Restoring Whitebark Pine in the Sierra Nevada: Prescribed Burning Suitability Analysis

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ABSTRACT

Whitebark pine is a keystone species of the upper subalpine ecosystem of western North America. Unfortunately, it is in danger of extinction in as few as two generations. In the recent past, humans have played a major role in the decline of whitebark pine, not only by introducing an invasive pathogen and expanding the range of deadly bark beetles through climate change, but also by preventing periodic fires, which increases competition with other species of trees. Although vegetation management and prescribed burning restoration efforts in whitebark pine's devastated northern ranges have had limited success, the less infected forests of the Sierra Nevada Mountain Range provide an excellent opportunity to implement prescribed burning. In this study, a suitability analysis was used to prioritize stands for prescribed burning that vary in terms of ecological parameters, such as the presence of the mutualistic bird, Clark's nutcracker, and environmental parameters, which affect the practicality of setting a controlled fire. The addition of these weighted opportunities and constraints resulted in a map that highlights the high elevation, mid and central areas of the Sierra Nevadas as good regions for restoration. 1.6% of the land is suitable, covering over 87 thousand acres, according to the final suitability map. Given the availability of suitable restoration sites and their locations, federal land managers can begin the process of planning prescribed burns to protect this endangered species.

KEYWORDS

Subalpine community, ArcGIS, site selection, Clark's nutcracker, fire

INTRODUCTION

Interspecies interactions play a critical role in shaping forest ecosystems (Bertness and Callaway 1994). The dynamics between species are often disrupted when invasive species are introduced. Invasive pathogens and insects, such as the chestnut blight fungus, the Dutch elm disease fungus (Castello et al. 1995), and the elm ash borer (Poland and McCullough 2006) all influence forest ecosystems via tree mortality. These and other pathogenic invasive species have created the need for forest protection and restoration across the United States. Entire landscapes are changing because once dominant trees are dying off. High tree mortality after infestation leads to accelerated succession, increased fuel loading, increased stream flow, and altered chemical cycling on large scales (Raffa et al. 2008).This problem is exemplified by the keystone species whitebark pine, *Pinus albicaulis*, which is declining throughout its range in the subalpine communities of western North America, predominantly due to the introduction of white pine blister rust (WPBR) and other anthropogenic influences.

Over the last few hundred years, humans have contributed to the decline of whitebark pine by promoting threats including disease, fire suppression, and climate change. Humans introduced the invasive tree disease species WPBR, a native of Eurasia, to British Columbia in 1910 (Hoff and Hagle 1990). Since then, WPBR has been slowly killing five needle white pines, by infecting their cone bearing branches and then girdling their trunks with blisters, as it spreads south over whitebark pine's entire range (Maloney 2011, Tomback et al. 2001). By implementing a policy of fire suppression, which alters stand dynamics, humans have also influenced the health of this forest ecosystem (Arno 1996). Instead of being periodically killed by burns, the shade tolerant species mountain hemlock (Arno and Hoff 1989) and lodgepole pine (Peterson et al. 1990), compete with and replace whitebark pine (Tomback et al. 2001). The added stress from competition and the increased age of whitebark pines have also made them more susceptible to infestation and death by the mountain pine beetle (MPB) (Cole and Amman 1969, Peterman 1978). MPB is of heightened concern because climate change has allowed it to expand its range northward and to higher elevations (Carroll et al. 2003). These pressures similarly threaten other aspects of the pine's life-cycle strategy, including reproduction.

The success of the next generation of whitebark pine is affected by a complex series of ecological interactions including mutualism and predation. Whitebark pine cones are indehiscent, meaning that they cannot distribute their own seeds, and therefore obligately rely on Clark's nutcracker, *Nucifraga columbiana* (Tomback 1982). This mutualism is critical to whitebark pine population regeneration and its success is multifactorial. First, there must be a large enough seed crop available to granivores, the animals that rely on seeds as a food source. In this case, Clark's nutcrackers are able to bury many more times the number of seeds they can retrieve and eat, leaving the rest to germinate (Tomback 1982). Other granivores include rodents, such as the red squirrel and Douglas squirrel, which forage on whitebark pine cones and predate the seeds. Large population sizes and high mobility of these rodents have a negative effect on seed dispersal probabilities (Siepielski and Benkman 2007). Unfortunately, whitebark pines are not producing enough seeds to exceed the demands of granivores and this natural system is no longer working. In as little as 120 years, whitebark pine is in danger of becoming extinct (USFWS 2014). Thus, restoration efforts are needed to help this endangered species.

Currently, management and prescribed burning restoration efforts are centered in whitebark pine's northern ranges, the Rocky Mountains and Cascade Range, where mortality is highest (Keane and Parsons 2010a, Warring and Six 2005, Burns et al. 2008). The prevalence of WPBR increases with latitude (Maloney 2011) and the worst MPB outbreaks occurred in Idaho and Montana (Bartos and Gibson 1990). This region is where restoration techniques have been tested. The preferred restoration technique involves prescribed burning that mimics historical fire regimes to kill the understory and promote areas where Clark's nutcracker caches seeds (Keane 2001). Prescribed burning is a good strategy because whitebark pine is better at surviving and regenerating after fire than associated species because of its thicker bark, thinner crowns and deeper roots (Arno and Hoff 1990). Unfortunately, prescribed burning has failed in areas surrounded by high mortality and low seed producing stands, due to the birds reclaiming all cached seeds within the newly burned, open areas (Keane and Parsons 2010a). In cases where the seed sources are too low, seedlings must be hand planted in treated areas, which is much more expensive and labor intensive than burning techniques (Keane and Parsons 2010b). The Sierra Nevada Mountain Range, located much further south than current restoration areas, provides an excellent opportunity to implement prescribed burning because disease rates are still low. However, areas where restoration efforts should be directed have not yet been identified.

The objectives of study were to determine where prescribed burning is likely to be successful in managing populations of whitebark pine in its Sierra Nevada distribution. I located sites where ecological parameters, such as the presence of Clark's nutcracker, serve as opportunities and constraints to the success of the next generation of whitebark pine. I also included environmental parameters like slope, temperature, and wind speed, which all affect the practicality of safely and successfully burning a site. I used suitability analysis to prioritize stands that vary spatially in terms of twelve key ecological and environmental considerations for setting prescribed burns. Ultimately, this produced a series of maps that highlight areas that are good candidates for restoration as well as unsuitable areas that should be avoided.

METHODS

Study system

To study whitebark pine restoration using prescribed burning, I chose to focus on the subalpine region of the Sierra Nevada Mountain Range. This range is home to the southernmost population of whitebark pine. Whitebark pine's complete distribution includes regions in western Canada, as well as regions extending through the Sierra Nevada Mountains, the Cascade Range, and throughout the northern half of the Rocky Mountains. It occurs, although not continuously, between 107° and 128°W and between 37° and 55°N (McCaughey and Schmidt 1990). The Sierra Nevada is composed of nine national forests, three national parks and two national monuments. It covers almost 100,000 km^2 and extends latitudinally from 35°06′08″N to 40°21′32″N and longitudinally from 118°16′58″W to 120°52′3″W. Although the Sierra Nevada Mountain Range covers a large area, whitebark pines only grow in the subalpine zone, in elevations from 3000 to 4000m (Peterson et al. 1990). The area I analyzed is restricted by both the boundary created by the seven national forests and two national parks that whitebark pine exists within and the boundary created by the farthest a Clark's nutcracker has been known to carry whitebark pine seeds, which is 22 miles from the source (Lorenz 2011).

Data collection

To determine what parameters would affect the restoration suitability of an area, I found evidence through expert biologists' input and published research findings. Limited by the data readily available, I narrowed the countless variables down to twelve (Table 1).

Table 1. Description of parameters used for the suitability analysis.

