# Prioritizing locations for managing forest disease in complex landscapes

by
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**Prioritizing locations for managing forest disease in complex landscapes**

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## Abstract

Management of invasive plant pathogens in natural ecosystems is often challenging in complex landscapes comprised of significant social and ecological heterogeneity. *Phytophthora ramorum* is an example of an invasive pathogen, responsible for the emerging forest disease sudden oak death (SOD), killing millions trees along the Pacific Coast. The tanoak tree, one of the most vulnerable hosts in northern California is considered a valuable species for ecosystem functioning and local tribes' culture. Disease outbreaks in this region are expected to cause substantial tree mortality and therefore a robust disease management plan is vital. However, expensive treatment costs and budget constraints in conjunction with a remote geographic area and a variety of legal considerations present obstacles for effective management. To help overcome these challenges and assist stakeholders and policy makers with strategic planning, we developed geospatial models to prioritize locations for disease management, using Humboldt County as a case study. We considered three control strategies currently utilized to manage SOD: (1) clear cutting, (2) mechanical tree removal, and (3) prescribed fire. We prioritized potential management areas based on 1) site accessibility (proximity to roads) and 2) site conditions, such as vegetation density and slope. Using multicriteria decision analysis we quantified different combinations of site factors and produced management suitability maps for each control strategy. This research provides a tool to evaluate where management option are most cost-effective and may serve as an initial step in SOD management planning.

## I. Introduction

Nonnative plant pathogens and pests are important agents of forest change in many regions around the globe (Davis et al., 2010; Cobb et al., 2012; Anderson et al., 2004). In North America, they have become a "plague" of the 21st century for a number of plants across the continent, driving into oblivion environmentally, culturally and economically valuable tree species (Lovette et al 2016; Cobb et al., 2013, Hansen, 2008; Davis, 1981; Waller, 2013). In turn, management of these disturbances is often complicated by landscape heterogeneity and complex socio-ecological factors that substantially affect strategic planning at different levels of implementation (Parnell et al., 2010; Condeso and Meentemeyer, 2007; Thompson et al., 2016). Significant logistical and epidemiological constraints along with budget limitations, unsuitable control efforts, and disparities in management goals among the key stakeholders create significant impedance for effective management (Cunniffee, 2016; Thompson et al., 2016). In addition to those limitations, management site accessibility and conditions often come into play (Martell, 1998). Some recent research on timber harvesting in small scale private forests (Poje et al., 2016) indicate that the factors associated with terrain conditions and road networks (Martell, 1998) may negatively affect harvest intensity and overall forest management performance by increasing working hours and management costs. Addressing those challenges is critical to manage the places with especially diverse topography and land cover and needs to be incorporated into strategic management planning and decision-making process.

California and Oregon are currently experiencing an invasion of the exotic plant pathogen, *Phytophthora ramorum,* which is responsible for the emerging infectious disease sudden oak death (SOD) and the mortality of millions of oak and tanoak trees along Pacific coast (Davis et al., 2010; Cobb et al., 2012). This region is characterized by a variety of topographical surfaces from wide coastal plains to extremely rugged mountain lands with rocky ridges and upper elevation slopes. These two environmentally complex regions support a variety of plant communities including mixed coniferous forests, chaparral shrublands and annual grasslands along with mixed oak woodlands and redwood-tanoak forests that compose primary habitat for *P. ramorum* (Meentemeyer et al., 2008).

The sudden oak death pathogen currently infects over 40 native coastal plant species in 16 counties in California and one county in Oregon (Curry County) (Figure 1).


Figure 1. Distribution of sudden oak death in California. Infected counties depicted in red

Despite wide variety of hosts, the lethal form of the disease only kills several ecologically important trees, including tanoak (*Notholithocarpus densiflora*), coast live oak (*Quercus* *agrifolia*), California black oak (*Quercus kellogii*), canyon live oak (*Quercus chrysolepis*) and Shreve's oak (*Quercus parvula*) (Cobb et al., 2012; Rizzo et al., 2002; Meentemeyer et al., 2004). Tanoak, the most vulnerable to mortality, readily supports sporulation of *P. ramorum* followed by mortality, while other hosts, like the reservoir host California bay laurel (*Umbellularia californica*) may support pathogen sporulation without experiencing die off (Hansen et al., 2008). Tanoak is also a valuable environmental and cultural component, providing both critical habitat for a number of species and important cultural and spiritual artifacts for multiple northwestern California tribes including Hupa, Karuk, Wailaki and Yurok (Bowcut, 2015; Frankel, 2008). Therefore, protecting this tree from functional extinction is a paramount goal of regional and local management strategies. Among the control strategies currently implemented in both regions, host removal was recognized as the most effective (Cunniffe et al., 2016), and was implemented along with herbicide applications (Alexander and Lee, 2010) and prescribed burnings (Valachovic et al., 2008).

To embrace existing challenges and assist decision-making process, many GIS tools have evolved to address epidemiological challenges and efforts to estimate the disease spread (Meentemeyer et al., 2004) or optimize eradication control campaigns (Parnell et al., 2010). For example, Cunniffe et al. (2016) developed a spatially explicit model to optimize the set of locations to manage infected and susceptible forests based on radius around infected trees and spread vectors. In the same year, Thompson et al (2016) presented a tool that tracks the density of susceptible and infected hosts. However, these models do not account for physical barriers to management such as accessibility and conditions of a management site.

We developed a spatial model to provide additional guidance for land managers in decision-making process when prioritizing locations and estimating its suitability for managing forest disease. Under management suitability we imply physical difficulties, such as terrain steepness, density of vegetation and host vegetation that affect overall time and costs of implementing management at particular locations. The model consists of two parts, and incorporates the effects of accessibility and site conditions on management performance in complex landscapes. First part, evaluates the management feasibility based on physical efforts to reach a particular location when traversing various geographical surfaces and land covers. It uses a least-cost path algorithm to create a cost-surface with the costs expressed as time in seconds to travel through a grid cell under different geographical conditions and proximity to the road network. The second part, incorporates a rule-based modeling approach, where 1) slope steepness,

2) vegetation density and 3) host density variables were weighted and ranked according to their relative significance when carrying out the following control strategies: 1) clear cut, 2) tree removal and 3) prescribed fire. The choice of site condition variables and its weights and rank are based on expert opinions, related publications and personal experience of working in the field. Maps of management suitability for selected control strategies were computed by combining cost-surface map with maps of site conditions, and summarizing total suitability index.

## II. Materials and Methods

*The model*

We developed a spatial model to quantify and map the relative suitability of implementing sudden oak death management across the different range of landscapes based on site accessibility and conditions. To test the model we chose three distinct *P. ramorum* control strategies: (1) clear cutting, (2) tree removal and (3) prescribed fire. For our study, clear cutting is referred to complete host removal within certain buffer zone around infected tanoak tree or patch of trees. Tree removal, in turn, implies selective removal of trees around tanoaks to maintain canopy gaps and prevent pathogen spillover. Consisting of two parts, the model combines cost-distance analysis used to estimate accessibility of areas and places, and a rule-based weighting technique that allows for both research data and expert knowledge to determine the importance of each input variables. A surface containing the costs of traversing one grid cell in time was combined with the factors related to management performance on the site. In order to parameterize the factors representing relative difficulty to manage under different site conditions, we assigned a weight of importance to each variable for each control strategy and ranked them to encode the magnitude and direction of each variable's effect on management. The equation used to calculate management suitability is the sum of the product of each ranked variable and its weight of importance, divided by the sum of the weights and multiplied by traveling costs.

$$S = C * sum(Wi * Rij)/sumWi \qquad (1)$$

Where S is the suitability parameter for a grid cell in the model output, Wi is the weight of the *i*th site conditions variable, R*ij* is the rank of *j* depending on the variable's value at a given grid cell, and C is the traveling costs measured in seconds of traversing a grid cell. We ran the model utilizing combined functionality of GRASS GIS and ArcGIS 10.4.1 to generate a series of suitability maps. We reclassified model output into 5 equally spaced suitability-level categories from "Very Low" to "Very High" with additional 6th category of "Not suitable" land that included all areas where management cannot be conducted overall (herbaceous grasslands, impervious surfaces, etc.).

*Study area*

We focused our research on 864 $km^2$ area located 32 km northeast from Eureka Spring in Humboldt County, California (Figure 2). This geographic extent was selected to capture landscape-scale variability of topographic features and types of vegetation, as well as represent a diversity of stakeholders involved in Sudden Oak Death management projects. There are 6 key players in the region, who influence management decisions and launch actions: National Park Service, Bureau of Indian Affairs, Bureau of Land Management and Private Timber companies. Bureau of Indian Affairs, including Hupa and Yurok lands, occupies more than 50% of total study area. The second and the third place by area is held by Redwood National Park and private timberland, while Bureau of Land Management only represents 4% in total share.

