MODELING THE RISK FOR PHYTOPHTHORA RAMORUM WITH AN ANTHROPOGENIC FOCUS IN NORTHERN CALIFORNIA

A Thesis

Presented

to the Faculty of

California State University, Chico

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Environmental Science

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by

Alexandria S. Thornton

Fall 2018

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ABSTRACT

MODELING THE RISK FOR PHYTOPHORA RAMORUM WITH AN ANTHROPOGENIC FOCUS IN NORTHERN CALIFORNIA

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Phytophthora ramorum is an oomycete plant pathogen found in both North America and Europe that is commonly referred to as Sudden Oak Death (SOD). Since its initial detection in California in 1995, SOD has killed over a million trees, primarily tanoaks (*Lithocarpus densiflorus*), coast live oak (*Quercus agrifolia*), California black oak (*Quercus kellogii*), and Shreve's oak (*Quercus parvula* var. *shrevei*). Northeastern California has thus far remained uninfected with the exception of one *Rhododendron* tree in Placer County. In order to contribute to the prevention of SOD spread to northeastern California, I created several models that depict where the risk for SOD development is highest based on four variables: host vegetation, climate suitability, proximity to roadways, and proximity to nurseries and lumber mills. I used a weighted overlay analysis to combine these variables at differing weights under five conditions. I applied the same analyses in Mendocino County, where sampling for SOD has resulted in 73

positive cases and 326 negative cases, to assess the accuracy of each condition. I calculated Cohen's Kappa coefficient to measure the agreement between each condition and the recorded points. Though the Kappa values do not show strong agreement in the conditions, they do illustrate a trend of increase in agreement with the addition of proximity to roadways and nurseries. Suitable climate and host vegetation for SOD also exist along the coastal Pacific Northwest, and most of that area lies too far away from SOD incidence for natural spread to be the primary concern. Similar risk models incorporating human introduction variables could be applied to all of this area.

CHAPTER I.

INTRODUCTION

Overview

Phytophthora ramorum Pathogen

Phytophthora ramorum (Werres et. al, 2001), is an oomycete plant pathogen found in both North America and Europe that is commonly referred to as Sudden Oak Death (SOD). It was found on both continents during the mid-1990s, where different woody plant species were experiencing disease symptoms (Svihra, 2001). Researchers in parts of Germany and the Netherlands found dieback on species of *Rhododendron* spp. and *Viburnum* spp. (Werres et. al, 2001), while central California had multiple reports of tanoaks (*Lithocarpus densiflorus*) dying suddenly (Svihra, 1999a). On both continents SOD is considered an invasive species and although the first incidents likely trace its entry via infected nursery plants, its origin is unknown (Werres et. al., 2001).

P. ramorum can spread asexually when sporangia or zoospores are distributed by waterways, however it more commonly spreads via wind or rain splash (Davidson et. al., 2001). Chlamydospores can also be produced on host species, and though they are inadequately understood in current research (Smith and Hansen, 2008), are thought to have an important role in the survival of the pathogen in more extreme conditions (Hwang and Ko, 1978). Sporangia that disperse onto foliage typically spreads to twigs, branches, and trunks as water is carried down the tree (Parke and Lucas, 2008). The role of soil in the SOD pathogen's reproduction cycle is not well understood, however some research suggests that it serves as a reservoir for the inoculum

during drier and hotter seasons (Eyre and Garbelotto, 2015; Tooley and Carras, 2011). The pathogen can infect unwounded bark and cause cankers. SOD infects over 96 different woody plant species which all exhibit different symptoms, including cankers, foliage dieback, and death (Davidson et. al., 2003). Many oak species can have a sudden browning of the foliage crown after the pathogen has inoculated, which is the origin of its common name.

The devastating effects of just two decades can be seen along the United States' Pacific coast, where over one million tanoaks, coast live oak (*Quercus agrifolia*), California black oak (*Quercus kellogii*) and Shreve's oak (*Quercus parvula* var. *shrevei*) have perished from SOD infection (Garbelotto et. al., 2003; Lee et. al, 2010). Other species act as pathogen hosts and suffer from foliage decay and branch dieback but survive and continue to remain a source of inoculum spread for other trees. For example, California Bay Laurel *(Umbellularia californica)* is a primary host that survives the pathogen and is a strong vector of inoculum spread (Kelly and Meentemeyer, 2002). The United States Department of Agriculture (USDA) has a complete list of all recorded species, 96 in total, found to be associated with the SOD pathogen (El-Lissy, 2013). It is updated regularly as new associated species are discovered.

The consequences for both humans and wildlife from SOD are abundant. The costs of the treatment, removal, and replacement of infected trees has been estimated at $7.5 million in California alone (Kovacs et. al., 2011), and dead trees and diseased foliage increase fuels resulting in greater fire risk in high mortality areas (Forrestel et. al., 2015). The reduction in ecosystem structure, habitat, and food for many wildlife species that rely heavily on oaks is predicted to reduce the diversity and abundance of those species (Fischer and Hadj-Chikh, n.d; Monahan and Koenig, 2006). The ability of high SOD mortality areas to sequester carbon could also be

significantly reduced on a regional scale and take decades to recover (Hicke et. al., 2012). The long-term damages are yet to be seen as we enter the third decade of SOD infestation.

There is no known cure for trees infected with SOD. The only way to restrict its spread is through preventative methods or to remove infected materials. Preventative methods include, reducing the number of California Bay Laurel trees near susceptible oaks, restricting pruning of susceptible species to certain seasons, and the strategic use of the chemical treatment, Agri-Fos, a fungicide (Lee et. al., 2010). All of these methods are relatively tedious, especially the most well-proven preventative treatment, Agri-Fos, since it requires spraying or injecting individual tree trunks (Agri-Fos, 2017; Lee et. al., 2010). This demonstrates a need to invest in large scale prevention, which is just as important, if not more so, than actively removing infected material from forestland. The process of preventing SOD spread can be extensive, especially since the presence of the pathogen must be confirmed by laboratory methods (Lee et. al., 2010), but the use of a predictive risk model for uninfected areas can be a vital resource to ensure efforts are as effective as possible.

Previous Geospatial Modeling

With a combination of climate suitability, host species presence data, and topography, researchers have generated geospatial models to highlight where favorable conditions overlap to host the production of spores, and thus where the risk for the development of the pathogen is highest. These models depict the relative risk for the development of SOD based on current conditions across spatial scales, including the entire United States and the individual states of Oregon and California (Kelly et. al., 2006; Kluza et. al., 2007; Meetenmeyer et. al., 2004; Václavík et. al., 2010), and with consideration of potential future climate predictions (Meetenmeyer et. al.,

2011). All of the aforementioned models show that the northeastern portion of California has both the climatic conditions and host species necessary to create moderate risk for SOD development (Meetenmeyer et. al., 2004; Meetenmeyer, 2011). Two northeastern counties, Butte and Yuba, have been predicted to be infected with SOD by 2020 from the expansion of existing SOD infections (Kovacs, et. al., 2011). Thus far there has been only one confirmed case of SOD on a *Rhododendron* near this area, which was found in Placer County in 2014 (SOD Blitz, 2014). The rest of the nearest confirmed cases of SOD are over 80 km away from these moderate risk patches, which has reduced the overall risk predicted in many models since it is unlikely that natural sources of SOD span that great of a distance.

Nurseries as a Potential Infection Source

In 2004, a California wholesale distribution nursery shipped SOD infected host plants across the United States to 783 other nurseries (Stokstad, 2004). Nationwide efforts ensued to remediate the situation through regulations and import bans. SOD pathogen surveys conducted in nurseries between 2001 and 2009 by the USDA found 466 positive cases of infection in eleven states across the U.S., including California (Kliejunas, 2011). The most recent survey conducted in 2017 found 16 nurseries positive with SOD infection in California. The USDA has implemented regulations and Best Management Practices (BMPs) for nurseries in infected states under Title 7, section 301.92 of the Code of Federal Regulations (CFR). Additional state regulations exist that are enforced by the California Department of Food and Agriculture (CDFA) for California nurseries in quarantined counties. Despite the risk that nurseries pose to the spread of the SOD pathogen, they have yet to be relatively scored and included in a risk

assessment model. Similarly, lumber mills that handle raw logs have potential to carry infected tree species, though they have not been included in any USDA nursery surveys.

Roads as Vectors of Spread

Since spores of *P. ramorum* can be aerially dispersed, the transport of infected plant materials has the potential to spread the SOD pathogen to areas adjacent to roadways. Logging trucks or even the average consumer that carries plant materials in open back vehicles are providing a source of inoculum as air passes over the infected plants. Additionally, infected soils have the potential to be carried on vehicle tires and distributed along roadways. Although roadways have been incorporated into some risk models in Oregon (Peterson et. al., 2014), they have yet to be utilized in California and have not been rated relative to their travel frequency.

Research Objectives

To contribute to the prevention of SOD spread to northeastern California, I addressed the following objectives:

(1.) Examined the relationship between nursery and lumber mills containing host species and proximity to confirmed sites of SOD infection,

(2.) Examined the relationship between relative travel on roadways to confirmed sites of SOD infection, and

(3.) Created multiple geospatial models that depict the combination of host vegetation presence, climate suitability, host-carrying nursery proximity, and roadway proximity in five weighted analyses to assess the risk for SOD pathogen infection.

CHAPTER II.

METHODS

Site Description

Study Area

My seven-county study area encompasses 26,313 km^2 in north eastern California and includes Butte, Plumas, Sierra, Nevada, Placer, Yuba, and El Dorado counties (Figure 1). It is divided by three different ecoregions: the Great Central Valley, the Sierra Nevada Mountain Range, and Cascade Ranges. The area receives between 270-2960 mm of precipitation annually (PRISM, 2017), with lower elevations receiving 270 mm and higher elevations receiving 2690 mm. Annual minimum temperatures range from -4 to 12°C, while average maximum temperatures range from 8-24°C. The western side of the study area is within the Central Valley with the lowest elevation at 9 meters. Land use is predominantly agriculture and vegetation is dominated by orchards and farmland. Slightly east of this the vegetation changes broadly to Californian Annual Grassland & Forb Meadows, then to Californian Broadleaf Forest & Woodland, which is dominated by Coast Live Oak, California Black Oak, Canyon Live Oak (*Quercus chrysolepis*), Blue Oak (*Quercus douglasii*), Valley Oak (*Quercus lobata)*, and Interior Live Oak (*Quercus wislizeni*) (USNVC, n.d.). Continuing east into the Sierra Nevada mountain range, elevations reach 3,038 meters and vegetation is dominated by Californian Montane Conifer Forest & Woodland (USNVC, n.d.). The eastern side also includes four national forests: Lassen, Plumas, Tahoe, and El Dorado.

Model Validation Area

I chose Mendocino County as a model validation location because many cases of SOD infection currently exist in the area (Figure 1). Mendocino County is located on the northern coast of California and encompasses 9097 km^2. The coast is dominated by the Redwood and Douglas Fir vegetation alliance, and California Montane Conifer Forest and Woodland (USNVC, n.d.). Elevation ranges from 2-2010 meters. Annual precipitation ranges from 883 mm at the lower elevations and increases to 2486 mm at higher elevations (PRISM, 2017). Annual minimum temperatures range from 2-10°C, and average maximum temperatures range from 12-24°C.

