 13 Here are shown mean ratio values for each mortality group. These ratios depict the prevalence of holocellulose to lignin with in the samples. Lower ratios indicate decay and a lowering of the holocellulose component of the wood structure.

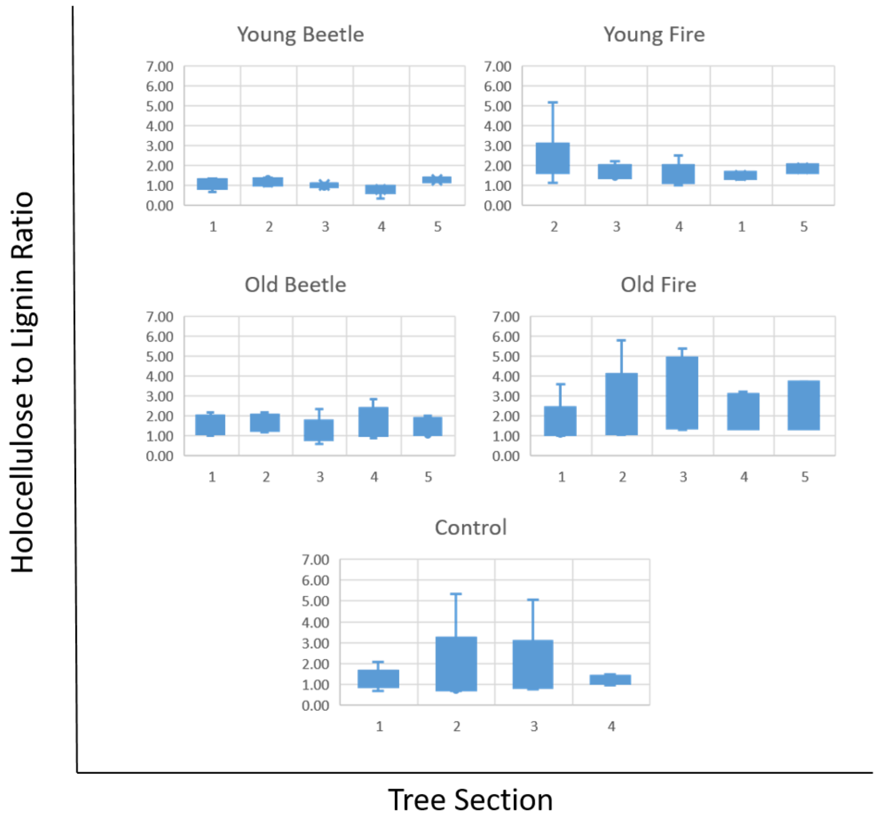

Figure 16 Depicts the holocellulose to lignin ratios for each mortality group separated by section within the tree. Note that the none of the trees sampled for the control group had an intact section 5 hence a lack of data depicted

When the holocellulose and lignin values for the samples were analyzed using a two-way ANOVA only the Disturbance term was shown to be significant. The Age term as well as the interaction term showed no indication of significance, Table 14.

Holocellulose to Lignin ANOVA Output Table	
Factors	P-value
Disturbance	0.053*
Age	0.176
Disturbance*Age	0.964

Table 14Two-way ANOVA output table showing the significance of the factors tested. The only factor shown to be significant is that of disturbance. Note: P-values delineated with a (*) are considered significant

When looking at the least squares means of the holocellulose to lignin ratios plotted for disturbance and separated by age in Figure 18, we see that the mortality vector, or “disturbance” that causes the tree to die seems to have a lasting effect on the holocellulose to lignin ratio of the tree. Even as the trees move from the Young age class to the Old age class the trend of the Fire group having a measurably higher holocellulose to lignin ratio continues.

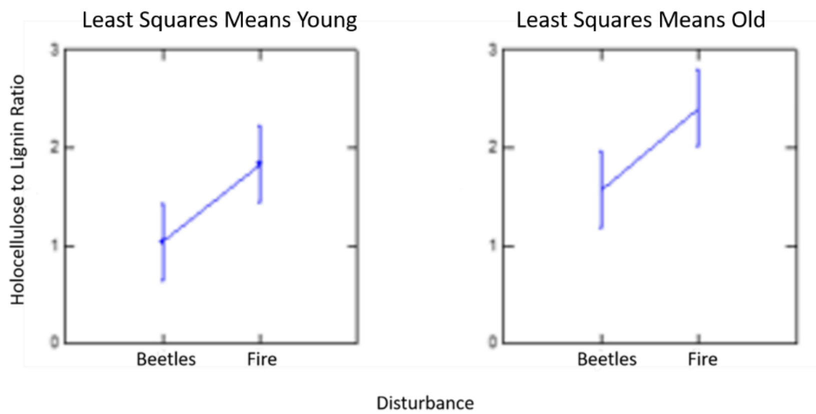

Figure 17 Least squares means as produced by SYSTAT© of Disturbance type by Age class for holocellulose to lignin ratio data. Unlike previous data that has been seen in this study the differences seen in H:L that are seen in the Young age class maintain into the Old age class. This differs from what has been seen within the MoR and MoE data

.