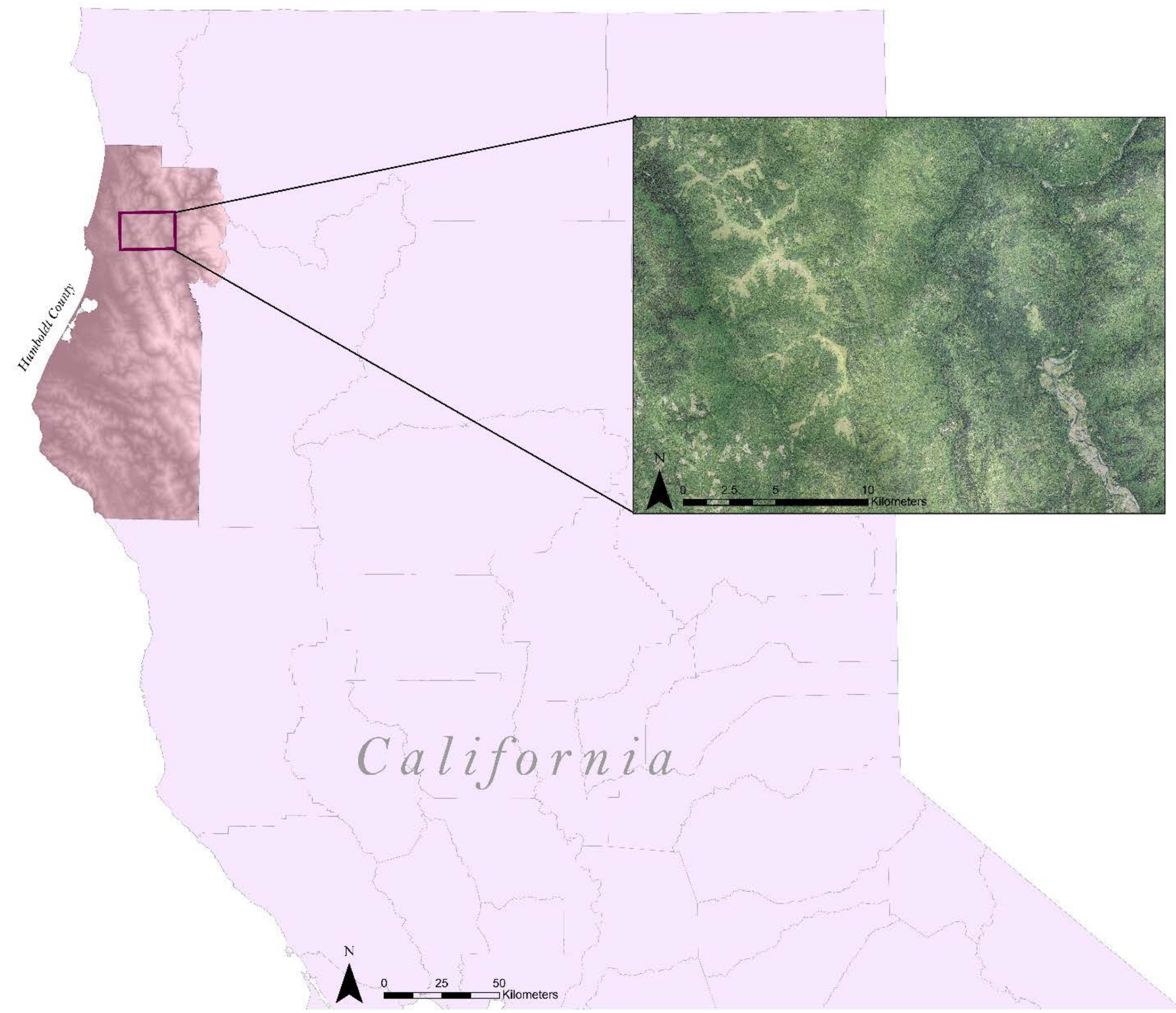



Figure 2. The area in focus

The pathogen arrived to Humboldt relatively recently and has stayed in geographically isolated locations showing promise to be taken under control if management actions will be implemented timely and collaboratively. Previous management experience showed that “border” effect can knock out all the progress and positive results made if control efforts are not implemented equally between locations (Thompson et al., 2016). Humboldt County is important disease “hub” on its way to north to Oregon borders, and to prevent or, at least slow the spread, a collaborative approach is critical.

*Estimating accessibility*

The site access part uses least-cost path approach to assess difficulty of getting to each particular location within the focus area by creating a cost surface, where costs are expressed in time units. Proximity to road network plays important role in forest management as proximity to road often determine harvest intensity as more distant sites tend to have less forest operations (Poje et al., 2016). Although, this modeling approach is gaining popularity (Davidson et al., 2013; Sitzia et al., 2014; Avon and Berges, 2016), there is a gap in the literature on how least-cost path can be implemented for forestry management purposes, and how the terrain and land cover overall influence the number of working hours and consequent costs of management. Jobe and White (2009) presented the first cost-distance model for human accessibility that measures energy expenditures while traversing terrain and hiking off road. Their model assesses biases in vegetation sampling and showed significant positive correlation of plot sampling with access to those plots. Doherty et al. (2009) created mobility model that provides an estimate of how far a missing person could go under certain terrain conditions, land covers and proximities to road network. In that research, the authors calculate least-cost path based on Tobler's Hiking Function and Travel Time Cost Surface Model (Sherrill et al., 2010).

We built our cost-surface using GRASS GIS *r.walk* module that allows the user to create a raster map showing the anisotropic cumulative cost of moving between different geographic locations on an input raster map whose cell category values represent cost (GRASS Manual, 2016). The algorithm used in the module is based on Naismith's rule for walking times improved by Langmuir in 1984. The formula estimates the cost parameters of specific slope intervals.

$$T = a*\Delta S + b*\Delta H + c*\Delta H + d*\Delta H \qquad (2)$$

Where T is time of movement in seconds, ΔS is the horizontal distance covered in meters and ΔH is the altitude difference in meters. The a, b, c, d walking coefficients parameters are constants proposed by Langmuir and take into account movement speed in the different conditions based on man walking effort in standard conditions (4968 m/hr from Langmuir). They are linked to (a) time in seconds it takes to walk for 1 meter a flat surface (1/walking speed), (b) additional walking time in seconds, per meter of elevation gain on uphill slopes, (c) additional walking time in seconds, per meter of elevation loss on moderate downhill slopes (use positive value for decreasing cost), and (d) additional walking time in seconds, per meter of elevation loss on steep downhill slopes (use negative value for increasing cost) (GRASS Manual, 2016). The final equation that estimates impedance of traversing landscape under different types of land cover is presented below:

$$\text{Total cost} = T + \lambda * \text{friction cost} * \Delta S \quad (3)$$

Where T is movement time cost, $\lambda$ is a dimensionless scaling factor and $\Delta S$ is the horizontal distance covered in meters. Friction cost is an additional time (or time penalty in seconds of additional walking time to cross 1 meter distance) to traverse a cell with particular land cover type.

Spatial variables for cost-distance analysis were obtained from multiple sources including USGS National Elevation Dataset, USDA California Vegetation Classification and Mapping program (CALVEG) and Humboldt County GIS website. We computed a total time costs to travel from a focal area (the study site) to a source areas (roads) based on 30 meter resolution DEM and added friction costs (land cover and hydrological objects) obtained by reclassifying CALVEG dataset.

Doherty et al. (2009) defined cost surface as function of the impedance to foot traffic that would be imposed by the presence of various geographical features compared to nominal paved surface such as a sidewalk or roadway. In their research, to obtain a cost surface they used Travel Time Cost Surface Model (TTCSM) developed by National Park Service in 2010 (Sherrill et al., 2010). The TTCSM is designed to model overall travel time in national parks units using available geospatial data (ex., roads, trails, and streams networks, digital elevation models and land cover data). As an output TTSM generates point-to-point specific travel time least cost paths and raster maps in which each cell value is the modeled time required to reach the given cell from the specified starting point (Sherrill et al., 2010). This model uses The Percent of Maximum Travel Speed (PMTS) algorithm that ranges impedance (friction) values from 0 to 100 percent with 0 being no impedance (ex., paved roadway or well-maintained trail) and 100 being absolute impedance (ex., large water body). Thus, a value of 50 would represent a feature that is 50% slower to cross than the nominal surface (Doherty et al., 2014). Following Doherty et al., we incorporated PMTS principles into our cost-surface model using land cover values derived from Anderson land-use and land-cover classification field in CALVEG dataset for Humboldt, and hydrological dataset containing stream status information from the Census Bureau's Tigerline program. As described in Doherty et al. (2014), we used the inverse principle, classifying costs from TTSM as an impedance, making it 1/PMTS (Table 1).

Table 1. Assigned impedance based on land cover

| Land cover type | Friction |
|---|---|
| Reservoir, Intermittent Lake or Pond, Perennial Lake or Pond, River/Stream/Canal | 99 |
| High Water Line, Gravel, Sand Bar, Forested wetland, Shrub and brush rangeland | 90 |
| Hardwood type forest land, Mixed conifer hardwood type forest land | 70 |
| Conifer type forest land | 60 |
| Mixed barren land, Herbaceous rangeland, Cropland and pasture | 50 |
| Mixed urban or built-up land, Agricultural land, Residential, Orchard, vineyard, nursery, horticultural areas | 30 |
| Urban or build-up land, Commercial and services, Industrial and commercial complexes, Other urban or built-up land | 20 |
| Transportation, communications, utilities | 10 |

The same algorithm was applied to assign friction to water streams in the area based on their status: perennial, intermittent or ephemeral (Table 2).

Table 2. Assigned friction based on stream status according to the National Hydrologic Dataset.

| Stream Status | Impedance in % |
|---|---|
| Large stream | 99 |
| Perennial stream | 99 |
| Intermittent | 75 |
| Ephemeral | 50 |

Considering that walking coefficient "a" in Langmuir formula measures time to traversing the cell (s/m) but the impedances in PMTS represents a speed (m/s), made them comparable by implementing following formula that converts speed into traversing time.

(a / (1 - impedance)) - a (4)

Where “a” is walking coefficient equivalent to 0.72 (according to Langmuir) and impedance is the value in percent assigned to particular land cover. The values from this formula represent the additional time to cross the cell. For example, value 0.30 s/m would mean an additional to 0.72 s/m time to traverse pasture or agricultural land, so the total time would be 1.02 s/m.

Calculated surface was reclassified from meters per seconds to kilometers per hour (Figure 3) and imported to ArcMap for further integration with site condition rasters.

