Exploring the Relationship between Bark Beetle and
Drought Induced Tree Mortality in the Sierra Nevada

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ABSTRACT

From 2012- 2015 CA experienced one of the worst droughts in the state's history leaving a lasting imprint on California's forest health. When a tree is stressed, it puts all its energy into survival, impairing defense mechanisms against insects and pathogens. As a result, trees are left vulnerable to attack from outside forces, especially bark beetles. Studies attribute 86% of large tree mortality to insects and pathogens, crediting 40% specifically to bark beetles. To understand the dynamics between bark beetles and tree mortality in the Sierra Nevada after a period of prolonged drought, I analyzed tree mortality and bark beetle presence and variation for eight sites over the Sierra Nevada. I then tested predictor variables for their significance in predicting the presence of the western pine beetle and the fir engraver beetle. Out of eight sites analyzed, five showed spatial trends of bark beetle and tree mortality dynamics. In general, in sites with higher presence of bark beetle, an increased number of dead trees occurred. The highest prediction in the landscape for beetle presence and tree mortality occurred in Yosemite Pine Forest, with 79.3% beetle presence 44.2% mortality. The most reliable predictor variable for the western pine beetle in Yosemite National Park was basal area. Higher incidences of western pine beetle occurred in sites with higher basal area. In contrast, the strongest predictor of fir engraver beetle presence was tree density (trees per hectare). Fir engraver beetle population decreased as tree density increased.

KEYWORDS

Ecosystem ecology, forest management, geospatial analysis, predictor and response variables.

INTRODUCTION

Global climate change is causing temperature fluctuations across the world. In North American forests, this climate shift increased average temperatures and decreased precipitation leading to higher rates of tree mortality (Fettig et al 2007). Tree mortality has increased by a greater magnitude in places experiencing higher average temperatures and lower average rates of precipitation (Young et al. 2017). Consequently, historically warmer and drier areas will be affected the most by intensified temperature increases (Young et al. 2017). This finding dispels the hypothesis that forests located in places with historically higher average temperature and low precipitation will adapt to "drought" environment (Young et al. 2017). Accompanying an increase in average temperature, decreased average forest canopy water availability places additional stress on trees and forests become more vulnerable to prolonged periods of drought (Paz-Kagan et al. 2017). Moreover, tree mortality increases even after a drought periods have concluded (Paz-Kagan et al. 2017). The forests of Northern California are prime examples of forests being affected by temperature change.

Native species of bark beetles occur in Northern California (Raffa et al. 2008). In addition, they are a natural part of the forest ecosystem and contribute to the natural succession of a forest landscape (Raffa et al. 2008). Bark beetles kill trees by eating the phloem, subsequently cutting off access to nutrients to the tree (Kolb et al. 2016). When one tree species dies from beetle infestation, the canopy opens and the dead material cycles nutrients back into the soil, promoting forest succession and new tree growth. (Raffa et al. 2008). These new trees are often different species than the one that is being replaced, leading to a natural succession that helps promote a healthy forest mosaic (Raffa et al. 2008). However as result of increases in temperature, beetles are shifting to higher elevations, attacking vulnerable drought affected trees and rising in population (Mikkelson et al. 2013). Insects and pathogens are now responsible for 86% of large tree mortality with bark beetles accounting for 40% (Das et al. 2016).

Between 2012 and 2015, California experienced one of the worst droughts in the state's history. Drought-stressed trees are forced to direct energy away from defense mechanisms and into survival, leaving trees more vulnerable to beetle attack (Fettig et al. 2007). Resin, a trees natural defense against insects, functions to inhibit the beetle from making its way into the phloem (Fettig et al 2007 and Kolb et al. 2016). Resin contains terpene, a toxic chemical that then kills the beetle

(Fettig et al 2007 and Kolb et al. 2016). However, drought can hinder this automatic defense. When a tree is living under drought conditions, the stomata of a tree may close to preserve water, but this closure constrains terpene, hindering the trees defense mechanism (Kolb et al. 2016). In addition to lowering the efficiency of the tree's natural defenses, the increased temperatures during a drought provides a preferred environment for bark beetles (Kolb et al. 2016). As a result of the increase in warm winters, bark beetle mortality has decreased in the traditionally colder winter months (Kolb et al. 2016). Additionally, warm summer temperatures shorten the regeneration time of beetles (Kolb et al. 2016). The magnified consequences of drought on a trees defense and a beetle's regeneration combine in an ongoing threat to future forest management. An in-depth understanding of the variation of beetle infestation along a landscape and its correlation with tree mortality in different plots with different characteristics is important in tailoring management styles to be most effective at every location. Understanding the relationship between post drought conditions and its long-lasting effect on tree and beetle mortality will help plan for future droughts that are predicted to follow.

In this study, I address the central research question: What are the consequences of prolonged drought on bark beetle and forest dynamics in the Sierra Nevada? I will answer the following two questions to fully explore this main research goals: How does bark beetle presence and tree mortality vary along a landscape? What environmental, climatic, plot, or tree level measurements can act as predictors of specific beetle species?

METHODS

Study site

To further understand the interaction between drought and bark beetle mortality in trees in the Sierra Nevada, eight unique study sites with differing management style and ownership were tracked for tree mortality. The sites were chosen by Professor Jodi Axelson and Professor John Battles at the University of California, Berkeley as a part of their larger research project, understanding how massive tree mortality in the Sierra Nevada affects forest health, carbon storage and wildfire hazard (Axelson et al. 2017). All eight sites were a mixture of yellow pine and mixed conifer forests (YPMC) (Axelson et al. 2017). The eight plots differ in land managers (ie. National

forest, national park, etc.) and management style (ie. Old growth, reserve, etc). Plumas National Forest, Sequoia and Kings Canyon National Park, Yosemite National Park, Burton Creek State Park, Cottonwood Gulch Watershed (located in the Stanislaus National Forest) and Mountain Home State Forest are all old growth wilderness forest (Figure 1). Blodgett Forest Research Station is a second growth reserve (Figure 1). In addition, all forests differ in the extent of drought related mortality (Axelson et al. 2017).

Figure 1: Site Locations. All site locations and their placement throughout California can be seen here. All abbreviations are explained.

Study organism

To understand how bark beetle populations have fluctuated and how they interacted with the forest landscape, four species of bark beetle that are known to frequent the Sierra Nevada were tracked in each plot by the Axelson and Battles research team. The four bark beetle species important in this study are the Fir Engraver Beelte (*Scolytus Ventralis*), Jeffery Pine Beetle (*Dendroctonus Jeffreyi*), Mountain Pine Beetle (*Dendroctonus Donderosae*), and Western Pine Beetle (*Dendroctonus Brevicomis*). All of these beetles have different characteristics that make them unique and cause them to interact with the landscape in different ways (Table 1). Adult bark beetles reproduce by burrowing into a tree and then laying eggs in the phloem (USDA 2015). The phloem of a tree is the inner bark that consists of living tissue and transports organic compounds created during photosynthesis, like sucrose (USDA 2015). Once hatched, the larval beetles feed on the living tissue of the tree, cutting off nutrients (USDA 2015). Attacking beetles can release a pheromone that will attract other beetles of the tree (USDA 2015). This combined attack often results in tree mortality.

Table 1. Beetle Species Characteristics. Table laying out unique qualities of different species tracked in this study.

Species	Primary Tree Species attack	Newborn emergence time	Preferences	How many eggs	Source
Fir engraver	Fir (#1) Subalpine fir, Douglas fir, mountain hemlock and Engelmann spruce (#2)	June - September Most likely controlled by temperature (earlier emergence when warmer)	Prefers larger trees. Prefers larger diameter trees. Present with trees weakened by disease and often after with freshly windblown trees or recent logging slash	300 eggs – hatch within 2 weeks	Fir Engraver Beetle (Scolytus ventralis) | Nevada Division of Forestry. NDF. http://forestry.nv.gov/forestry-resources/forest-health/fir-engraver-beetle/

Jeffery pine beetle	Jeffery Pine	As early as April in warm years	Carries a fungus with it that helps kill tree by clogging vascular system. Single slow growing trees with reduced vigor	Eggs incubate 1-3 weeks	Jeffrey Pine Beetle (Dendroctonus jeffreyi)	Nevada Division of Forestry. NDF. http://forestry.nv.gov/forestry-resources/forest-health/jeffery-pine-beetle/
Mountain pine beetle	lodgepole, ponderosa sugar and white pines, pinyon pines, scotch pines	Summer months July – September	Carries fungus that stops water flow in tree	100 eggs- 10-14 days	Mountain Pine Beetle (Dendroctonus ponderosae)	Nevada Division of Forestry. NDF. http://forestry.nv.gov/forestry-resources/forest-health/mountain-pine-beetle/
Western pine beetle	Ponderosa pine	Late Spring	Large ponderosa pines (6")	Hatch in 1-2 weeks	Western Pine Beetle (Dendroctonus brevicomis)	Nevada Division of Forestry. NDF. http://forestry.nv.gov/forestry-resources/forest-health/western-pine-beetle/

Forest data collection

The data collected in each plot was used to help analyze the relationship between bark beetle and tree mortality two years after the 2012-2015 drought. Data was collected in all eight plots in 2017 and 2018. General random tessellation sampling was used to pick the plots within each study site, and this is the same design that is used by the national park service inventory and

monitoring program (Axelson et al. 2017). Each study site had 10-15 plots and plot sizes were standardized between 1.5-2 km^2 (Axelson et al. 2017). Each plot was measured using a circular fixed are design with a radius of 12.62m (Axelson et al. 2017). Axelson et al's (2017) study focused on overstory trees which are defined by having a diameter at breast height of 10cm or larger. I used the following variables: mortality of tree (live/dead), elevation, slope and aspect of each site, diameter at breast height (cm) (DBH), trees per hectare, basal area (cm), tree height (cm), average precipitation (cm), temperature (Celsius), height at live base at crown (cm), and canopy status (live/dead, vigor, snag). The most important data for the geospatial analysis was trees with evidence of beetle attacks and mortality of the tree (live or dead).