Parameter	Category	Description and Reasoning	Weight
Whitebark pine	Ecological	A nearby seed source is needed for regeneration.	20
Lodgepole Pine	Ecological	This is a climax species that competes with Whitebark pine for resources.	10
Mountain Hemlock	Ecological	This is a climax species that competes with Whitebark pine for resources.	10
Clark's Nutcracker	Ecological	A seed disperser is needed to open cones and cache seeds.	15
Temperature	Environmental	Higher temperatures allow for high intensity burns.	15
Wind	Environmental	Fires become unpredictable in no wind or quickly spreading in high wind conditions.	10
Developed Land	Environmental	Fires must be as far away from buildings as possible.	15
Barren Land	Ecological	Although these are open areas, seedlings will not germinate on rock.	10
Slope	Environmental	Easier to control burns on moderate slopes compared to flat or extremely steep slopes.	10
Aspect	Environmental	Dryer, south facing slopes burn better than wetter north facing slopes.	10
Distance to Roads	Environmental	Roads allow access to a site and act as fire breaks. Also reduces cost.	20
Fire Return Interval Departure	Ecological	Lack of recent burns, increases competition and risk of disease outbreak.	15

To obtain spatial data on whitebark pine and Clark's nutcracker to create species distributions, I searched a number of online databases and publications. From "The distribution of forest trees in California" (Griffin and Critchfield 1972), I hand-digitized the ranges of whitebark pine, lodgepole pine, and mountain hemlock in ArcGIS 10.1 (ESRI 2011). To create the distribution map of Clark's nutcracker, I also downloaded species occurrence data from the Nature Mapping Foundation's California Gap Analysis Bird Maps (Davis et al. 1998).

In addition to these species distributions, this study required data on environmental characteristics of the landscape. One set was climate data, in the form of mean temperature, which was downloaded from the PRISM Climatic Group (Daly 2008). Wind data was found through the National Renewable Energy Laboratory (http://www.nrel.gov/gis/wind.html). I also downloaded land cover types, which are categorized based on their distinct spectral signatures, at the 3 arc second resolution level from the USGS National Map Viewer (viewer.nationalmap.gov/). Specifically, I added the building/urban cover and rock cover categories as layers in this study. I also downloaded elevation data from the USGS National Map Viewer. Using the Digital Elevation Model (DEM), I calculated slope and aspect. Spatial data on Californian infrastructure, such as roads, was downloaded from TIGER/Line (US Census Bureau, *census.gov/geo/www/tiger/*). Finally, fire return interval departure (FRID) was included to represent the ratio of the time elapsed since the last burn and the time between burns given a pre-settlement fire regime. I obtained this from the Forest Service's GIS Clearinghouse (fs.fed.us/r5/rsl/clearinghouse/r5gis/frid/).

Suitability model

To produce a composite map highlighting high priority stands for restoration, I used a land-use suitability mapping analysis in ArcGIS 10.1 (ESRI 2012). A suitability analysis is a method of site selection analysis to identify the optimal site for a desired activity given the set of potential sites (Malczewski 2004). After the initial data collection, each layer was stored into a single geodatabase and added into ArcMap as either a raster—a set of uniform squares on a grid, where areas are groups of adjacent cells with the same value—or a vector—a set of polygons, lines, and points that are coordinate based. Many layers contained extraneous attributes, which were removed. Layers that were undefined or used a different geographic coordinate system were defined or transformed to NAD 1983.

To prioritize certain sites within a layer, the next step in the suitability analysis involved giving each location an ordinal rank, 1 through 3, depending on the level of concern for that trait (Appendix A). For example, locations between 0 and 5 miles from a road were ranked 3 because they are most favorable based on the increased accessibility, fire break benefits, and lower costs of being closer, while locations 5-10 miles away were ranked 2. Whitebark pine was ranked highest within a distance of 2.1 miles from its known distribution because that is the average distance Clark's nutcrackers will carry seeds before caching them (Lorenz 2011). Lodgepole pine and mountain hemlock were given smaller distances from their distributions because wind is their primary mode of seed dispersal (Wall and Joyner 1998, Means 1990). For all layers that were given ranks based on "distance from", a set of buffering operations was performed for vectors and the Euclidean distance was calculated for rasters. For other layers that already had a complete set of values over the study area, the reclassification tool was used to divide the existing values into the 3 ranks. A new field was added to the attribute tables of each layer, where ranks were either entered manually or calculated using VB Script (Appendix B). All layers were clipped to fit inside the borders of the study area and converted to rasters with a cell size, or "site" size, of .01 decimal degrees, which equates to a 216 acre square, the size of a large controlled burn (Van Wagtendonk 1995).

Then, the layers were weighted, based on their relative importance to a restoration project (Table 1). I selected the weights by searching through literature on whitebark pine restoration and prescribed burning techniques. I was also guided by a number of experts in the fields of forest management, tree diseases, and forest fires. Finally, the weighted layers were overlaid and added together using the raster calculator tool (Appendix B). The result was a map where each location corresponds to a relative score, a composite of all layers weighed positively. A higher score represents a higher priority for restoration. I created a total of three scenarios that focus on solely ecological layers, solely environmental layers, or include all layers, where environmental and ecological categories are represented equally. The final suitability map is the result of the third scenario.

Data analysis

Although the results of this study are primarily meant to be disseminated visually, to better evaluate my r
of sites considered suitable, moderately suitable, and unsuitable. General trends across the study area were descri
which layers are constraining. To determine the prevalence of statistically significant clumped suitable locations
more clustered in the model than if the same set of scores were randomly distributed. I used α=.05 to classify lov

To determine the sensitivity of the model, I looked at all layers individually and in relation to each other
determine which are unlikely to have high ranks that overlap. For layers with suspected negative correlations, I r

Ecological map

The scores of the ecological map range from 80 to 240 (Figure 1a) and are distributed normally. These s
percentages equate to 1,174,176 acres of unsuitable area, 3,831,408 acres of moderately suitable area, and 543,6

Four sites have a score of 240 because they have the highest rank for all six ecological layers. The satelli
and a few are missing the highest rank for the FRID layer. One is missing mountain hemlock and another is miss

