Understanding the Understory Structure of Californian Eucalyptus Forests by mapping the density of Oak (*Quercus agrifolia*) and Bay Laurel (*Umbellularia californica*)

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ABSTRACT

Globalization and the mass transplanting of species by human beings have created a state of modern ecological confusion, as ecosystems across the planet have become composed of locally unprecedented assemblages of species. For example, in the eastern hills of the San Francisco Bay Area, native trees and shrubs have infiltrated the understory of hundred-year-old eucalyptus plantations, creating a novel forest. The novel eucalyptus woodland has been the subject of local aesthetic and ecological debate, and now is the target of a multi-million-dollar fuel reduction and thinning plan funded by the Federal Emergency Management Agency (FEMA). No spatially related survey of the understory vegetation exists, leaving uncertainties about how such a disturbance that will affect the native species in the forest. I conducted a survey of the densities of the native trees *Quercus agrifolia* (Coast Live Oak) and *Umbellularia californica* (Bay Laurel) in a matrix through the forest in order to determine where and in what relative abundances those native trees grow, and whether changes in their abundances can be associated with known environmental variables that affect the structures of other forests (slope aspect, slope steepness, distance from forest edge, canopy cover, and history of mechanical thinning). Thinning history was significantly correlated with changes in the densities of the native trees in the understory, while other variables were not.

KEYWORDS

Novel ecosystems, GIS, inverse density-weighted (IDW) interpolation, thinning, restoration

INTRODUCTION

We find the world today in a state of ecological confusion. The past several hundreds of years of global trade and travel have resulted in a massive transplanting and relocation of crops, livestock, pests, people, and culture (Jenkins 1996, Vitousek *et al*. 1997). As part of these massive migrations, areas have been conquered, colonized, and settled by foreign powers, changing the manner in which landscapes are managed and dramatically altering the ecological state of many places in the world. California, the setting of this study, reflects in its own history this global phenomenon. Spanish colonialism saw the end of anthropogenic burning and the introduction of European grasses and ranching where deer and elk once roamed in wide oak savannah (Anderson *et al*. 2013, Nowak 1993). As the Spanish gave way to the Mexicans and then eventually American manifest destiny, ranches gave way to streets and homes, and under the banner of Smokey the Bear, fire suppression saw an end to the primary tool of landscape management that had defined the land for thousands of years (Keeley 2005). Changes in land ownership, and as a result land use and management, would alter the state of the landscape.

A symptom of this era of globalization, and a poster-child for its effects, can be found in Tilden Regional Park near Berkeley, California. A forest of *Eucalyptus globulus*, the Tasmanian blue gum, grows in what was once oak savannah (Nowak 1993). The trees were originally planted to supplement a waning local timber supply (Groendall 1983). Unlike the centuries-old virgin forests of Tasmania, the timber the California trees produced was very poor, and would twist and crack during milling and treatment. Having lost their economic viability, the blue gum plantations were abandoned (Dost 1983), and today they grow together with native vegetation, a locally unprecedented assemblage of species that creates a diverse, novel ecosystem (Hennessey 2012, Sax 2002, Hobbs *et al*. 2006). The Eucalyptus trees are often the subject of local controversy and debate; some argue that the trees are a beautiful, naturalized part of the ecosystem, while others would insist that they are an eyesore, ecological suppressor, and fire hazard (Hennesey 2012). In 1991, sections of eucalyptus forest that were part of the same plantation project as that in Tilden was blamed for the Oakland Firestorm (Williamson 1992), a massive fire in the wild-urban-interface of the Oakland Hills. Reacting to that disaster, the Federal Emergency Management Agency has granted $4.65 Million to the East Bay Regional Parks District for a thinning and fuels reduction project aimed at removing the eucalyptus and as a result reducing the risk of another catastrophic fire in the San Francisco East Bay (EBRPD 2016a).

Though the eucalyptus forests were planted in a monoculture, their understory is now populated with native vegetation, ranging from grasses and forbs to shrubs and trees (Sax 2002). Similar instances of native succession in eucalyptus forests have occurred in South Africa and many tropical regions, where eucalyptus plantations were established in clear-cut patches of native forest. Once established, the eucalyptus canopy facilitated the regrowth of native vegetation in the understory from neighboring woodlands by providing services that would have been absent otherwise, such as shading, trapping moisture, and attracting pollinators (Lugo 1997, Geldenhuys 1997). Native understory vegetation may also be affected by landscape-level variables as well. In Australian eucalyptus forests, slope-aspect is correlated with changes in understory vegetation (Ashton 1976), and in many forest types slope steepness has been correlated with vegetation density as well (Trimble & Wietzman 1956). Changing distance from the forest edge can also create gradients in temperature, relative humidity, and light availability that can affect species composition and abundance (Murcia 1995). Finally, though the FEMA plan has not yet gone into effect, parts of the eucalyptus forests in Tilden have been under a thinning treatment (EBRPD 2016b), creating openings for understory succession (Ares *et al*. 2009). The combined forces of eucalyptus presence, slope aspect, slope steepness, forest edge distance, and thinning history likely produce a variable understory structure, though to date no spatially-correlated vegetation survey has been conducted to verify that likelihood. As the plans are laid for a massive disturbance event – the thinning and eventual removal of the eucalyptus – filling that knowledge gap can improve the ecological efficacy of the project.