Analysis

Prediction Kriging and Spatial Analysis

To explore the relationship between drought and bark beetle induced tree mortality in the Sierra Nevada, I created spatially interpolated surfaces to characterize trends. To be able to spatially join bark beetle presence and tree mortality data to the sites within each plot, I took the average of both mortality and beetle presence for each site. Bark beetle presence and absence data were represented by ones (present) and zeros (absent) and tree mortality data (one = alive, zero = dead). These averages were then spatially joined to each site.

To create a spatial interpolation surface, I used simple prediction kriging in ArcGIS 10.6.1. (ESRI 2011). Simple prediction kriging uses known values to estimate the predicted values of nearby points. (ESRI 2011). Kriging uses the fitted model from variography, the spatial data configuration, and the values of the measured sample points around the prediction location, to predict values of unknown points (ESRI 2011). These resulting maps estimate where bark beetles are likely to occur across the landscape and where dead trees are expected. Before running the kriging analysis, I accounted for the variation in the number of trees recorded and sampled within each plot by using the decluster transformation. This transformation corrects for preferentially sampled data. Preferentially sampled data means a higher density of sample points were at some sites than others. I created spatial interpolation surfaces for all eight sites for both beetle presence and tree mortality.

The interpolation surfaces were created as temporary layers, so I converted them to raster layers. The resulting maps spatial patterns were then compared to determine where beetle presence and mortality coincide. To make these maps easier to interpret visually, I created a TIN for each plot using USGS digital elevation model data. The rasters were then overlaid on the TIN, allowing for the topography of each site to become more pronounced. Both the raster and the site location points were floated on top of the TIN surface.

Predictor and response variables

To test predictor variables of each beetle species presence, I used random forests algorithms and multivariate logistic regression. First, I narrowed down the species I would be testing based on where the data indicated high frequency of certain beetles. I focused on the Western Pine Beetle in both Yosemite Mixed Conifer plot and the Yosemite Pine plot. I also tested predictor variables for the Fir Engraver Beetle in the Cottonwood Gulch Watershed plot. To run an initial analysis of all predictor variables to narrow them down, I ran each through a random forest algorithm. I used DisplayR, a user-friendly data science and data visualization online software (Bock 2003). Random Forest works to construct a multitude of decision trees as training data and then outputs the class and predictions of individual trees. Random forests can be used to rank the importance of variables in a regression or classification problem. Features with large values are ranked as more important than features with small values.

To determine which variable had the greatest statistical significance as a predictor variable for each beetle species, I used multivariate logistic regression with the top 8 variables with the highest importance values in R-Commander 3.4.1 (Fox 2017). Multivariate logistic regression measures the affect of the predictor variables on the response variable. In this study, the predictor variables were the collected climatic, plot level, tree level, and site level data. The response variables included were the presence of each beetle species, Western Pine Beetle or Fir Engraver Beetle, represented as one (present) or zero (absent) in the respective plots. After all eight variables were run through multivariate logistic regression, I ran the statistically significant predictor values, less than 0.05, through multivariate logistic regression again to reduce covariance. Covariance describes the relationship two predictor variables can have on each other. In the second round of multivariate logistic regression, I also included slope as it was seen as an important predictor in

the Yosemite Pine Forest, and it had the potential to have been affected by covariance. By reducing the number of predictor variables run through multivariate logistic regression, the measure of these variables as predictors becomes more accurate. I graphed these predictor variables to examine the relationship between presence of each beetle species.

RESULTS

Bark beetle and drought induced tree mortality variation over the landscape

Simple prediction kriging revealed that five out of eight plots reflected spatial variation of predicted bark beetle presence and tree mortality surfaces. These five plots were Sequoia Kings Canyon National Park (Figures 2a and 2b), Yosemite Pine (Figures 3a and 3b), Cottonwood Gulch Watershed (Figures 4a and 4b), Plumas National Forest (Figures 5a and 5b) and Mountain Home State Forest (Figures 6a and 6b).

The highest prediction in the landscape for beetle presence occurred in Yosemite Pine Forest, with the highest predicted value of 79.3% beetle presence (Figure 3b). The highest predicted percentage of tree mortality in the Yosemite Pine Forest was 44.2% (Figure 3a). Yosemite Pine Forest had both the highest predicted presence of beetles and the highest predicted percentage of dead trees.

The lowest presence of bark beetle presence and tree mortality occurred at Plumas National Forest. The highest predicted percentage of beetle presence inside the plot was 2.95%, while the highest predicted percentage of dead trees found within the plot was 11.5% (Table 2).

Table 2: Spatial Analysis Results. Highest predicted percentages of both tree mortality and beetle presence for eight plots.