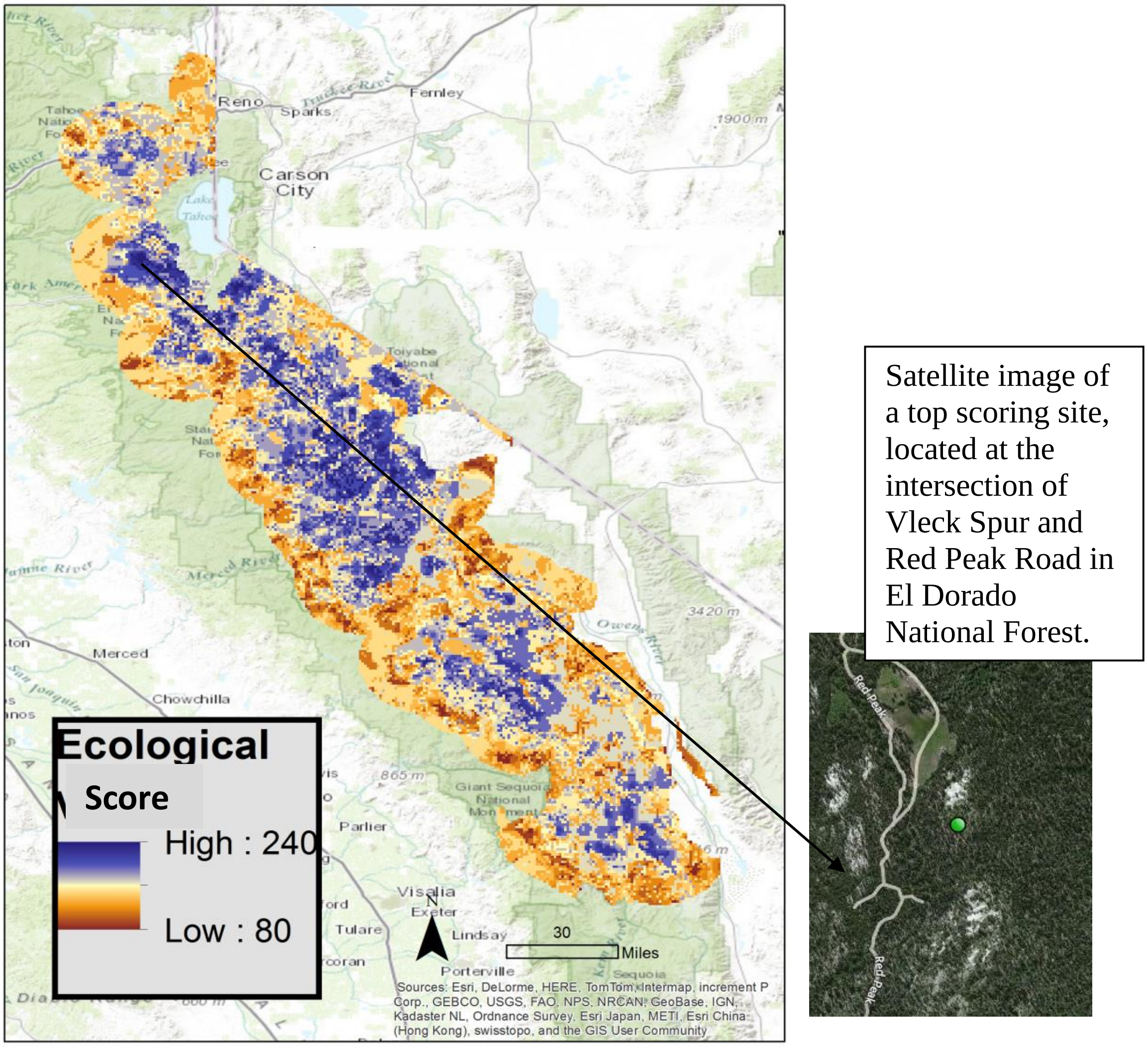


Figure 1.

Suitabiliy of areas for the Ecological Scenario. The warmer, redder colors represent a higher suitability and the colder, bluer colors rep

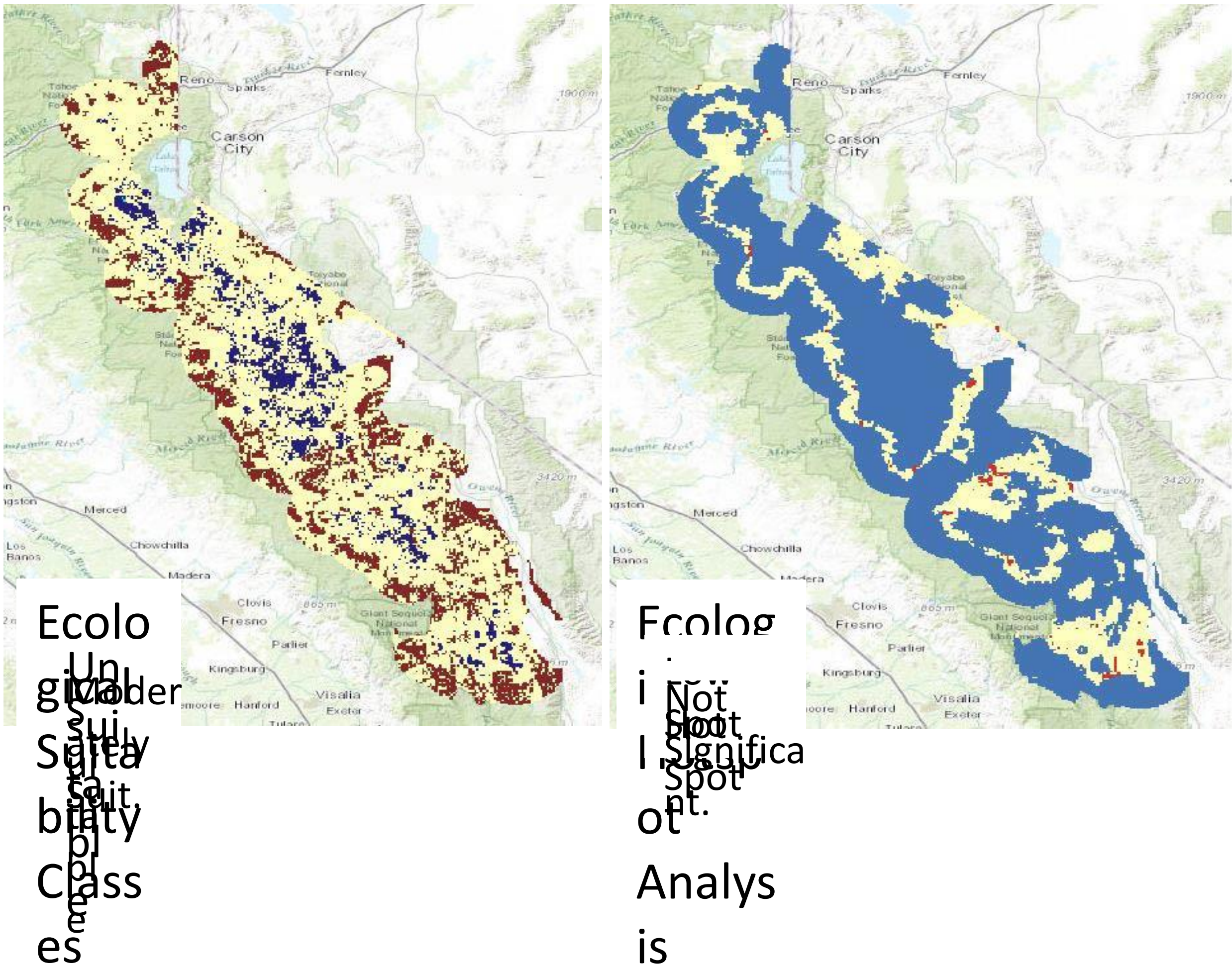


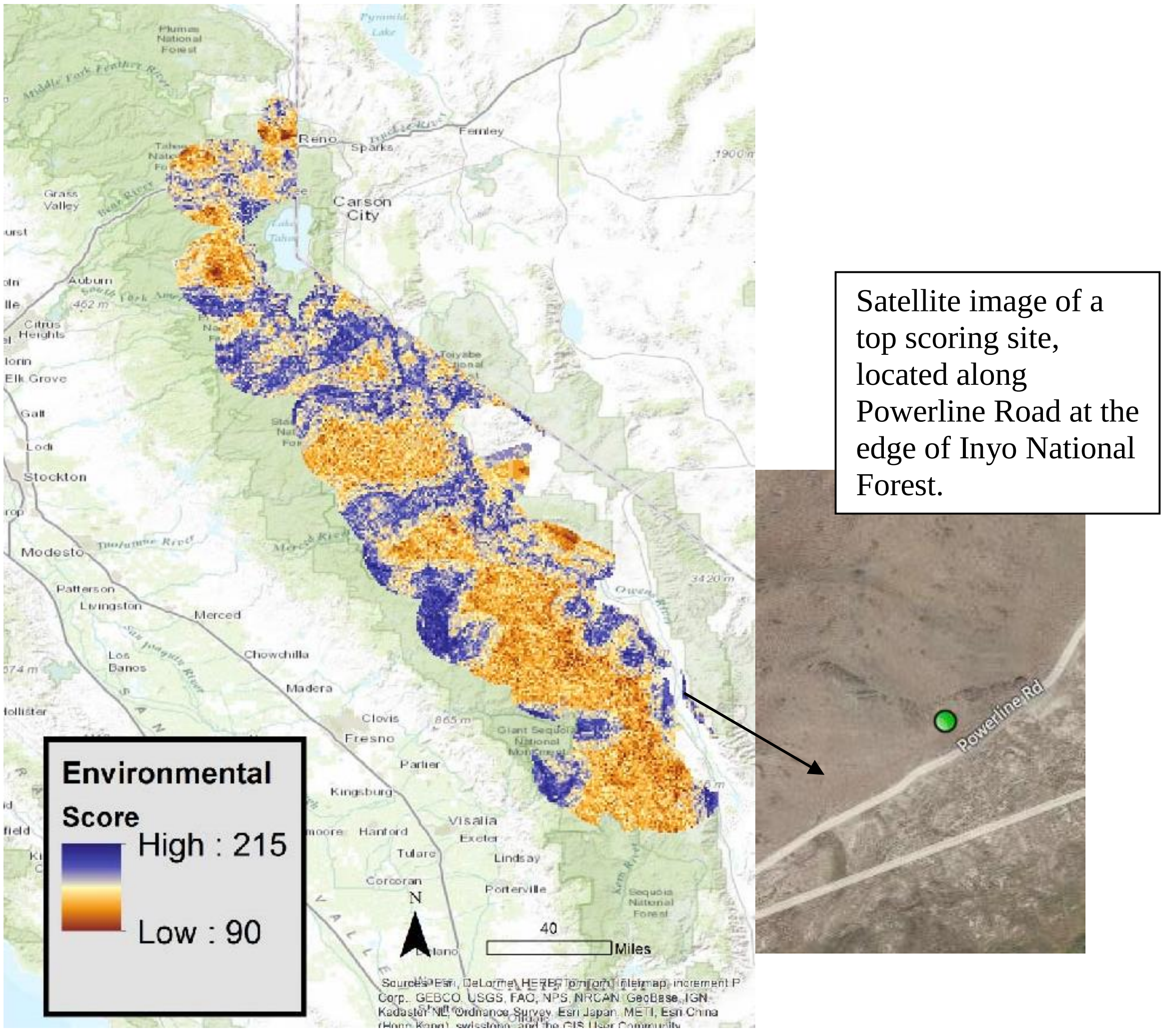
Figure 2.