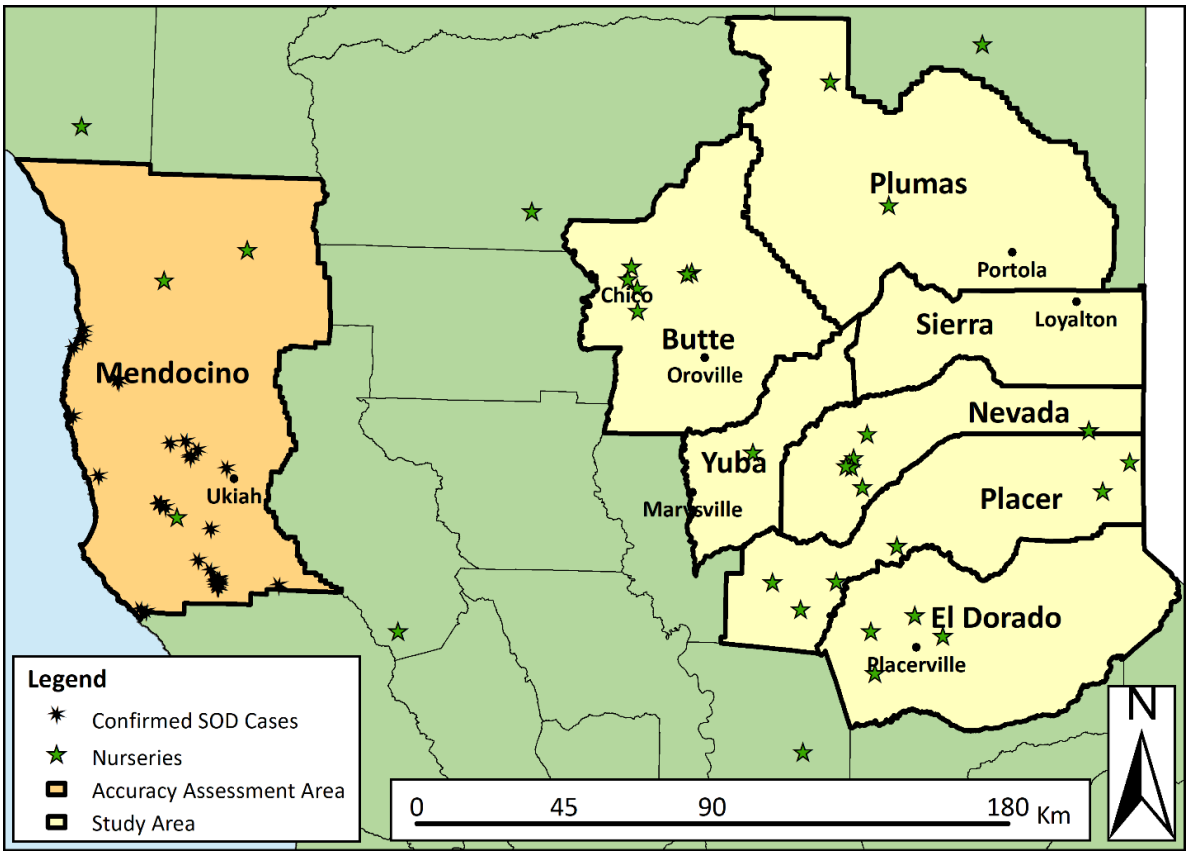

Figure 1: The study area including Butte, Plumas, Sierra, Nevada, Placer, Yuba, and El Dorado counties in yellow. Mendocino County, the model validation area, in orange. All coast SOD incidences are representing as black spikes along the coast, while nurseries included in the weighted overlay analyses are represented with green stars.

Host Vegetation

Data Source

The Classification and Assessment of Visible Ecological Groupings (CALVEG, USDA 2004) is a polygon feature class data layer that divides California into ecological zones based on dominant plant species. Derived from Landsat satellite imagery (30 m resolution), it is currently the highest resolution vegetation map that completely covers the study area plus Mendocino County for accuracy assessment (USDA, 2004). The ecological zones that cover the study area were updated in 1999-2001 and 2005. The zones that cover Mendocino County were updated in 2007, 2013, and 2014.

Procedure

There are 46 primary host species for the SOD pathogen (APHIS, 2013). Each species was assigned a score based on its ability to host and pass on the inoculum (Appendix A). Each host species received a starting score of one point. An additional two points were added for each type of spore (chlamydospores and zoospores) that can develop on that species, as demonstrated in previous studies (Kliejunas, 2010). California Bay Laurel, due to extreme efficacy to host and pass on the inoculum, was assigned an additional two points (for a total of seven points) to represent its relative high risk.

Species level data is not directly in the CALVEG GIS data, but rather each polygon is assigned a vegetation alliance. All alliances are detailed in nine manuals which qualitatively describe the species presence within each one using terms such as “typical associate” and “mixes with” (USDA, 2004). I assigned each of the different phrases used to describe the presence of the species an abundance score from 1-10 (Appendix B). This score was then multiplied by the risk

score of the individual host species (Figure 2). For example, an excerpt from the CALVEG alliance manual description for the Sugar Pine Alliance is shown in Figure 2. This quote is broken down into the two components that were used to quantify a partial risk score. The descriptor of the host species "typical… associate" was given an abundance score of five, while the host species, Canyon Live Oak's calculated risk score is one. The abundance score and the host species risk score were multiplied together to get the total risk score that Canyon Live Oak contributes to the Sugar Pine Alliance. Each sentence in each alliance that mentioned any of the 46 host species was similarly deconstructed and scored. The products of the individual species scores and their abundance scores were summed so that each alliance had a total host vegetation presence score. Each vegetation polygon was then assigned this host presence score based on its corresponding CALVEG alliance. This feature layer was then rasterized. The raster was reclassified to a 1-20 score range to allow for easy visibility of variation within the study area. Those scores made up the host vegetation variable in the weighted overlay geospatial analysis (Figure 3)(Meetenmeyer et. al., 2004).

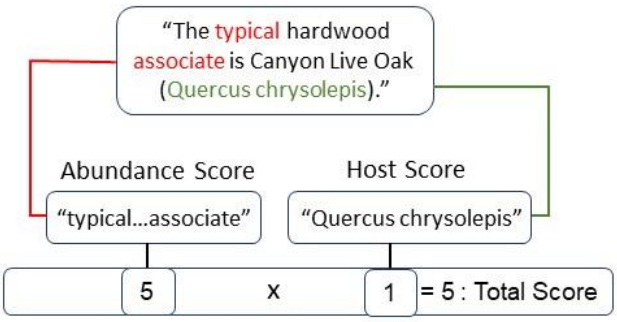

Figure 2: Depiction of the equation used to quantify the CALVEG alliance manual descriptions. Each description had multiple sentences like the one above to describe the vegetation in each alliance.

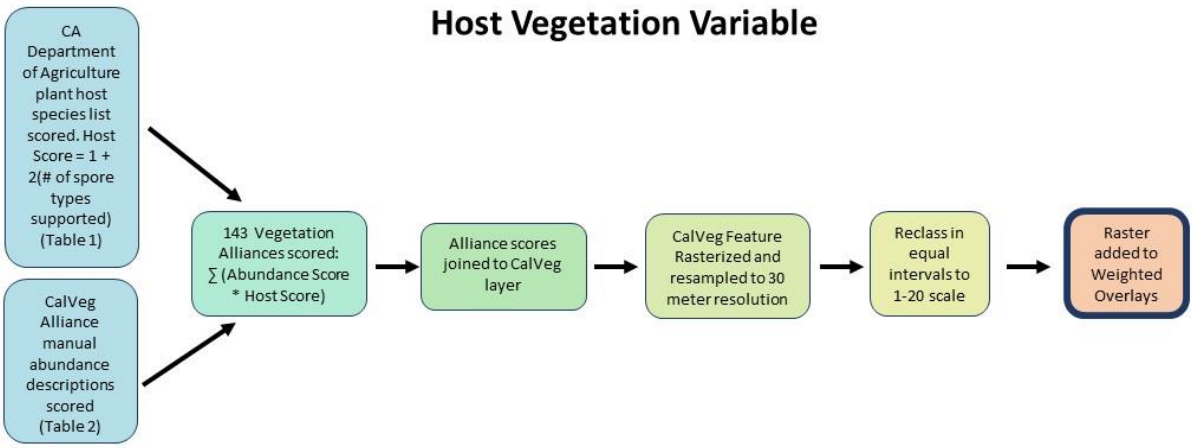

Figure 3: Workflow depicting each step taken to create host vegetation variable before adding it into the final weighted overlay analyses. All individual host species scores are listed Appendix A, and all abundance description scores are listed in Appendix B.

Climate Suitability

Data Source

I used climate data provided by the PRISM (Parameter-elevation Relationships on Independent Slopes Model) (PRISM, 2017) database as the basis for the climate suitability variable. To identify areas that could potentially sustain the pathogen, I combined five variables from PRISM at 800-meter resolution (the finest available): maximum temperature, minimum temperature, mean dew temperature, average temperature, and precipitation into one predictor variable of climate suitability. Each variable was the average of the 30-year normals for the months of December through May which is reproductive season for SOD.

Procedure

Relative Humidity. I calculated relative humidity with the mean temperature and mean dew temperature rasters and the formula (Moss, 2007) in Figure 4. The SOD pathogen thrives in areas with the highest relative humidity (RH) and cannot survive in areas with less than 40% RH (Browning et al, 2008). The RH in the study area ranged from 50-84%, so no location

was below the lethal lower limit. This range was divided into 20 equal intervals to clearly see variation within the study area and designated scores of 1-20, with 84% receiving the highest score of 20.

Temperature. Mild temperatures, ranging from 18°-22° C, are ideal for the growth and natural spread of the SOD pathogen (Venette and Cohen, 2006). The average minimum and maximum temperatures in the study area ranged from -9°C to 19°C during its reproductive season. Previous research on extreme temperature effect on the pathogen demonstrates lethal temperatures limits of -25°C and +40°C (Browning et al, 2008). Scores were assigned a gradual decrease as temperatures decreased, but no location received a score of zero as none reached the lethal limits. Temperatures in the optimal range received the highest risk score of 20, decreasing by one point for every two degrees Celsius (Table 1).

Table 1: Risk scores assigned to the minimum and maximum temperature ranges of the study area and Mendocino County.

Temperature Range (°C)	Risk Score
-10 - -8	6
-8 - -6	7
-6 - -4	8
-4 - -2	9
-2 - 0	10
0 - 2	11
2 - 4	12
4 - 6	13
6 - 8	14
8 - 10	15
10 - 12	16
12 - 14	17
14 - 16	18
16 - 18	19
18 - 20	20

Precipitation. Precipitation appears to aid in the dispersal of SOD but does not seem necessary for survival as long as relative humidity is high enough (Browning et. al., 2008). In the study area, precipitation ranged from 30-360 mm monthly average during the reproductive season. The range was divided into 20 equal intervals, with the highest range receiving a score of 20, decreasing in increments of one until the lowest range was reached. Precipitation scores started at one.

Climate Suitability Variable. The value for each of the four variables were combined within their own weighted overlay analysis to generate a new layer that represented the total climate suitability for the SOD pathogen (Figure 4). These relative weights were assigned based on their importance for pathogen survival according to the current literature (Browning et al, 2008). The percent of influence for each variable were relative humidity 60%, minimum and maximum temperatures, 10% each, and precipitation 20%. Temperatures and precipitations were assigned relatively lower weights because their ranges in the study area are all within the pathogen's survival requirements. The resulting raster was then reclassed to a 1-20 scale and resampled to 30-meter resolution.