Plot	Beetle Presence Prediction	Tree Mortality Prediction
Sequoia Kings Canyon	29%	33.2%
Yosemite Pine Forest	79.3%	44.2%
Cottonwood Gulch Watershed	15.3%	5.49%
Plumas National Forest	2.95%	11.5%
Mountain Home State Forest	38.7%	30.8%
Yosemite Mixed Conifer Forest	7.86%	40.6%
Burton Creek State Park	3.06%	2.4%
Blodgett Forest Research Station	1.89%	11.6%
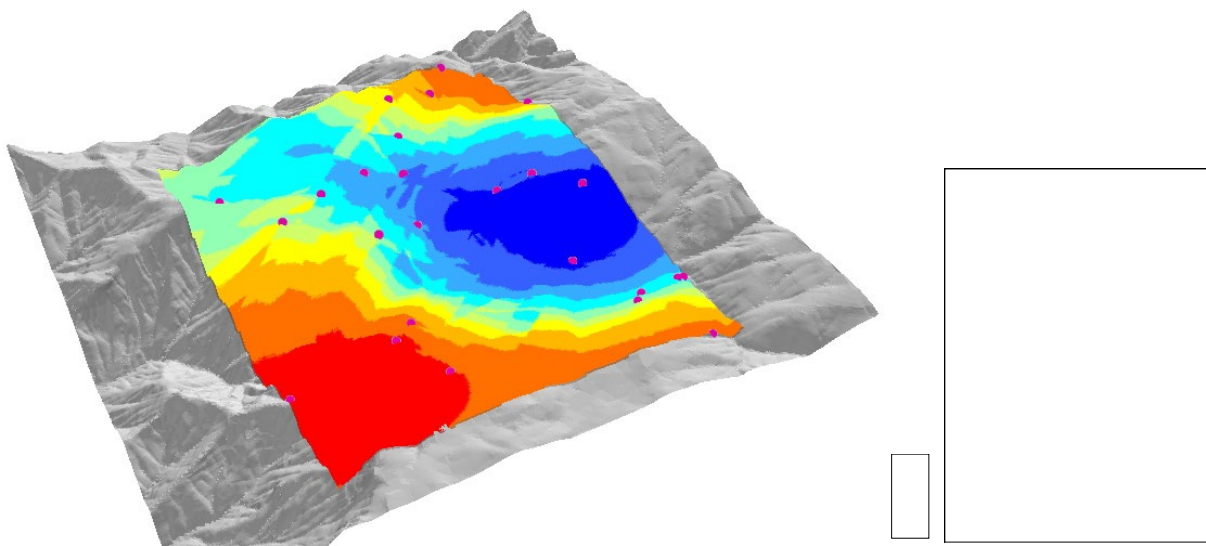
Figure 2a. Tree mortality Kriging surface of Sequoia Kings Canyon. Visualizes spatial interpolation of Alive/Dead trees. Red represents a high incidence of tree mortality, with blue representing a low incidence. The floating pink dots represent each site at which the data was collected. The highest probability of dead trees is in the Southwest quadrant of the plot. The highest incidence of tree mortality is 33.2% in this quadrant.
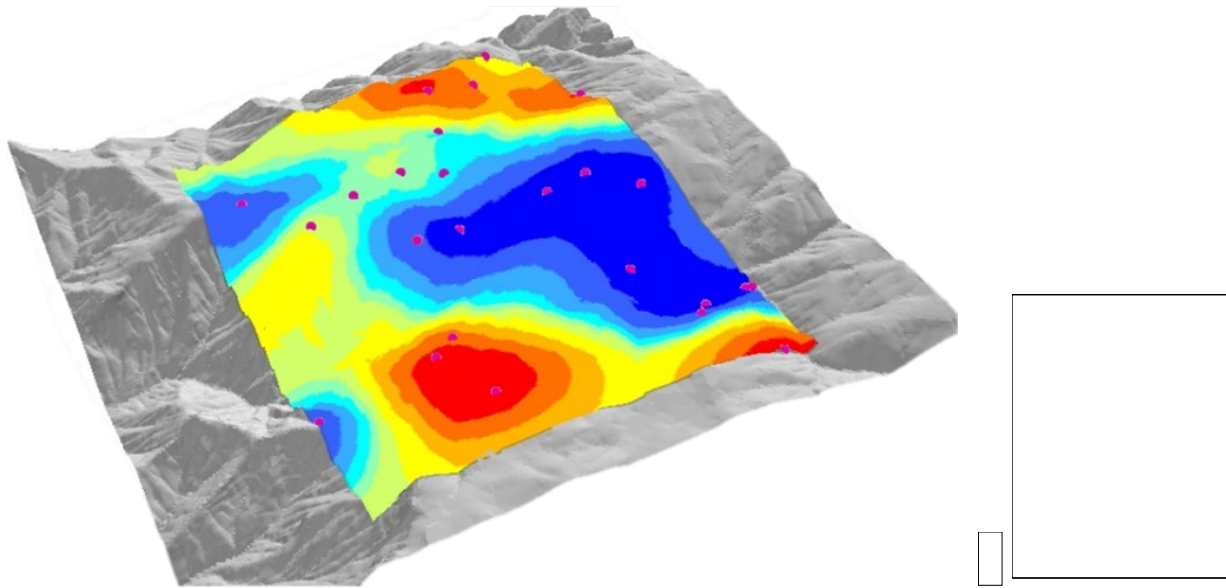
Figure 2b. Beetle Presence Kriging surface of Sequoia Kings Canyon. Visualizes spatial interpolation of beetle presence. Red represents high incidence of beetle presence while blue represents low beetle presence. The highest bark beetle presence was found in the Northeast quadrant of the plot and the highest estimated beetle presence was 29%.
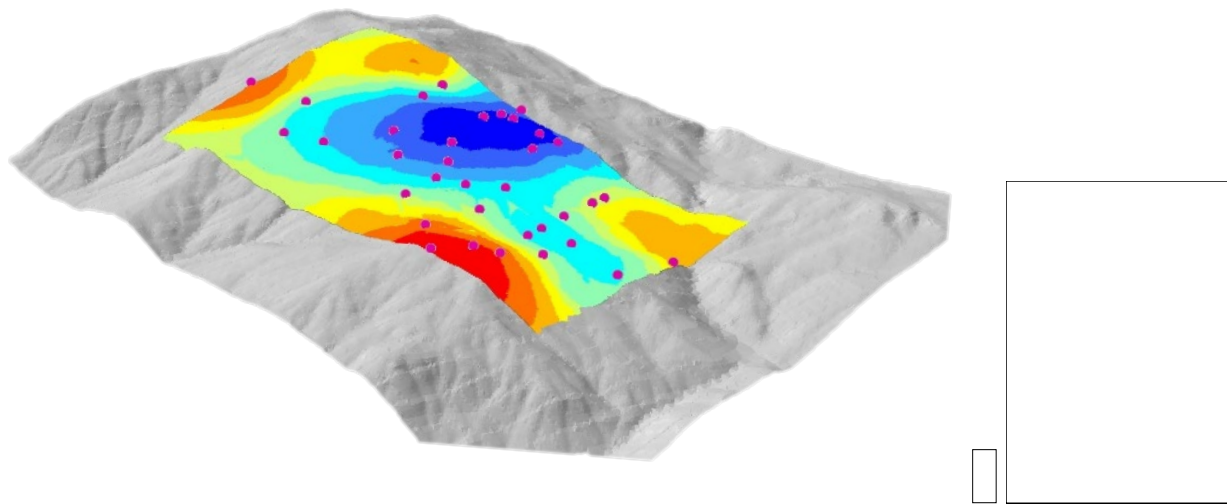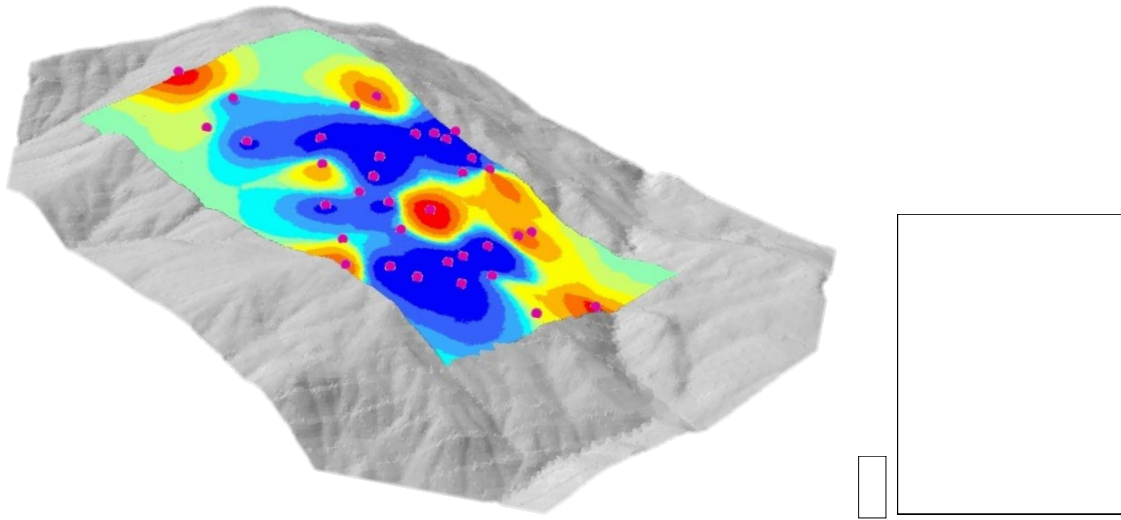

Figure 3a. Tree Mortality Kriging surface of Yosemite Pine Forest. Visualizes spatial interpolation of tree mortality. Red represents a high incidence of tree mortality, with blue representing a low incidence. The floating pink dots represent each site at which the data was collected. The highest probability of dead trees is in the Southwest quadrant of the plot. The highest concentration of dead trees was found at the Southwestern side of the plot and the most North. The highest incidence of tree mortality was 44.2%.

Figure 3c. Beetle Presence Kriging surface of Yosemite Pine Forest. Visualizing spatial interpolation of beetle presence. Red represents high incidence of beetle presence while blue represents low beetle presence. The highest incidence of beetle presence was found in the center of the plot and most northern section. The highest estimated beetle presence was set 79.3%.
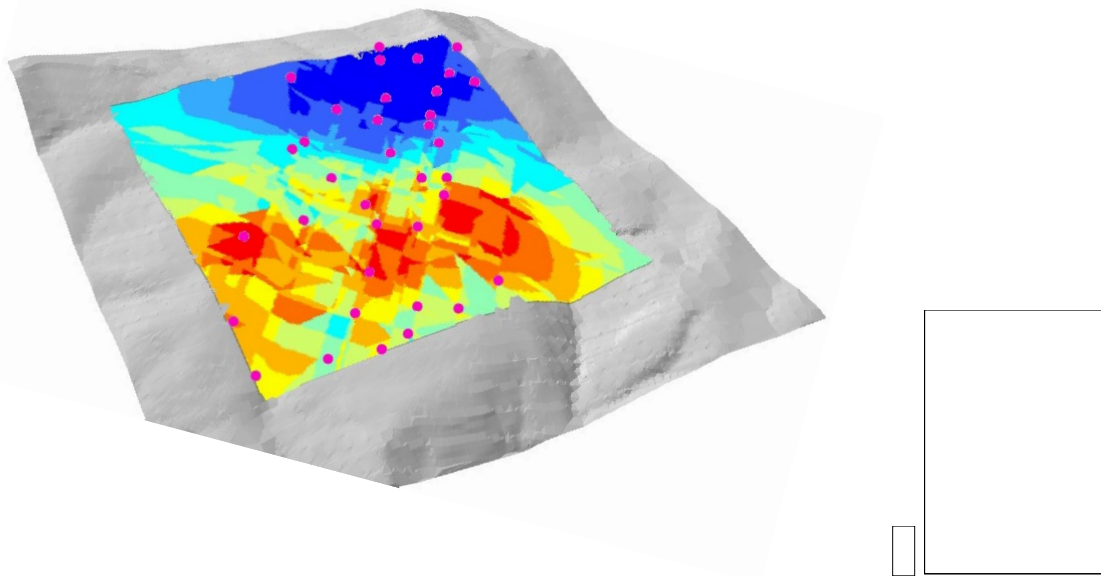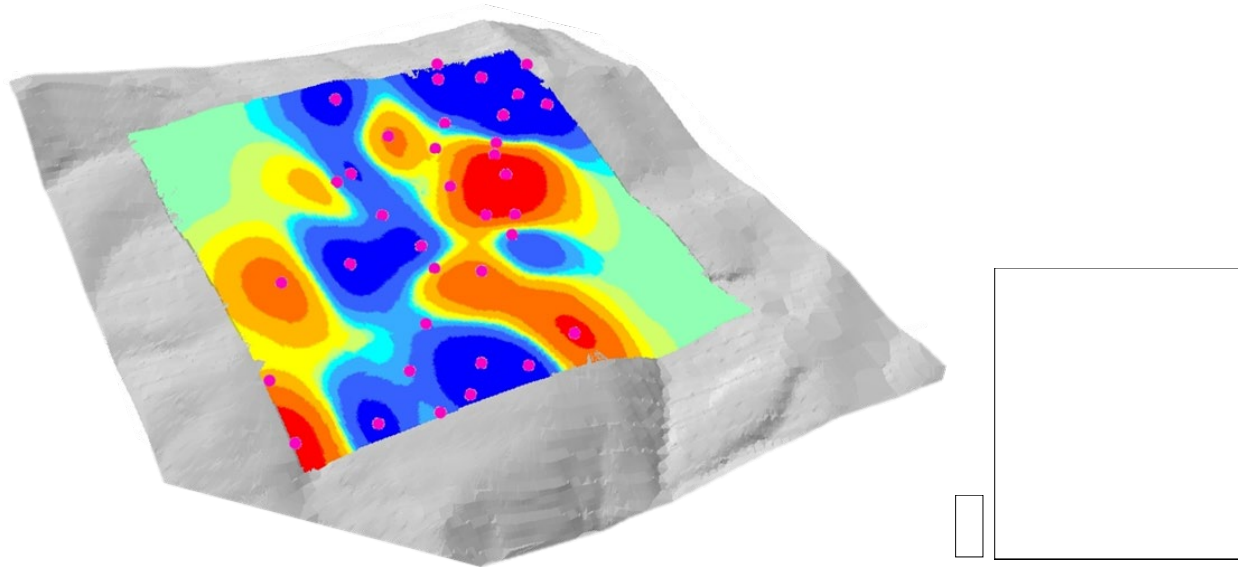

