Monterey Pine Conservation Considering Various Future Climate Change Scenarios

University of California, Los Angeles
Geography 178
Instructor: Dr. Glen MacDonald
Emma Gobbell, Alexis Hatalski, Dexter Robinson,
Sophia Speckhahn, Olivia Toledo
December 11th, 2023

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Monterey Pine (*Pinus radiata)* is a vital species native to the California coast, with a history of Indigenous cultural relevance, economic status as a current tourist attraction, and a significant ecological role. In the face of anthropogenic climate change, it is necessary to evaluate the way the conditions ideal for the species will change. The conservation of *Pinus radiata* depends on a multi-pronged research strategy, melding a strong understanding of the ecology and climatology of the tree's habitat with accurate estimations of the climactic threats it will face under different climate change scenarios in the future. To that end, we have combined literature reviews of ecological research and forest management strategies with spatial analysis methods including Maxent analysis, NDVI analysis, and terrain analysis.

We had several key findings, one being that the Monterey Pine is fog-dependent and, therefore, very vulnerable to predicted climate change scenarios with increased temperatures and variable precipitation. The future suitable habitat, based on 19 bioclimatic variables, is expected to recede from the southernmost distribution near the Cambria stand. The NDVI analysis found that the species is more resilient to historical drought than hypothesized.

Key management strategies include quasi in-situ plantings, controlled burnings, local monitoring, and assisted migration. Our plan for planting new stands integrates suitability from a climate perspective as well as from the analysis of the pine's native terrain in the Cambria stand, with a focus on locating coastal and north-facing aspects in fog-laden territory.

ACKNOWLEDGMENTS

Our team EcoLogic would like to thank Dr. Glen MacDonald, Zoe Malot, and Ben Nauman for supporting our research and contributing valuable feedback throughout our process. We would also like to thank the staff from White Mountain Research Center, Camp Ocean Pines, and K.S.N. Rancho Marino Reserve, for making our research and learning experience possible. Lastly, we thank the UCLA Geography Department for its continued support for Geography 178.

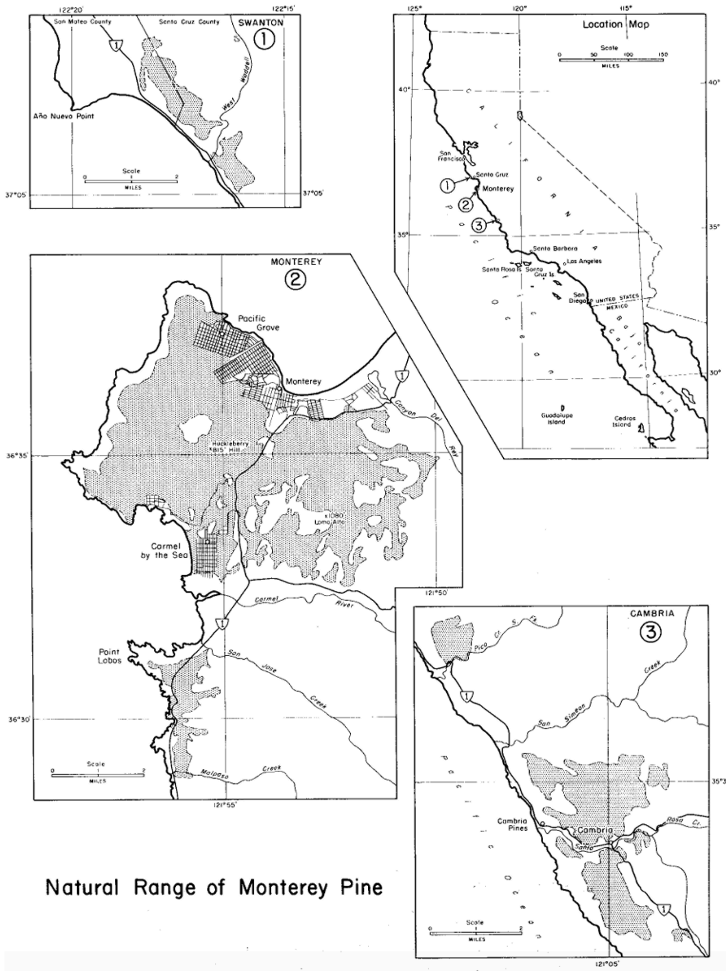

Figure 1. The natural range of the Monterey Pine (Roy, 1966).