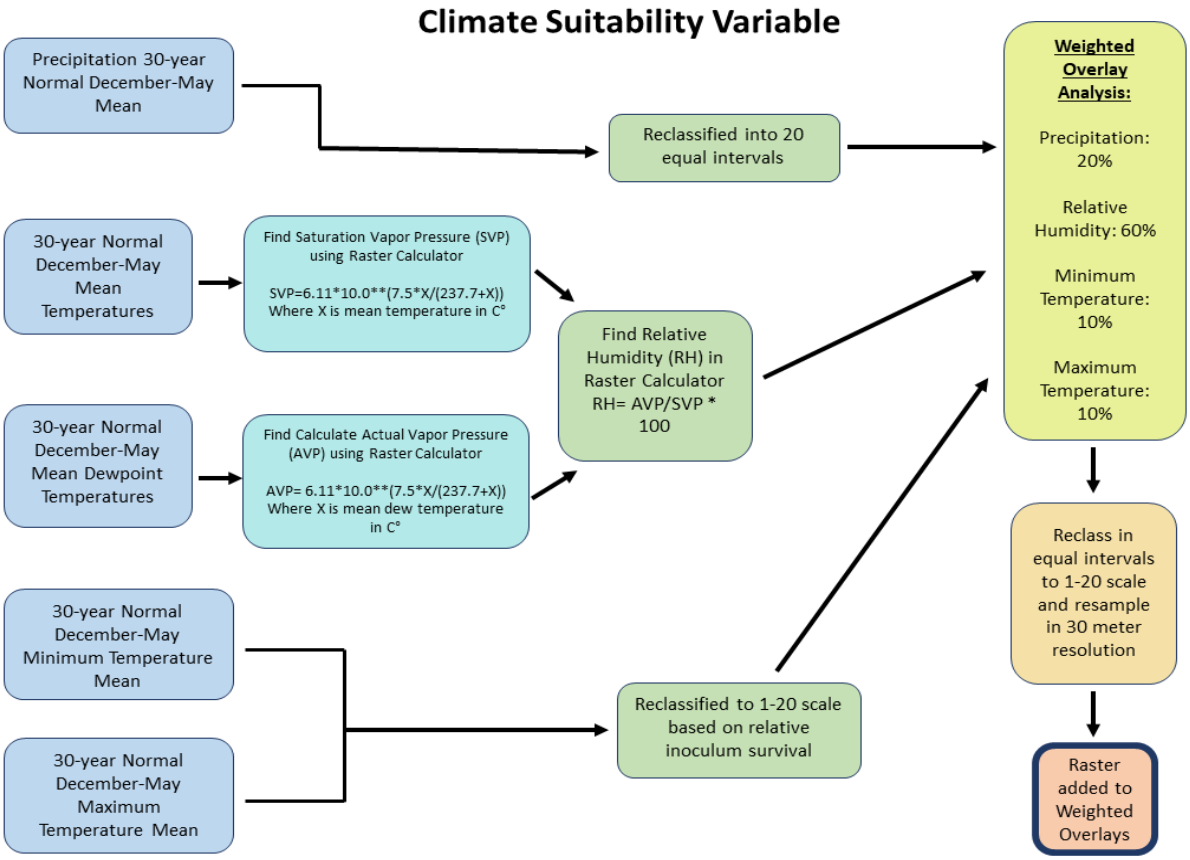

Figure 4: Workflow depicting each step taken to prepare the four climate suitability variables; precipitation, relative humidity, and minimum and maximum temperatures, into one climate suitability variable to be added into the final weighted overlay analyses.

Roadway Proximity

Data Source

The California Road System Unofficial Functional Classification (CDOT, 2017) was the foundation for the variable of proximity to pathways transporting potentially infected materials. Managed by California Department of Transportation (CDOT, 2017), all roads in California are classified as one of seven functional classifications: interstate, freeways/expressways, principal arterial, minor arterial, major collector, minor collector, and local roads (CDOT, 2017).

To estimate the relative travel on each road, I created a population density multiplier for each one using human population data from the U.S. Census Bureau, Geography Division's (2018) collection of block-group level shapefiles (USCB, 2018). The most recent dataset is from a 2018 update of the 2010 US census.

Procedure

Each of the seven road functional classifications was assigned a value in descending order, with interstate given the highest score of 9 and local roads given the lowest score of 3. These classifications indicate how frequently the roads are traveled, and consequently how likely infected plant materials are to be transported on them.

I hypothesized that the second predictor of the average volume of traffic on these roads would be the population density of the area immediately surrounding the road. Each road was assigned a population density multiplier based on the census block population, divided by the block size in square kilometers. Its population multiplier was then multiplied by its functional classification score to get an estimated frequency of use score (Figure 5).

Previous research has demonstrated that the SOD pathogen can travel up to 15 meters by natural transmission methods, primarily rain splash (Davidson et. al, 2001). In order to represent this distance, I added a 15-meter buffer to the road feature layer. The frequency of use scores were transferred to the buffer. This buffered feature layer was then rasterized at one-meter resolution, reclassed to scores of 1-20, and added to the final weighted overlay analyses (Figure 5).

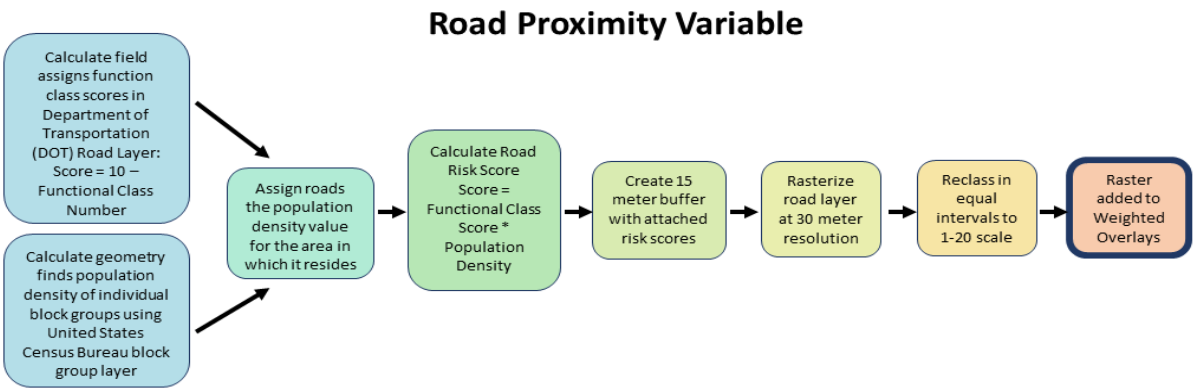

Figure 5: Workflow depicting each step taken to create roadway proximity variable before adding it into the final weighted overlay analyses.

Nursery and Lumber Mill Proximity

Data Source

I created a database of all nurseries and lumber mills within 30 km of the study area and the assessment area using the Yellow Pages website (http://www.yellowpages.com; accessed August 2017*)*. After establishing initial contact with these 156 businesses, I used Google Earth to map each of their locations. I asked each of these locations to quantify how much of each of the plant host species they sold or processed annually via a short survey. I then calculated a nursery risk score using the formula in Figure 6.

Procedure

Each of the nursery/lumbermill locations was contacted either via telephone or email or both and asked if they sold any of the 46 species on the CDFA's list of host species for the SOD pathogen. If those species were sold by nurseries, or processed by the lumber mills, an approximate number of annual individuals sold/processed was requested. The number of host individuals sold was multiplied by the individual species scores used in the host vegetation layer

(Appendix A). These scores were then summed to get a total risk value for the location. A total of 38 nurseries had scores greater than zero. Locations that sold no host species were not included in the layer.

Multiple ring buffers were created around each nursery location to assign relative risk to the surrounding area. Each buffer consisted of three 10 km wide rings. The first ring encompassed the nursery and any area within 10 km, the second ring encompassed the area 10-20 km away, and the third encompassed the area 20-30 km away. Each of the nursery buffer rings was individually scored as a function of its distance from the nursery. The score of the nursery was divided by each ring's outer limit distance to decrease the score as the distance from the location increased. If a given area was in between two areas where buffers intersected, that area's proximity risk was the sum of the buffer ring intersections. The scores represented the variable known as the proximity to the nurseries or lumber mills carrying potentially infected materials and was added to the weighted overlay geospatial analysis model.

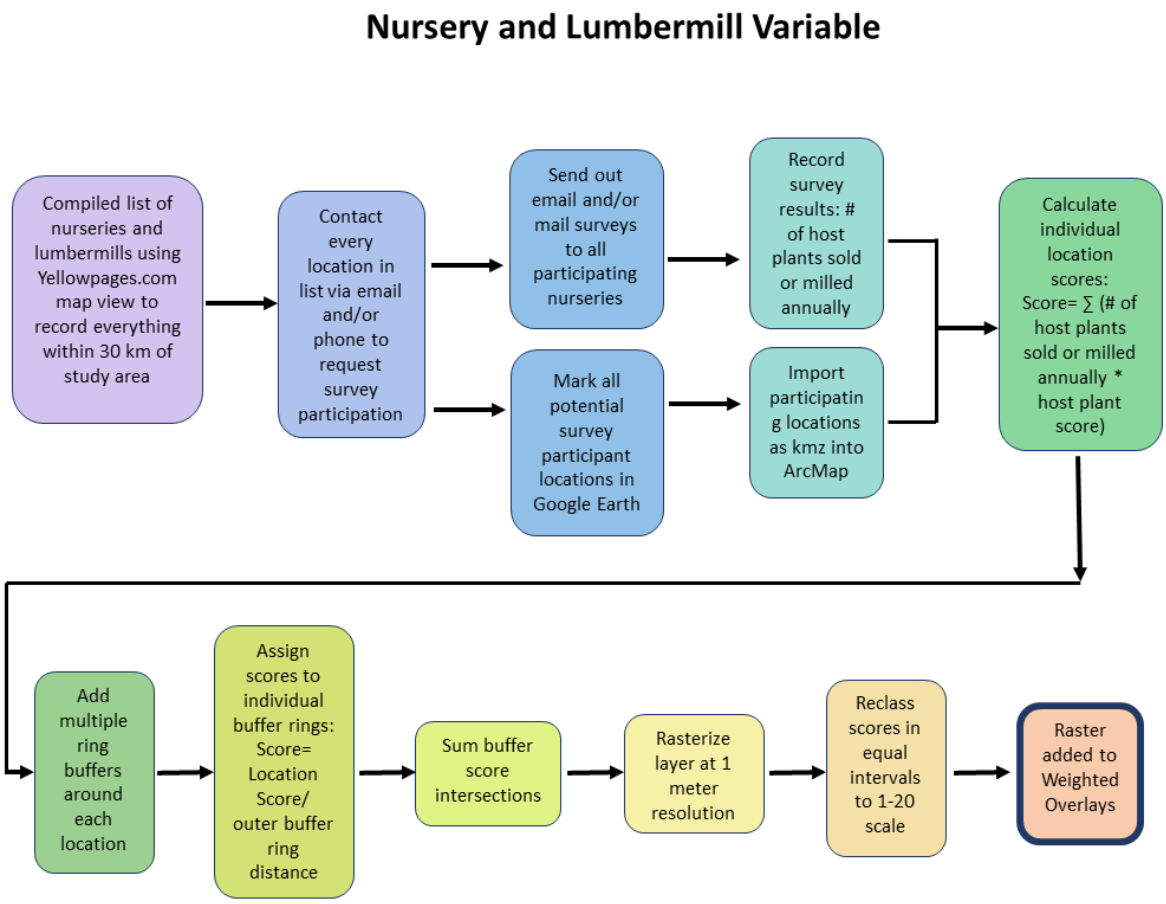

Figure 6: Workflow depicting each step taken to create the nursery and lumbermill variable.

Weighted Overlay Analyses: Combining All Four Variables

After each one of the four variables was complete, they were reclassified into ranges of 1-20. I generated a corresponding map for each of the individual variables, to visualize and identify spatial patterns in each one. The final models were developed by incorporating the four variables at various weights and combinations (Figure 7) into five different weighted overlay analyses in ArcGIS 10.6.1 (ESRI, 2018). The resulting rasters were also reclassified into a one to

five scale of SOD risk, where one is considered very low, two is low, three is moderate, four is high, and five is very high SOD risk.