The first map (left) is the Ecological Scenario classified into the 3 equal range categories, and (right) is the result of the hotspot analysi

Environmental map

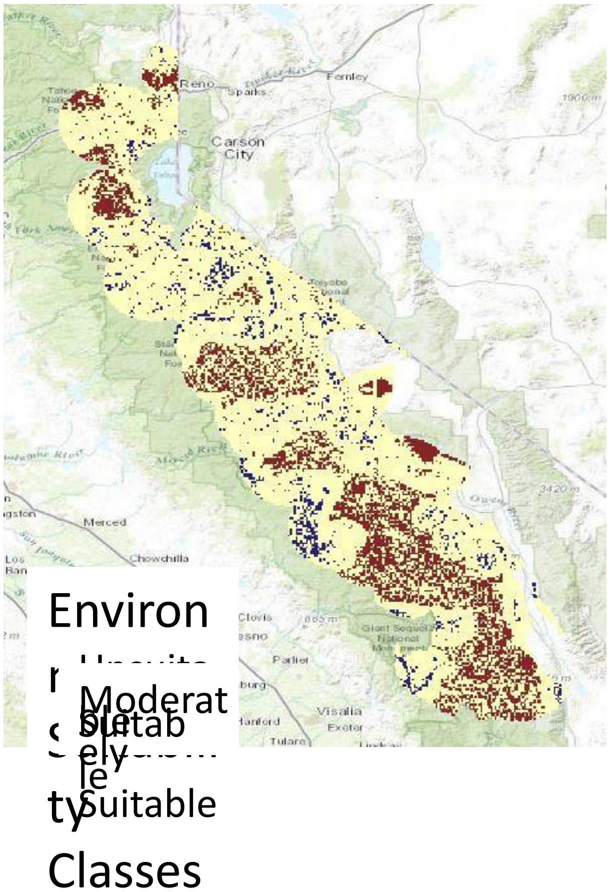
The Environmental Scenario had a possible range of 80 to 240, but actual scores ranged from 90 to 215 (unsuitable area, 4,186,664 acres of moderately suitable area, and 269,784 acres of suitable area. Suitable areas a mid to low latitude Sierra Nevadas.

None of the sites were ranked high for all six layers. Two sites scored 215, and were missing a combinat little purpose for land managers who have the objective of restoring whitebark pine. Eighteen other sites have a smaller and more isolated from each other (Figure 4). However, both types of clusters are less contiguous, espec



F**igure 3.**

Suitabiliy of areas for the Environmental Scenario. The warmer, redder colors represent a higher suitability and the colder, bluer colors



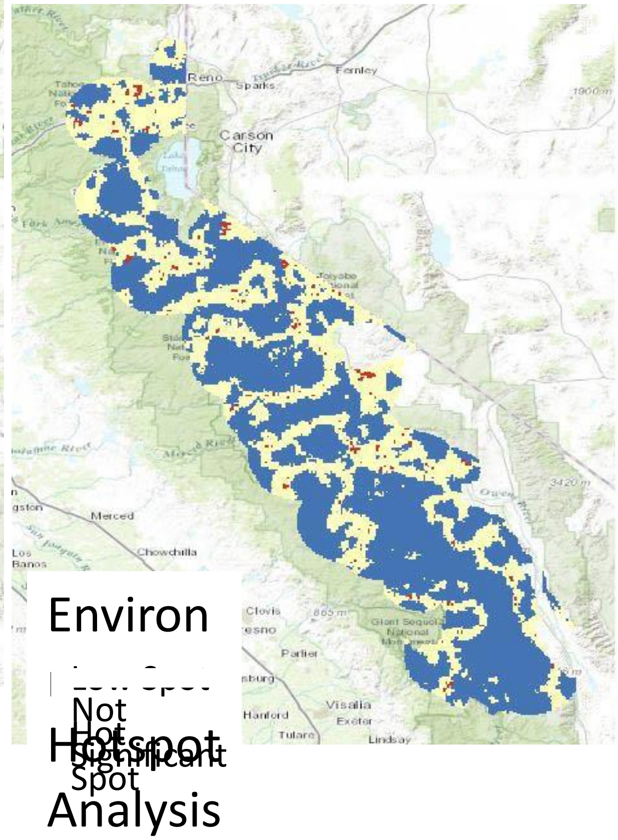


Figure 4.

The first map (left) is the Environmental Scenario classified into the 3 equal range categories, and (right) is the result of the hotspot ana

Composite final map

The Final Scenario had a possible range of 160 to 480, but actual scores ranged from 210 to 425 (Figure 5 6). These percentages equate to 476,712 acres of unsuitable area, 4,977,936 acres of moderately suitable area, an

The most suitable site received a score of 425 because it is not ranked highest in the temperature, FRID, sites in the Ecological and Environmental Scenarios. The one site that scored second highest at 420 and the nine developed land are positively attributed to all eleven high scoring sites. Compared to the other scenarios, the sig