INTRODUCTION

The Monterey pine, *Pinus radiata*, is an evergreen pine and is part of the closed cone pine group, as its cones only open from fires or extreme heat conditions (Roy 1966; Stephens et. al., 2004). This species is relatively short-lived and only lives to a maximum of 150 years. As seen in their range map in Figure 1, they are solely isolated to coastal populations in Año Nuevo, the Monterey Peninsula, Cambria, and two islands off the coast of Baja California. An important climatic factor that connects all of these locations is the consistent fog that supplies them with a constant water supply, especially during the summertime. This pine occurs in areas with a moderate climate, without long frost periods or extreme heat. *P. radiata* is considered endangered in its native range, and while it is a protected species, it is under threat from urbanization as well as climate-related factors (Millar, 1998). The main species that co-occurs with the endemic Monterey pines is the coast live oak, *Quercus agrifolia*, which is confined to the understory, as well as the bishop pine, *Pinus muricata*, and other various California chaparral shrubs and bushes that are spread throughout the understory.

The Monterey Pine's range extends along the Central Coast of California, a region characterized by its variety of ecosystems and its foggy weather. The general climate along the central coast is largely influenced by the Santa Lucia Mountain range. These mountains create a wall behind the coastal hillsides that are able to trap humid and cool air traveling inland from the neighboring Pacific Ocean. This impacts factors such as temperature and humidity by creating a more moderate climate. The landscape of the central coast relies upon the formation of this humid air which lowers air temperatures and provides water to the existing vegetation (Langridge et al., 2018).

The Monterey pine is also of great cultural, historical, and economic value to California. In precolonial times, the Salinan and Ohlone peoples used it as a source of food, weaving material, and medicine. Today, it is one of California's most iconic trees and a symbol for the central coast communities in which it is found, which see significant tourism in part from the relative rarity and the unique appearance of the Monterey pine. However, its economic importance exceeds the boundaries of California. The Monterey pine is one of the most important trees in the global timber and paper industries. Monterey pine plantations are found on at least five continents, in countries as far-flung as Spain, Chile, New Zealand, South Africa, and Australia. As of 2004, over 10 million acres were dedicated to its cultivation (Rogers, 2004). The health of the native stands, with their broader genetic diversity, is crucial to protect artificial stands around the globe and bolster their resilience in the face of ecological threats, including climate change and pathogens.

In order to evaluate the current and future relationship of the Monterey Pine to climatic conditions, this study utilized methodical reviews of ecological literature as well as various conservation strategy approaches. NDVI analysis, Maxent modeling, and terrain analysis methods were used to visualize spatial information and changes in the species distribution under different climate scenarios.

The paper begins by discussing the relevant ecological information about the Monterey Pine as well as its evolution and current adaptations to threats. The ecological implications relating to these threats are also discussed. The next section discusses the vulnerability of the species to climate change. The general climatic trends occurring in the range of the Monterey are first discussed. The methodology and implications surrounding the various analyses performed then follow. Lastly, suggested climate change adaptation strategies and management recommendations conclude the report.

Overall, this report intends to address multiple questions. The ecology section addresses what threats the Monterey Pine faces as well as how the species responds to past and current ecological, anthropogenic, and climatic threats. The climate section addresses how climate change impacts the current and future distributions of the Monterey Pine. This section also addresses how drought and differences in terrain impact the species' vulnerability and capacity to withstand changes in climate. The last section addresses what management practices and conservation strategies are most appropriate for protecting the species.