The purpose of this study is to gain an initial understanding of how the eucalyptus forest understory varies in vigor over space and in relation to environmental variables. To serve as an index for the vigor of native vegetation, this study focused on two tree species that would compose the canopy if the eucalyptus were not present: the coast live oak (*Quercus agrifolia*) and the bay laurel (*Umbellularia californica*). In addition to providing the essential services of shade and shelter, they produce acorns and bay nuts respectively, a major source of food for the local food web (USDA and NRCS 2015, Clotfelter *et al*. 2007). Addressing the coast live oak and bay laurel collectively as “native trees”, I attempted to answer the following central research question: Are there spatially correlated patterns of native tree growth in the understories of East Bay eucalyptus forests? I answered this question by pursuing five sub-questions:

(1) Do native trees occur more often on North-facing slopes or South-facing slopes of eucalyptus forests?

(2) Do native trees grow less often on steeper slopes in eucalyptus forests?

(3) Do native trees occur less often as distance inward from the edge of a eucalyptus forest increases?

(4) Do native trees grow less often as eucalyptus canopy density increases?

(5) Do native trees grow more often in areas that have a history of recent thinning than those that do not?

METHODS

Study site and structure

My study was conducted in the eucalyptus forests of Tilden Regional Park, Alameda County, California from January through the end of March, 2016. To locate the eucalyptus forest, I used a vegetation map provided by the East Bay Regional Parks District (*unpublished data*). Using ArcMap, I selected and isolated every area in Tilden Regional Park that the vegetation map associated with the keyword "eucalyptus", ranging from pure eucalyptus woodland to mixed species with eucalyptus present. For the purpose of my study, the areas selected using this method were considered the eucalyptus forests. In order to capture changes in measured variables throughout the forest, I laid a square grid of points ("sample points") evenly spaced 300 feet apart over the forest (fig. 1). For each sample point, I collected and associated data for tree density, canopy cover, slope aspect, slope steepness, distance to forest edge, and fuels treatment history.

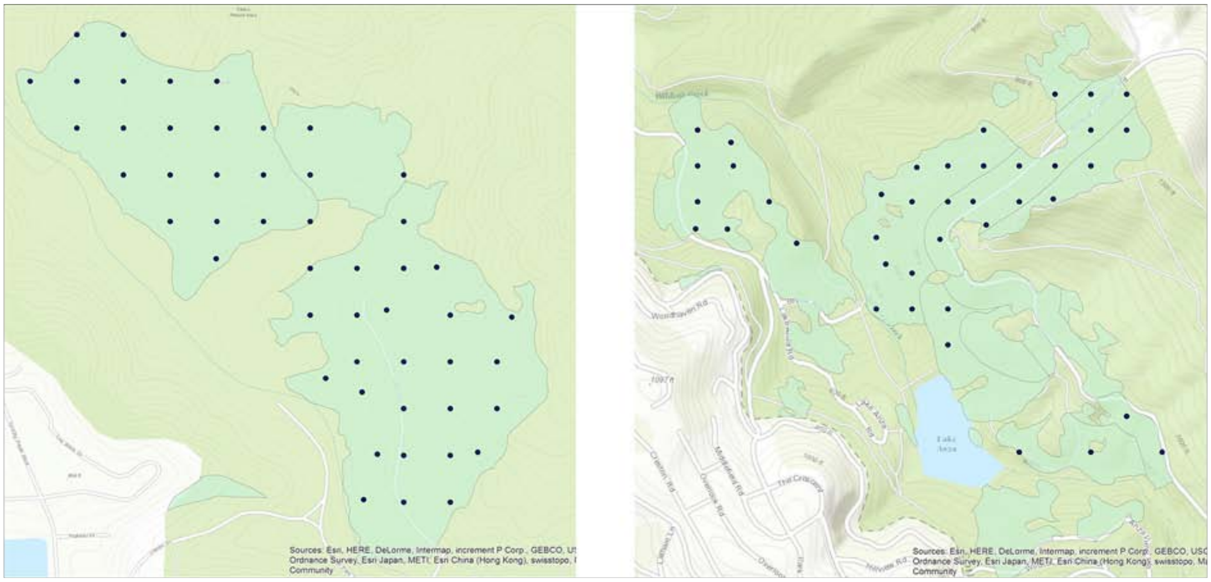


Figure 1. The study site. These polygons outline the two eucalyptus forests I focused on for my study, which I refer to as the northwestern forest (left) and southeastern forest (right), based on their location relative to each other. The dots on the maps are the sample points. The sample points do not form a perfect grid because the original location was not under a continuous canopy of eucalyptus trees. Sample points that were just beyond the forest edge were randomly relocated to just within the forest edge, while points that were very far from the eucalyptus were removed from the study.

Data collection

Tree Density

I used a plotless sampling method to determine the relative densities of native tree stems around each point. The plotless sampling method, called the point quarter method (Pollard 1971), assumes that an effective measure of density can be acquired by measuring the distance to a set number of trees, rather than counting the total number of trees in a set area. In order to do this at each sample point I divided the world around the point into four equal, theoretical quadrants. In each quadrant, I measured the distance to the nearest tree using a laser range finder. I used those four distance measurements, to calculate tree density using the following equation:

$$Density = \frac{4(4n-1)}{(\pi \sum_{i=1}^{n} \sum_{j=1}^{4} r_{ij}^{2})}$$

Where n = the number of sample points (1 in this case), and r_{ij} represents the distance to the tree in the j^{th} at sample point i.

In order to standardize effort, I only recorded the distance to a given tree if I could locate it and identify it without moving from the sample point. If I could not locate a tree, I recorded a distance of 300 feet, signifying an absence of trees until the next sample point. For this study, I stratified my measurements by the two species of interest: coast live oak and bay laurel. I also stratified each tree species by age, differentiating seedlings from all other trees in order to account for the fact that the majority of seedlings die rather than recruit successfully. I considered all trees that were below knee height with few, sparse, twig-like branches (less than 3 mm diameter) seedlings. Trees below knee height that were more robust, with many thick branches and a growth form that strongly suggested an apical meristem were considered mature, as were all other trees that were larger than knee height. I used ArcMap 10.3 to generate a map of how native tree density changes throughout the forest using inverse density weighted (IDW) interpolation (ESRI 2016).