Volumetric Heat Content

The volumetric heat content of the samples was calculated by multiplying the specific gravity of each sample by its corresponding heat content. This measure represents the energy content of a sample in relation to its density. When the volumetric heat content was calculated for each of the age classes and mortality groups and a two-way ANOVA was performed only the age term was shown to be significant. Neither the Disturbance term nor the interaction term were remotely close to the 0.05 significance cutoff level Table 15.

Volumetric Heat Content ANOVA Output Table	
Factors	P-Value
Disturbance	0.749
Age	0.027*
Disturbance*Age	0.912

Table 15 ANOVA output table for volumetric heat content data set. Age is the only factor that shows any significance with a p-value below the 0.05 significance level. Note: P-values denoted with a (*) are considered significant.

Figure 19 shows the least squares means for both mortality types at both age classes. No difference between disturbance types is shown but a difference can be seen between age classes. The old age class shows a lower volumetric heat content for both the beetle mortality group as well as the fire mortality group than does the Young age class.

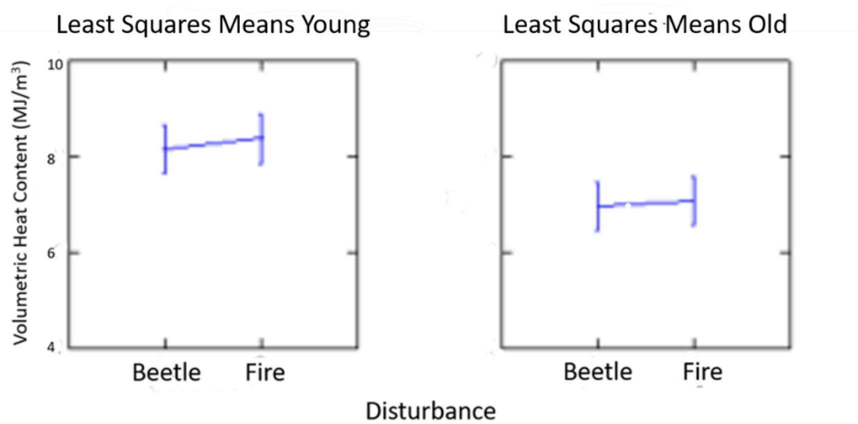

Figure 18 Plotted least squares means as produced by SYSTAT© for volumetric heat content of samples for both mortality types by age class. Volumetric heat content can be seen to drop between age classes regardless of mortality type intimating that as a snag ages the energy available to be released upon combustion is reduced.

Discussion

Modulus of Rupture/Elasticity and Specific Gravity

The ecological environment associated with post disturbance landscapes varies greatly both within and between disturbance types. Any discussion and quantification of the changes in standing dead timber needs to take into consideration the wide array of variables that impact the trajectory upon which snags can embark. The structural integrity of snags can be evaluated by obtaining an estimate of their modulus of rupture and modulus of elasticity. These two measurements are commonly used to measure the maximum load able to be supported by a material before failure (MoR) and the ability of that material to deform or bend and then return to its original state before the strain was applied (MoE). The benefits of testing these two moduli are that we can begin to compile a complete “picture” of the structural qualities of a material. Not only is a measure of strength garnered by calculating the MoR but by following these ASTM standards any variation in terms of sample width, thickness, slope of grain, and location of knots is mitigated and accounted for. The same is true for the calculation of the MoE.

In this study, we were not only able to compile and compere the modulus of rupture and modulus of elasticity for both beetle and fire killed trees over a segment of the post mortem spectrum but we were also able to gather a vertical profile of how the structural properties of snags change throughout the tree. It has been known for years that the density of wood, which is measured as specific gravity, decreases the higher up the stem it is sampled (Kotch 1972), but we are now able to see how the MoR and MoE change as the height increases. In Figure 12 we see the relationship between the MoR and height in the tree. There is an overall lessening in MoR as height up the tree increases. This relationship is expected due to the change in ratio of mature wood to juvenile wood as you increase in stem height (Forest Products Laboratory - USDA, 2010). As stem height increases the cross section of the stem becomes dominated by juvenile wood resulting in a lower overall measure of specific gravity and mechanical properties. Again, in Figure 12 we see the Dry Control group follows this pattern as well suggesting this is a normal progression and not a unique characteristic of dead trees. All the groups followed this general trend but with some variations. The Young Beetle, Old Beetle and Old Fire groups all showed distinct increases in MoR from the first section in the bowl to the second section before starting to lose MoR value, Table 8. These increases were greatly varied and ranged from a 6.19% to a

50.67% increase MoR. The increase from the first to second sections are also seen in the MoE data, Figure 15 and Table 12. Again, the Young Fire group is the only group that does not follow this pattern. One possible reason for these first sections having a lower modulus of rupture could be the presence of snowline in this area of the stem. Even with the bark jacket still intact, as it was on all the trees sampled, the prolonged presence of moisture against the stem could be providing a more hospitable environment for decay fungi to take hold and proliferate.