Figure 4a. Tree Mortality Kriging surface of Cottonwood Gulch Watershed. Visualizing spatial interpolation of tree mortality. Red represents a high incidence of tree mortality, with blue representing a low incidence. The floating pink dots represent each site at which the data was collected. The highest probability of dead trees is in the Southwest quadrant of the plot. The highest incidence of tree mortality is seen on the southern half of the plot. The highest incidence of tree mortality was 5.49%.

Figure 4b. Beetle Presence Kriging surface of Cottonwood Gulch Watershed. Visualizing spatial interpolation of beetle presence. Red represents high incidence of beetle presence while blue represents low beetle presence. The highest incidence of beetle presence is seen as a vertical strip on the eastern and western side of the plot. The highest estimated beetle presence was 15.3%.
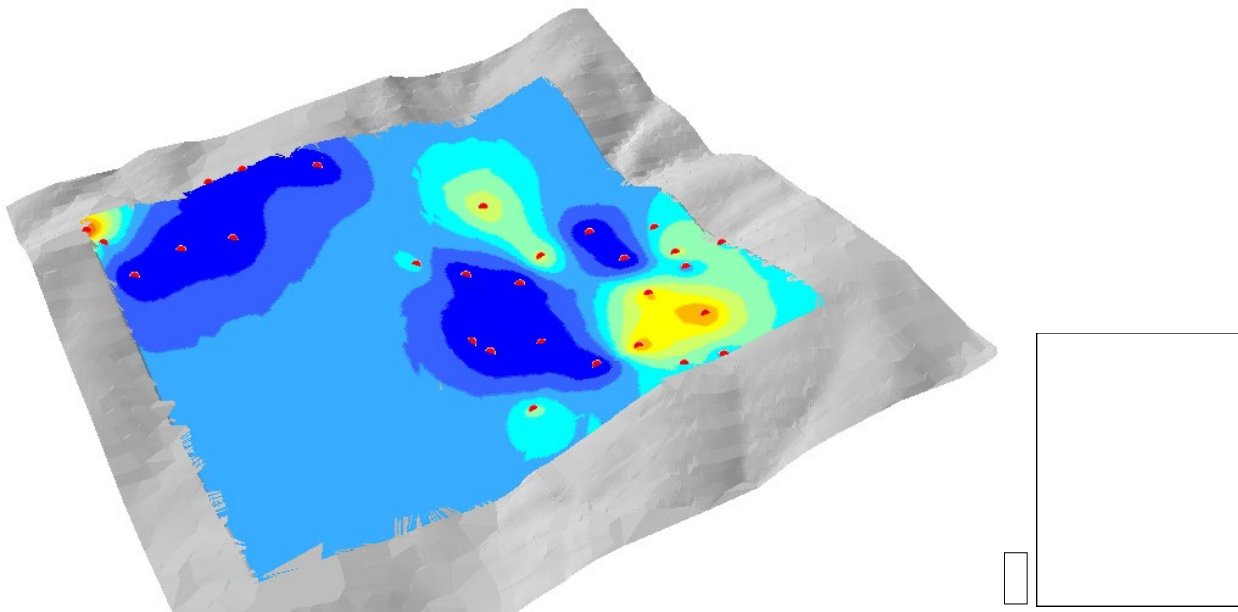

Figure 5a. Tree Mortality Kriging surface of Plumas National Forest. Visualizing spatial interpolation of tree mortality. Red represents a high incidence of tree mortality, with blue representing a low incidence. The floating pink dots represent each site at which the data was collected. The highest probability of dead trees is in the Southwest quadrant of the plot. The highest incidence of tree mortality is seen at the northwestern corner of the plot as well as the southeastern. the highest incidence of tree mortality to be 11.5%.
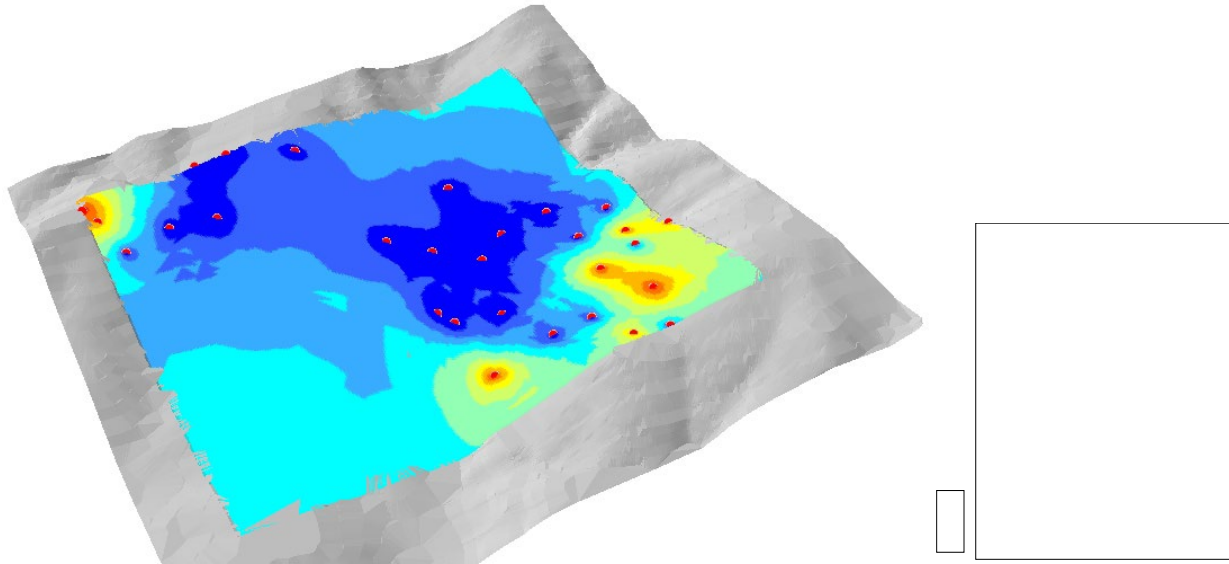
Figure 5b. Beetle Presence Kriging surface of Plumas National Forest. Visualizing spatial interpolation of bark beetle presence. Red represents high incidence of beetle presence while blue represents low beetle presence. The highest incidence of beetle presence is seen in the northwestern section and the southwestern. The highest estimated beetle presence was set at 2.95%.
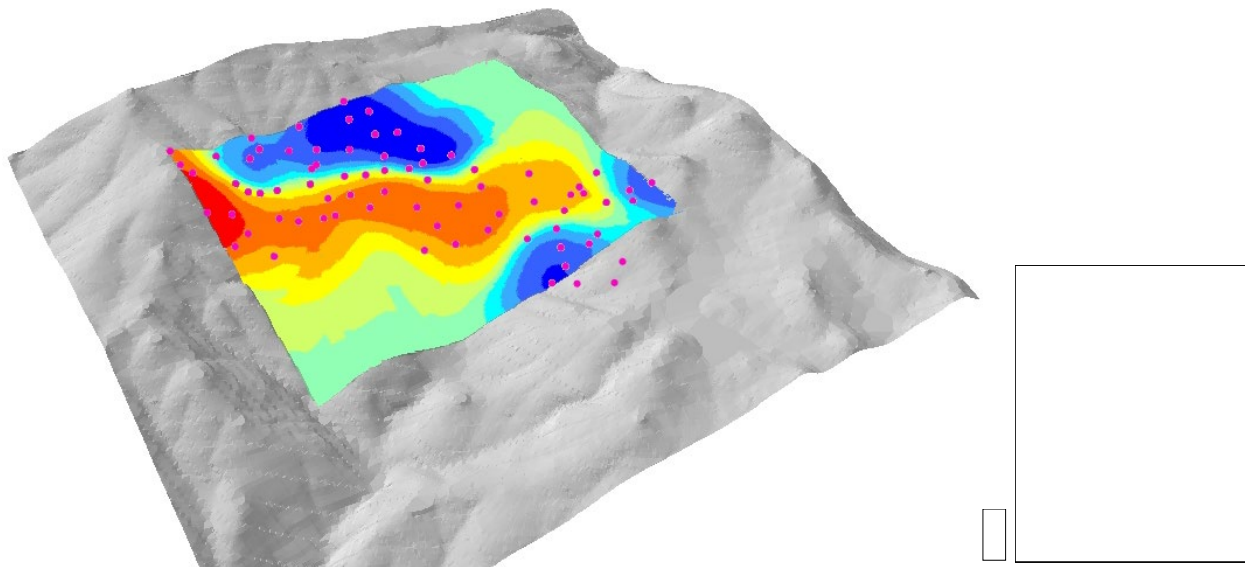