Canopy Density

I used a spherical densiometer to measure canopy density. The mirrored surface of the densiometer had 25 dots drawn on it in concentric circles. At each sample point, I held the densiometer in front of me at chest height, counting the number of dots that were silhouetted against the sky. I made four repetitions of this measurement at each sample point, one facing each cardinal direction, in order to determine the number of dots out of 100 that marked open sky, a percentage of the canopy that was open. I subtracted that percentage from 1 to produce a final measure of the percent of canopy cover at each point. I checked the correlation between canopy density and native tree density using a linear regression in R (R Core Team 2016), $\alpha = 0.05$.

Slope Aspect and Steepness

I generated measures of slope aspect and steepness from 1m-resolution National Elevation Dataset files provided by the US Geological Survey (USDA 2016). Using ArcMap 10.3, I used the "aspect" and "slope" geoprocessing tools to determine the aspect in degrees and slope in percent rise of each point. I then used the method provided by Beers *at al.* (1966) to recode the aspect from degrees to a factor ranging from 0 to 2 using the following equation:

$$aspect\ factor = \sin(aspect\ in\ degrees + 45) + 1$$

Under this system, 0 represents a Southwest-facing slope, which theoretically receives the most solar radiation in the Northern hemisphere, while 2 represents a Northeast-facing slope, which theoretically receives the least solar radiation. All other possible orientations scale evenly and symmetrically between 0 and 2. I checked the correlation between native tree density and slope aspect and slope steepness respectively using a linear regression in R, $\alpha = 0.05$.

Forest Edge Distance

Using ArcMap 10.3 and satellite imagery from the Naitional Agricultural Imagery Program (USDA) as a template, I drew polygons around the eucalyptus forests in which I conducted my study. I used the "near" tool in ArcMap to find the shortest distance to the edge of the forest for each point. I checked the correlation between forest edge distance and native tree density using a linear regression in R, $\alpha = 0.05$.

Thinning History

Finally, I used ArcMap and a map of areas that have been under thinning treatment provided by the East Bay Regional Parks District to determine whether a point was inside of an area currently being thinned for fuel treatment, coding a binary yes or no. I used R to conduct a

Wilcoxon test for non-normal data to detect whether the density of native trees was significantly different in treated areas compared to untreated areas, $\alpha = 0.05$.

Multi-dimensional analysis

In addition to the tests stated above, I used non-metric multidimensional scaling (NMDS) in R (Okansen *et al*. 2016) to cross-check the results from the linear regressions and the Wilcoxon test, as well as to determine whether interactions between any of the environmental variables may be significantly correlated with native tree density, $\alpha = 0.05$.

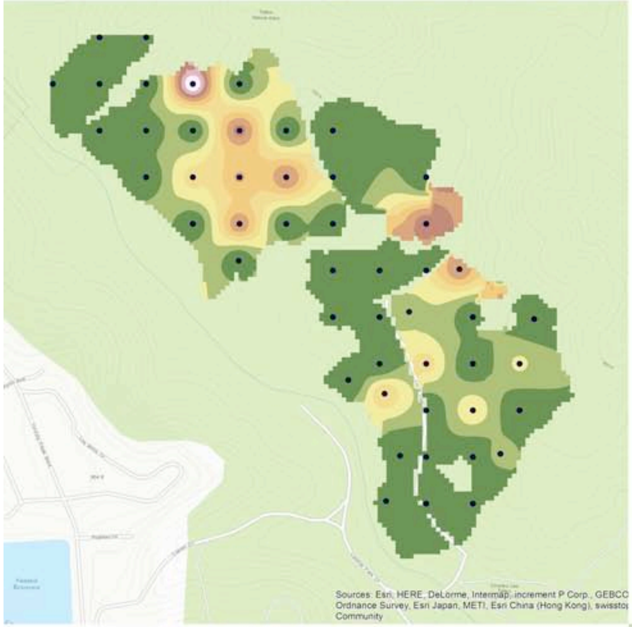
RESULTS

Variability of native tree density over the landscape

The density of native trees at each sample point was highly variable across the landscape, ranging from 1.14 stems per hectare to 3,414.11 stems hectare (figs. 2, 3, 4, and 5). Oak and bay seedlings were more common in the northwestern section of the forest, where they occurred in high densities together in the central and northern edge of the major northwester stand. Mature oaks and mature bays were less abundant than seedlings overall, and tended to have just a few small points of high density near stand edges.

Environmental Variables

Linear regressions of percent canopy cover, slope aspect, slope steepness, and forest edge distance against native tree density all produced p-values significantly higher than 0.05 with very poor r-squared values, failing to reject the null hypothesis that each of those variables is correlated with the density mature and seedling oaks and bay laurels (fig. 6). I also transformed the data using a log scale, exponent scale, and by removing data points that indicated less than 5 trees per square hectare, a near-zero measurement in comparison to other values. All data transformations failed to reject the null.