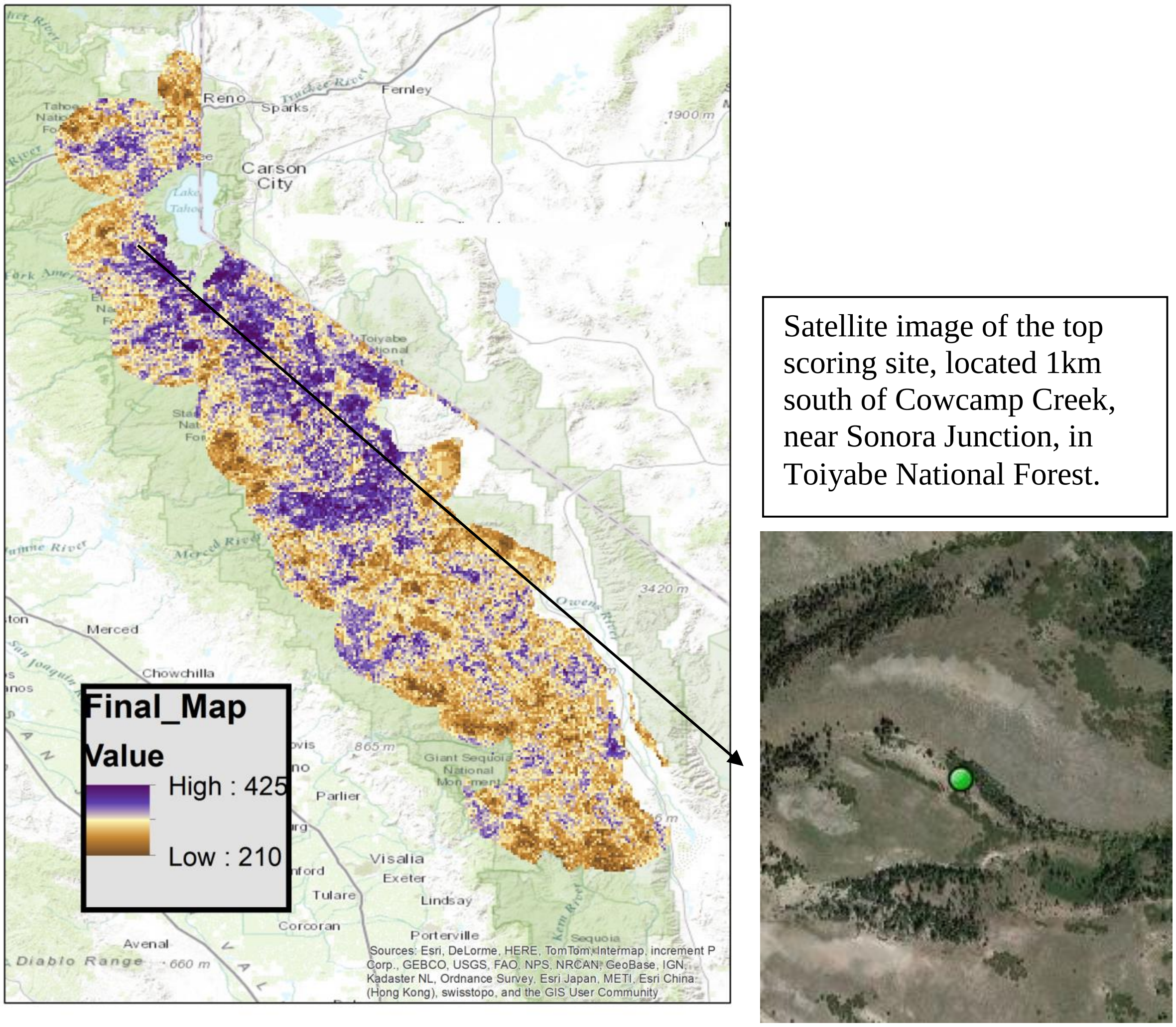


Figure 5.

Suitabiliy of areas for the Final Scenario. The warmer, redder colors represent a higher suitability and the colder, bluer colors represent

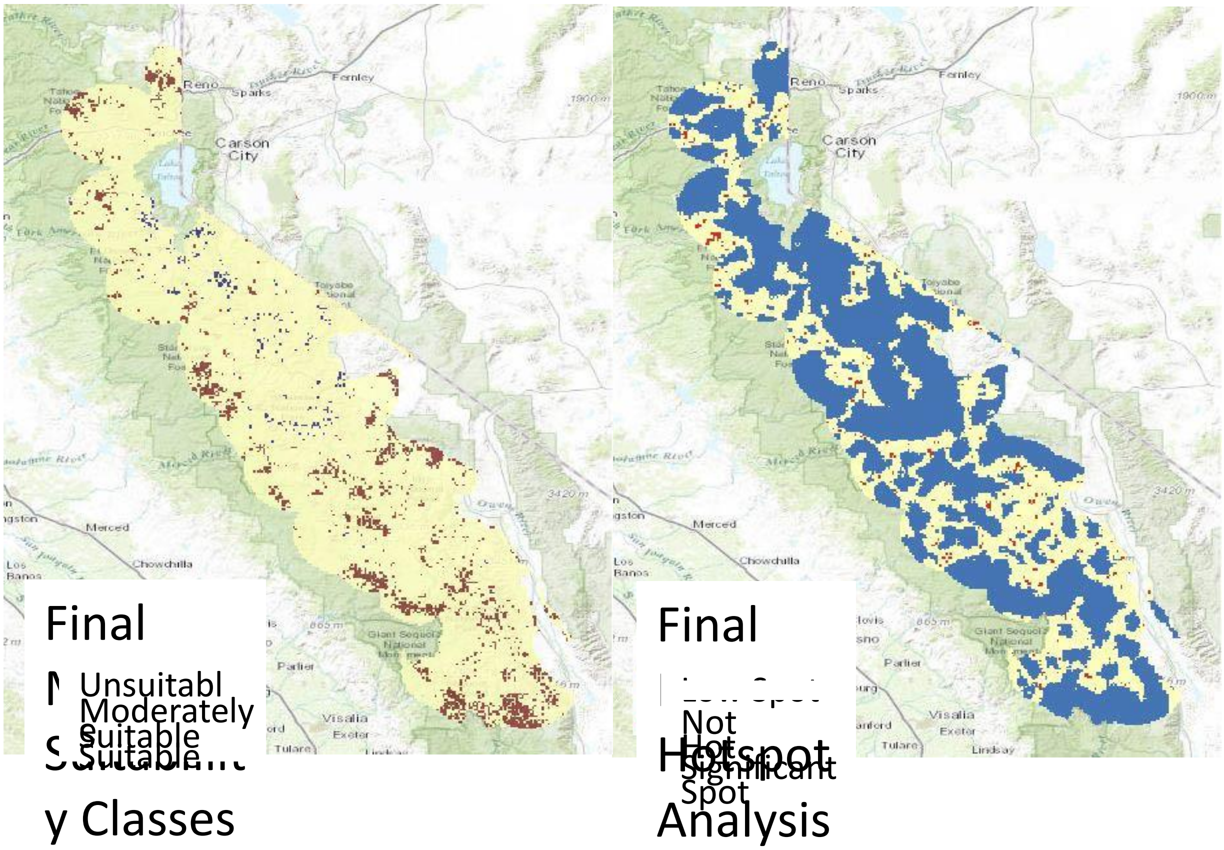


Figure 6.

The first map (left) is the Final Scenario classified into the 3 equal range categories, and (right) is the result of the hotspot analysis clas

Model Sensitivity

Each layer had a distinct distribution of high, medium, and low ranked sites (Appendix C). Layers with t were mountain hemlock (μ=1.19) and wind (μ=1.24). Mountain hemlock has a relatively small range compared

Although the barren land layer has a mean of 1.99, it is a constraint for many of the top suitable sites in b negatively correlated (-0.21) and FRID and barren land are negatively correlated (-0.134). Another reason why t ranks at higher elevations.

The lack of suitable locations to implement prescribed burning to restore whitebark pine is evident in th tended to also have fewer suitable environmental layers and vice versa. However, in the past, the entire Pacific S

The majority of the highly suitable locations in the final map are widespread in southeast El Dorado Nati the locations of suitable restoration sites, federal land managers can begin the process of planning prescribed bur

Scenarios

The two categorical scenarios have different spatial trends, suggesting that areas with highly ranked ecol whitebark pine stands occur, along with the other sub-alpine species mountain hemlock and lodgepole pine. This reached late successional stages. There were four sites that rank highest for all layers, which I consider perfectly to make tradeoffs, for example, between sites located away from barren land and sites with a high FRID Index. Pl of hot spots and cold spots also proves that the scores are not distributed randomly, signifying the model's succe

In contrast to the Ecological Scenario, the most suitable areas in the Environmental Scenario (Figure 2) inversely (Lookingbill et al. 2003, Hadley and Smith 1986). There are no sites that rank highest for all six factor Environmental Scenario and the Final Scenario allows for selection in more regions, but their smaller size is less

Because the ecological and practical layers are not in agreement, it is especially necessary for land mana management to make decisions about tradeoffs between factors like convenience, likelihood of whitebark pine Environmental Scenario will be less costly, more efficient, safer, and easier to burn (Biswell 1989).

Final suitability of whitebark pine distribution

Highly suitable areas were located mainly in the northern central Sierra Nevadas (Figure 6). This makes location that fulfilled all of the requirements, which is consistent with the findings of similar studies performed i (Tomback et al. 2001). In that study, even the stand that was found to be the top priority lacked two factors and r

The suitable areas are located within El Dorado, Toiyabe, and Stanislaus National Forests and Yosemite Each site will need to be looked at individually because in some cases where the fire prerequisites like slope, wi next generation is to plant rust resistance seedlings after a burn clears and area. However, this technique is more

Model sensitivity

The layers that were the most important to the map were barren land and temperature, due to their lack of al. 2001, Biswell 1989). Fortunately, some of these constraints can be relaxed. For example, even if a site is not a not include mountain hemlock should still be considered, because it is still necessary to open up late succession r

Slope and aspect had almost no influence on the model, given that they are evenly distributed across the l
of whitebark pine is primarily in wilderness lands (Taylor et al. 2014). Whitebark pine, lodgepole pine, and FRID
model, given its widespread distribution. This finding does not match the literature, which puts a larger emphasis

Unfortunately, I did not have access to a panel of land managers, who would directly influence the weigh
investigate prescribed burning restoration sites over whitebark pine's entire range in southern Canada, the Casca
similar species of concern, in which scientists have yet to identify of areas for restoration.