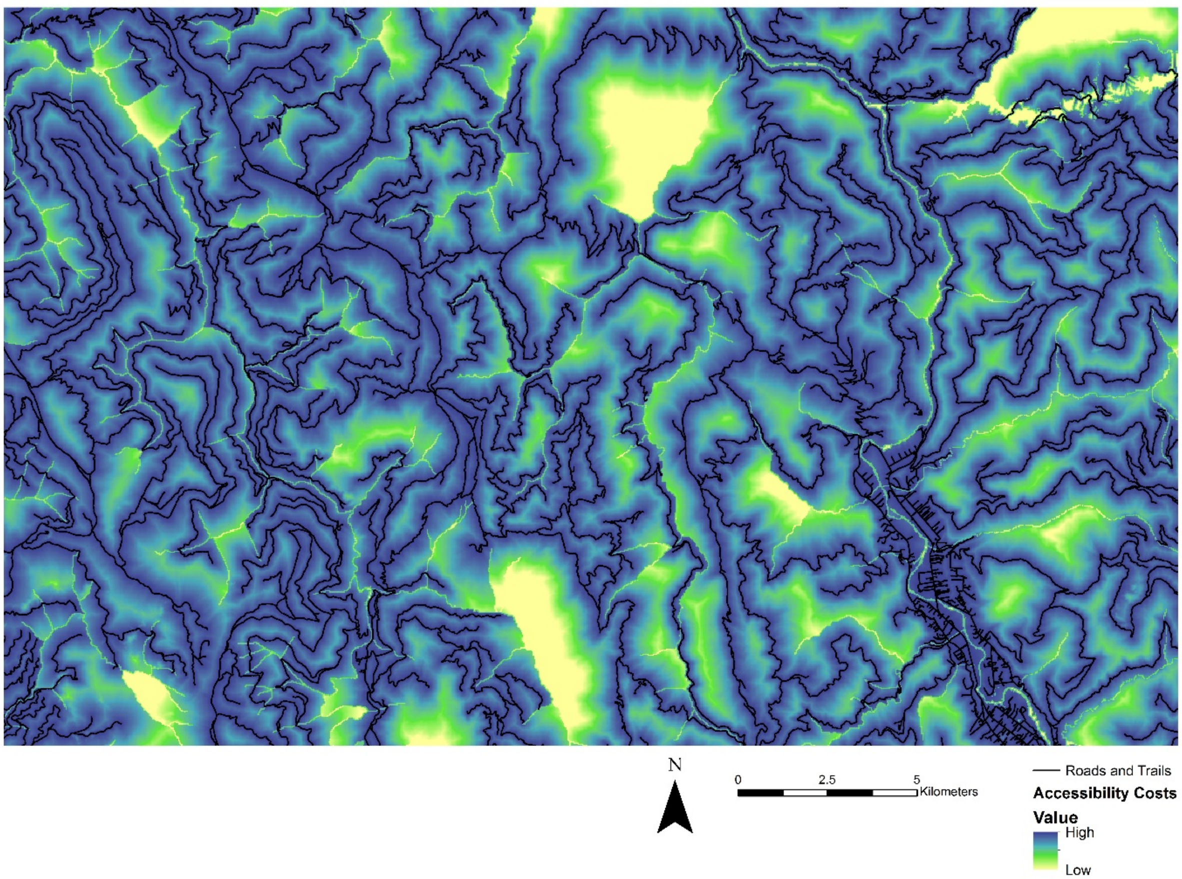



Figure 3. Cost-surface map reclassified from low to high accessibility costs.

*Estimating site conditions*

Although, effects of slope and highly vegetated areas on hiking ability were previously studied (Doherty et al., 2009), there is little information how those variables, along with road networks and technology used, influence working productivity while implementing forest management. Functional dependence between these two factors was not studied explicitly. In context of forest disease management, abundance of host species also seems to play significant role affecting number of working hour and following management costs. Martell et al. (1998) and Poje et al. (2016) in their timber harvesting studies noted that forests located on steep terrain are less accessible and present more difficult working conditions with higher harvesting costs. Road network characteristics, technology used, and physical demands of the work are considered to be major impedances not only for timber management (Poje et al., 2016), but for forest disease control efforts as well.

Current in-place *P. ramorum* control practices are based on pathogen biology and behavior (Davidson et al., 2002). Studies indicate that *Phytophthora ramorum*, once produced sporangia on the foliar host plants (Rizzo et al., 2002) can be splashed with rainwater over several meter infecting neighboring hosts (Davidson et al., 2002). Research conducted by Hansen et al. in 2008, indicated that clustered trees showed higher potential to be infected than trees with some distance apart. Following this discovery, new emerging management strategies started to incorporate host removal around infected tree that has shown to be an effective SOD treatment (Cunniffe et al., 2016). Removal was usually followed by herbicide application to prevent re-sprouting (although it raised a big concern among public and some of the stakeholders group (Bowcutt, 2015)), and pile burning as fire had proved to have inhibiting effect on P. ramorum spores, significantly slowing the spread (Moritz and Odion, 2005).

For the purpose of our research, we assumed that (1) clear cutting, (2) tree removal and (3) prescribed burns are most common SOD management strategies that could be implemented both individually and together. For the sake of simplicity, we assumed individual implementation and excluded herbicide use. We assumed, as well, that following factors: (1) slope, (2) vegetation density, and (3) host density are universal for all three treatment strategy and have significant effect on working difficulty on site, response time, speed of treatment and associated management costs.

Every factor was assigned specific weight according to its relative importance for each of the treatments on a scale from 1 to 6 (Table 3).

Table 3. Importance weight assigned to site condition variables.

| **Variable** | **Weight (Wi)** | | |
|---|---|---|---|
| | Tree removal | Clear cut | Prescribed fire |
| Slope | 6 | 6 | 2 |
| Tree density | 4 | 1 | 1 |
| Host density | 4 | 6 | 6 |

Mechanical tree removal is implemented manually and very labor intense process. Presumably, crews that work on steep terrain will need more time to finish the same amount of work on flat surface. From this perspective we assigned highest weight to slope variable. Tree density and host density in this case would have equal importance because the goal of removal is to create canopy gaps rather than remove all hosts. Although we assumed that clear cutting is conducted with the use of machines, slope greater than 40 degree is generally not traversable by regular clearcutting machines. On the opposite site, slope doesn't present significant impedance for prescribed burns, it depends a lot on the weather and conditions of particular location. For our study, we assigned the highest weight to host density because it will greatly affect the location choice rather than management conditions.

For this part of the model, the data on slope was derived from Humboldt DEM, and both vegetation and host data was acquired from the Landscape, Ecology, Modelling, Mapping and Analysis (LEMMA) project database. We tested our model on 864 sq.km of focus area, and acquired a set of three suitability maps in accordance with selected control strategies. Using equal intervals, we reclassified the resulted range of values for every map into five categories from "Very low" to "Very high" management suitability with "No data" values assigned to sixth, "Not suitable", category.

## III. Results

The model quantifies and maps management suitability distribution across the complex landscapes. Combination of accessibility and site conditions factors creates a unique spatial suitability pattern for each of chosen treatments (Figures 4.1, 4.2, 4.3 and Figure 5.1, 5.2, 5.3). We analyzed those patterns using an acres as a measuring unit, since the acre is the smallest management unit utilized for forest management and planning.

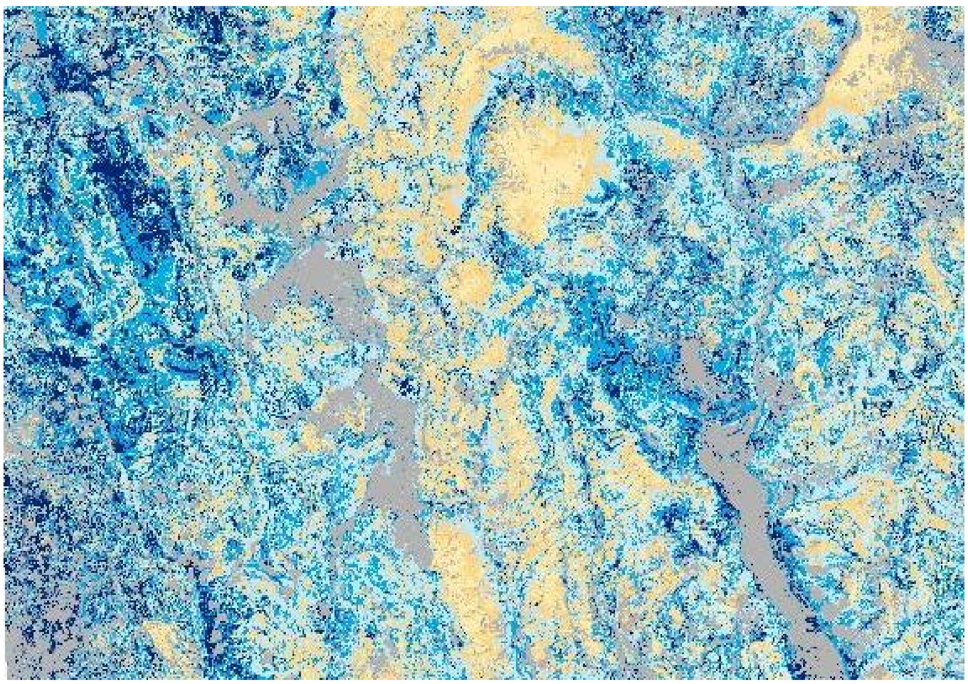
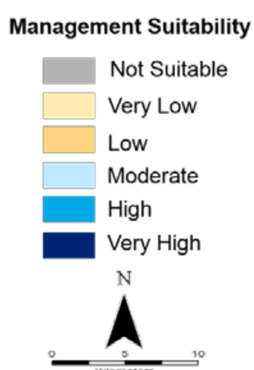