Figure 6a. Tree Mortality Kriging surface of Mountain Home State Forest. Visualizing spatial interpolation of tree mortality. Red represents a high incidence of tree mortality, with blue representing a low incidence. The floating pink dots represent each site at which the data was collected. The highest probability of dead trees is in the Southwest quadrant of the plot. The highest incidence of dead trees occurs in the northwest of the plot with the highest incidence of tree mortality to be 30.8%.
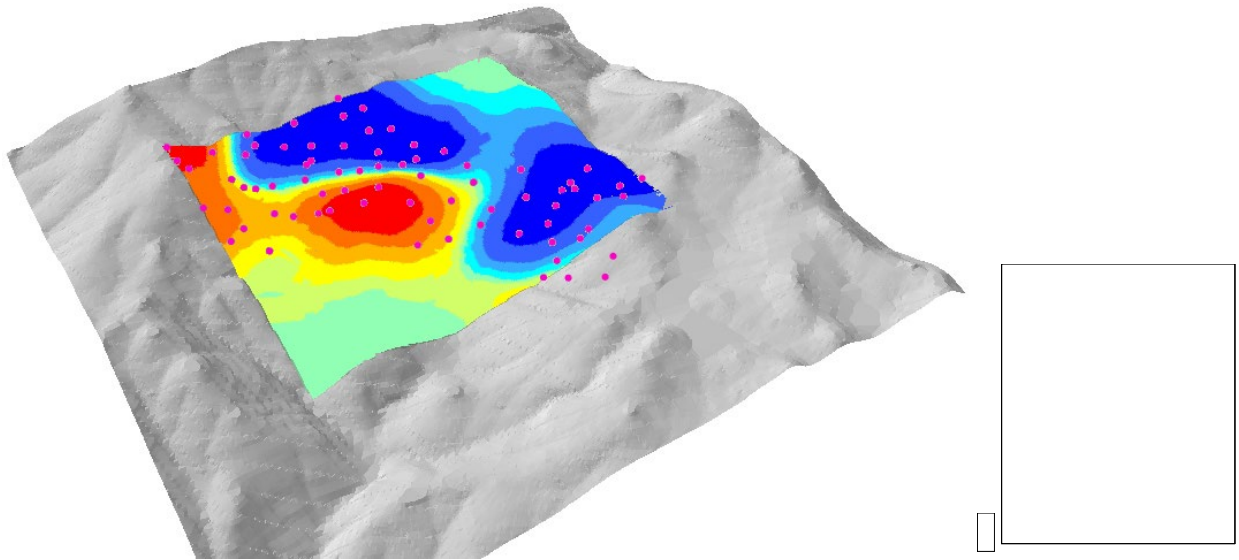
Figure 6c. Beetle Presence Kriging surface of Mountain Home State Forest. Visualizing spatial interpolation of bark beetle presence. Red represents high incidence of beetle presence while blue represents low beetle presence. The highest incidence of bark beetles is seen in the northwestern part of the plot. The highest incidence of beetle presence is 38.7%.

The three plots that showed no spatial trends of either tree mortality or bark beetle presence when put through simple prediction kriging were Yosemite Mixed Conifer Forest, Burton Creek State Park, and Blodgett Forest Research Station (Appendix A and Figure 7a and 7b). These plots can be determined to have no spatial variation because even with data representation manipulation, there is no change in values across the landscape.

Blodgett Forest Research Station did show some landscape variation of tree mortality, but not with bark beetle presence (Figure 7a and 7b). Because the comparison was being made between bark beetle presence and tree mortality, this plot also showed no significant variation.
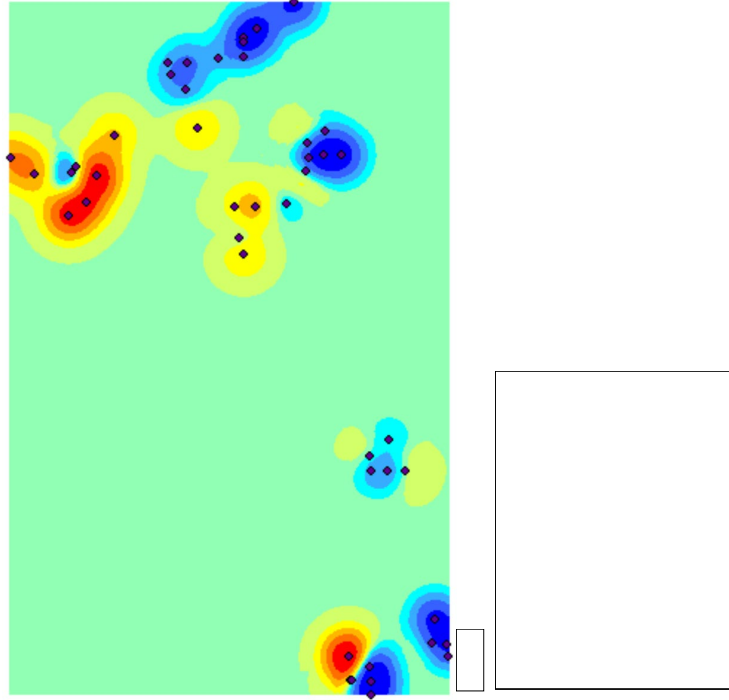
Figure 7a. Blodgett Forest Research Station prediction kriging surface of tree mortality. There is a high concentration of dead trees where red is seen on the map. The highest incidence of tree mortality across the surface was recorded at 11.6%.
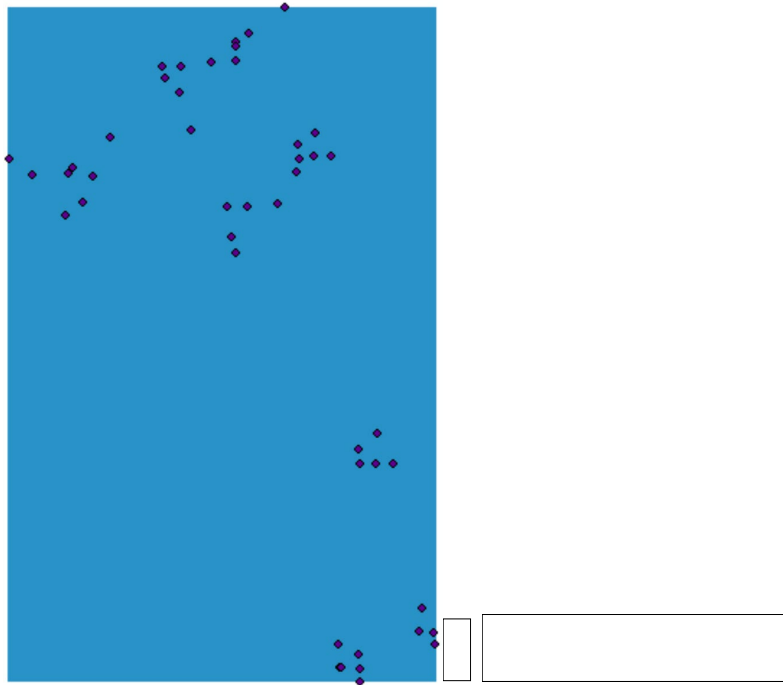

Figure 7b. Blodgett Forest Research Station prediction kriging surface of beetle presence. The constant predicted incidence of beetle presence was 1.89%.

Predictor and response variables for western pine and fir engraver beetle

I identified eight variables as important predictors for beetle presence in all plots: basal area sum, sum of trees per hectare, slope, diameter at breast height, basal area, elevation, aspect and trees per hectare were all seen as having importance values. The variable with the highest importance value for both species and plots was sum of basal area (Table 2). In addition, the variable ranked with the lowest importance value for all plots and beetle species was trees per hectare (Table 4).

Of three plots, sum of basal area as a predictor of the western pine beetle in the Yosemite Pine Forest had the highest importance value overall, 99.80/100 (Table 2). The lowest importance value out of all three plots was trees per hectare in the Cottonwood Gulch Watershed as a predictor of Fir Engraver Beetle presence with an importance value of 0.13 (Table 4).

Table 2. Random Forest Algorithm Results for Yosemite Pine Forest. Highest importance value: sum of basal area (99.80). Lowest importance value: trees per hectare (3.49).

Predictor Variable	Importance Value
Basal area sum	99.80
Trees per hectare sum	71.66
Slope	26.46
Diameter at breast height	23.51
Basal area	21.96
Elevation	20.01
Aspect	14.44
Trees per hectare	3.49

Table 3. Random Forest Algorithm results for Yosemite Mixed Conifer Forest. Highest importance value: sum of basal area (16.40). Lowest importance value: trees per hectare (0.75).

Predictor Variable	Importance Value
Basal area sum	16.40
Slope	7.38
Trees per hectare sum	6.94
Elevation	6.66
Diameter at breast height	6.26
Basal area	5.20
Aspect	3.79
Trees per hectare	0.75

Table 4. Random Forest algorithm results for Cottonwood Gulch Watershed. Highest importance value: sum of basal area (8.32). Lowest importance value trees per hectare (0.13).