Condition 1 weighted climate and vegetation evenly (50% vegetation, 50% climate) and was used as a control to see how the subsequent conditions affected the risk scores associated with each of the 73 confirmed points of SOD infection and 326 confirmed points of no infection (Figure 7). Condition 2 more heavily weighted vegetation at 60% with climate at 40% to examine the overall effect of vegetation. I carried this heavier weighting of vegetation at 60% because of the necessity for the vegetation to exist in any given area in order for a SOD infection to develop. Condition 3 and 4 added the nurseries/lumbermills and roads respectively by themselves to determine if they alone contributed to higher risk values; each weighted at 20%, with climate also at 20%. Condition 5 combined all four variables to observe the effects of their interactions, with climate at 20%, roads and nurseries/lumbermills each at 10%, and vegetation remaining at 60%.

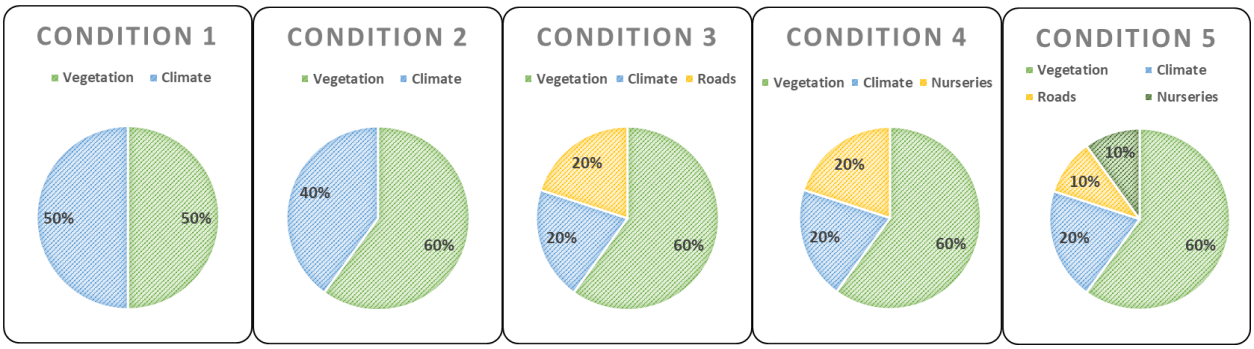

Figure 7: Percent weighting of each variable in each of the five conditions.

Accuracy Assessment

I utilized 73 points confirmed positive for SOD infection and 326 points confirmed negative (SOD Blitz, 2017) for SOD located within Mendocino County to assess the accuracy of each condition. I executed the same weighted overlay processes and reclassification in

Mendocino County and then extracted the reclassified risk values of each conditions at each of the 399 points. The number of points in each reclassified risk category were recorded to identify which of the five conditions best predicted higher risk values.

In addition to comparing the positive and negative point scores in each category, I calculated Cohen's Kappa coefficient to assess the agreement between the recorded points and each of the five conditions using a binary categorization. Cohen's Kappa coefficient range of negative one to positive one shows the agreement between each of the models while accounting for agreement by chance, where perfect agreement is equal to one. All points with risk scores one and two were categorized as negative for SOD, and all points with risk scores three to five were categorized as positive for SOD.

Output

Each of the conditions has three corresponding risk maps: one with reclassified one to five scale risk values depicting Mendocino County; one of the study area under the same reclassed conditions; and one of the study area without reclassification. These maps without reclassifications were based on the raw scores from the weighted overlay analyses which consequently depict greater variation.

CHAPTER III.

RESULTS

Host Vegetation

The relative risk scores from host vegetation in both the assessment area and my study area are depicted in Figure 8. The highest risk is shown in red on the coast of Mendocino County where tanoaks and redwoods are abundant. Within the study area there are some patches of moderate risk that run mostly throughout Sierra Nevada ecoregion in the middle of the area, where there are relatively few tanoaks, but many other less susceptible oak species and conifers, like California Black Oak, Canyon Live Oak, and Douglas Firs (*Pseudotsuga menziesii).*

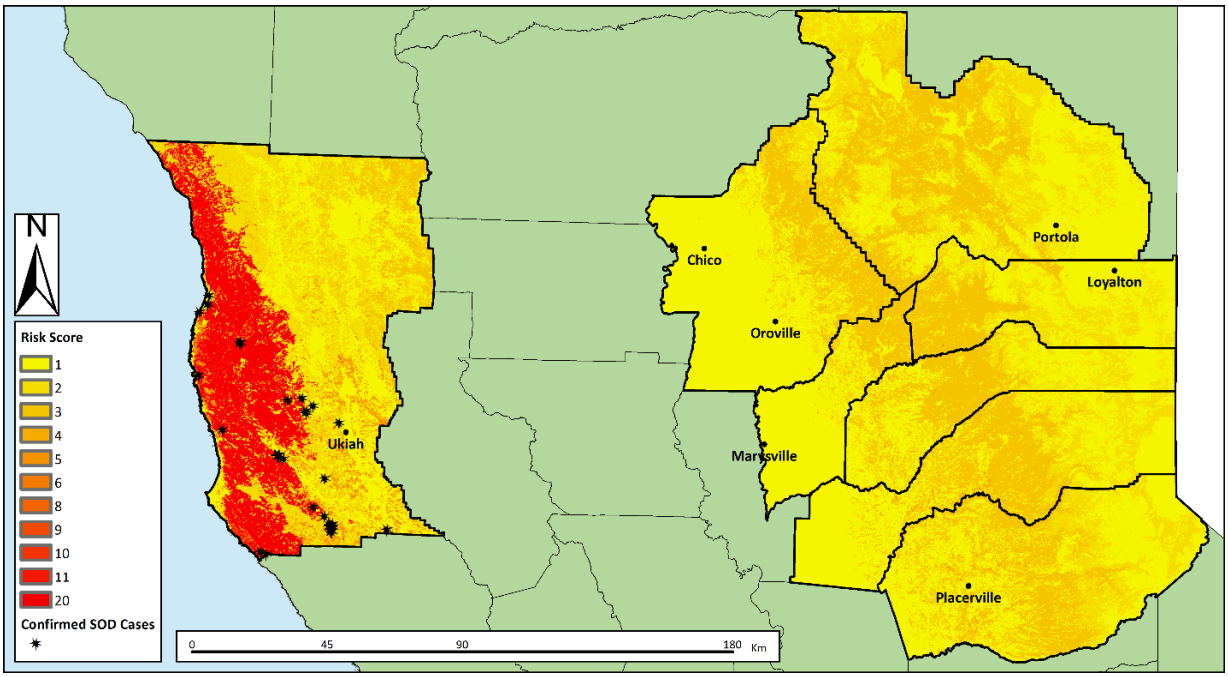

Figure 8: Risk scores of host vegetation reclassified to a 1-20 scale in both the study area on the right, and the accuracy assessment area on the left. Patches of very low risk are depicted in bright yellow, while the highest risk is shown in red and follows the coastline on the west, narrowing toward the northern end (USDA, 2004).

Climate Suitability

The risk scores for climate suitability are pictured in Figure 9. Since these scores were determined by the absolute suitability for the SOD pathogen, no areas received greater than a score of fifteen, as they were not more suitable. Similarly, no score received a 1, as no areas were on the extreme end of unsuitable. The highest risk is pictured along the coast of Mendocino where high relative humidity contributes to the higher total score. The patches of deep orange and red in my study area are attributed to the higher annual precipitation and higher relative humidity. The east side of the study area drops in risk value due to lower precipitation, lower relative humidity, and lower minimum temperatures.

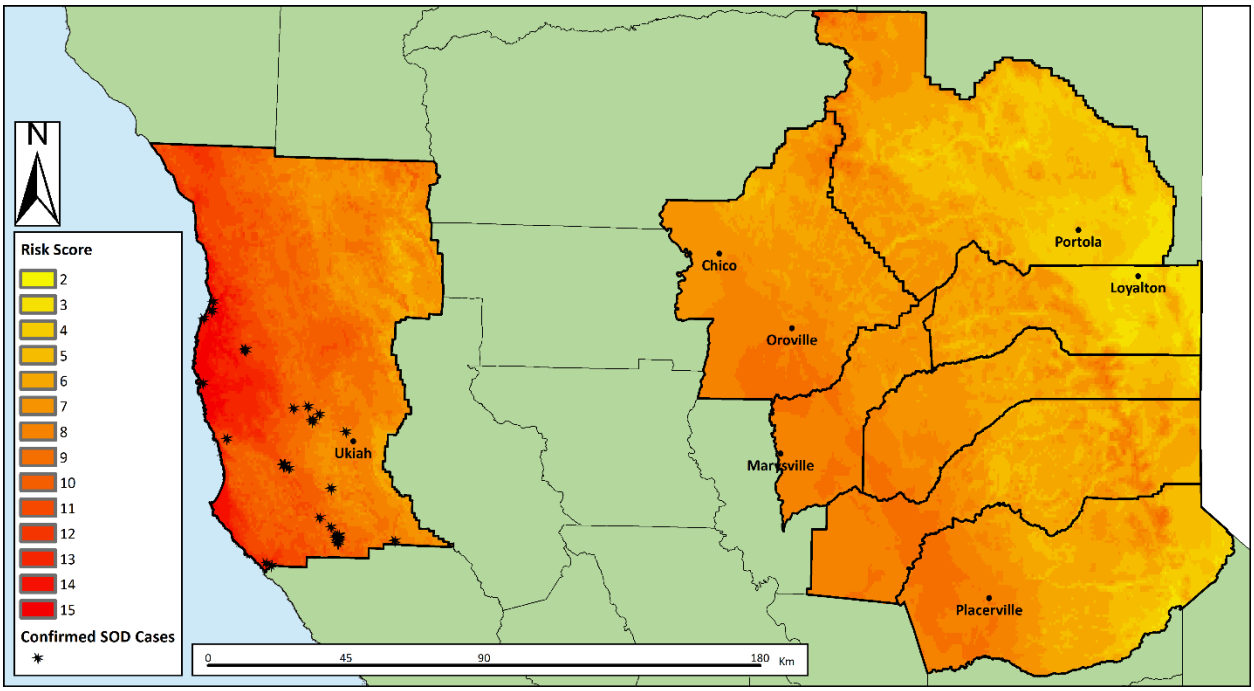

Figure 9: Risk scores of climate suitability reclassified to a 1-20 scale in both the study area on the right, and the accuracy assessment area on the left. The highest scores are shown in red near the coast in Mendocino County, while the lowest scores are shown in yellow on the east side of the study area.

Road Proximity

The rasterized and reclassified road buffer variable had high variation in risk scores (1-20) on a local scale (Figure 10). Patterns are difficult to observe on county scales because of the relatively smaller size of the 15-meter road buffers. Higher risk, shown the by the red and orange colors in Figure 10, is attributed to the functional classification assigned to them. These roads are freeways and principal arterial roads that handle heavy intercity traffic. The shorter, yellow colored roads are more frequently residential roads that are less frequented with no through traffic. The population density of the census blocks also create variation within the residential areas. Figure 11 depicts roads in the city of Mendocino, which are all scored relatively low due to the low population density in the area.