Figure 4.1 Tree removal



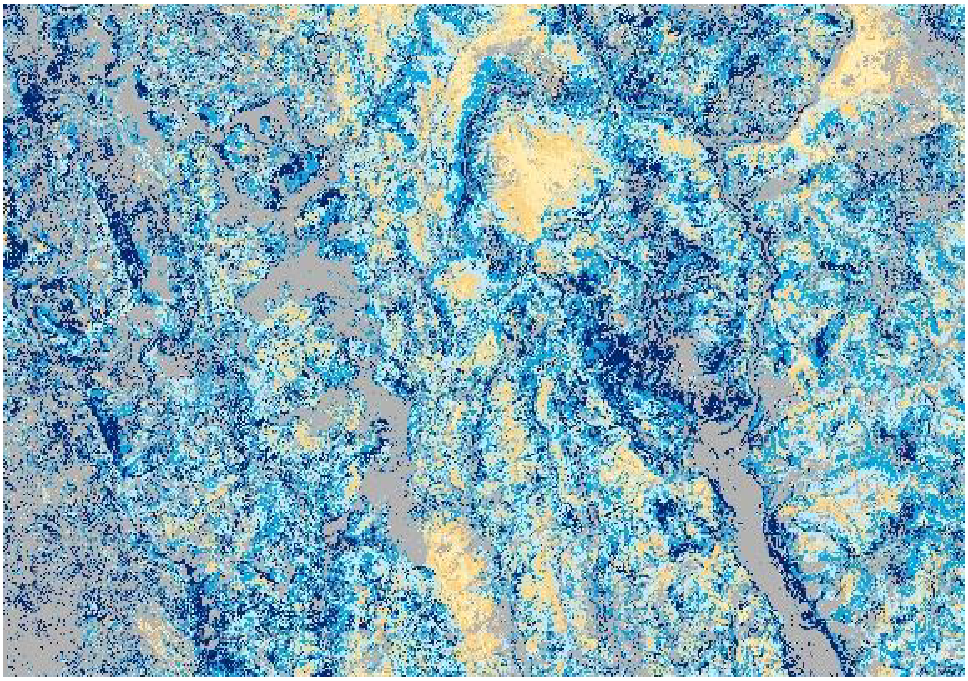


Figure 4.2 Clear cut

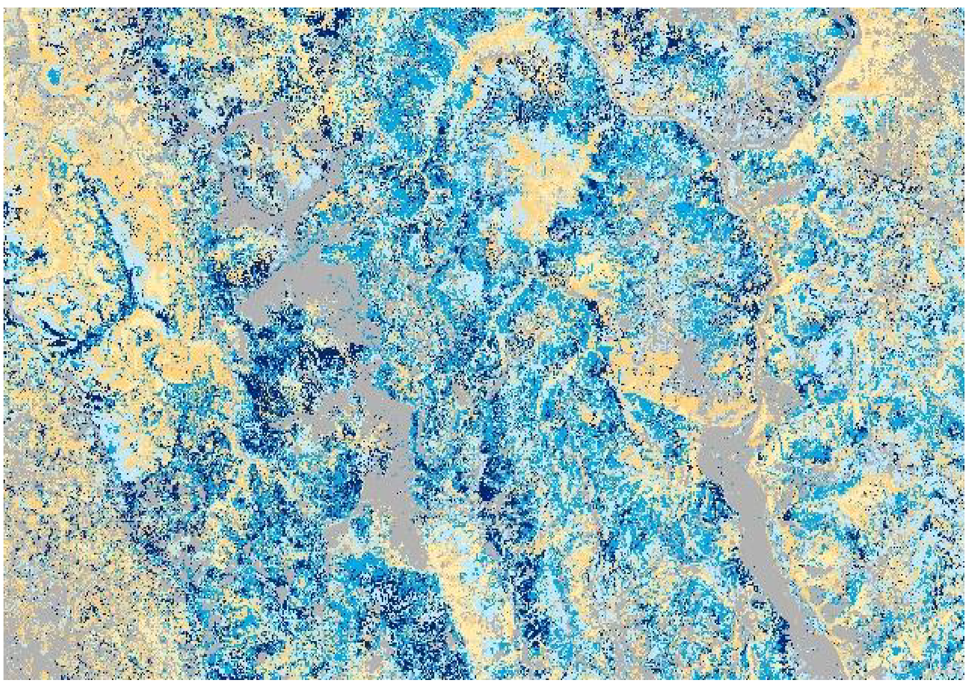


Figure 4.3 Prescribed fire

The modeling results indicate that on average, 15% of the study area had shown to be either very suitable or suitable in general, and 10 % refers to low suitability. About 50% of the area appeared as unsuitable due to the presence of impervious surface and large water bodies or absence of two key host species (*Notholithocarpus densiflora* and *Umbellularia californica*).

In comparison with prescribed fires and tree removal, area not suitable for clear cut is almost twice larger and occupies 72 thousand acres across the study area. Considering that clear cut cannot be implemented in residential areas and requires certain host density, the number of unsuitable acres increases. However, on the other hand, clearcutting also possesses the largest number of highly suitable acres - almost 30,000 in comparison with 20,000 for tree removal and prescribed burns. In turn, prescribed burns is the most “restricted” treatment as approximately half of the study area falls into categories of low, very low or not suitable for management. Intersection of all suitability surfaces (Figure 6) revealed that areas classified as “High” are dominant by the number of acres, and areas of “Very Low” suitability reflect topographical features of the study area (it predominantly occupies steep terrains) and the road network.

Areas most suitable for clear cut tend to dominate in western and northwestern parts where majority of national park and timber land lies, as well as in the northern part of Hoopa Valley. Prescribed fire is more concentrated towards the center of the area where it follows roads pattern.

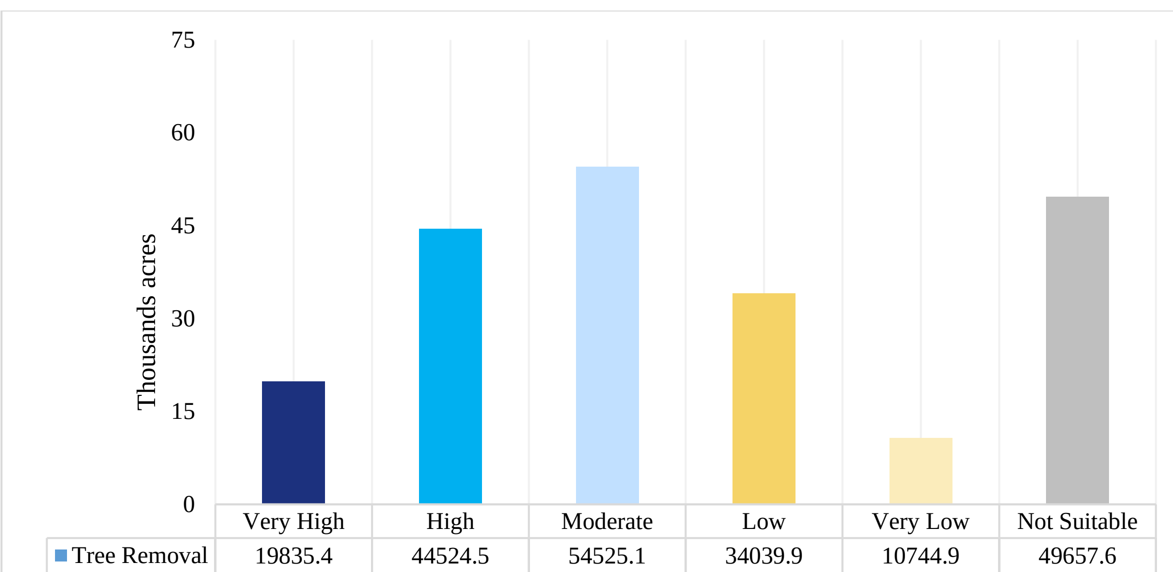



Figure 5.1 Management land suitability distribution by category. Tree removal

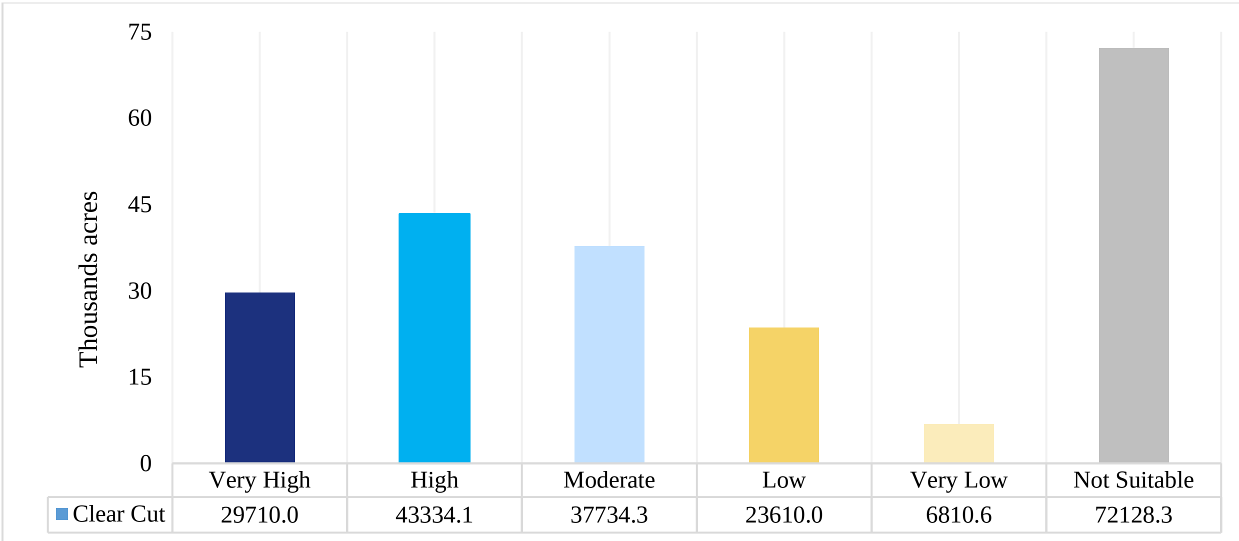



Figure 5.2 Management land suitability distribution by category. Clear Cut

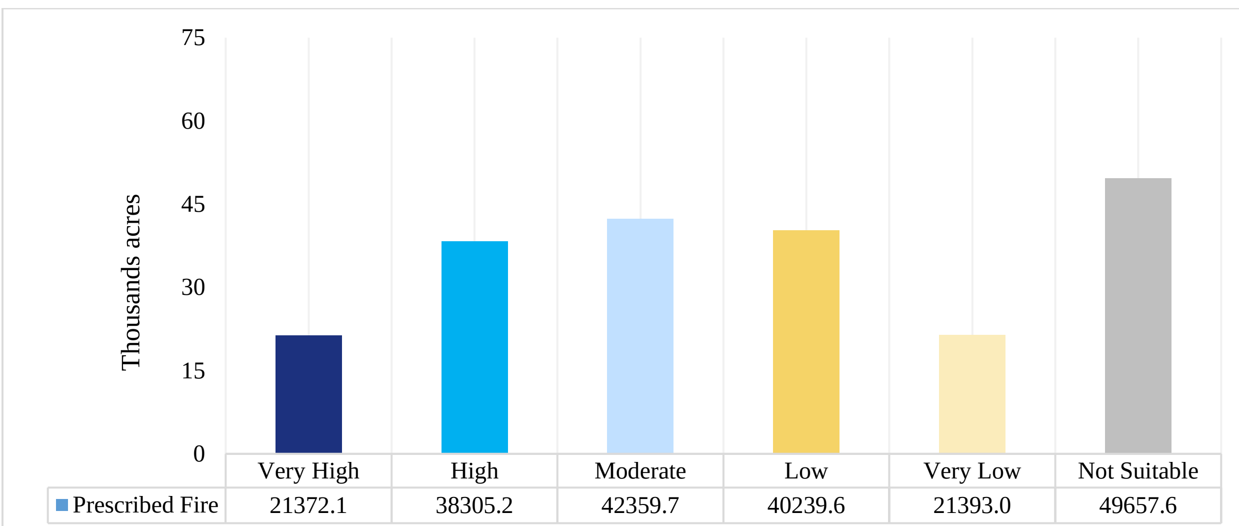



Figure 5.3 Management land suitability distribution by category. Prescribed burn

Overall, it appeared that “High” suitability and “Moderate” suitability present more intersection across the study area. “Very Low” suitability was found in the areas with greater gradient change and less developed road network.