Stems per hectare

- 🟩 1.14208734 - 184.9873432
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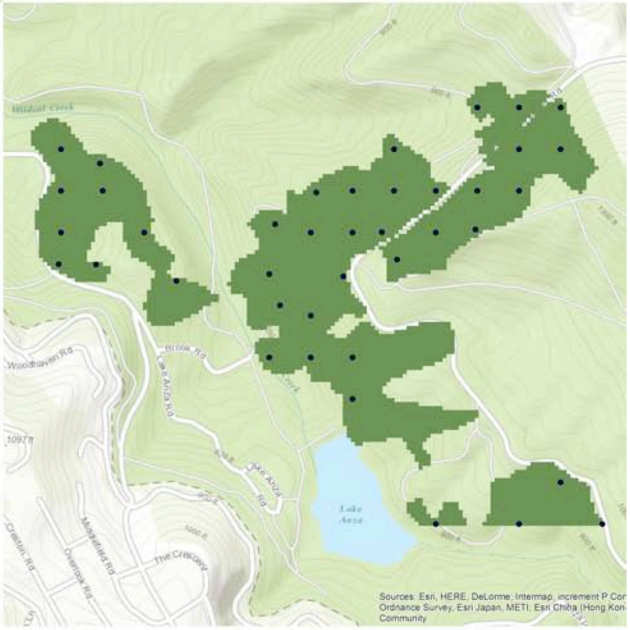
Figure 2. Map of oak seedling density. Densities ranged from 1.142 stems per hectare to 1,655.749 stems per hectare. Oak seedlings were generally denser in the northwestern forest, with the highest density occurring at the northern edge. Other high-density areas were present at both forest edges and interiors. The southeastern forest was less populated by oak seedlings, showing no variation across the landscape.



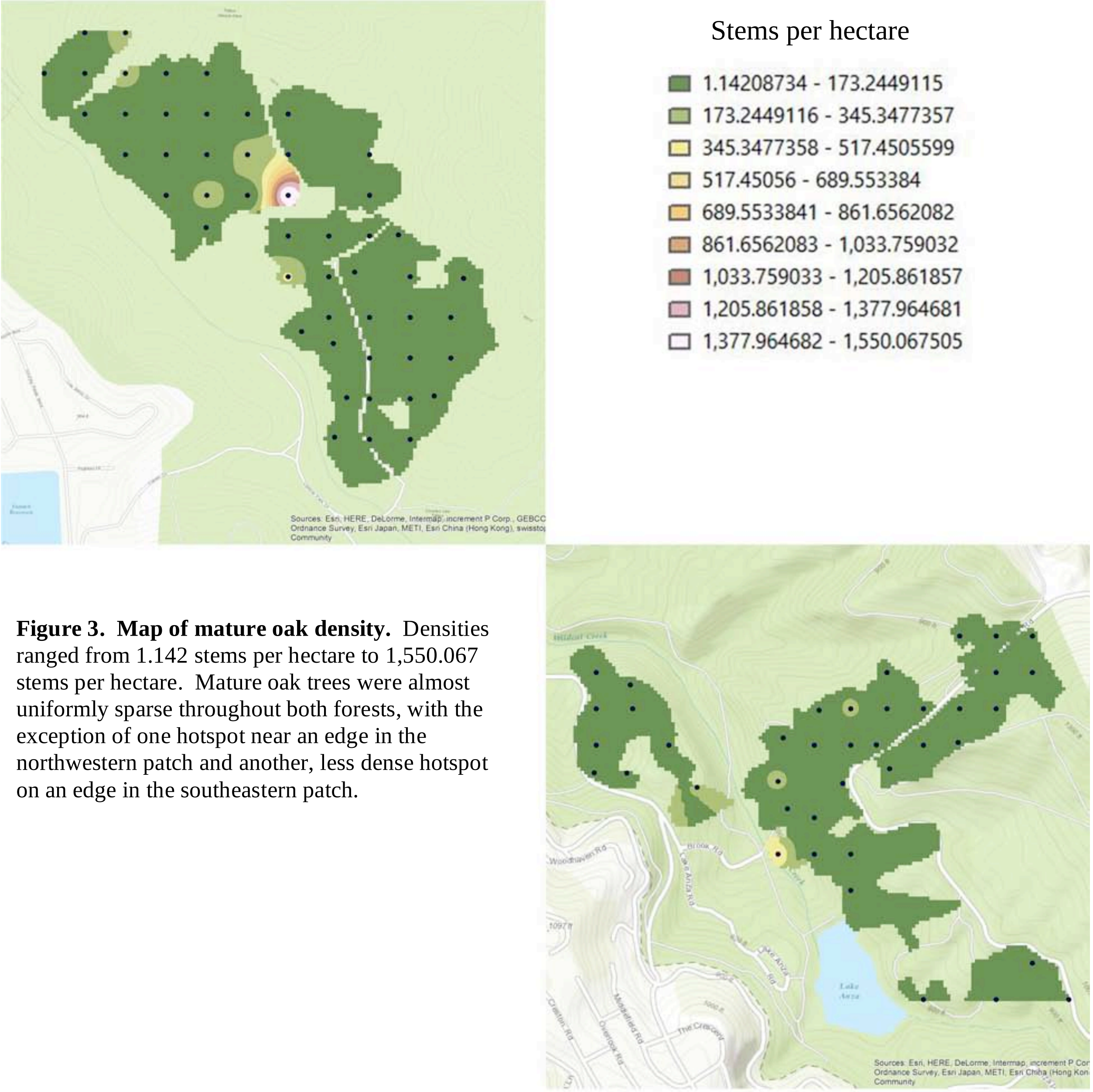


Figure 3. Map of mature oak density. Densities ranged from 1.142 stems per hectare to 1,550.067 stems per hectare. Mature oak trees were almost uniformly sparse throughout both forests, with the exception of one hotspot near an edge in the northwestern patch and another, less dense hotspot on an edge in the southeastern patch.