ECOLOGY OF PINE AND HABITAT

A key factor that controls the growth and range of the Monterey Pine is a consistent year-round water supply. This can only be achieved through fog drip water dripping off needles from fog onto the ground), because the annual seasonal droughts that occur in our Mediterranean climate provide irregular and seasonal precipitation. There is a significant isotopic difference between fog water and rainwater, which allowed studies to look into the importance of fog as opposed to precipitation in populations of closed cone conifers (Fischer et. al., 2016). Increased levels of fog increase growth rates, and influence stand dynamics. There is a proven ecosystem sensitivity to fog with these trees and other closed cone conifers, with many studies on fog done on Bishop and Torrey pines (Williams et. al., 2008; Fischer et. al., 2016; Fischer et. al., 2009). There was also an associated sensitivity to soil temperature, soil type, and slope aspect on which the trees were growing; the importance of terrain and its relation to fog exposure will be explained more in-depth in our terrain analysis (Sawaske & Freyberg, 2015). In Cambria, California's southernmost native stand of the Monterey Pine, the trees grow on well-draining sandy loamy soils derived from limestones, sandstones, cherts, and slates. In addition to the moisture gathered from the fog belt, the soil provides a robust reservoir of moisture and nutrients due to an underlying clay layer that stores winter rainfall, as well as acidic pH that promotes moisture-gathering mycorrhizae to grow on the pine's roots. Their geographic range is coastal and constricted to northern aspects where there is concentrated fog exposure blowing in from the Pacific, gentle to moderately sloping terrain, and elevations from sea level to around 1000 feet (McDonald, P., and Laacke, R., 2018).

While there is no consensus on the exact drivers of pitch canker, cure, or proper management, there is some proposed research based on the ecology of the pines. For one, pitch canker is known to outbreak following drought stress. It is also known that there are varying degrees of infections to pitch canker, which suggests some trees may be more resistant than others. Storer et. al. (1999) suggests that the higher genetic diversity in native stands compared to planted stands brought a better resistance to the pathogen. This study concludes by suggesting that introducing controlled burns in native stands could potentially increase resistance to pitch canker by killing off the more susceptible and weaker trees, but more research needs to be done to fully understand it.

There have been no major fires in the native Cambria stand in over 100 years, making it hard to observe natural fire regimes with modern data collection. However, there was a fire in Monterey in 1987, which is currently regenerating with Monterey Pines, so we can see the effects of fire in a native stand with this case study. Following mass settler colonization in the 1800s, the frequency of fire from lightning decreased from the baseline of 30-135 years to 215 years due to fire suppression. This has caused a build-up of over-mature trees, and underbrush, which has various negative consequences (O'Brien et. al., 2007). With climate change, we expect to see an increase in the frequency and intensity of fires, but it is impossible to predict just when a devastating fire will occur in any of the 3 native Californian stands (Looney et. al., 2023).

When looking at the fossil footprint, the Monterey pine has been proposed to have acted as a metapopulation as opposed to isolated fragmented populations (Millar, 2000). Because of the changing patterns of fossil locations, correlations with climate fluctuations, and patterns of genetic variation, it is said that Monterey pines have long maintained a dynamic metapopulation structure, implying cycles of colonization and extinction. This means that many areas on the California coast could be considered historically native ranges, and could encourage the conservation and planting of the pine in these areas as opposed to only encouraging the current native stands. However, because of the known difficulty in confirming metapopulation dynamics, this theory remains to be fully tested and confirmed with additional studies, but this does seem like an area of research that could benefit the future conservation of these important pines.

When looking at future climate trends, we know we will see wetting and an increase in temperature, however, we also know there will be large variability in these in the future climate, and the effects of this will need to be monitored closely with the Monterey Pines, as we know they have a sensitive ecosystem to climatic changes. We also know that drought affects the health of Monterey pines, as it is closely tied to pitch canker stress (Reynolds et. al., 2019). From the implications of an increase in the intensity and frequency of fires, proper underbrush management and the study of controlled burns is an important area of research to conserve these stands. There also needs to be continued close monitoring of the coast live oaks, which have the potential to become the dominant tree in these stands if the combination of these stressors proves to be too much for the Pines (O’Brien et. al., 2007).

CLIMATE CHANGE VULNERABILITY

Potential Climate Changes by 2100 in Current Geographic Area of Species

In order to analyze Pinus radiata’s response to future climate conditions, understanding the specific climatic changes that will be occurring in the current geographic area of the species is crucial. Since the Monterey Pine is restricted to areas where fog formation occurs along the coast, climate change poses an especially large threat, impacting a species with an already restricted range.

The maximum temperatures are predicted to increase significantly across California. The most severe climate models project that the average annual maximum temperature is expected to increase by around seven to eight degrees Fahrenheit by 2100 when compared to current temperatures within the five central coast counties. For example, the average annual maximum temperature in Monterey County is expected to rise from 72.4 degrees Fahrenheit during the years 2010-2039 to 77.5 degrees Fahrenheit during the 2070-2099 range (Langridge et al., 2018).