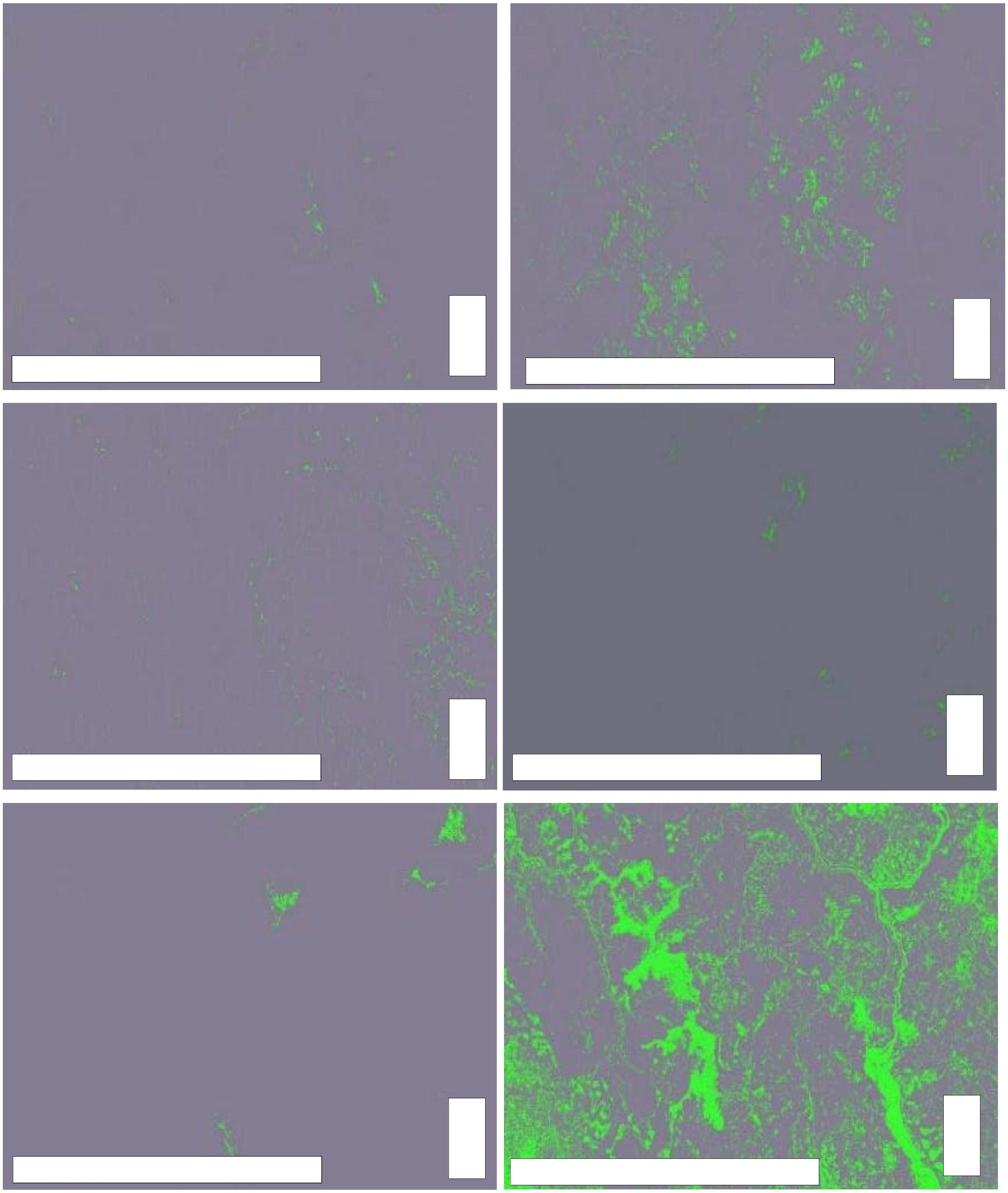


Figure 6. Represent an intersection of three SOD control suitability maps in between same categories. From left to right first row: “Very High”, “High”. From left to right second row: “Moderate”. From left to right third row: “Low”, “Very Low”, “Not suitable”. The interactions depicted in green.

One of the major parameters for choosing our focus area was diverse stakeholders group that includes both governmental and non-governmental sectors. We selected 6 major stakeholder groups that possess the greatest land share in the area. They are represented in Figure 7.

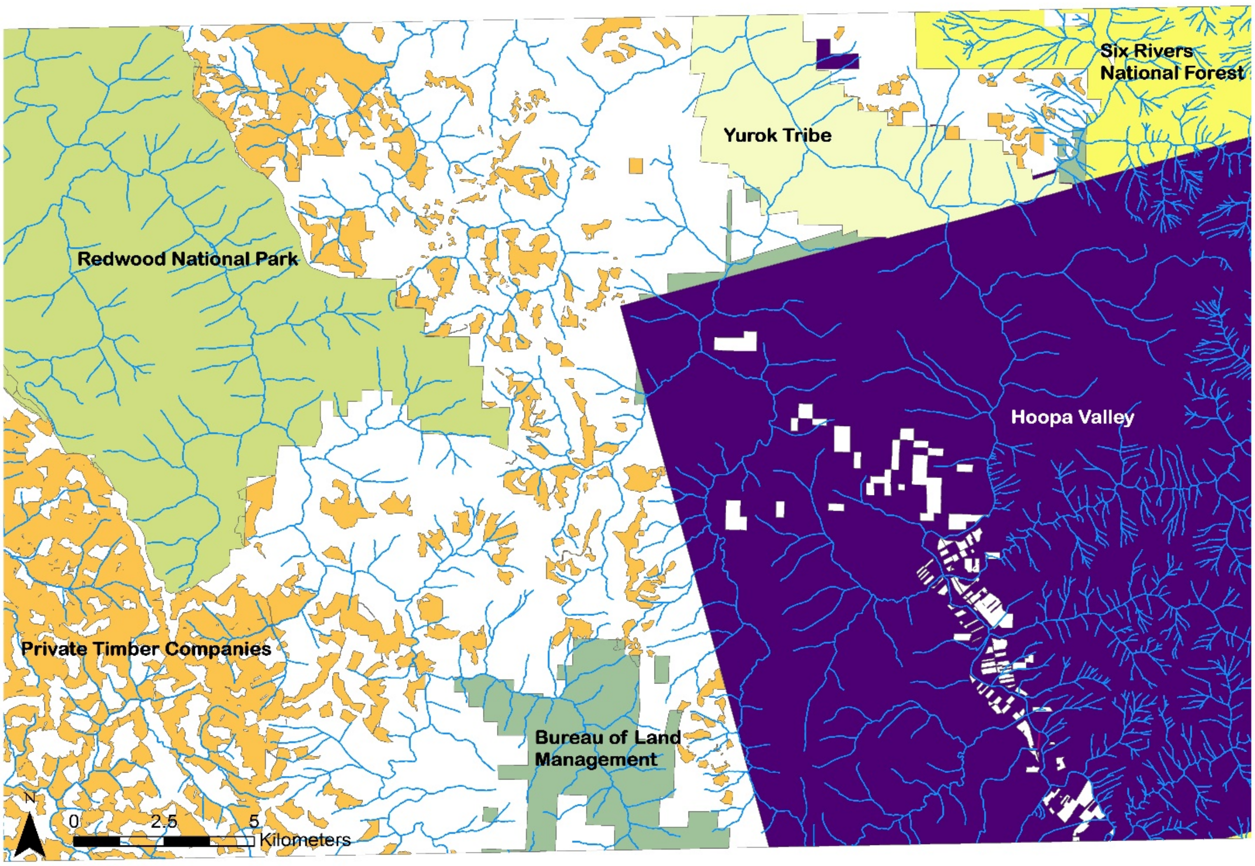



Figure 7. The map of six key stakeholders in the study area.

We used epidemiological SOD spread model developed by Meentemeyer et al. (2004) to estimate the amount of land under the highest risk of spread along with number of treatable acres for each of the control strategy. The results show that alarmingly high spread risk is currently present on Yurok tribe land - almost 50% of the stakeholder's area, while for the rest of the stakeholders it is equally distributed.

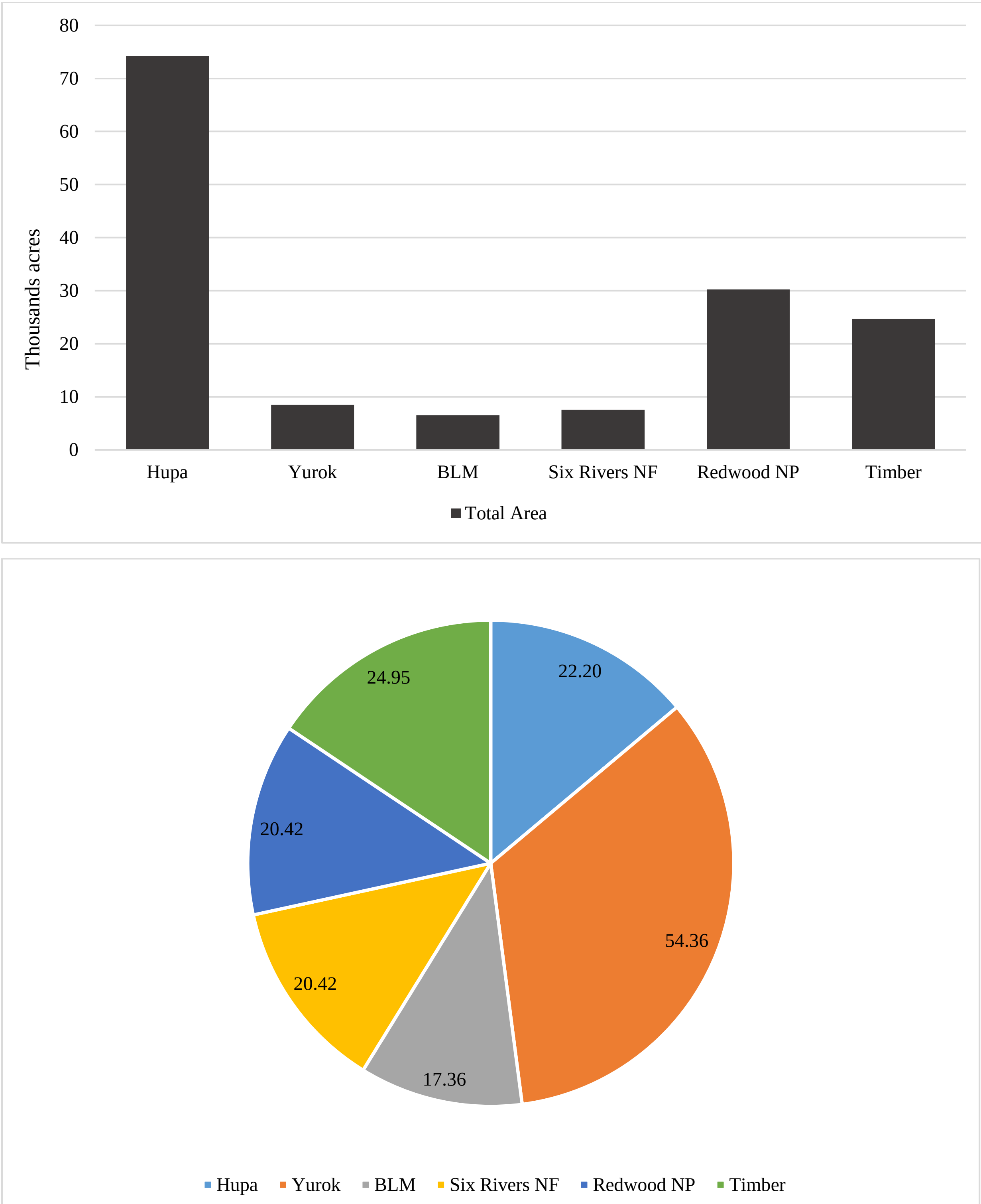



Figure 8. Total area of landowner and Sudden Oak Death spread risk (very high category) normalized by landowner area