Predictor Variable	Importance Value
Basal area sum	8.32
Trees per hectare sum	8.08
Diameter at breast height	2.35
Basal area	2.15
Elevation	1.84
Aspect	1.35
Slope	1.10
Trees per hectare	0.13

After running all eight predictor values that showed importance in the Random Forest algorithm, the most statistically significant variables were identified using multivariate logistic regression. For Yosemite Pine Forest, seven predictor variables showed significant p-values: basal area at the tree level (1.03×10^{-5}), basal area sum which measures the plot level data (1.89×10^{-12}), diameter at breast height measured in cm at the tree level (8.81×10^{-7}), elevation (2.29×10^{-9}), slope (8.36×10^{-9}), trees per hectare (8.363×10^{-9}), and trees per hectare sum, a plot level measurement (2.22×10^{-8}).

Once run through multivariate logistic regression for a second time to reduce the effects of covariance, four variables came back as having a statistically significant p-value: aspect (0.01283), basal area sum $(<2 \times 10^{-16})$, elevation (6.21×10^{-8}), and slope (2.12×10^{-8}). As aspect increases, the presence of western pine beetles increases (Figure 8). As the sum of basal area at the plot level and the slope increases, so does western pine beetle presence (Figure 8). As elevation decreases, there is a decrease in western pine beetle (Figure 8).
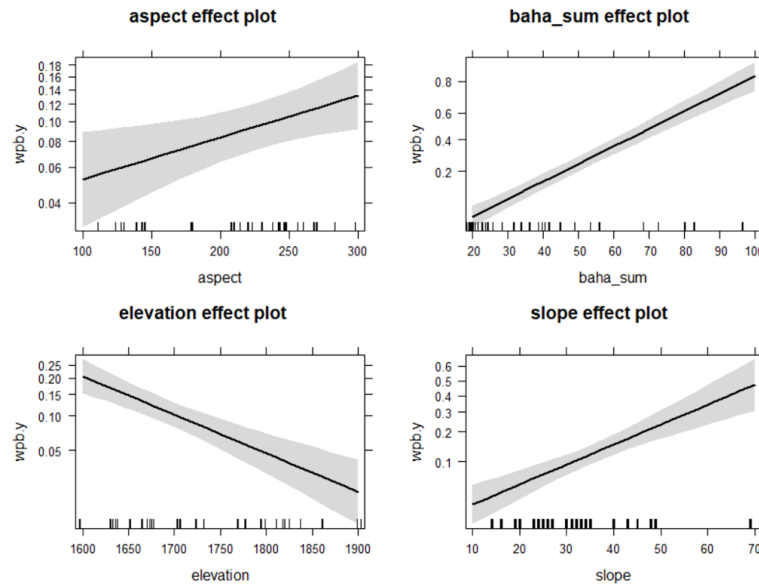
Figure 8: Predictor v Western Pine Beetle Presence Graph of Yosemite Pine Forest.

For Yosemite Mixed Conifer Forest, out of the eight values from the random forest, only three variables returned significant p-values: basal area at the tree level (0.02062), basal area sum which measures the plot level data (5.25×10^{-8}), and elevation (0.00113).

In the second run of multivariate logistic regression three variables were statistically significant p-value: aspect (0.01283), basal area sum (5.73×10^{-8}), elevation (0.00065), and slope (0.02477) (Figure 9). As aspect decreases, the presence of western pine beetles decreases (Figure 9). As the sum of basal area at the plot level, slope, and elevation increase, western pine beetle presence also increases (Figure 9). As elevation decreases, presence of western pine beetle decreases (Figure 9).
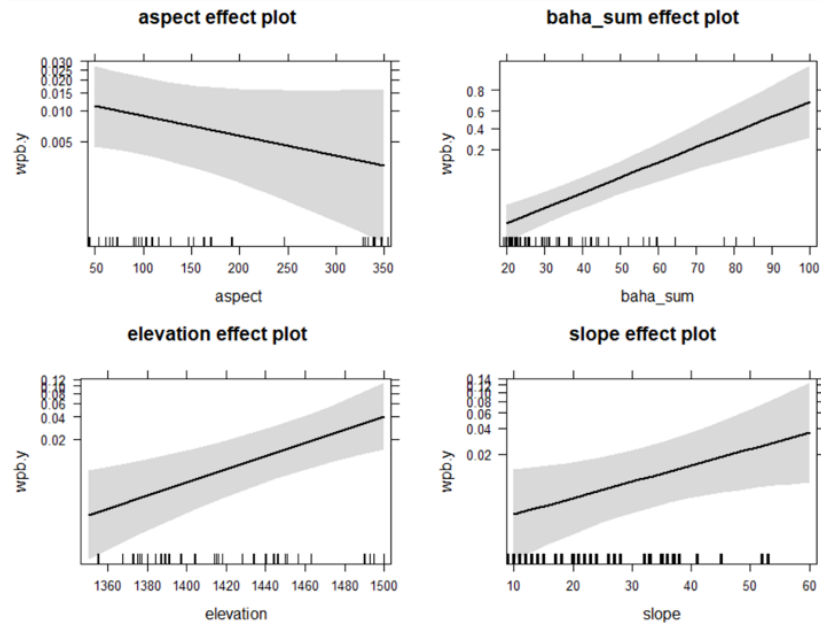
Figure 9: Predictor v Western Pine Beetle Presence Graph of Yosemite Mixed Conifer Forest.

The most significant predictor variable for the western pine beetle in both the Yosemite Mixed Conifer and Yosemite Pine forests was basal area.

For Cottonwood Gulch Watershed plot predicting for fir engraver beetles, only the sum of trees per hectare predictor variable was statistically significant (p-value of 7.32×10^{-7}) (Figure 10). As tree density increases, presence of fir engraver beetle decreases (Figure 10).
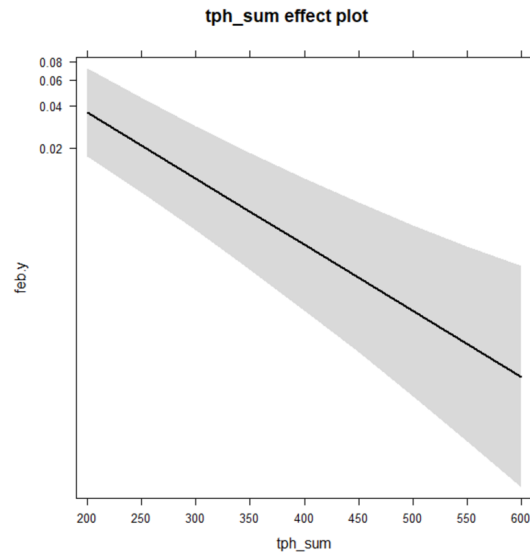
Figure 10: Trees per hectare sum predicting presence of Fir Engraver Beetle in Cottonwood Gulch Watershed.

DISUCSSION

The relationship between bark beetles and forests in a post drought Sierra Nevada forest environment was explored using both spatial and statistical analysis. Through comparing tree mortality and bark beetle presence across the landscape and testing to understand if certain variables could act as predictors for certain beetle species, a more focused and small-scale view of the bark beetle and tree epidemic is understood. Only five out of eight plots showed spatial variation of beetle presence and tree mortality. And spatial correlation between bark beetle presence and tree mortality occurred in four out of those five plots. Highest prediction of beetle presence, 79.3%, and tree mortality, 44.2%, was in Yosemite Pine Forest. In addition, aspect and elevation are predictor variables of western pine beetle in two different plot sites, Yosemite Mixed Conifer and Yosemite Pine in opposing directions. Fir engraver beetle only had one statistically significant predictor variable, tree density measured in trees per hectare, compared to the western pine beetle which was predicted by more variables.

Variation Over the Landscape Discussion

After analyzing eight plots for spatial variation of bark beetle presence and tree mortality, only five plots showed spatial variation. Because of the prolonged drought and the lasting effects drought can have on forest health and susceptibility of attack, I expected higher rates in general of both bark beetle and tree mortality to be found in the plots.

Because this study focused on larger overstory trees, this could have played a role in the presence or lack thereof of bark beetles and tree mortality. Larger trees can take longer to both fall, decay and repopulate after attack and death (Raphael and Morrison 1987). This was proven by Raphael and Morrison as they tracked standing trees in the Sierra Nevada for eight years (Raphael ad Morrison 1987). Those forests were tracked longer than the trees I studied, but due to this prolonged time frame, it may take longer for these larger overstory trees to be categorized as dead, leading to a lower tree mortality count in my data (Raphael and Morrison 1987).

One unique landscape variation map created was Cottonwood Gulch Watershed. Visual inspection of the maps of tree mortality and bark beetle presence do not show a clear correlation or correspondence in location. An example of a clear correlation between beetle presence and tree mortality is shown in Sequoia Kings Canyon (Figures 2a and 2b). On the Sequoia Kings Canyon maps, you can see high probability of beetle is spatially correlated with high probability of dead trees (Figures 2a and 2b). With further exploration of site-specific characteristics, Cottonwood Gulch Watershed has high incidence of mistletoe (Axelson 2019, personal communication). Mistletoe could potentially have caused a high biotic disturbance where the fir engraver beetles attacked the mistletoe instead of the trees, as fir engraver beetles have been known to attack and infect white firs (Ferrell 1974). White fir infected with mistletoe had a higher rate of successful attacks from fir engraver beetles than the white firs without infection (Ferrell 1974). This research shows fir engraver beetles may favor mistletoe, explaining the unique landscape variation.