Limitations and future directions

Accuracy of some of the spatial data was limited to what I could freely access online or in print. There ar
introduced human error and ignored the changes in the distributions over time. To reduce these errors, the next
improve the accuracy of the FRID, fires that occurred after 2011 should be incorporated. For example, The Rim

To fine tune the model beyond including more up to date and accurate sources of data, other variables th
infection rates of MPB and WPBR. On a much smaller scale, the percent canopy cover is an important variable
interactions, geography, and land characteristics must be oversimplified. To address this problem, the next ste
characteristics of a suitable site (Hyypa et al. 2000).

Broader Implications

The results of this study are meant to influence decisions of park managers in order to conserve whitebark
burn (AEU Strategic Fire Plan). Planning should begin soon, while prescribed burning is still a viable option for
endangered species depends on actions taken now, in the Sierra Nevada Mountain Range.

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REFERENCES

Arno, S. 1996. The seminal role of fire in ecosystem management-impetus for this publication. Pages 3-5 *in* Hardy, Colin C.; Arno, Stephen F., editors. The use of fire in forest restoration. General Technical Report INT-GTR-341. USDA [United Stated Department of Agriculture] Forest Service, Intermountain Research Station. Ogden, UT, USA.

Arno, S., and R. Hoff. 1989. Silvics of whitebark pine (*Pinus albicaulis)*. USDA [United Stated Department of Agriculture] Forest Service. General Technical Report INT-253. Intermountain Research Station. Ogden, UT, USA.

Arno, S., and R. Hoff. 1990. *Pinus albicaulis* Engelm. whitebark pine. Pages 268-279 *in* USDA [United Stated Department of Agriculture] Forest Service. Silvics of North America. Vol. 1. Conifers. Agriculture Handbook 654. Washington, DC, USA.

Bartos, D. L., and K. E. Gibson. 1990. Insects of whitebark pine with emphasis on mountain pine beetle. Pages 171-178 *in* Schmidt, W., and McDonald, K., comps. Whitebark pine ecosystems: ecology and management of a high mountain resource: Proceedings-Symposium on Whitebark pine Ecosystems: Ecology and management of a high mountain resource. USDA [United Stated Department of Agriculture] Forest Service. General Technical Report INT-270. Intermountain Research Station. Ogden, UT, USA.

Bertness, M. D., and R. Callaway. 1994. Positive interactions in communities. Trends in Ecology & Evolution 9:191–193.

Biswell, H. H. 1989. Prescribed Burning in California Wildlands Vegetation Management. University of California Press. USDA[United Stated Department of Agriculture] Forest Service. General Technical Report RMRS-GTR-206. Fort Collins, CO, USA.

Burns, K. S., Schoettle, A. W., Jacobi, W. R., and M. F. Mahalovich. 2008. Options for the management of white pine blister rust in the Rocky Mountain region. USDA [United Stated Department of Agriculture] Forest Service. General Technical Report RMRS-GTR-206. Fort Collins, CO, USA.

Carroll, A., S. Taylor, J. Regniere, and L. Safranyik. 2003. Effect of climate change on range expansion by the mountain pine beetle in British Columbia. Pages 223-232 *in* T.L Shore et al., editors. Mountain Pine Beetle Symposium: Challenges and Solutions, Oct. 30-31, 2003. Kelowna BC. Natural Resources Canada, Information Report BC-X-399, Victoria.

Castello, J. D., D. J. Leopold, and P. J. Smallidge. 1995. Pathogens, patterns, and processes in forest ecosystems. BioScience 45:16–24.

Cleaves, D. A., J. Martinez, and T. K. Haines. 2000. Influences on prescribed burning activity and costs in the National Forest System. General Technical Report. USDA [United Stated Department of Agriculture] Forest Service, Southern Research Station. Asheviile, NC, USA.

Cole, W. E., and G. D. Amman. 1969. Mountain pine beetle infestations in relation to lodgepole pine diameters. USDA [United Stated Department of Agriculture] Forest Service, Intermountain Forest & Range Experiment Station. Ogden, UT, USA.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28:2031–2064.

Davis, F. W., D. M. Stoms, A. D. Hollander, K. A. Thomas, P. A. Stine, D. Odion, M. I. Borchert, J. H. Thorne, M. V. Gray, R. E. Walker, K. Warner, and J. Graae. 1998. The California Gap Analysis Project—Final Report. University of California, Santa Barbara, CA, USA. <http://legacy.biogeog.ucsb.edu/projects/gap/gap_rep.html>

ESRI 2011. ArcGIS Desktop: Release 10. Environmental Systems Research Institute. Redlands, CA, USA.

Griffin, J. R. and W. B. Critchfield. 1972. The distribution of forest trees in California. Res. Paper PSW-RP-82. USDA [United Stated Department of Agriculture], Forest Service. Pacific Southwest Forest and Range Experiment Station. Berkeley, CA, USA.

Hadley, J. L., and W. K. Smith. 1986. Wind Effects on Needles of Timberline Conifers: Seasonal Influence on Mortality. Ecology 67:12–19.

Hoff, R., and S. Hagle. 1990. Diseases of whitebark pine with special emphasis on white pine blister rust. General technical report INT (no. 270) p. 179-190.

Hyyppä, J., H. Hyyppä, M. Inkinen, M. Engdahl, S. Linko, and Y.-H. Zhu. 2000. Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. Forest Ecology and Management 128:109–120.

Keane, R. E. 2001. Can the Fire Dependent Whitebark Pine be Saved? Fire Management Today 60: 17-20.

Keane, R. E. and Arno, S. F. 1996. Whitebark Pine (Pinus albicaulis) Ecosystem Restoration in Western Montana. In: Arno, S.F.; Hardy, C.C., eds. The Use of Fire in Forest Restoration: A General Session at the Annual Meeting of the Society of Ecosystem Restoration, "Taking a Broader View"; 14–16 September 1996; Seattle, WA. Gen. Tech.

Keane, R. E., and R. A. Parsons. 2010a. Restoring whitebark pine forests of the Northern Rocky Mountains, USA. Ecological Restoration 28:56–70.

Keane, R. E., and R. A. Parsons. 2010b. Management guide to ecosystem restoration treatments: Whitebark pine forests of the northern Rocky Mountains, USA. USDA [United Stated Department of Agriculture] Forest Service. General Technical Report RMRS-GTR-232. Rocky Mountain Research Station, Ogden, Utah, USA.

Keane, R E., Tomback, D.F., Aubry, C.A., Bower, A.D., Campbell, E.M., Cripps, C.L., Jenkins, M.B., Mahalovich, M.F., Manning, M., McKinney, S.T., Murray, M.P., Perkins, D.L., Reinhart, D.P., Ryan, C., Schoettle, A.W., and C.M. Smith. 2012. A range-wide restoration strategy for whitebark pine (Pinus albicaulis). General Technical Report RMRS-GTR-279. USDA [United States Department of Agriculture] Forest Service. Rocky Mountain Research Station. Fort

Collins, CO, USA.

Lookingbill, T. R., and D. L. Urban. 2003. Spatial estimation of air temperature differences for landscape-scale studies in montane environments. Agricultural and Forest Meteorology 114:141–151.

Lorenz, T. J., K. A. Sullivan, A. V. Bakian, and C. A. Aubry. 2011. Cache-site selection in Clark's nutcracker (Nucifraga columbiana). Auk 128:237–247.

Maloney, P. E. 2011. Incidence and distribution of white pine blister rust in the high-elevation forests of California. Forest Pathology 41:308–316.