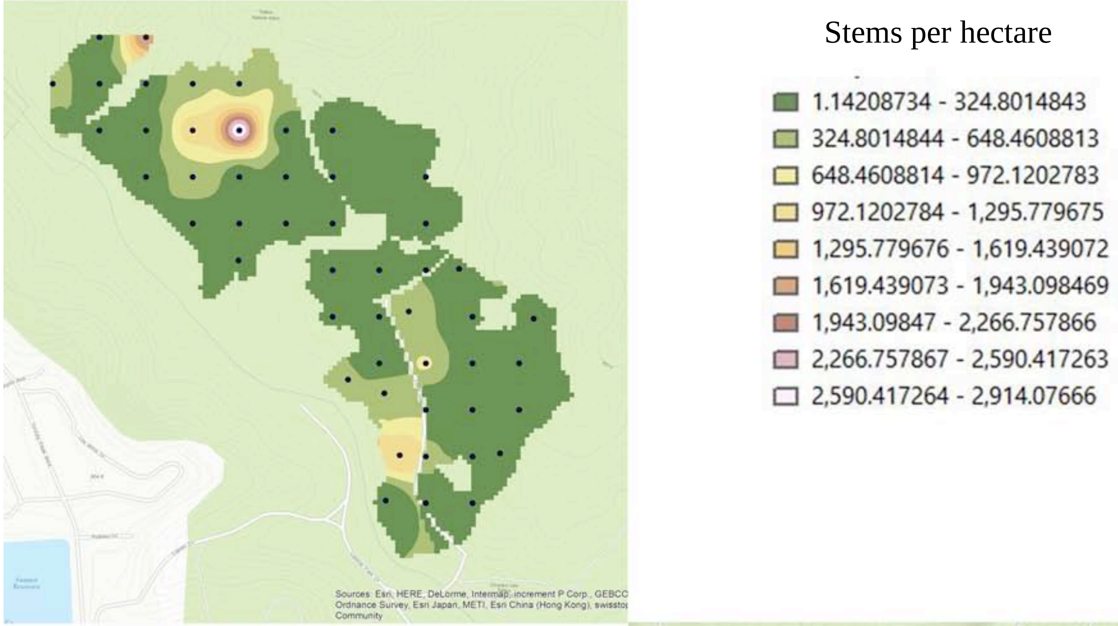
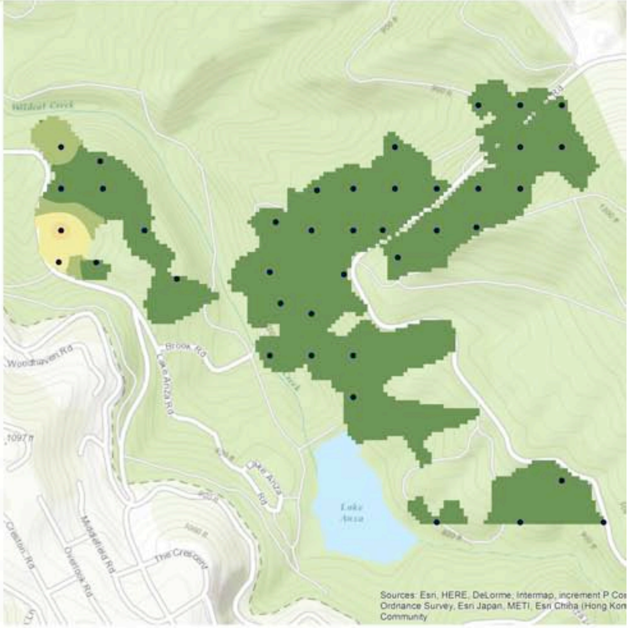
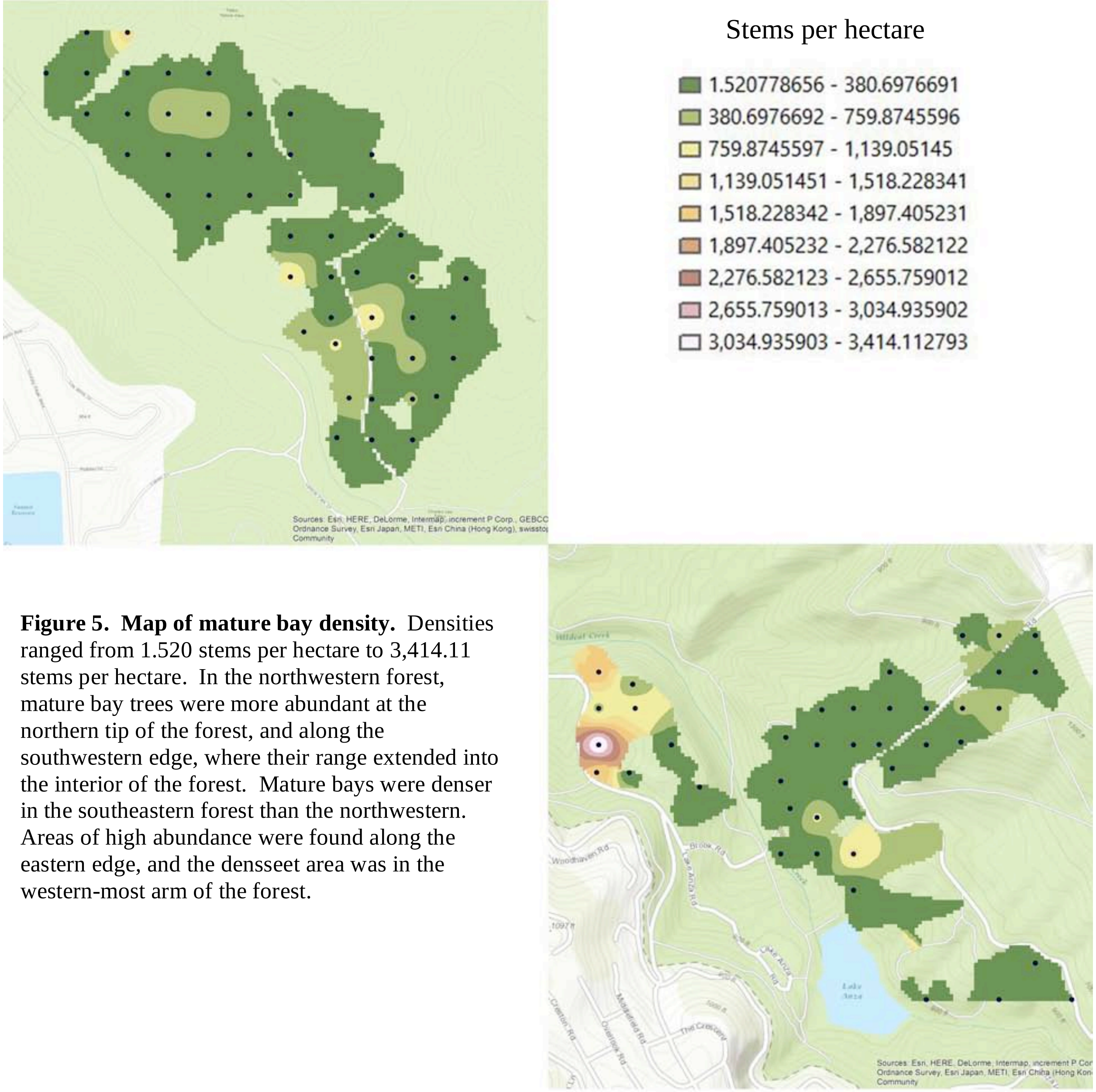