Beetle Species Predictor Variables

Western pine beetles had contrasting relationships to elevation in Yosemite Mixed Conifer Forest and Yosemite Pine Forest. In Yosemite Pine Forest analysis showed with an increase of elevation, there was a decrease in western pine beetle presence. In Yosemite Mixed Conifer Forest,

there was an increase in western pine beetle presence with an increase in elevation. This contrasting information within the same site is not easily explained. I hypothesized that because each plot potentially had abundances of different tree species, which I did not directly explore, this could have played a role. This would be seen through an affinity of the western pine beetle to specific tree species that are differentiated between each plot. Shift in elevation of bark beetle habitat is known to occur with rising temperatures (Mikkelson et al. 2013). This could also be an explanation for the inverse relationship.

In a shift to a warmer climate, bark beetles are shifting to higher elevations (Mikkelson et al. 2013). Analyzing direct and indirect effects of climate change on bark beetles in North America and Canada, analysis of population models suggest that beetles are moving to higher altitudes and elevations to find more suitable habitats (Bentz et al. 2010). These regions with known bark beetle populations will now be identified with higher bark beetle risk and associated with tree mortality in the coming century (Bentz et al. 2010). The relationship between increasing elevation with an increase in western pine beetle is supported by this research.

A major finding at these sites was the relationship between fir engraver beetles and tree density. Tree density was measured in trees per hectare. As trees per hectare increased, bark beetles decreased. This finding was not expected because of the generalized bark beetle characteristic where there are more trees more beetles are present (Schwilk et al. 2006). With increased tree density, trees are smaller (Schwilk et al. 2006). In a less dense forest, you potentially could find wider diameter trees (Axelson 2019, personal communication). This conclusion leads me to believe that fir engraver beetles prefer larger diameter trees and less dense forests.

Population fluctuations of fir engraver beetles can be predicted by the quantity of susceptible trees and ultimately regulated by intraspecific competition (Berryman 1973 and (Berryman and Ferrell 1988). Parasite competition and interspecific competition modify and regulate abundance of the fir engraver beetle (Berryman 1973). With more tree density, other beetle species may increase, this increase however in other beetles would act as intraspecific competition to deter fir engraver populations. In Cottonwood Gulch Watershed this relationship should be explored.

Limitations

There is much more work that needs to be done on this research topic and there is much more than can be done with this data as well. Tree species could be influential in both the spatial and statistical analysis of bark beetles. Due to the time constraints and scale of my project, I did not include difference in tree species in my beetle presence of tree mortality spatial analysis. Although all plots were Yellow Pine and Mixed Conifer Forests, they had different specific tree species that were unique to them and had unique counts of each of these trees. Fir engraver beetles prefer genus *Abies* (fir trees), the mountain pine beetle favors ponderosa pine, jeffery pine beetle favors jeffery pine, and western pine beetle favors ponderosa pine (Schwilk et al. 2006) (Table 1). To get a more accurate and wholistic view of the relationship between bark beetles and specific tree species at each of these sites, maps could be created that only looked at the high rates of tree mortality and bark beetle presence focusing on tree species. Also, predictor variables of all species in the data set should be tested at each site. In addition, only two beetle species were analyzed. With the addition of the jeffery pine beetle and mountain pine beetle, results can be compared to evaluate how each plot interacts with specific beetle species.

Future Directions

In the past, there have been studies analyzing how climatic data has affected both bark beetle and tree mortality dynamics (Axelson 2019, in person communication). Through my research, I took a unique approach to see the way tree specific and plot specific measures and characteristics effect beetle presence (Axelson 2019, in person communication). To tackle the problem of drought and bark beetle induced tree mortality, there may need to be a shift to smaller scale research projects, like this one, which focus on one unique environment and its unique characteristics. Each plot had unique forest structure with differences in abundance of tree species, focusing on small forest dynamics can help impact smart forest management.

To get a more wholistic view of the how forest environments and bark beetle infestations are changing as California Forests move away from the 2012-2015 drought, the same tests I conducted need to be run on the 2018 forest data collection. The dataset I recommend to use are the 2018 Axelson and Battles research team data. This data collection design was done as an exact replica of the 2017 data I explored. By doing this, we can gain a better understanding on the recovery, or lack thereof, of Sierra Nevada forests as they attempt to recover from drought. This

recovery would be quantified by the decrease in beetle presence and the decrease in tree mortality from beetle attack.

Broader Implications

Because of the influx of both fires, droughts, and bark beetle outbreaks, all resulting in tree mortality, site specific land and forest management plans need to be adjusted and tailored to each environment (Schwilk et al. 2006). Even within the Yosemite National Park, beetles react differently to unique plots characteristics. As California forests move away from the 2012-2015 drought, the lasting impacts need to be tracked and analyzed. Droughts in California are only supposed to become more frequent (Diffenbaugh et al. 2015). With an increase in prolonged droughts, California forests will also see an increase in tree mortality (Guarín and Taylor 2005). This tracking can be used to inform management decisions for droughts of the future. Future research also needs to explore plot level characteristics effect on tree and forest health. Unique forest characteristics and small-scale management strategies could be the climate change adaptation technique and management style the Sierra Nevada need to survive.

In addition, there needs to be a focus on the shifting altitude and elevation seen in beetle populations. With an increase in temperatures, bark beetle habitat will continue to shift upward in elevation and latitude (Fettig et al 2017). Although I only analyzed the western pine beetle's response to elevation change in plots within the Yosemite National Park, more focus on and preparation of this shifting habitat behavior is important to forest management adaptation strategies.

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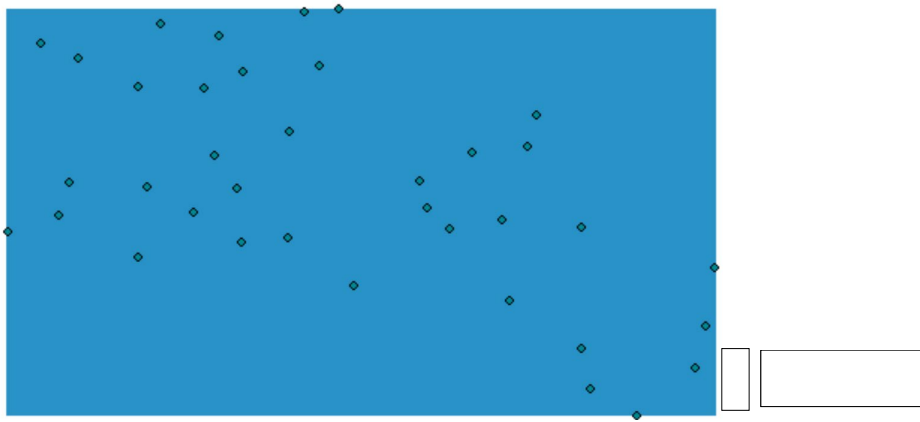
APPENDIX A: SITES WITH NO SPATIAL TRENDS

Figure A1. Yosemite Mixed Conifer Forest Alive/Dead Prediction. The constant predicted value of tree mortality was 40.6%.
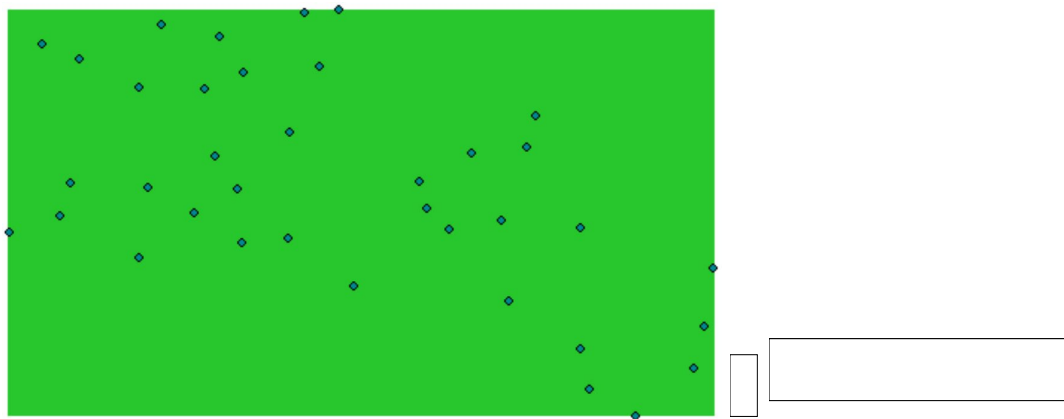