Analysis of the distribution of treatable acres for each control strategy within major stakeholder groups (Figure 9.1, 9.2 and Figure 10) has shown that the land, suitable for implementation of control measures, is not distributed uniformly between and within stakeholder's properties. Hupa tribe land has a great potential for clear cutting treatment, while the same option will not suit Bureau of Land Management. The 1/5 part of Redwood National Park can be treated with both tree removal and clearcutting, and majority of timber property can successfully combine all the treatments. Prescribed fire treatment would be relatively easy to implement on the territory of Yurok tribe and timber lands. On the other hand, it might not be a preferred option when managing Hupa land or within Redwood National Park boundaries.

Private timber land appeared to be the only stakeholder in whose area is equally suitable for implementation of all three types of treatments with only minor variations. However, it is important to note that in a real world timber companies do not manage specifically for sudden oak death, and gain profit from such actions as clear cut or tree removal. Considering that, management there can go beyond suitable locations as management cost for timber companies will pay off with profit from sold wood.

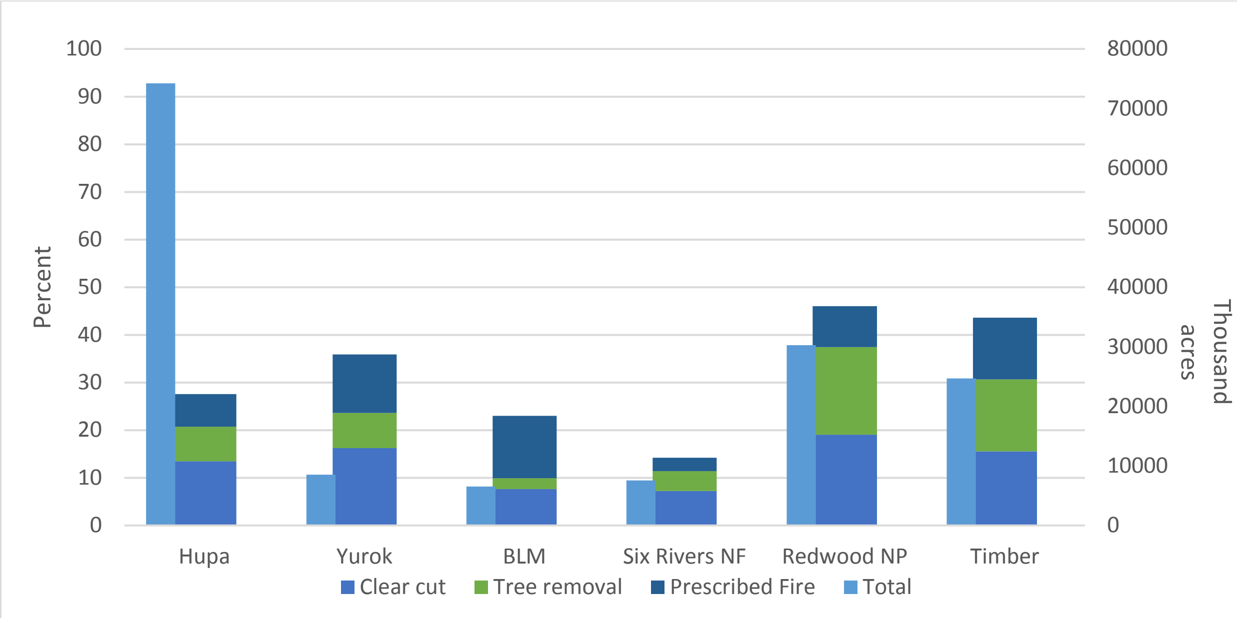



Figure 9.1 The most treatable land in percent of total and total area by stakeholder in acres

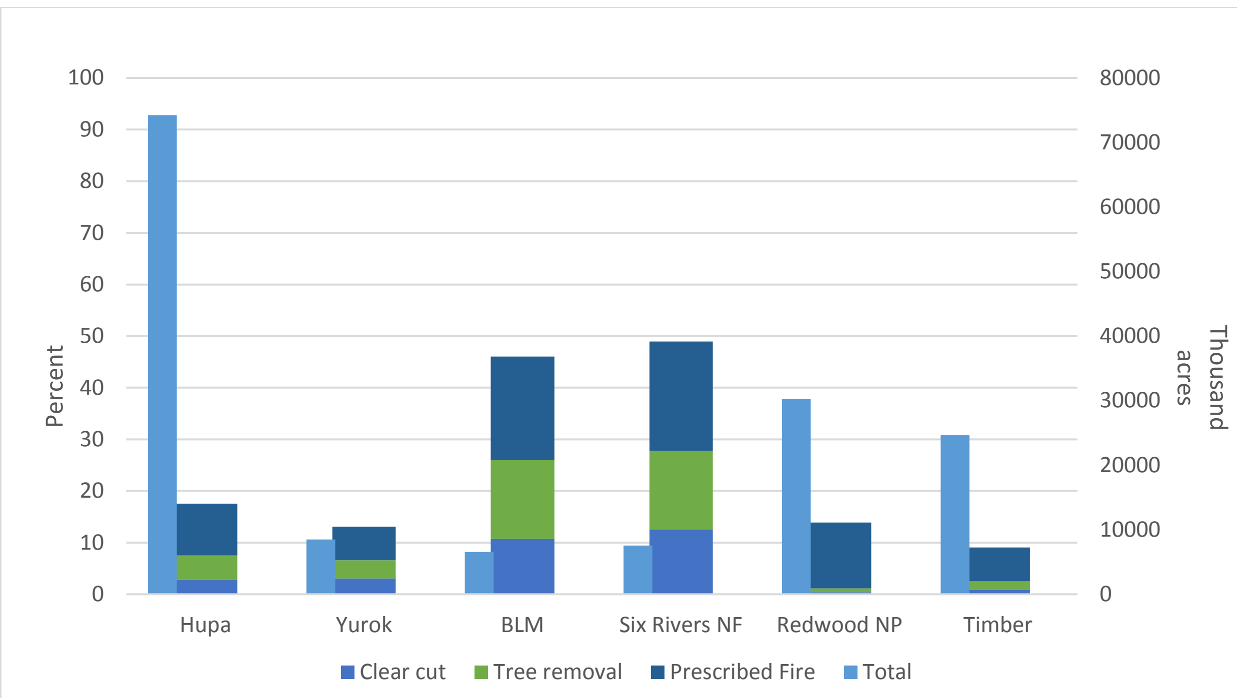
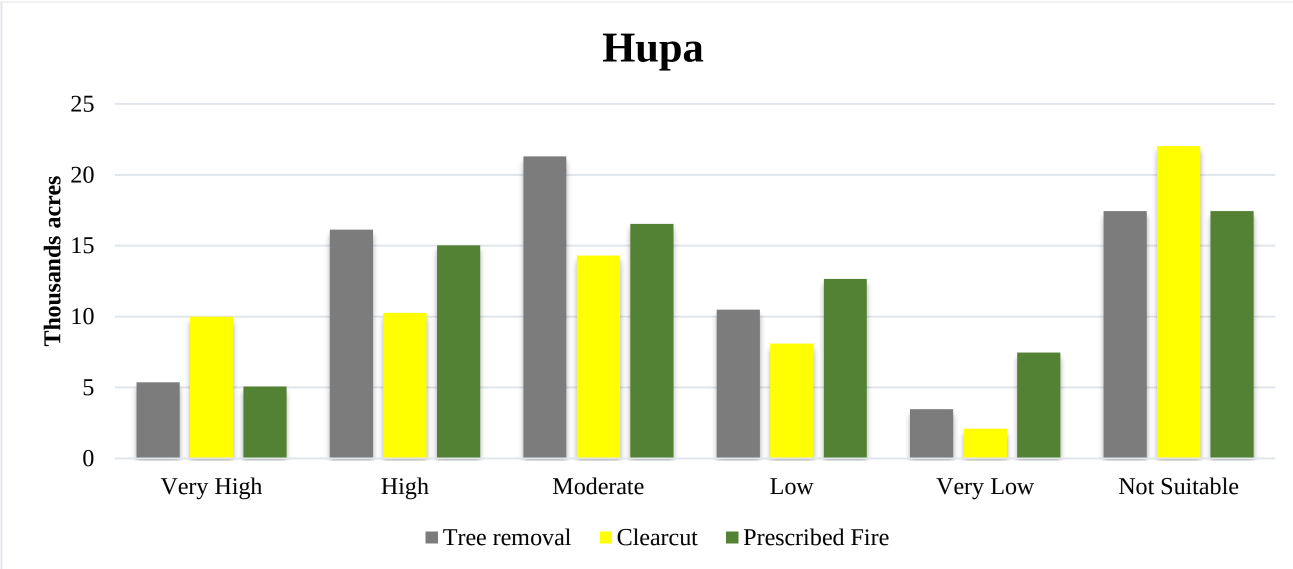
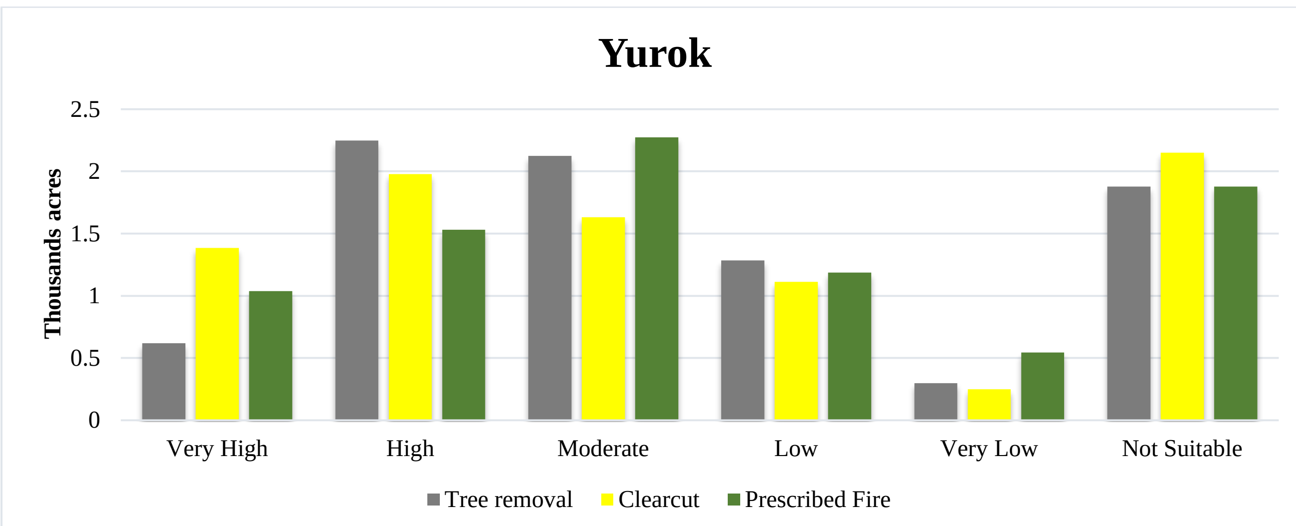
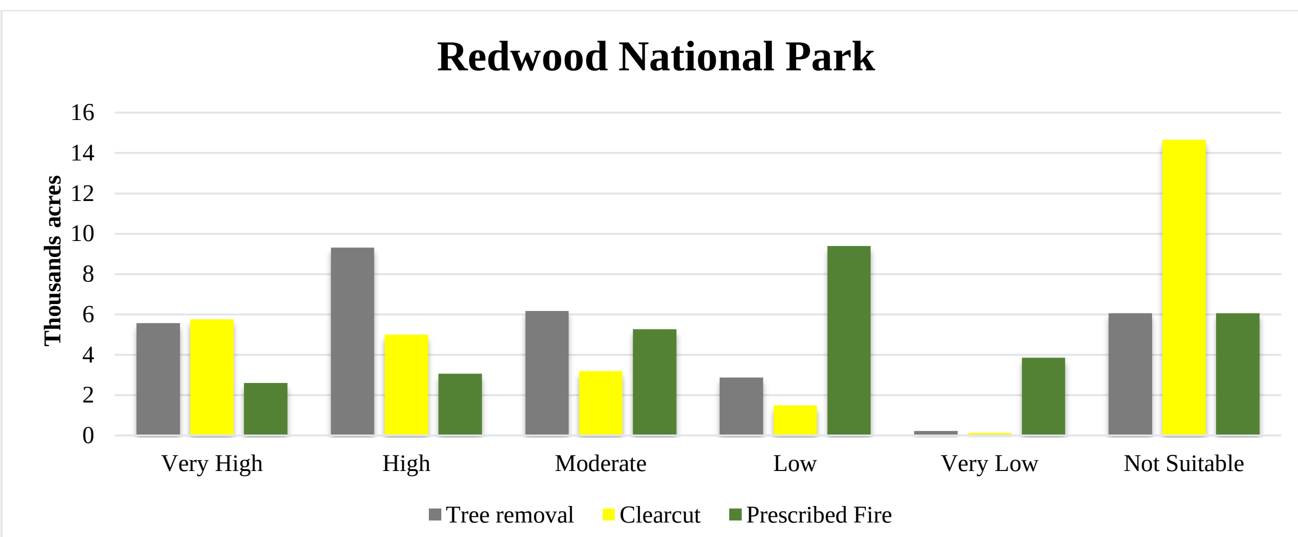