Figure 4. Map of bay seedling density. Densities ranged from 1.142 stems per hectare to 2,914.076 stems per hectare. Bay seedlings were denser in the northern range of the northwestern forest. Though they showed an increase in density along that edge, they were most abundant nearby, towards the center of the stand. Another stretch of higher density bay seedlings occurred near the interior and western edge of the northwestern forest. In the southeastern forest, bay seedlings were unabundant in almost all places except for a small patch of forest near the western edge.





Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO
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Figure 5. Map of mature bay density. Densities ranged from 1.520 stems per hectare to 3,414.11 stems per hectare. In the northwestern forest, mature bay trees were more abundant at the northern tip of the forest, and along the southwestern edge, where their range extended into the interior of the forest. Mature bays were denser in the southeastern forest than the northwestern. Areas of high abundance were found along the eastern edge, and the densseet area was in the western-most arm of the forest.

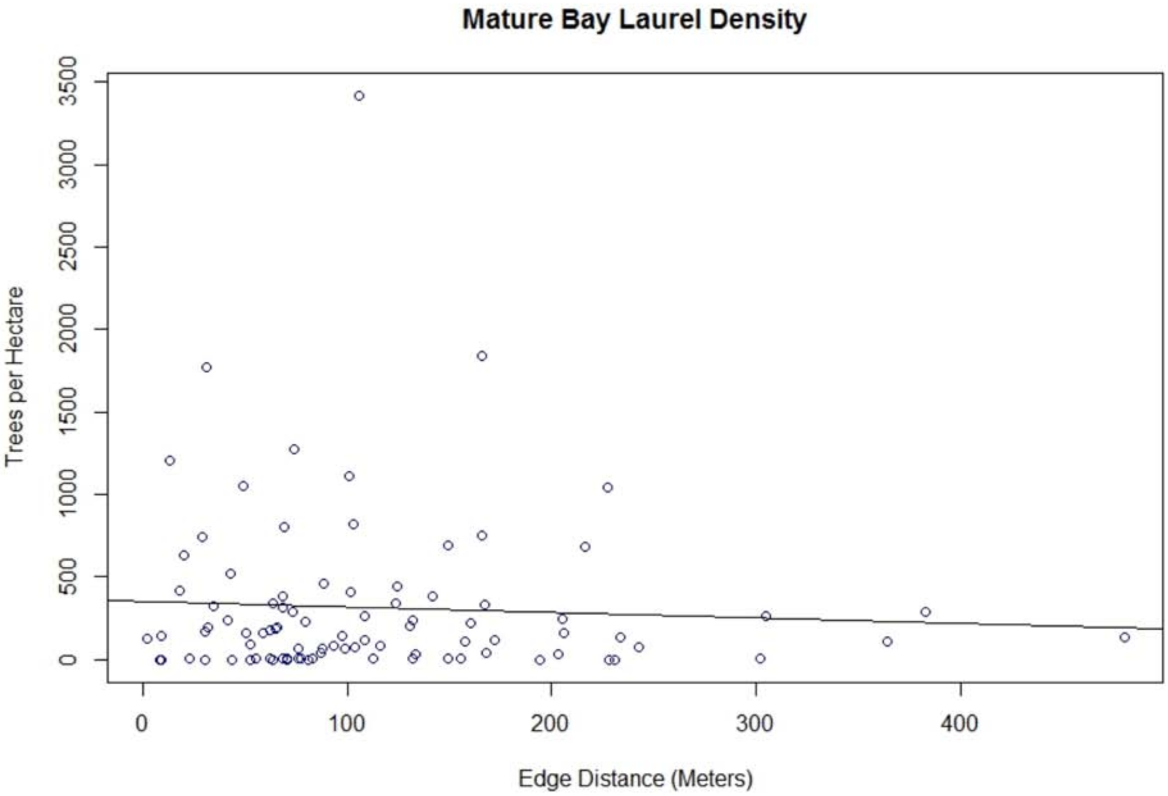

Figure 6. Mature bay laurel density as a function of edge distance – example plot of all linear regressions. This plot effectively demonstrates the correlation found in all other linear regressions performed for this study. Some of the data does appear to follow the linear model, especially as distance increases past 200 meters. However, an abundance of sample points with zero or near-zero stems per hectare throughout the range of edge distance, and unusually high measures of stems per hectare such as 3,500 stems per hectare 100 meters from the edge, demonstrate an apparently random distribution of bay laurels. Though high-density measures do drop off around 250 meters, there is no significant correlation at $\alpha = 0.05$.