Malczewski, J. 2004. GIS-based land-use suitability analysis: a critical overview. Progress in Planning 62:3–65.

Means, J. E. 1990. Tsuga mertensiana (Bong.) Carr. Mountain hemlock. Silvics of North America 1: 623-631.

McCaughey, W. W. 1988. Determining what factors limit whitebark pine germination and seedling survival in high elevation subalpine forests. Unpublished paper, Study No. INT-4151-020, on file at: USDA [United Stated Department of Agriculture] Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, Bozeman, MT.

McCaughey, W. W. and W. C. Schmidt. 1990. Autecology of whitebark pine. Pages 85-96 in: Schmidt, Wyman C. and Kathy J. McDonald, compilers. Proceedings-symposium on whitebark pine ecosystems: ecology and management of a high-mountain resource. USDA [United Stated Department of Agriculture] Forest Service. Gen. Tech. Rep. INT-270. Ogden, UT, USA.

Peterson, D. L., M. J. Arbaugh, L. J. Robinson, and B. R. Derderian. 1990. Growth trends of Whitebark pine and lodgepole pine in a subalpine Sierra Nevada forest, California, U.S.A. Arctic and Alpine Research 22:233–243.

Peterman, R. M. 1978. The ecological role of mountain pine beetle in lodgepole pine forests. Pages 25-27 *in* Theory and practice of mountain pine beetle management in lodgepole pine forests. Pullman, WA, USA.

Poland, T. M., and D. G. McCullough. 2006. Emerald ash borer: invasion of the urban forest and the threat to North America's ash resource. Journal of Forestry 104:118–124.

Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. BioScience 58:501–517.

Samman, S., J. W. Schwandt, J. L. Wilson, and U. S. F. Service. 2003. Managing for healthy white pine ecosystems in the United States to reduce the impacts of white pine blister rust. USDA [United States Department of Agriculture] Forest Service. Missoula, MT, USA.

Siepielski, A. M., and C. W. Benkman. 2007. Extreme environmental variation sharpens selection that drives the evolution of a mutualism. Proceedings of the Royal Society B: Biological Sciences 274:1799–1805.

Taylor, S., Sikes, K., Kauffmann, M., and J. Evens. 2014. Whitebark pine pilot fieldwork report. Unpublished report. California Native Plant Society Vegetation Program, Sacramento, CA. 15 pp. plus Appendices.

Tomback, D. 1982. Dispersal of whitebark pine seeds by clark nutcracker - a mutualism hypothesis. Journal of Animal Ecology 51:451–467.

Tomback, D. F., S. F. Arno, and R. E. Keane. 2001. Whitebark pine communities: ecology and restoration. Island Press, Washington D.C., USA.

USFWS [United States Fish and Wildlife Service]. 2014. Whitebark pine. fws.gov/mountain-prairie/species/plants/whitebarkpine/

van Wagtendonk, J.W. 1995. Large fires in wilderness areas. In: Brown, J.K., Mutch, R.W., Spoon, C.W., Wakimoto, R.H. (Tech. Coord.). Proceedings of the Symposium on Fire in Wilderness and Park Management. USDA [United States Department of Agriculture] Forest Service. General Technical Report INT-GTR-320, pp. 113–116.

Veraverbeke, S., Hook, S., and R. Green. 2013. The rim fire in Yosemite, CA: opportunities for the HyspIRI prepatory airborne campaign. HyspIRI Science and Application Workshop, Pasadena, California, USA.

Wall, S. B. V., and J. W. Joyner. 1998. Secondary dispersal by the wind of winged pine seeds across the ground surface. American Midland Naturalist 139:365–373.

Waring, K. M., and D. L. Six. 2005. Distribution of bark beetle attacks after whitebark pine restoration treatments: a case study. Western Journal of Applied Forestry 20:110–116.

Wright, H. A., and A. W. Bailey. 1980. Fire ecology and prescribed burning in the Great Plains - a Research Review.60 pp.

APPENDIX A. Rank Classifications

Parameter	Rank	Source of Information
Whitebark pine (miles from)	1=>10, 2=2.1-10, 3=<2.1	Tomback et al. 2001, Lorenz 2011
Lodgepole Pine (km from)	1=0, 2=<1, 3=>1	Peterson et al. 1990, Wall and Joyner 1998
Mountain Hemlock (km from)	1=0, 2=<1, 3=>1	Arno and Hoff 1989, Means 1990
Clark's Nutcracker	1=0-1, 2=2-3, 3=4-5	Tomback 1982
Temperature (^{o}F)	1=<35, 2=35-70, 3=70-90	Wright and Bailey 1980
Wind (wind power class)	1=1&7, 2=2&6, 3=3&4&5	Biswell 1989
Developed Land (miles from)	1=0, 2=<1.5, 3=>1.5	Mc McCaughey 1988
Barren Land (miles from)	1=0, 2=<1.5, 3=>1.5	Joe McBride, McCaughey and Schmidt 1990
Slope (%)	1=0-4&>45, 2=5-14&30-44, 3=15-30	Biswell 1989
Aspect (^{o})	1=0-44&315-360, 2=45-134&225-314, 3=135-224	Biswell 1989
Distance to Roads (miles from)	1=>10, 2=5-10, 3=<5	Tomback et al. 2001
Fire Return Interval Departure (NPS Index)	1=low, 2=moderate, 3=-999	Tomback et al. 2001, Tim Kline

APPENDIX B:Examples of field calculator and raster calculator verbatim scripts.

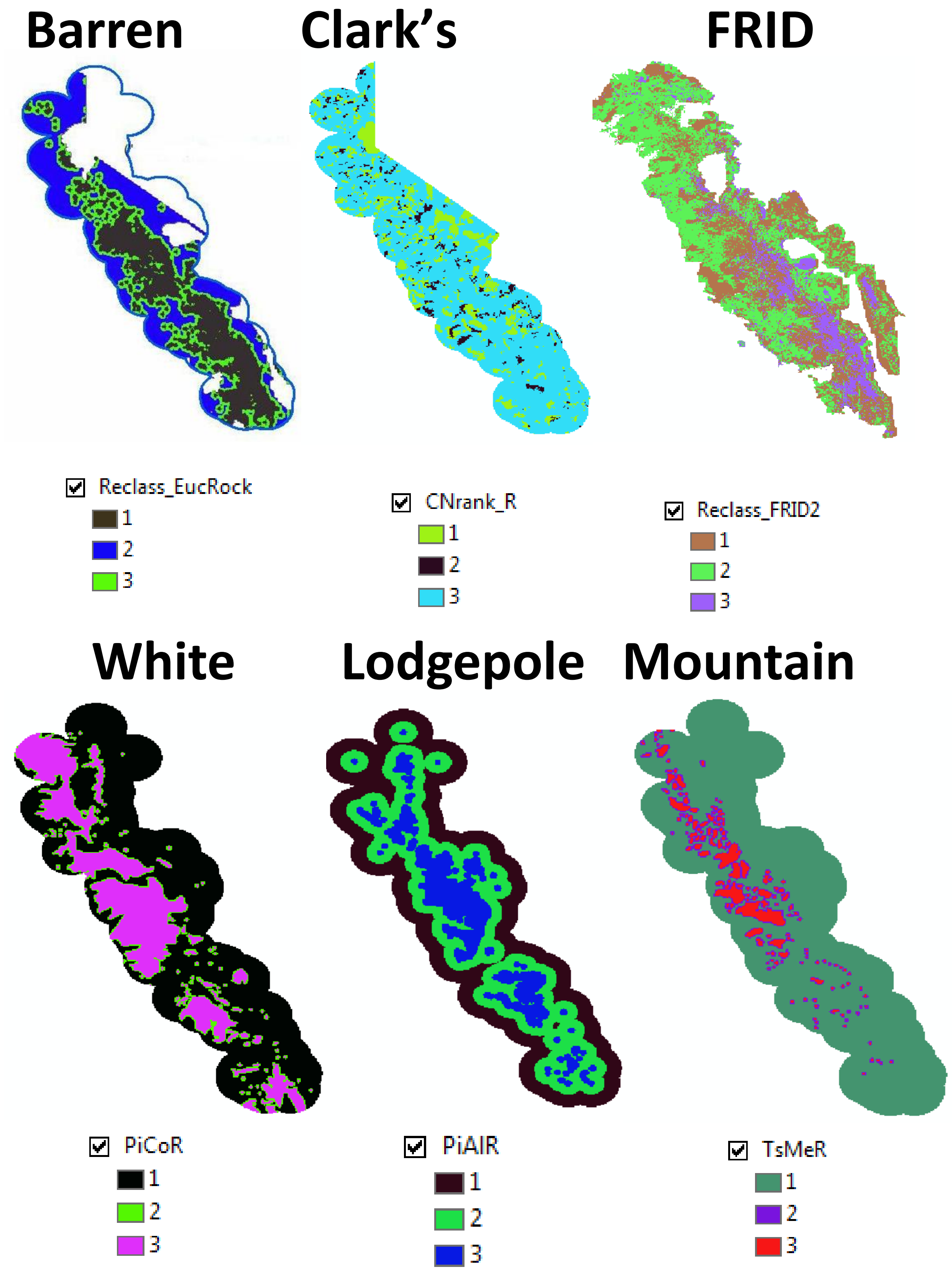
For ranking slope, where “Value” is % and the rank field is “f2”:

```
dim f2
if [Value] > 14 AND [Value] < 31 then
f2 = 3
end if
if [Value] > 4 AND [Value] < 16 then
f2 = 2
end if
if [Value] > 29 AND [Value] < 46 then
f2 = 2
end if
if [Value] > -1 AND [Value] < 6 then
f2 = 1
end if
if [Value] > 44 then
f2 = 1
end if
```