The main result gathered from this study in terms of the MoR and MoE data, is how the difference in values between disturbance types seen in the Young age class, disappear in the Old age class. With both the MoR and the MoE the results show that in the Young age class there is a clear difference between the Beetle mortality group as compared to the Fire group. For both measures the Beetle mortality group falls below that of the Fire group as was seen in Figures 11 and 14. Equally as interesting is what else can also be seen in both of those figures. We also see that when the least squares means are compared in the Old age class for both the MoR and the MoE there is no longer any observable difference in the groups. Whatever caused the initial differences in the structural integrity of the snags as measured by the modulus of rupture and elasticity seems to have been negated over time.

The findings from the specific gravity data only somewhat coincide with what is seen in the MoR and MoE analysis. There is no indication that the disturbance that lead to mortality had any influence on the specific gravity of the trees sampled. Instead it was the Age factor that showed to be significant in characterizing this part of the data. The only discernable pattern seen in the specific gravity analysis was that the Young age class had higher values than did the trees in the Old age class, regardless of the vector of mortality. What becomes interesting is that if we are to believe as it has been shown before that MoR and MoE are both correlated to specific gravity

(Forest Products Laboratory - USDA, 2010), and specific gravity shows no influence based on disturbance, then why is there a distinct separation in MoR and MoE values in the Young age class based up on disturbance type?

An insight into the answer might come in the form of incipient decay. Previous work has shown that significant strength loss can occur during brown rot decay before a measurable effect can be detected in weight loss (Curling et al., 2001; Winandy & Morrell, 1992). In such a case as this, where there is no distinguishable difference in specific gravity yet a measurable difference in mechanical properties it appears a difference in the sensitivity of the measurements is at the root of the discrepancy. Specific gravity although correlated with MoR and MoE in clear straight grained specimens of wood quickly loses its correlation to these measurers of mechanical properties once there is decay added to the equation. The loss of predictive ability of specific gravity on MoR can be shown using this study if a correlation is calculated between the MoR and specific gravity for all the age classes and mortality groups. For the control group a correlation coefficient of 0.86 is shown and for the Young and Old beetle groups an r squared value of 0.60 and 0.61 is seen. The fit is even poorer for the Fire groups with calculated r squares of 0.55 for the Young group and 0.47 for the Old group. This shown loss of correlative ability is strictly due to the presence of decay in the samples, some of which is undetectable to the naked eye or at the scale to which specific gravity is measured. Even with the understanding of how the results for the MoR and MoE can have occurred even with the seemingly contradictory results of the specific gravity analysis, the question still stands as to why the difference in mechanical properties exists between beetle killed and fire killed trees.

The answer might lie in the differences of the post disturbance environment. On beetle killed sites, trees have not only been attacked by the beetles which breach their bark defenses but have also had blue-stain fungus, most likely *Grosmannia clavigera* (DiGuistini et al., 2011), introduced into the living vascular system, including the living phloem, vascular cambium and living axial and ray parenchyma of the sapwood as a symbiont of the mountain pine beetle. The hyphae of the stain fungus occupy and move through the ray cells, spreading into the tracheids by degrading the toris of and moving through bordered pits. In doing this the blue-stain fungus eventually disrupts the entire vascular system impeding the movement of nutrients and water and causing the tree to die(Ballard, Walsh, & Cole, 1984). The galleries created by the breeding adult beetles and their developing larva, loosen and separate the bark from the stem of the tree creating pathways and pore space for moisture to enter and accumulate. The lack of other disturbance in the stand leaves the existing fungal, bacterial and insect communities in the area intact allowing for rapid colonization and secondary infestation of the recently killed trees. Although mountain pine beetles have a large impact on the landscape in terms of dead trees along with eventual hydrological implications (Potts, 1984), their direct, or first order effects are relatively few. Mountain pine beetles have limited tree host species and do not directly cause other vegetation or plant mortality, although their disturbance does allow for the release of suppressed and understory trees as well as herbaceous, graminoid and shrub vegetation (A. Dhar, Parrott, & Heckbert, 2016; Amalesh Dhar, Parrott, & Hawkins, 2016). A site disturbed by mountain pine beetle has many of its ecological systems unchanged and intact.