Minimum temperatures are also expected to rise by the end of the century. Based on the same climate model, increases of up to four to five degrees are projected by the middle of the century, and increases of up to seven to eight degrees are expected by the end of the century across the central coast region. San Luis Obispo County should expect to see a rise from 44.8 to 49.8 degrees in annual average minimum temperature (Langridge et al., 2018).

One of the most significant changes that is predicted to occur surrounds changes in temperature extremes. When looking at historical as well as future data, clear increases in the average number of days with extreme maximum temperatures are present. The average number of extremely hot days across all coastal counties remained around 4.3 days based on data from 1961-1990, whereas projected data for the 2070-2099 range predicts up to 50 extreme days (Langridge et al., 2018). This has rather large implications for the growing season and future stress tolerance of the Monterey Pine.

Another major factor influencing the survival of Pinus radiata is precipitation which is generally expected to increase, displaying changes in variability as well as overall amount. Across California, increased year-to-year variability is expected to become more pronounced, with wetter days occurring during high precipitation periods and fewer overall days with precipitation occurring. The interaction between hotter temperatures and wetter conditions may result in potential severe flooding as well as periods of drier conditions and water stress, meaning vegetation must adjust to heightened climatic variability. By 2100, wetter conditions are projected across the state, and when looking specifically at the Central Coast, the northern and more mountainous regions are expected to receive the largest increases in precipitation. Southern and more inland areas are expected to have smaller increases. Historical data shows that annual average precipitation varied between 16.1 inches to 37.2 inches. In contrast, averages of up to 47 inches are projected by the end of the century. Under severe climate models, overall increases of three to ten inches are forecasted for the future along the Central Coast (Langridge et al., 2018).

As previously mentioned, fog is a major determining factor in the survival of the Monterey Pine, which is one of the hardest climatic conditions to predict. Fog serves a very important function for the species in foggy regions that are adapted to rely upon fog for their water source. In fact, up to a third of the overall water this region receives is provided by fog. Therefore, fog provides many benefits including reducing evapotranspiration among plants, cooling the overall temperature of the land, and decreasing water demand. In lower elevation areas that are subject to summer winds coming from the northwest, fog may be present for an average of fifteen hours a day. Fog formation is dependent upon multiple large-scale processes including the location of the North Pacific atmospheric high-pressure zone that creates the necessary temperature inversion for fog to form (Langridge et al., 2018).

Studies surrounding the future of fog have come to different conclusions. Dorman (2017) found that fog formation varied depending on land or ocean formation. The study concluded that there would be an expected increase in the fog that forms over the ocean and a decrease in the fog that forms over land. O'Brien et al. (2013) modeled fog conditions and predicted an overall decrease in fog by twelve to twenty percent by the 2070 marker. Due to difficulties in simulating complex atmospheric and oceanic processes such as coastal upwelling and shifts in high-pressure zones, the future of fog is fairly unknown, implying challenges for projected Pinus radiata distributions (Langridge et al., 2018).

Maxent Modeling

In order to assess the future distribution of Pinus radiata and the species' response to climate change, a technique known as Maxent maximum entropy modeling was utilized. This analysis created an output displaying a probability distribution where each grid cell represents the "predicted suitability of conditions for the species" (Phillips, 2009). Thus, based on the results, the probability of the presence of the Monterey Pine can be estimated across a geographic region solely based on different sets of climatic conditions.

Since the range of the Monterey Pine is restricted to areas where fog formation is possible, only California counties located near the coastline were selected to use as the geographic extent of the analysis. The citizen science app known as iNaturalist was used as the data source for the Pinus radiata observation points. Research-quality sample points located in California were queried to create a more realistic and representative output which can be seen in Figure 2. The climatic data layers were derived from WorldClim and include a wide variety of nineteen separate bioclimatic variables. These bioclimatic variables measure specific climatic averages for historical as well as future conditions such as the mean diurnal range as well as the annual temperature range. Variations based on seasonality are also taken into account by including variables like the mean temperature of the coldest quarter as well as the precipitation in the wettest month. By utilizing both historical as well future data sets, the Monterey Pine's vulnerability and capacity to adapt to differences in climatic conditions can be gauged. The current data set contains bioclimatic averages from 1970 to 2000, and the future data sets contain the averages of the same bioclimatic variables from 2041-2060 and 2081-2100 based on the CMCC-ESM2 global climate model. These time ranges were selected since they contain both the mid and end-of-century climate markers.