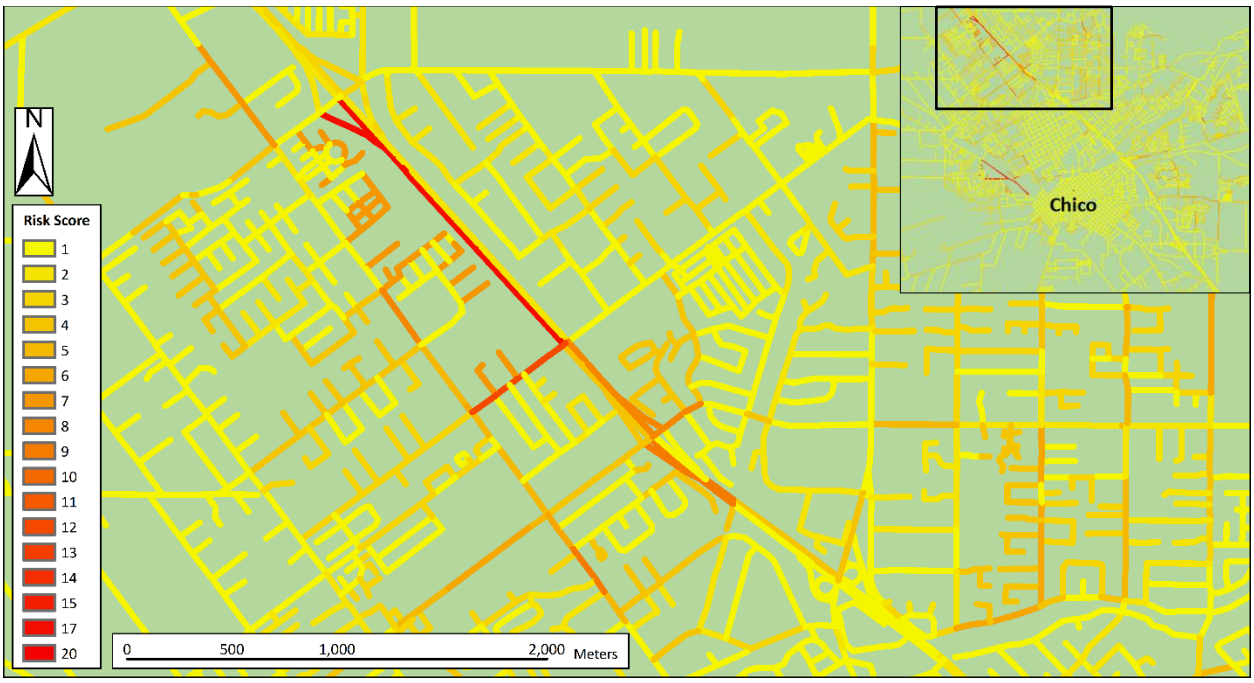

Figure 10: Risk scores of 15 meter road buffers reclassified to a 1-20 scale in the study area in northern Chico. The highest scores are shown in red, while the lowest scores are shown in yellow.

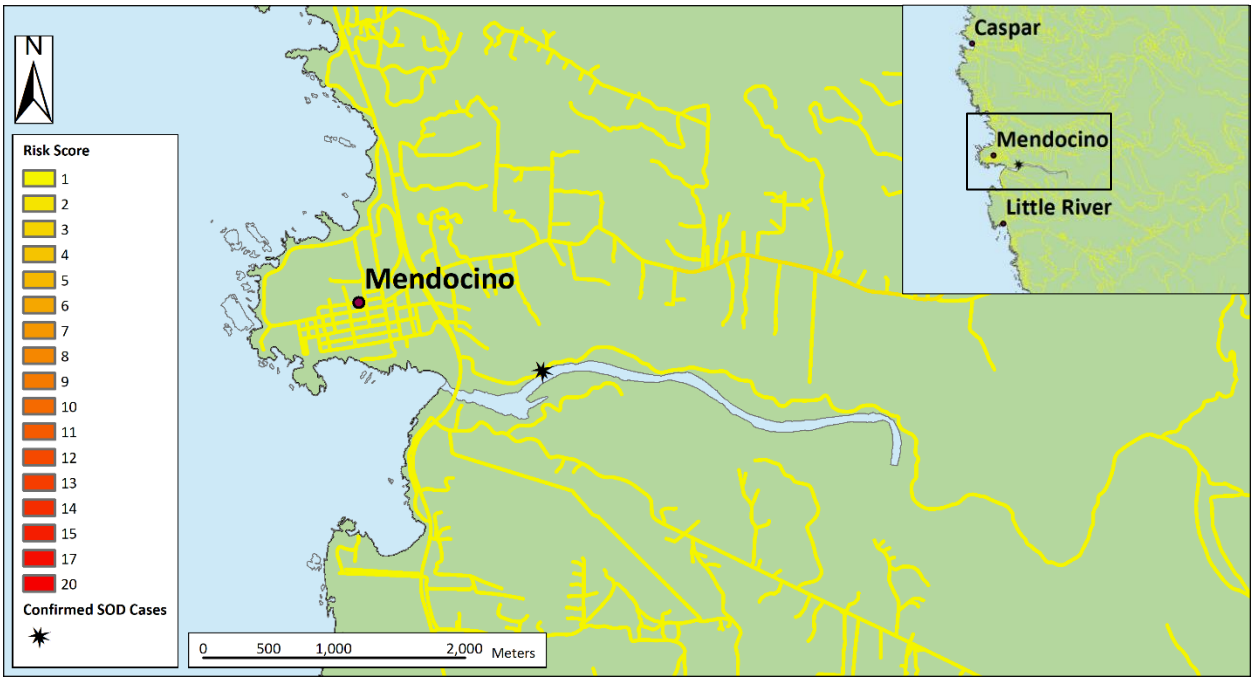

Figure 11: Risk scores of 30 meter road buffers reclassified to a 1-20 scale in the city of Mendocino within Mendocino County. The risk scores are all relatively lower in this county because of the low population density (24.9 people/km^2). One confirmed positive SOD case exists within the city and also falls within a road buffer.

Nursery and Lumbermill Proximity

A total of 156 nurseries and lumber mills were initially contacted for data submission. Many of these locations eventually did not qualify for a host species distribution survey. The various reasons for this were: locations had shut down, locations only sold supplies and no actual live plants, and locations had no viable working contact information (letters and emails were returned to sender and/or phone numbers were out of service). After all of these were omitted, 114 locations remained. Out of those 114 locations, 42 locations responded to contact and submitted a complete survey, and 38 sold at least one type of host species. Those 38 were included in the final nursery and lumber mill layer.

The relative risk score from proximity to nurseries and lumber mills that sell SOD host species is depicted in Figure 12. The highest risk scores are all in my study area, where greater numbers of host species are sold, in addition to higher volumes of those species. The deeper oranges and red colors are the highest risk that lie closer to the nurseries and lumber mills. The highest risk value is the western most tip of my study area, where a lumber mill that lies just outside the area has an extremely high volume of host species (Douglas firs) processed annually.

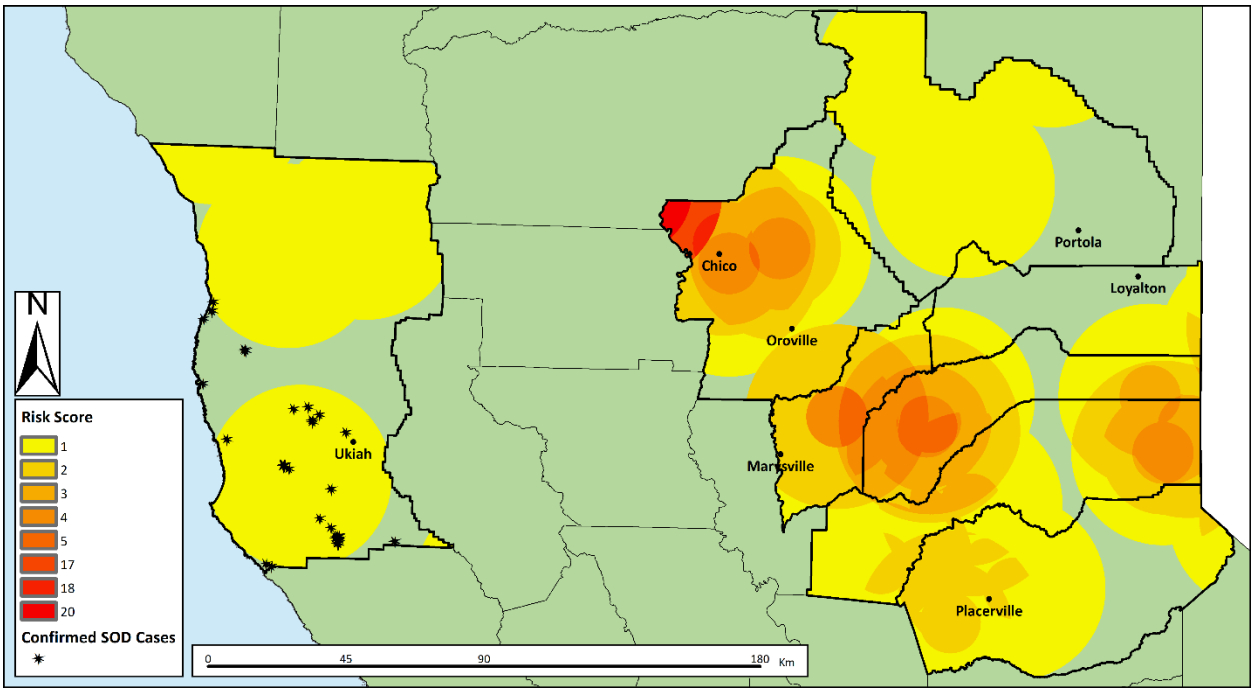

Figure 12: Risk scores of nursery and lumber mill buffers reclassified to a 1-20 scale in both the study area on the right, and Mendocino County on the left. Highest risk is depicted in bright red on the western most tip of the study area, while the lowest risk is depicted in bright yellow in both the study area and the accuracy assessment area.

Weighted Overlay Conditions

All of the five conditions showed higher risk in Mendocino County compared to my study area (Figures 13-17). Mendocino County's highest risk scores were all on the western coastal side of the county. The area of higher risk narrowed from the southern to the northern end. The highest risk in my study area varied slightly more by condition, but still showed repeating patterns of higher risk in the middle of the study area where the ecoregion transitions from the Great Central Valley to the Sierra Nevada and Cascade Ranges. All of the conditions also had a higher mean risk scores for the SOD sampling points, both negative and positive, than the average risk score for the overall assessment area (Table 2).

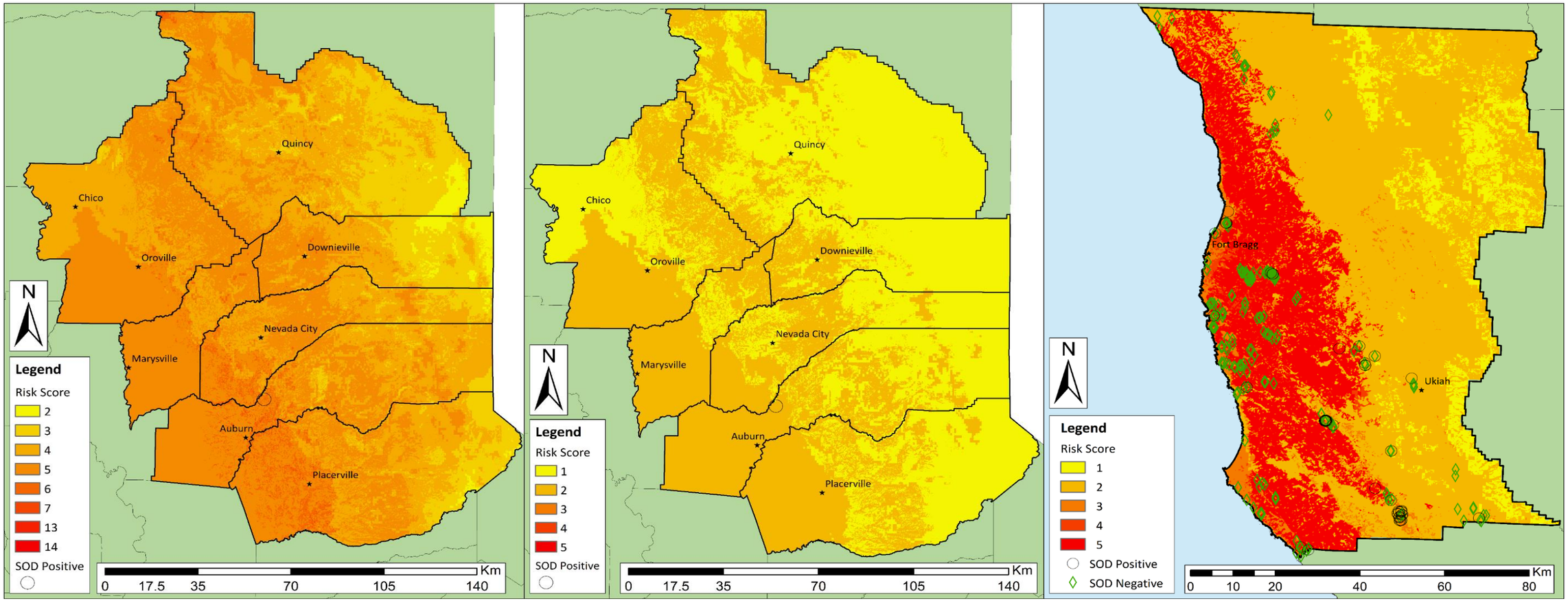

Figure 13. Condition 1 (Vegetation 50%; Climate 50%) risk scores before reclassification in the study area (left), and after reclassification in the study area (middle) and Mendocino County (right). Lowest risk scores are depicted in yellow and appear in patches on the eastern side of both the study area and Mendocino County. The highest risk scores are depicted in red patches on the coast of Mendocino County that narrow towards the north end. Within the study area variation is easier to observe before reclassification, where the highest risk is in sparse patches on the southern end where the Central Valley meets the Sierra Nevada Mountains.