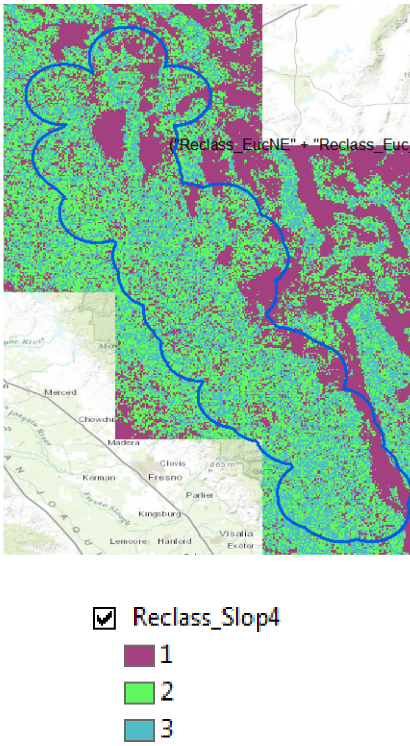
For calculating the final map where each layer is multiplied by its weight and added together:

```
"Reclass_EucNE" * 15 + "Reclass_Euc_SW" * 15 + "Euc_R" * 15 + "Reclass_EucN1" * 15 +
"PRISM_tmean_R" * 15 + "n40w121aspint_R" * 10 + "n40w120aspint_R" * 10 +
"n39w121aspint_R" * 10 + "n39w120aspint_R" * 10 + "n39w119aspint_R" * 10 +
"n38w120aspint_R" * 10 + "n37w119aspint_R" * 10 + "n38w119aspint_R" * 10 +
"n37w119slint_R1.tif" * 10 + "n38w119slint_R1.tif" * 10 + "n38w120slint_R1.tif" * 10 +
"n39w119slint_R1.tif" * 10 + "n39w120slint_R1.tif" * 10 + "n39w121slint_R1.tif" * 10 +
"n40w120slint_R1.tif" * 10 + "n40w121slint_R1.tif" * 10 + "windrank_R" * 10 + "roads_R" *
20
```

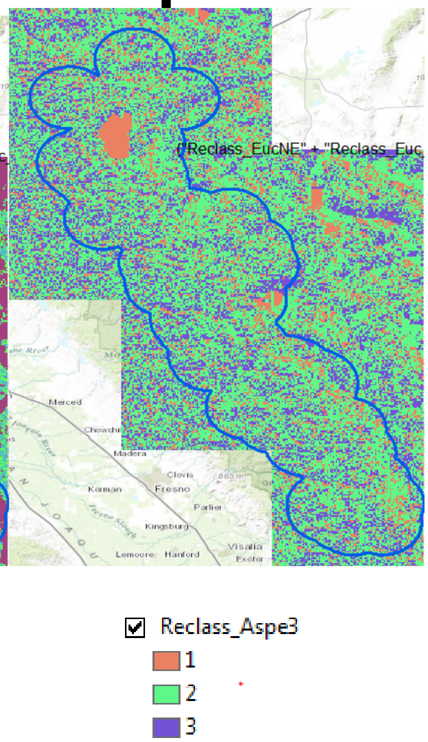
APPENDI C. GIS Layers



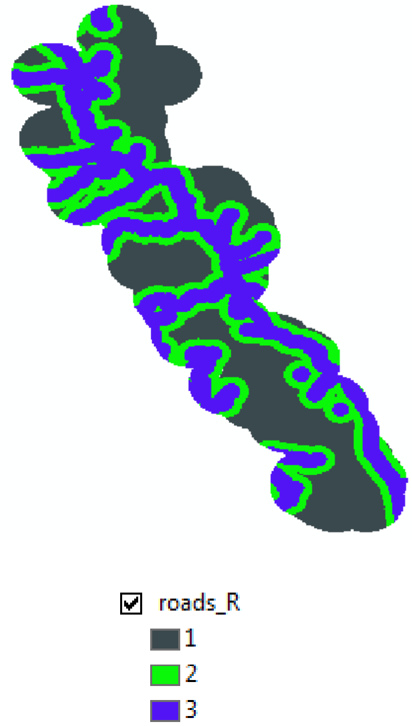
Slope



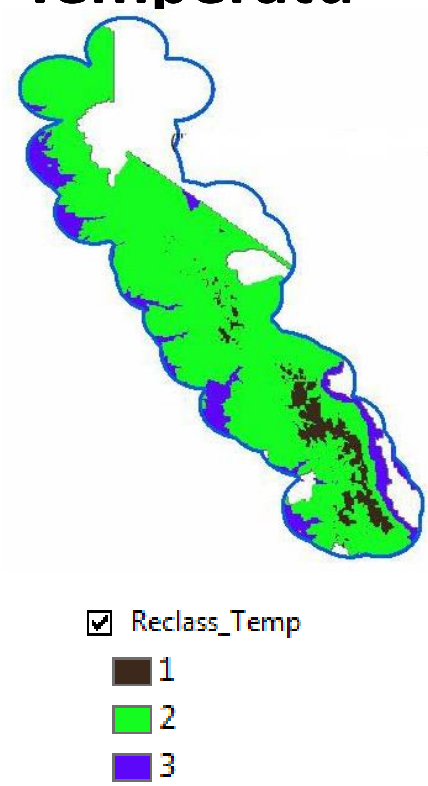
Aspect



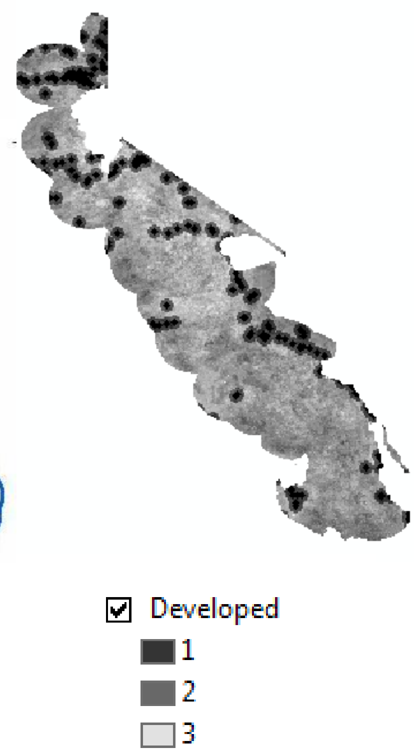
Roads



Temperatu



Developed



Wind