The Wilcoxon signed-rank test indicated that a history of fuels reduction treatment was correlated with significantly more oak and bay seedlings per unit area (fig. 7). The p-value for oak seedlings was 0.00162 and the p-value for bay seedlings was 0.00009314. The density of mature oaks and bays was not correlated with a history of fuels reduction treatment at $\alpha = 0.05$.

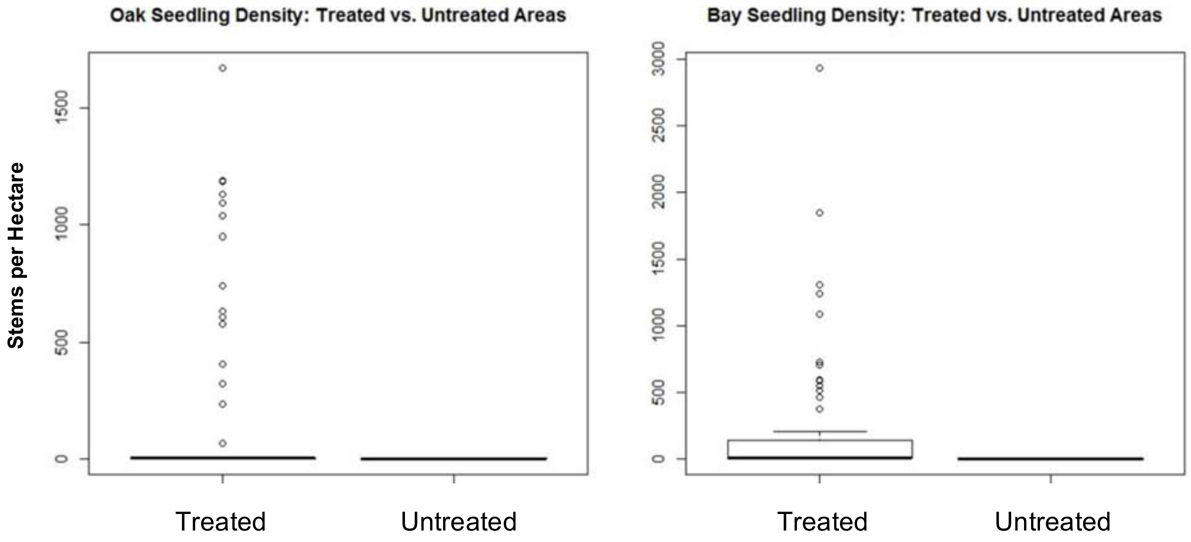

Figure 7. Comparison of the densities of oak and bay seedlings between treated and untreated areas. For both species, sample points without a history of thinning treatment had near-zero measures of density. While sample points with a history of treatment still had a median density of near-zero stems per hectare, positive outliers pulled the distribution past 1,500 stems per hectare for oaks and to 3,000 stems per hectare for bays. Bay seedlings also demonstrated a positive spread within the third quartile and the interquartile range, while oak seedlings did not. In both cases, sample points without a history of treatment had significantly fewer stems per hectare, producing p-values much lower than 0.05.

The NMDS plot demonstrated an apparent clustering of native trees both by species and age (fig. 8). Vectors for mature trees pointed opposite of those for seedlings, an indication that where mature trees were found, seedlings were likely to be less abundant. Vectors for oaks of both age groups were roughly opposite of those for bays, also indicating a tradeoff between the abundance of oaks and the abundance of bays. This difference was more pronounced in the vectors for mature trees, which were spaced farther apart than those of the seedlings. The plot did not reveal any synergistic effects between environmental variables. It did, however, confirm the correlation between treatment history and seedling density, with a p-value less than 0.001. The vector for treatment was spaced more closely to that of bay seedlings than that of oak seedlings, indicating a comparatively greater relationship between treatment history and bay seedling density.