The post fire environment is much different from mountain pine beetle disturbance. Fire is in and of itself is an indiscriminate source of vegetation mortality, and does not only kill vegetation but in many cases, consumes and removes that vegetation from the area. Many facets of a site are impacted once a fire event has occurred. Vegetation may have been killed, damaged and or fully consumed, while the duff and litter layers may too have been partially or fully destroyed. The soil may also have been impacted not only physically but also chemically (Verma & Jayakumar, 2012). It has been shown that the presence and intensity of fire in an area affects the soil biota and can cause a shift in the dominating fungal communities from basidiomycetes to ascomycetes (Penttilä & Kotiranta, 1996; Reazin, Morris, Smith, Cowan, & Jumpponen, 2016) thus impacting rates of decay. It is this highly-altered, post-disturbance environment that may be causing the observed difference in the MoR and MoE values between the disturbance types in the Young age class of this Study. The apparent lag in the observed fire mortality decay rates might not have so much to do with the effect of the fire on the tree itself but more importantly the effect of the fire on the larger surrounding area.

Holocellulose to Lignin Ratio and Volumetric Heat Content

Heat content data was collected for this study to better understand how the potential for energy release during a wildfire changes overtime and if the vector of mortality affects that potential. The conversion of the raw heat content data into a holocellulose to lignin ratio was used to compare the relative amounts of the two main components of woods' structure. As was seen in Table 14 and Figure 18 the Fire killed groups maintained a slightly higher ratio through both age classes although when tested the Disturbance factor showed only minor significance and neither of the other factors tested showed no significance at all. Not much was able to be garnered from this data. Further research would need to be conducted investigating not only the ratio or percentage of holocellulose to lignin in the sample but also the types of decay present. This would be done to better assess how much decay and of which kind is found in the samples and if the mortality groups showed differences in the decay communities that inhabit them.

Using the heat content data coupled with the specific gravity, a volumetric heat content was computed for each sample and modeled using a two-way ANOVA. The output table and least squares means are shown in Table 15 and Figure 18. Looking at Table 15 we see notice that the Age term of the model is the only significant factor. We expect this having used specific gravity to calculate this number and specific gravity also shows significance of the Age term when modeled. Disturbance type shows no significance here and this is clearly shown in Figure 18 with high overlap of the error bars and almost no difference in plotted means. Where there is a difference in Figure 19 is between the Young and Old age classes. This suggests that as the trees in this study aged and transition from the Young to the Old age class that there is a loss in the potential energy stored in those trees. This finding seems obvious and trivial enough as it would be expected for a snag to lose energy as time since death increases due to decay. What this finding does show is that when these trees do fall and become classified as a wildland fuel, their heating value is no longer that of sound wood. The lack of currently used fire models such as the Rothermel spread model (Rothermel, 1972), and the First Order Fire Effects Model (FOFEM) to consider the array of heating values that are on the landscape and the vast changes that take place between such ambiguous terms as “sound” and “rotten” is an oversight in current land management practices.

Developing better model inputs for heat content of fuels as they age, is an area where future research is needed to better classify the continual changes that take place on the landscape. The difficulties associated with quantifying the variables measured in this study across a watershed or even a single stand in terms standing dead timber from death, to when they fall, and beyond is daunting. But in a time where ever increasing acreage of our forest lands is seeing widespread disturbance resulting in dead trees, these questions can no longer be ignored and model inputs so broadly assumed. As our climate changes and land managers are forced to deal with new difficulties both naturally occurring, and anthropogenically induced, it would benefit all of us to see an increase in the accuracy of these management tools that are so heavily relied upon.

Conclusion Points

In this study, we sampled live and dead ponderosa pine in the attempt to characterize some of the physical and chemical changes that were thought to occur over time post mortem. It was also the goal of this study to determine if the type of disturbance that caused the mortality of the sample trees influenced the observations we recorded. These points that follow are the points of highest interest taken from the study.

- There was an observed difference in MoR and MoE values in the Young age class between the Beetle and Fire killed trees.
- The Observed differences seen for MoR and MoE in the Young age class were no longer seen in the Old age class
- Specific gravity measurements showed no difference mortality type in the Young age class, indicating a lack of sensitivity in the measurement as also seen in other studies.
- Environmental differences between post-disturbance sites could be driving the observed differences seen in the MoR and MoE.
- More research is needed with more narrowed goals to explore the analysis of the holocellulose to lignin ratio data.
- Observed significant drops in calculated volumetric heat content for values between the Young and Old age classes.
- More research is needed for improved model inputs for management applications.

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