Figure 9.2 The least treatable land in percent of total and total area by stakeholders in acres


Hupa
Thousands acres
25
20
15
10
5
0
Very High
High
Moderate
Low
Very Low
Not Suitable
Tree removal
Clearcut
Prescribed Fire


Yurok
Thousands acres
2.5
2
1.5
1
0.5
0
Very High
High
Moderate
Low
Very Low
Not Suitable
Tree removal
Clearcut
Prescribed Fire


Redwood National Park
Thousands acres
16
14
12
10
8
6
4
2
0
Very High
High
Moderate
Low
Very Low
Not Suitable
Tree removal
Clearcut
Prescribed Fire

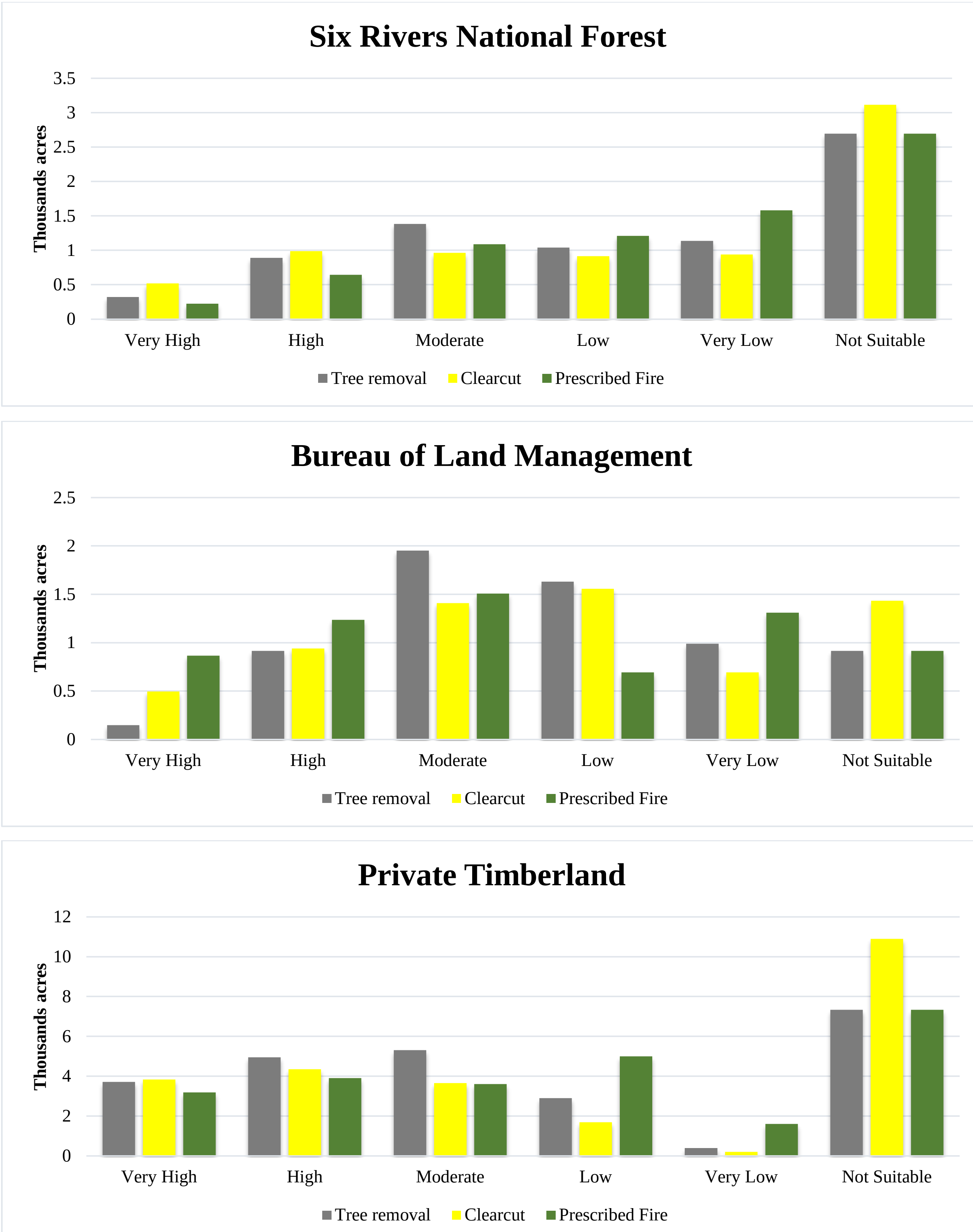



Figure 10. Distribution of management suitability by landownership type.

Overall, by area Bureau of Indian Affairs (Hoopa Valley and Yurok tribe land together) takes up more than half of research site and present about 10,000 acres of "Very high" suitability land. Second largest property belongs to Redwood National Park, and allows to treat up to 18% of highly suitable land. Comparison by stakeholders shows that the least suitable for management land belongs to Bureau of Land Management. On average, majority of moderately and low suitable land appeared to be within Redwood National Park and Six Rivers National Forest properties.

To estimate the percentage of highly suitable management areas per treatment type to risk of *P. ramorum* spread within stakeholder's property, we overlaid SOD risk map (Meentemeyer et al., 2004) with all three suitability maps to outline areas where demand of management and management suitability can potentially align (Figure 11). Timely response, when time between detection of threat and actions is minimal, sometimes plays essential role for effective control. Our analysis has shown that the largest area of the high spread risk within a single ownership is managed by Yurok tribe. Overall, almost 70% of the research area is considered either "Very High" or "High" pathogen spread risk. Having compared the risk distribution with maximum suitability land distribution, we conclude that there are at least 3,000 acres of high spread risk that can be managed by at least one of the listed control techniques.