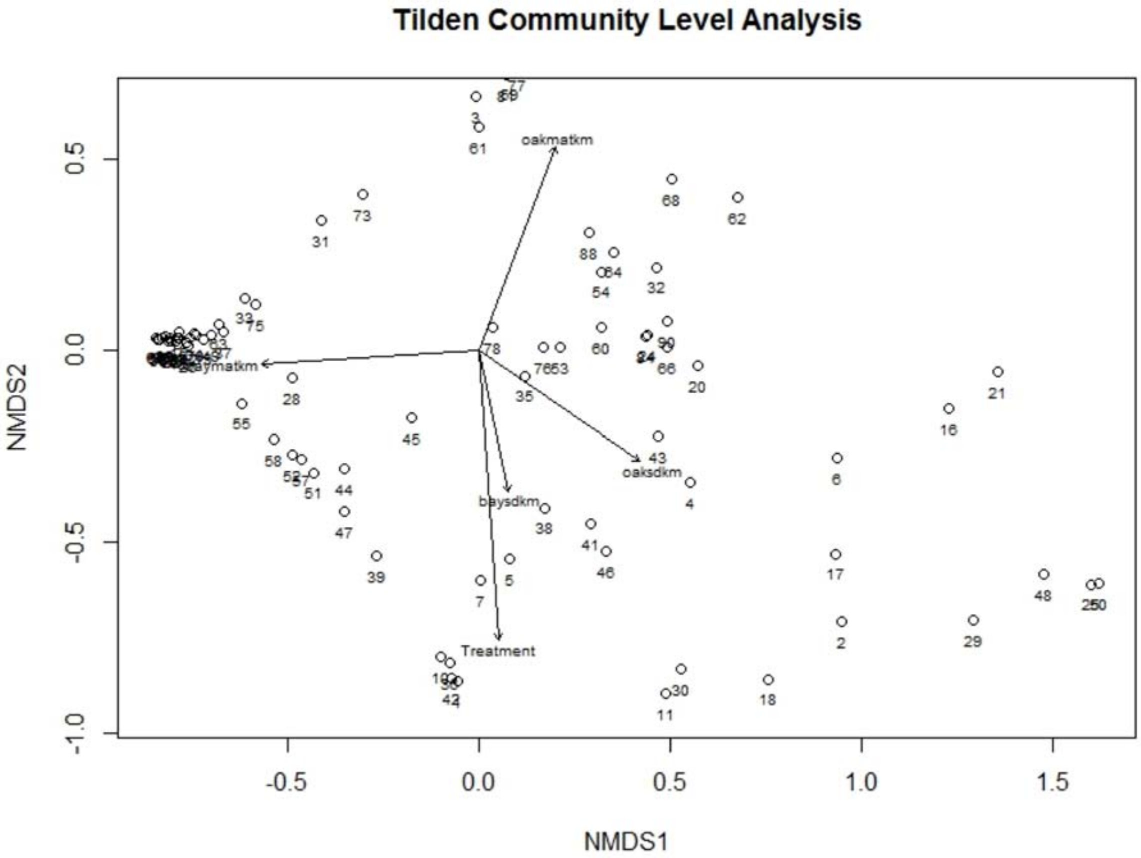

Figure 8. NMDS plot of all sample points, with determining factors. Variation in the densities of native trees between plots occurred along a uniform gradient, but could still be polarized based on species and age class. Treatment history was strongly correlated with a high presence of seedlings of both species, though it was more strongly associated with bay seedlings. Sample points with a high density of mature oak trees tended to be the most different from the other points.

DISCUSSION

Summary of Findings

The maps generated by interpolation demonstrate that the densities of native trees do vary throughout the understory of the eucalyptus forests in Tilden regional park. Oak seedlings, bay seedlings, and mature bay trees all appeared to share a preference for the center and northern edge of the northern stand in the northwestern forest. All tree types showed high concentrations in “hotspots” rather than changing in large gradients over the landscape. The effects of canopy cover, slope steepness, slope aspect, and distance to the forest edge are not being expressed in the eucalyptus forest, and therefore cannot explain the variation in native tree density, while thinning is associated with a higher density of seedlings for both species. Future researchers may wish to conduct a longitudinal study, comparing seedling density before and after thinning in order to ensure that the thinning process itself is actually the factor that contributes to increased seedling growth.

Limitations of the Study and Future Improvements

The point-quarter method was originally intended to provide a quick and accurate measure of density for a whole forest by being repeated in several random locations so that an average may be taken to determine the forest’s true density. I instead used the method to produce local density measures without averaging, and therefore may have limited the extent of the measure’s accuracy. While averaging the measure amongst many sample points may provide an effective global measurement, each measure on its own is only accurate to the farthest tree that was measured, and therefore is likely to over-exaggerate the abundance and magnitude of high density measures. Because of this, I recommend that the densities provided be considered on a relative basis, rather than an absolute one. Future studies may overcome this by measuring the three nearest trees in each quadrant, thereby mitigating the effect of trees that may be closely space around the sample point in an otherwise bare section of forest. Sampling to the third tree is a more accurate method (Engeman *et al*. 1994) that I overlooked for this study due to time constraints, but may be necessary in order to determine localized forest density more reliably.

Future studies may also want to consider other vegetative factors that may be affecting native tree density. While I was collecting data, I noticed that blackberry and poison oak vines were particularly abundant, sometimes forming continuous mats for the entire distance between sample points. These mats appeared to suppress the majority of other vegetation types, except eucalyptus and a few other adult trees, and I often found seedlings and saplings of oak and bay laurel that were being overtopped by the blackberry and poison oak vines growing on them. I suspect that those native plants may be having a greater direct suppression effect on the native trees than the eucalyptus themselves.

Management

An increased presence of seedlings in thinned areas of the forest is likely due to a cause-effect relationship that has been observed in other forests (Ares *et al*. 2009). The continuation and expansion of fuels reduction treatments is therefore very likely to positively affect the biodiversity of native species, and will provide an excellent opportunity to make before-and-after observations on changes in native tree abundance. Unfortunately, the ability of native vegetation to restore itself after the removal of the eucalyptus means the thinning project is likely to only be a short-term fix for fire danger in the area. As previously stated, before fire suppression, Tilden regional park was a grassland that was either grazed or burned frequently in order to keep the landscape open and fuel loads low. In order for fire danger to be reduced for the area, those natural processes need to be reintroduced, and the ecological state of the park needs to be returned to a historical baseline preceding American conquering of the area, ideally returning to the land management practices of the indigenous Californians that lived in the area before Spanish conquest. Though cutting down the eucalyptus is a good first step in restoring the landscape to that state, the residents of Berkeley, Alameda County, and the managers at the East Bay Regional Parks District need to agree on a path to more historically accurate management practices if they want to truly reduce the risk of fire in their hills indefinitely.

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