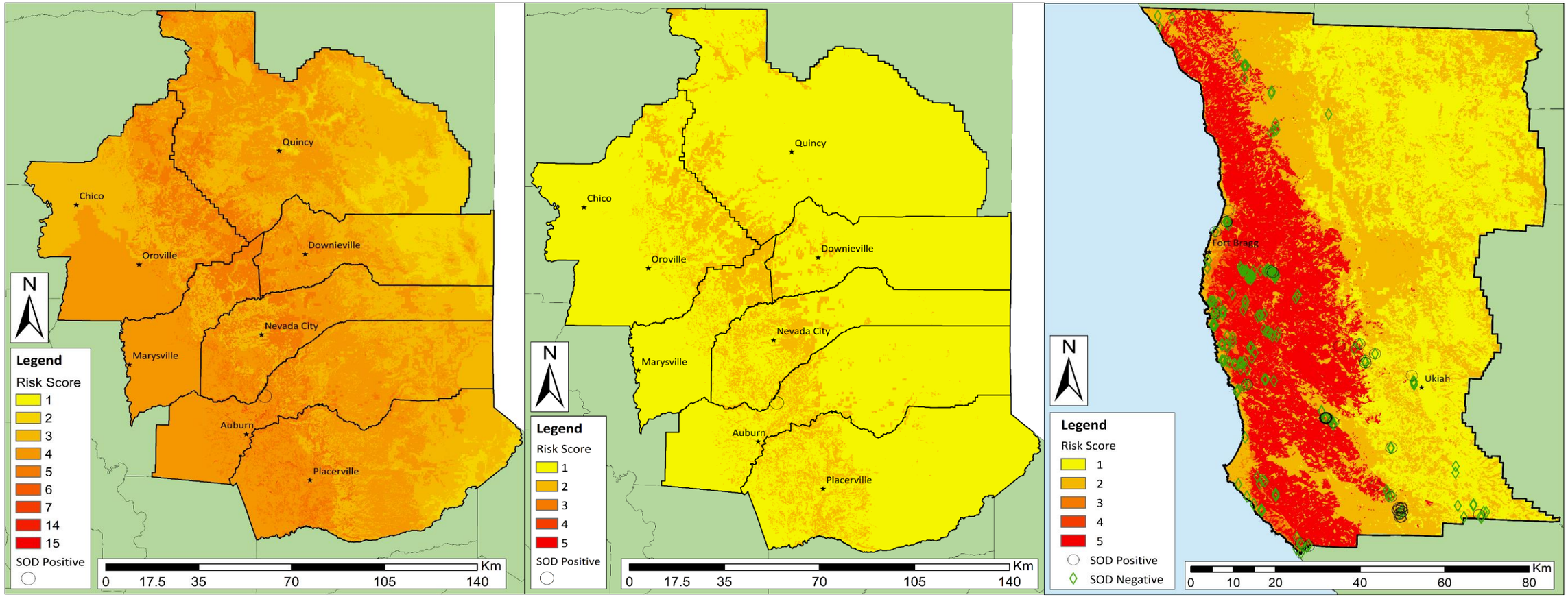

Figure 14: Condition 2 (Vegetation 60%; Climate 40%) risk scores before reclassification in the study area (left), and after reclassification in the study area (middle) and Mendocino County (right). Lowest risk scores are depicted in yellow and appear on the east side of both the study area and Mendocino County. The highest risk scores are depicted in red patches along the coast of Mendocino County that narrow towards the north end. Within the study area variation is easier to observe before reclassification. The highest risk is in dark yellow (middle) and dark orange (right) patches along the Sierra Nevada Mountains range edge.

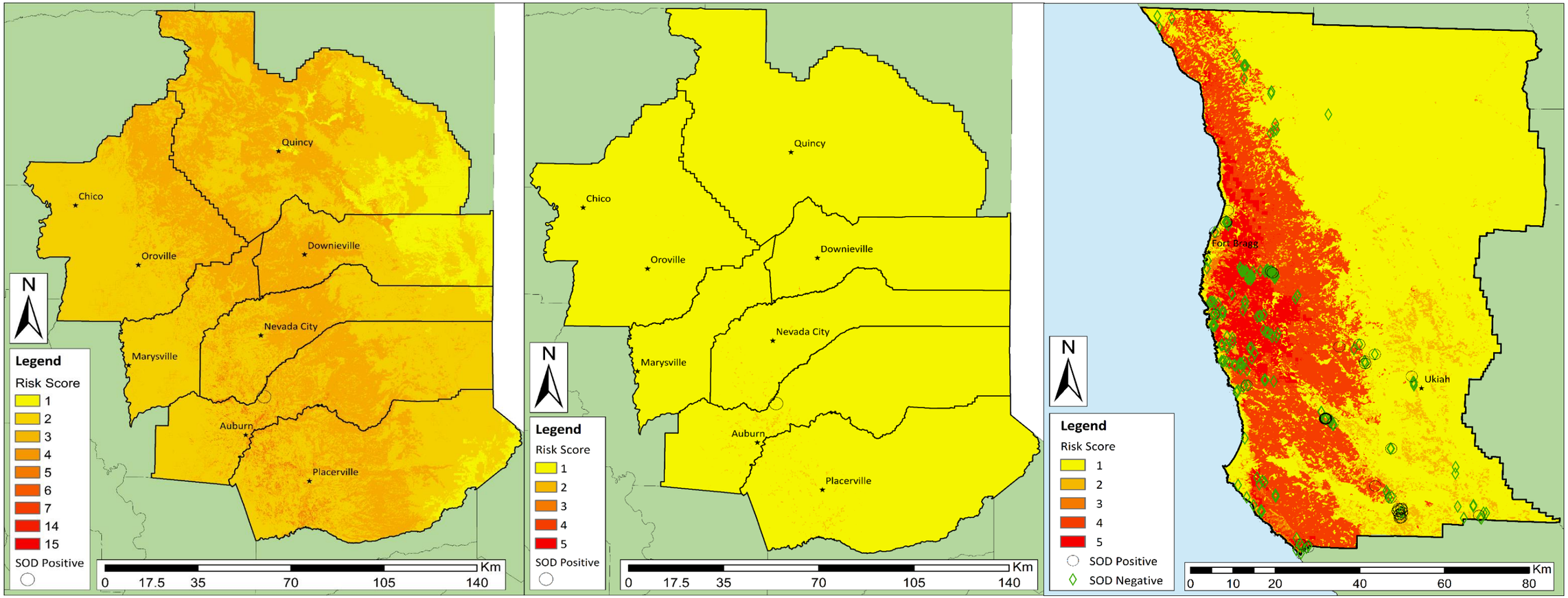

Figure 15: Condition 3 (Vegetation 60%; Climate 20%, Roads 20%) risk scores before reclassification in the study area (left), and after reclassification in the study area (middle) and Mendocino County (right). Lowest risk scores are depicted in yellow and appear on the east side of Mendocino County and most of the study area. The highest risk scores are depicted in red in patches on the coast of Mendocino County that narrow towards the north end. Within the study area variation is easier to observe before reclassification, where the highest risk is in a continuous orange patch along the Sierra Nevada Mountains range.

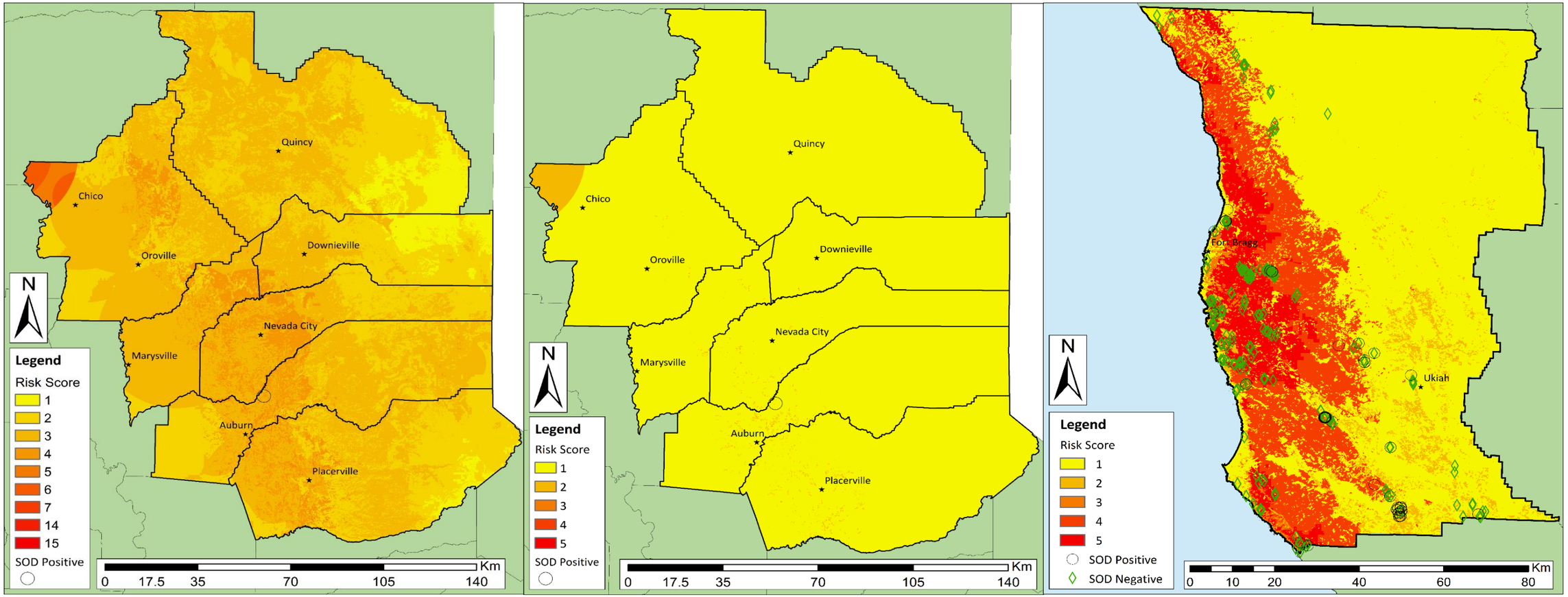

Figure 16: Condition 4 (Vegetation 60%; Climate 20%, Nurseries 20%) risk scores before reclassification in the study area (left), and after reclassification in the study area (middle) and Mendocino County (right). Lowest risk scores are depicted in yellow and appear on the east side of Mendocino County and most of the study area. The highest risk scores are depicted in red patches on the coast of Mendocino County that narrow towards the north end. Within the study area variation is easier to observe before reclassification. The highest risk in the study area is depicted in dark yellow (middle) and light red (right) on the west tip of Butte County.