Figure A2. Yosemite Mixed Conifer Forest Bark Beetle Presence/Absence. The constant predicted incidence of beetle presence was 7.86%.
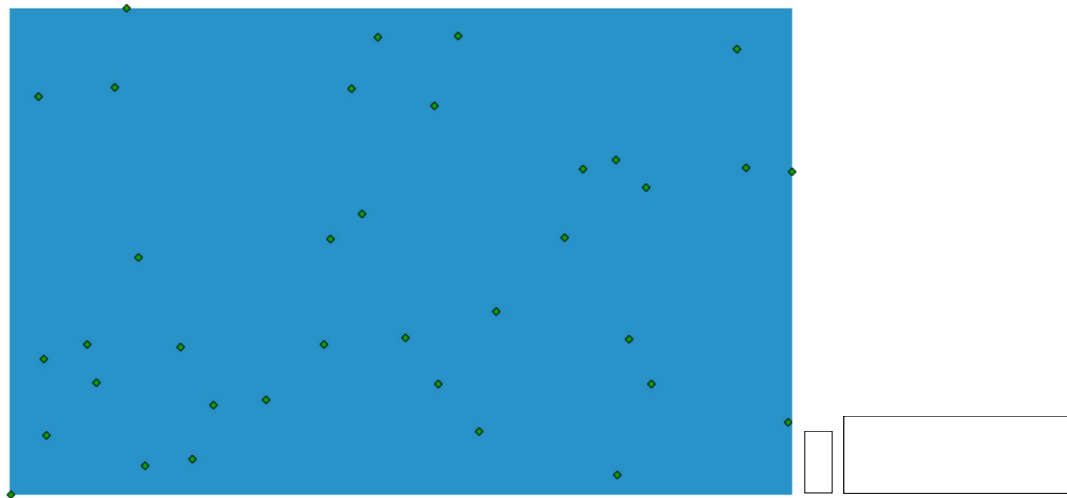
Figure A3. Burton Creek State Park kriging surface of tree mortality. The constant tree predicted tree mortality across the whole landscape was 2.4% mortality.
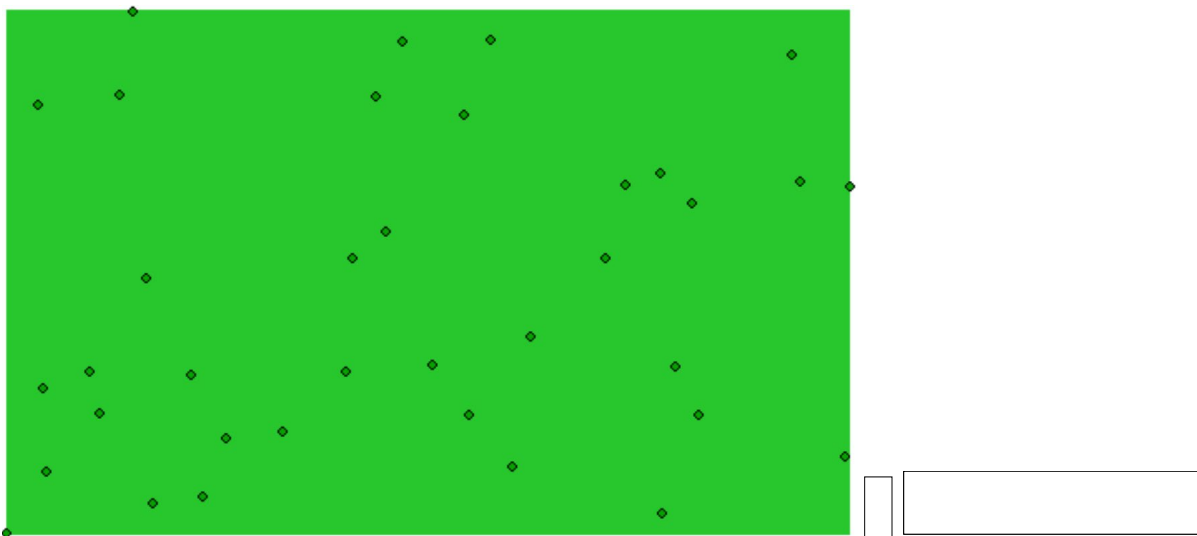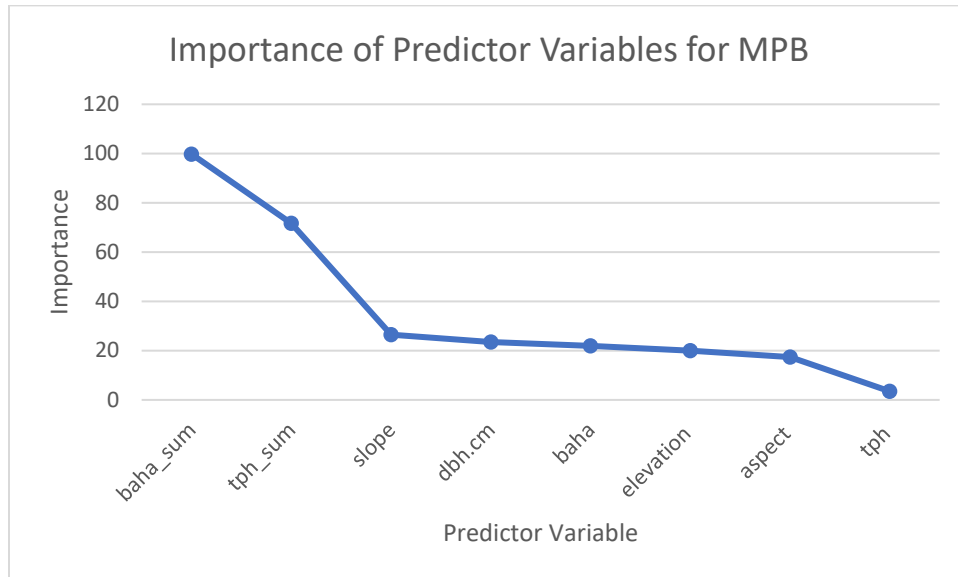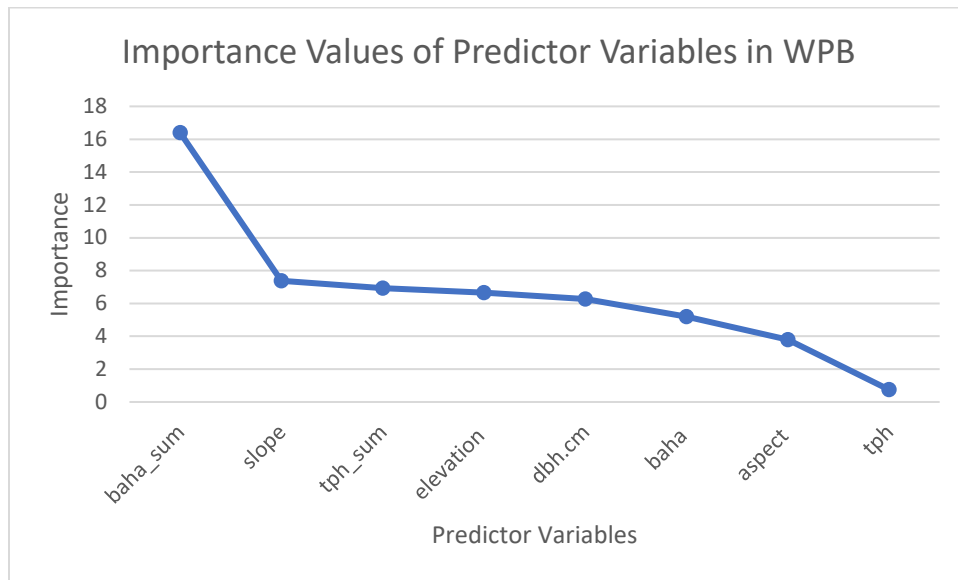

Figure A4. Burton Creek State Park prediction kriging surface of beetle presence/absence. The constant prediction of beetle presence across the landscape was 3.06% beetles.

APPENDIX B: GRAPHED IMPORTANCE VALUES

Figure B1: Importance Values of Western Pine Beetle in Yosemite Pine Forest.

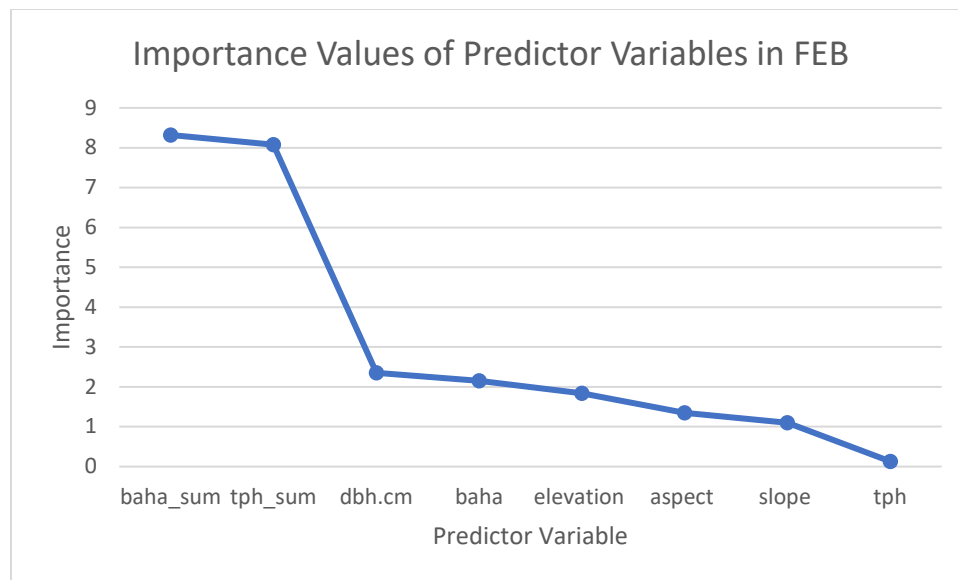**Figure B2: Importance Values of Western Pine Beetle in Yosemite Mixed Conifer Forest.**

Figure B3: Importance Values for Fir Engraver Beetles in Cottonwood Gulch Watershed