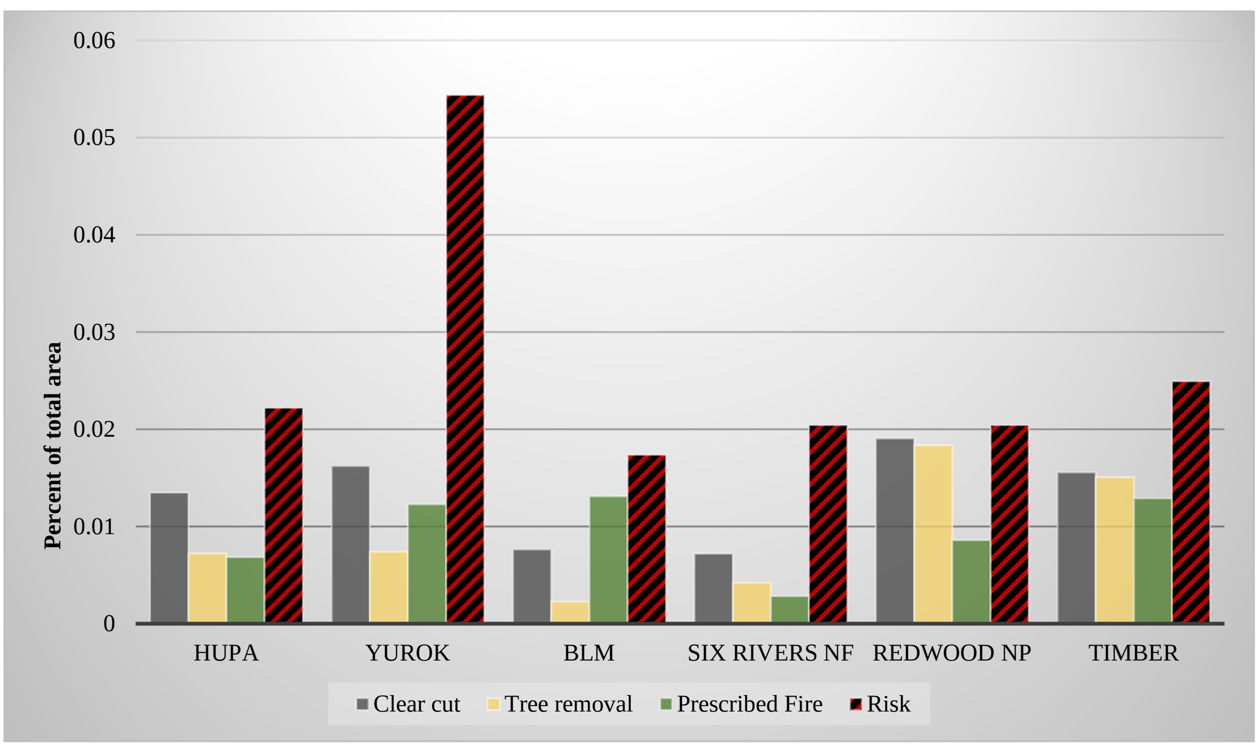


Figure 11. The highest suitability land distribution per type of landownership

Once *P. ramorum* arrives at the place, stand condition change significantly as progressively high percentage of canker hosts (oaks and tanoaks) becomes infected. As a result, objectives of control response is sensitive to the disease stage, that has three broad categories of Before, During and After (Swiecki & Berndhart, 2013). Although some locations in Humboldt County (and our focus area, in particular) have already been infested, predominantly isolated nature of the infected stands allows to consider remaining area to be relatively intact with a high risk of infestation in the nearest future. Following "A Reference Manual for Managing Sudden Oak Death in California" (Swiecki & Berndhart, 2013), we assumed that our research area is currently experiencing invading stage and major management objectives could be protection of non-infected hosts, minimization of *P. ramorum* spread and minimization of hazards associated with the disease. We applied our model to demonstrate how prioritization of management location can improve control response in the areas of relative importance (or usefulness) of management action to prevent new outbreaks of SOD in location where *P. ramorum* doesn't currently occur based on known distance to infected sites (Figure 12). We creates a series of buffers representing relative importance of management actions when proximity to known *P. ramorum* infected sites is low (5 to 10+ km), moderate (1-5 km) and high (less than 1 km).

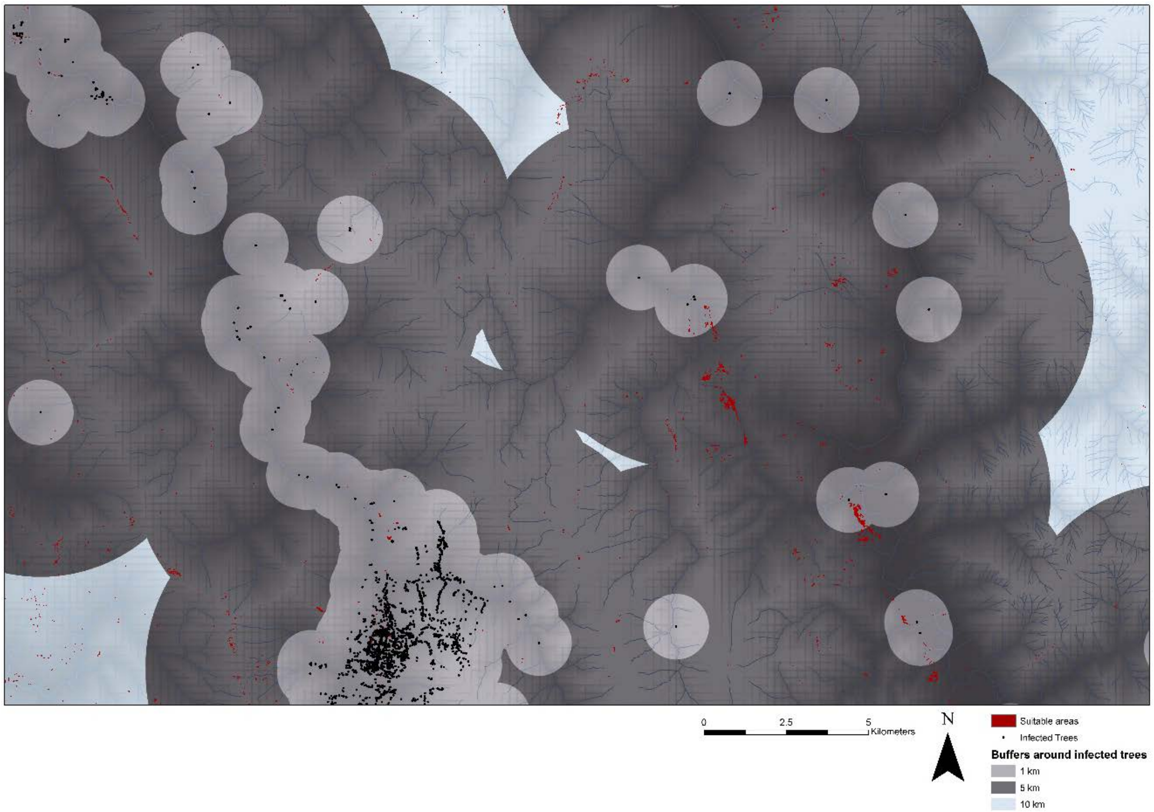



Figure 12. Distribution of the most suitable management land (for all control options) within proposed management buffers.

Overall, performance of management suitability distribution shows a clear patchy pattern with no single continuous area of very high or high suitability. This pattern represent a direct reflection of the landscape complexity and heterogeneity.

## IV. Discussion

Deciding where and what control strategy to implement in a given area is an essential task, yet a challenging one (Cunniffee, 2016). Prioritizing areas for forest disease management based on accessibility parameters and site conditions can potentially decrease management costs and shorten response time. Our model presents a significant supplementary tool to use in conjunction with epidemiological data and expert knowledge. Considering budget constraints and legal limitations, the entire landscape cannot feasibly be managed and prioritization of locations is a necessary planning step. Although, sometimes management in poorly accessible areas is unavoidable, prior knowledge of potential barriers may assist with better strategy development.

Selection of management sites depends on multiple factors including risk of infestation, weather conditions, current SOD locations, overall likelihood of success, etc. Taking into account peculiarities of different management approaches, certain places may hold natural or human-made constraints that may prevent implementation of one or several control strategies. Thus, it is very important to incorporate knowledge of physical management suitability into decision-making process at early stages of planning to increase likelihood of success and avoid unnecessary treatment costs.

Our study is the first attempt, to our knowledge, to estimates management feasibility from the point of accessibility and working conditions, while accounting for host distribution. The model framework is open and flexible and accommodates possible parameters changes, so users can customize it for each particular case. Potentially, other parameters (such as risk spread) can be incorporated to improve model performance. Moreover, parameters to every single control strategies are very individual, so we based our analysis on the general assumptions we made regarding every chosen control strategy. For instance, prescribe fire in a real life will account for much more than just slope and host density. Proximity to roads is a relative measure as it depends on topography and land cover. The model may not work well for timber companies who already is doing clearcutting and thinning for commercial purposes and SOD treatment is only embedded in existing strategies. However, the model's potential to incorporate expert knowledge and research data will help to facilitate basic understanding where certain management will be feasible based on the requirements for certain strategy to be implemented. We built the model based off the assumptions that (1) major factors affecting management feasibility will be proximity, topography, host presence and density, (2) clear cutting refers to heavy thinning and requires machine presence or a lot of manual work, and thus we accounted for having machine at place.

Although there are many examples of successful management of SOD on a local scale in the first stages of invasion, control efforts on a bigger scale was not that successful and many times failed due to multiple factors (Alexander & Lee, 2010; Valachovic et al., 2008). Cryptic infection (Filipe et al., 2012), failure to come with agreement between multiple stakeholders and "management within borders" (Thompson et al., 2016), budget constraints, and inaccessibility are among the most influential factors that limit management ability significantly. Despite some experts came to conclusion that the pathogen has spread far enough that eradication is no longer possible (Cunniffee eta al., 2016), on a very local scale invasion management is still important for reducing local spread and preserving high priority areas, such as old growth tanoak stands which possess cultural value (Alexander et al., 2010; Bueno et al., 2010).

Overall, through integration into adaptive management and coupling with epidemiological models, this management prioritizing approach will enable stakeholders to implement strategies in timely and effective manner.

## V. Conclusion

With all the existing constraints and uncertainties that forest disease management experiences, identification of "manageable" lands is vital for not only reducing budget expenses but also to provide timely response to the threats nonnative disease poses as well as management outcomes. The quicker land managers can respond, the more chances the disease will be controlled in early stages of invasion. Setting management priorities in terms of feasibility will also help to have a better track of the resources allocated to the control efforts and will help to understand where management is more costly and is whether it worth to manage there and will bring positive results afterwards. By applying knowledge and tools that could enhance control strategies, oak, and tanoak, mortality can be reduced not only because of applying management, but because of applying the right management that would bring no harm and preserve vulnerable ecosystems from structural and functional changes.

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