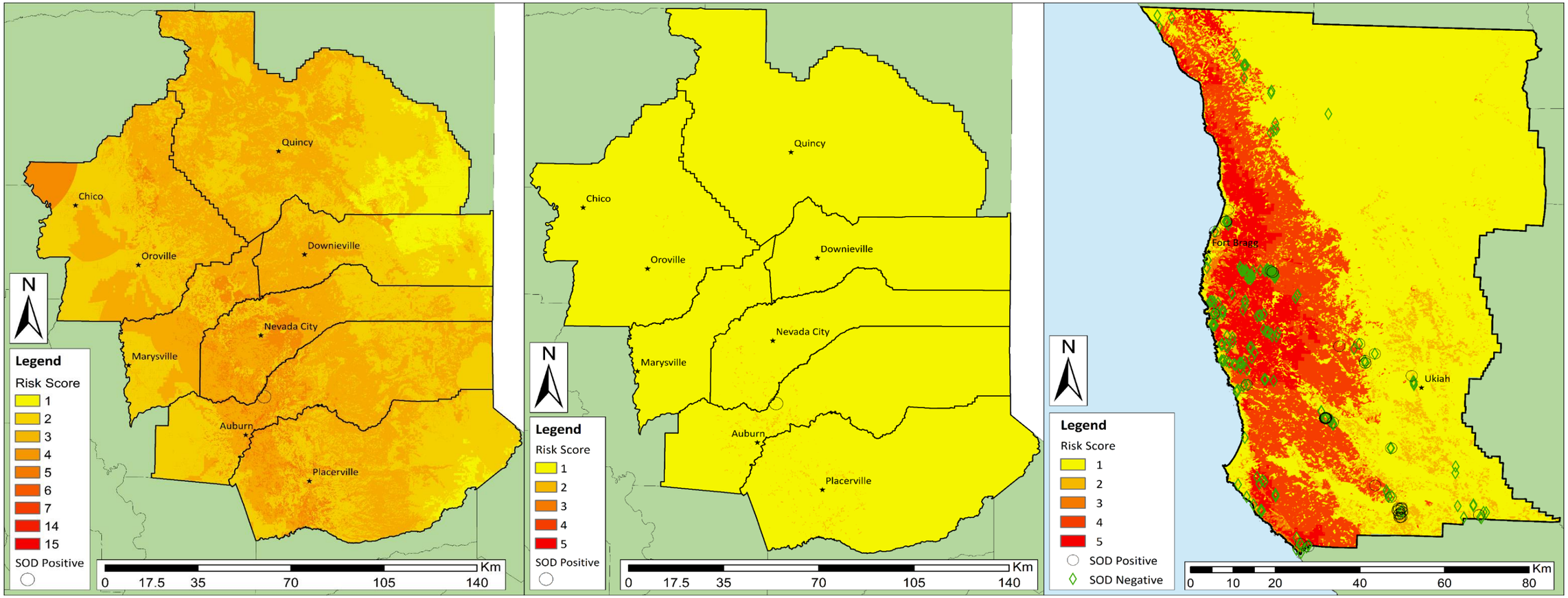

Figure 17: Condition 5 (Vegetation 60%; Climate 20%, Roads 10%; Nurseries 10%) risk scores before reclassification in the study area (left), and after reclassification in the study area (middle) and Mendocino County (right). Lowest risk scores are depicted in yellow and appear on the east side Mendocino County and most of the study area. The highest risk scores are depicted in red patches on the coast of Mendocino County that narrow towards the north end. Within the study area variation is easier to observe before reclassification, where the highest risk is in dark orange patches in the Sierra Nevada Mountain range and the tip of Butte Count

Table 2: Mean risk scores for all points under each condition, all positive points under each condition, all negative points under each condition, Mendocino County as a whole under each condition, the study area as a whole under each condition, and the assessment area and study area together under each condition. Scores ranged from 1-5.

	Mean Risk Scores					
	All Points	Positive Points	Negative Points	Assessment Area	Study Area	Total Area
Condition 1	3.85	3.42	3.94	2.76	1.46	1.79
Condition 2	3.56	3.07	3.67	2.47	1.11	1.46
Condition 3	3.22	2.58	3.36	1.93	1.00	1.24
Condition 4	3.20	2.52	3.35	1.96	1.01	1.25
Condition 5	3.21	2.58	3.36	1.96	1.00	1.25

The Kappa values for all conditions are negative, however the introduction of the nurseries and roads did slightly increase the Kappa values (Table 3). The higher Kappa values in Conditions 3-5 (-0.313, -0.298) compared to conditions 1 and 2 (-0.424, -0.388) indicate that nurseries and roads did improve the models with anthropogenic variables.

Table 3: Agreement between each of the conditions and the confirmed positive and negative points, and the Kappa coefficient for each condition.

	Positive Agreement (Sensitivity)	Negative Agreement (Specificity)	Cohen's Kappa Coefficient
Condition 1	0.671	0.202	-0.424
Condition 2	0.493	0.264	-0.388
Condition 3	0.507	0.307	-0.313
Condition 4	0.493	0.319	-0.298
Condition 5	0.507	0.316	-0.298

Condition Comparison

The number of points that fell into each reclassified risk category in each condition are shown in Figures 18 and 19. Figure 18 depicts all of the points confirmed positive for SOD. A higher number of points in the 3-moderate, 4-high, and 5-very high categories indicates that

the condition predicted higher risk where SOD was found. Figure 19 depicts all of the points confirmed negative for SOD. A higher number of points in the 1-very low and 2-low categories indicates that the condition predicted lower risk where SOD was not found.

Condition 1 assigned the highest scores overall and assigned the SOD points the highest average score (mean = 3.42) in the reclassified map (Table 2). Condition 2 had the second highest distribution of higher risk scores and also the second highest average point score (mean = 3.07). Condition 3 does vary in high risk spatial distribution, but it is not visible on the county scale since the road buffers were only 30 meters in width. Conditions 3, 4, and 5 had similar point scores (means = 2.58, 2.52, 2.58, respectively) as well as very similar spatial distributions in the reclassified maps, with the majority of my reclassified study area being ranked in the lowest risk category. The variation in spatial distribution is more evident in the non-reclassified weighted overlay scores (Figures 13-17). Conditions 4 and 5 are most noticeably different with semi-circle patterns where the nursery and lumber mill buffers increased risk. Most prominent are the higher risk values in the west most portion of Butte County. This resulted from a lumber mill that reported milling 4.3 million board feet of Douglas firs annually, whose location lay just outside the study area with the buffer overlapping the boundary.

Figure 18: Number of points confirmed positive in each risk score category in each of the weighted overlay conditions, where each of the conditions weighs the variables as follows: condition 1- vegetation and climate 50% each; condition 2- vegetation 60%, climate 40%; condition 3- vegetation 60%, climate 20%, roads 20%; condition 4- vegetation 60%, climate 20%, nurseries/lumbermills20%; condition 5- vegetation 60%, climate 20%, roads 10%, nurseries/lumbermills 10%.

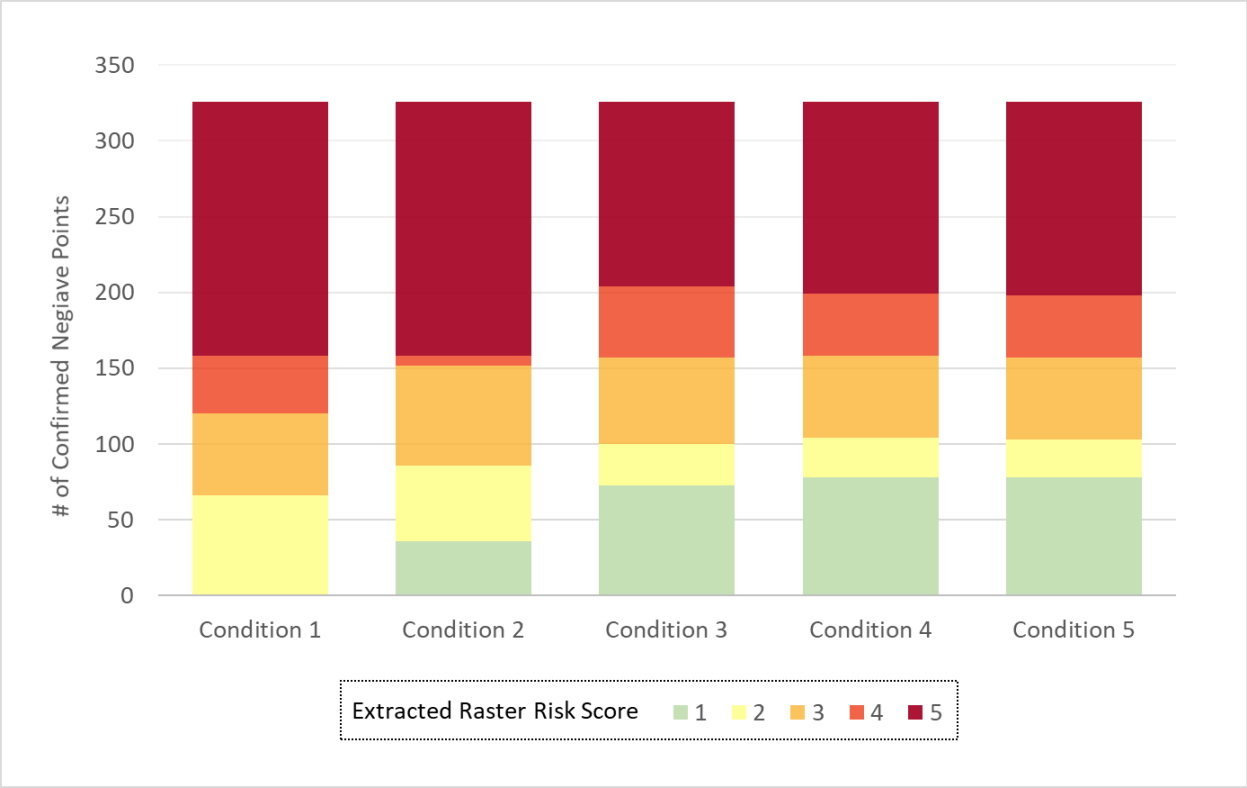

Figure 19: Number of points confirmed negative for SOD in each risk score category in each of the weighted overlay conditions, where each of the conditions weighs the variables as follows: condition 1- vegetation and climate 50% each; condition 2- vegetation 60%, climate 40%; condition 3- vegetation 60%, climate 20%, roads 20%; condition 4- vegetation 60%, climate 20%, nurseries/lumbermills 20%; condition 5- vegetation 60%, climate 20%, roads 10%, nurseries/lumbermills 10%.

CHAPTER IV.

DISCUSSION

In my analyses I combined four variables; host vegetation, climate suitability, proximity to roadways, and proximity to host carrying nurseries and lumbermills, into five weighted overlay analyses to examine their efficacy at predicting confirmed SOD infections. Both the maps and the point validation scores indicate that neither nurseries or roadways should be weighted as heavily as vegetation or climate, since their addition does not greatly increase the agreement with SOD occurrence. Still, there are many things to consider before drawing conclusions that minimize the importance of anthropogenic factors.

Agreement with other Geospatial Risk Models

The spatial distribution of higher risk areas in each model in my area is similar to that of other risk models which used other modeling techniques including simulation modeling (Venette and Cohen, 2006), rule-based modeling (Meetenmeyer, 2004; Meetenmeyer 2011), Support Vector Machines (SVM), Genetic Algorithm for Rule Set Production (GARP), logistic regression, and an average of multiple methods (Guo et. al., 2005). The similarities in the spatial patterns are attributed to the relatively lower host vegetation presence, but relatively higher climate suitability in the Great Central Valley compared to the Sierra Nevada Mountain and Cascade Ranges. This agreement is evident in the shape of the risk patches that form throughout the Sierra Nevada ecoregions, compared to the relatively lower risk on the western side where the Central Valley ecoregion lies. The same agreement can also be observed in Mendocino County between my model and other published work, where higher risk is more heavily focused

on the coast and slightly wider toward the southern end (Guo et. al., 2005; Meetenmeyer et. al., 2004; Meetenmeyer et. al., 2011). This similarity in spatial patterns between mine and other models is likely due to the highly scored host vegetation and high relative humidity present in coastal Mendocino. Finer scale comparisons are difficult as no other risk model has focused on this study area, but rather on statewide and national scales.

Nurseries and Lumbermills

The results indicate that the addition of nurseries as a risk variable does not greatly increase the accuracy of predicting SOD infection; however, differences between the study area and Mendocino must be considered. Deviations from other researcher's risk models in my study area are made the most apparent in conditions four and five by the nursery and lumber mill variable (Figures 16 & 17). Conversely in Mendocino County, nurseries had a lower impact due to the relatively lower assigned risk scores. This is likely because of the stricter regulations surrounding the transport of host species within the county, which could act as a deterrent to businesses to sell them. Additionally, nurseries in quarantined counties are encouraged to follow rigorous Best Management Practices (BMPs) and must remain in compliance with CDFA in order to continue operations (CDFA, 2016). Being in compliance requires an inspection of the establishment every six months until they have negative SOD results for three consecutive years. Strategies for nursery upkeep and early detection are still regularly investigated (Chastagner and Elliott, 2017; Junker et. al., 2017; Peterson et. al., 2017). Nurseries outside of quarantined counties, such as the seven in my study area, do not have the same restrictions or practices. It seems that incorporating relatively scored nurseries and lumber mills is still relevant and vital to

the study area considering the vast differences between relative nursery risks, the BMPs' influence, and the remaining prevalence of positive SOD nursery infection.

One factor that might be restricting the spread of SOD from nurseries is the differences in timing of high-volume host species sales and the reproductive season of SOD. Some of the nurseries did indicate in their surveys that they do not remain open during the entire year, and close for the winter season. Since SOD pathogen reproduces from December to May, there could be several months overlap where host species sales are reduced or even halted at the peak of the reproductive season. For this same reason it might also be true that seasonal Christmas tree farms, which often sell Douglas firs and were included in the nursery variable, present an even higher risk since their sales are limited to December only.

Road Proximity

Although the risk models and the infection point values did not indicate that roadway proximity increased SOD infection, a visual assessment showed many of the 73 infection sites exist close to roadways just beyond the rasterized 15-meter buffer on each side of the road. The sinuosity of the roadways also made the buffers slightly imperfect when the shapefile was rasterized, and some points that did fall within 15 meters of the road did not fall within the rasterized buffer. However, it must also be considered that since the infection sites are located through citizen science efforts, it is possible these confirmed sites are a product of sampling bias, as those searching for infected hosts are more likely to find them if they are in the vicinity of roadways.

It is possible that an extension of the buffer could increase efficacy of the roadway variable. Researchers in Oregon attempting to understand the relationship between SOD

occurrence and roads found a median distance of 102 meters between positive SOD occurrence and roadways (Peterson et. al, 2014). Expanding the buffer to 100 meters on either side of the road could potentially capture more of SOD infections but could also unjustifiably attribute risk to adjacent areas, as SOD is rarely known to travel more than 15 meters via its natural methods of wind and rain splash (Davidson et. al, 2001).

Importance of Anthropogenic Influence

The general agreement that my models have with other risk models echoes the importance of vegetation and climate. Previous research has predicted that my study area will have some degree of SOD infection worthy of concern by 2020 from the expansion of existing SOD infections (Kovacs, et. al., 2011; Meetenmeyer et. al., 2011). My models and others have demonstrated that the vegetation and climate that support SOD exist in my study area, though it remains over 80 kilometers away from any significant levels of infection. It has been suggested that the limiting factor is time, and perhaps these anthropogenic variables are no exception. It is possible that as more sampling occurs in our study area, more positive SOD will be found near these variables. The likelihood that humans will transport SOD infected materials to uninfected zones via roadways or infected nursery stock is not clear, but it should be acknowledged. The amount of effort focused on surveying uninfected areas understandably dwindles over time (Owen, personal communication, 2009), but perhaps with more detailed risk maps of those uninfected areas, minimal efforts will be sufficient to keep infection at bay.

CHAPTER V.

CONCLUSION

With the cumulative knowledge we have of SOD, most researchers believe it was first introduced to the United States via infected nursery stock. It is reasonable to assume that uninfected areas could become infected via this same route. Though my results do not indicate a strong correlation between nurseries and lumber mills and SOD incidence, the relationship between the two should be more thoroughly investigated. My results agreed with Peterson et. al. (2014) that there is no correlation between roadways and SOD incidence. However, both relationships could use more exploration, particularly in areas where single recorded infections lie further from other groupings.

Future Research and Recommendations

I would recommend a similar set of methods be used with a different accuracy assessment area chosen by a specific set of criteria. Specifically, positive SOD cases existing further than several kilometers in any direction from any other case in an unquarantined county would be appropriate. Examining those points and their distance from relatively scored roadways and nurseries would allow a better focus on anthropogenic introductions instead of neighboring infections. San Luis Obispo is the only county that has recorded infection points and, as of 2018, meets these criteria.

Additionally, as more fine scale and up-to-date vegetation datasets become available, they could be vital to the early detection of SOD infections. My contribution of a relatively scored nursery and lumber mill layer could also certainly be augmented if more participants were

to come forward, however, that seems unlikely unless some kind of state regulations require it. Many of the previous predictions from other risk models and maps hypothesize the movement of SOD to our study area by 2020, and though as of 2018 that area has only one confirmed infection, the focus on the agreeing higher risk areas depicted in my model and others could be vital to maintaining that record should it ever migrate. Given the low sampling rate of the study area, it is possible that it already has but it has not been captured.

Limitations

Current Infection Sites

A potential influence on my accuracy assessment process is the restrictions of the currently available SOD incident point data. As mentioned above, it is possible that the confirmed sites are only a small portion of the total infections and represent a sampling bias due to the higher likelihood of citizen scientists finding them in easily accessible areas that are already considered high risk. The UC Berkeley program that coordinates the collection of samples has a phone application that allows citizen scientists to find higher risk areas as opposed to sampling randomly (SODMAP, 2017). Because of this sampling protocol, it is more likely for citizens to collect in locations that are designated high risk according to the application. Thus, the negative sample points collected should not correlate with lower risk areas if my model is in agreement with the models used for the UC Berkeley application (SODMAP, 2017).

Nurseries in Mendocino

Mendocino was selected as an accuracy assessment site because of its general proximity and similar latitude range as the study area. There are however some inherent flaws that prevent it from being comparable to risk spread in our study area. The risk from nurseries

alone is dramatically lower in Mendocino County, in part due to the fewer nurseries overall, fewer host species being sold in them, and the quarantine restrictions in place. These flaws do not apply to the conditions that do not incorporate the nursery and lumber mill risk.

Data Restrictions

The finer the resolution of any risk assessment model, the more potential it has to be of use to institutions that set out for early detection. The vegetation mapping available is limited to the 30-meter resolution of the CALVEG data set, which we can see from mine and other models, is the most important predictor of SOD. As for the variables unique to this project, it must also be taken into consideration that this nursery layer was compiled with information only from the 37% of nurseries that responded, and only from self-reported information. It is possible that there are more epicenters of risk in both our accuracy assessment area and our study area that were missed due to non-participation of locations. Additionally, there is potential for some positive SOD that has not yet been sampled, especially in our study area. Thus, it is possible that my models are an underassessment of risk posed by anthropogenic variables.

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APPENDIX A

Table 5: Each of 46 host species designated by the CDFA and its calculated risk score. Risk scores were calculated by adding 2 points for each type of spore (zoospores via sporangia and chlamydospores) that can be produced on the species to a base score of 1. The only exception was California Bay Laurel which was assigned an additional two points for its proven ability to be a vector for SOD.

Host Species		Risk Score
Bigleaf maple	*Acer macrophyllum*	1
Planetree maple	*Acer pseudoplatanus*	1
Western maidenhair fern	*Adiantum aleuticum*	1
California maidenhair fern	*Adiantum jordanii*	1
California buckeye	*Aesculus californica*	1
Horse chestnut	*Aesculus hippocastanum*	3
Madrone	*Arbutus menziesii*	3
Manzanita	*Arctostaphylos manzanita*	1
Scotch Heather	*Calluna vulgaris*	1
Camellia*	*Camellia spp.*	3
Sweet chestnut	*Castanea sativa*	3
Camphor tree	*Cinnamomum camphora*	1
European beech	*Fagus sylvatica*	1
California Coffeeberry	*Frangula californica/ Rhamnus californica*	1
Cascara	*Frangula purshiana/ Rhamnus Purshiana*	1
European ash	*Fraxinus excelsior*	3
Griselinia	*Griselinia littoralis*	1
Witch hazel	*Hamamelis virginiana*	1
Toyon	*Heteromeles arbutifolia*	1
Mountain laurel*	*Kalmia spp.*	1
Tanoak	*Lithocarpus densiflorus*	1
California honeysuckle	*Lonicera hispidula*	1
Bay laurel	*Laurus nobilis*	1
Michelia	*Magnolia/Michelia doltsopa*	1
False Solomon's seal	*Maianthemum racemosum/ Smilacina racemose*	1
Persian ironwood	*Parrotia persica*	1
Red tip photinia	*Photinia fraseri*	1
Andromeda, Pieris*	*Pieris spp*	3
Douglas fir	*Pseudotsuga menziesii*	1
Coast live oak	*Quercus agrifolia*	5
European turkey oak	*Quercus cerris*	3
Canyon live oak	*Quercus chrysolepis*	1

Table 5 Continued

Host Species		Risk Score
Southern red oak	*Quercus falcate*	1
Holm oak	*Quercus ilex*	3
California black oak	*Quercus kelloggii*	1
Shreve's oak	*Quercus parvula var shrevei*	1
Rhododendron (including azalea)*	*Rhododendron spp.*	4**
Wood rose	*Rosa gymnocarpa*	1
Goat willow	*Salix caprea*	1
Coast redwood	*Sequoia sempervirens*	5
Lilac	*Syringa vulgaris*	3
European yew	*Taxus baccata*	5
Western starflower	*Trientalis latifolia*	1
California bay laurel, pepperwood, Oregon myrtle	*Umbellularia californica*	7
Evergreen huckleberry	*Vaccinium ovatum*	5
Viburnum*	*Viburnum Spp.*	3

*All species and hybrids

**All Rhododendron species can host sporangia, but only some species can produce Chlamydospores, so the score was averaged between 3 and 5 to arrive at 4. The CalVeg alliances also do not specify species.

APPENDIX B

Table 6: Abundance score of given to the various descriptions listed with the CalVeg Alliance Manuals.

Alliance Description	Abundance Score
Alliance type species	10
Dominated by	8
Most common/important/principal associates/indicators	8
Prominent; Important	7
Often associated/present/occurs/includes Occurs; includes; supports; occupies	5
Common associate; common; commonly occurs	5
Main associate	5
Typical associate; typical	5
Associate; associated	5
Intermingled with	4
Likely to be present; likely to be found	4
Sometimes; some associated	4
Are found	3
Mixture of	3
Mixes with	3
Mixes with… in lower abundance	2
May be present; may be associated; may include; may occupy; may occur	2
Occasional associate; occasional; may be occasionally present	2
Minor associate; sparsely but commonly present	2
May include but rare or infrequent; or minor amount	1