Multiple different climate severity models were selected to project future distributions during those two time periods based on variations in the amount of greenhouse gas emissions. The first scenario SSP3-7.0 is a more moderate scenario that lies in between the least and most severe scenarios. SSP8-5.0 represents the "business as usual" scenario that would occur if no steps toward more renewable energy were taken and, therefore, represents the worst-case scenario (Hausfather, 2019).

A total of five Maxent outputs were generated in this analysis. Figures 3, 4, and 5 show the outputs from the current period (1970-2000) and two future periods (2041-2060 and 2081-2100) using the SSP3-7.0 scenario. The most drastic shifts and contractions are shown between the mid-century estimates and the end-of-century estimates. There are major decreases in suitability scores along some portions of the northern coast as well as major shrinkages in suitable ranges along the southern coastline. Overall, decreases in suitability scores in the current stand locations are projected, with the most severe changes in climate conditions occurring in the region surrounding the Cambria stand which follows the usual ecological trend of northward range expansion. These results indicate significant changes in suitable climate conditions by the

2100 marker, meaning there is more time for climate action to be taken in the latter half of the century.

Figures 6 and 7 show the change in suitability scores between the current and projected data for the 2041-2060 range under both types of scenarios. Lighter-colored pixels (negative values) correlate to improvements in suitability and darker-colored pixels (positive values) correlate to declines in suitability scores. Both maps show great variation in differences with the largest decreases in scores present along a significant portion of the northern coastline, meaning a major contraction of possible reforesting locations. Año Nuevo and Cambria stands were most negatively affected by future climate conditions since large decreases also occurred along slim portions of the southern coastline and large areas along the central coast. However, there are some regions of the very northern coasts as well as some portions of the Monterey area that showed improvements in climatic conditions.

Figures 8, 9, and 10 display the outputs from the current period (1970-2000) again and two future periods (2041-2060 and 2081-2100) using the severe SSP8-5.0 scenario. These graphs show similar contractions in range, but there are major differences between when the decrease occurs. Since this is a more severe climate scenario, major contractions in range occur between the current period and the mid-century marker. More aggressive conservation strategies must be employed in this case since climatic conditions are expected to more drastically change earlier on in the century. Both the 2081-2100 graphs of both scenarios show similar final results, indicating severe climate changes in Pinus radiata's possible range regardless of the severity of greenhouse gas emissions. Current stand locations including the Año Nuevo and Cambria stands once again decrease in suitability score indicating that the species will be forced into a smaller range and will have to migrate to new locations under this scenario as well. This mainly applies to the Cambria stand due to its very southern location.

Figures 11 and 12 also show the changes in suitability scores between the current and projected data for the 2081-2100 range under both scenarios. These maps show possible improvements in some of the Monterey region as well as north of the Año Nuevo stand. Once again, the largest decrease occurs along the central coastal regions and the southern coastlines where many of the current samples reside.

Overall, these simulations predict range contractions and general northward shifts, demonstrating how the species will have to adapt through migration. Alas, since global climate models are unable to accurately model fog, they are not complete predictions. Bioclimatic variables do provide a unique and thorough set of variables that affect the formation and duration of fog, but it should be noted that some weather conditions are still unpredictable.

While running the Maxent model, a jackknife analysis was also performed which evaluated the proportion that each layer contributed to the overall analysis. A consistent pattern was evident across all analyses which showed the same factors contributing the most to the range predictions. Figure 13 displays the output jackknife of the current (1970-2000) data set. These results indicate that the mean diurnal range and the temperature annual range have a large impact on the future of suitable climate conditions for the Monterey Pine. Additionally, the annual mean temperature is the environmental variable that decreases the gain the most when not present. This variable is the most different from the others making it a significant one to study.

NDVI

Due to the concern about future drought, we performed a 30-year analysis of spatial and vegetation health changes of *Pinus radiata* in the Cambria forest stand. We were able to estimate the decrease in size of the forest stand over the past 30 years using change detection of multispectral images collected by NASA's Landsat satellite series from 1990-2022. Our findings estimate that since 1990, the size of the Cambria stand of *Pinus radiata* decreased by ~8 km^2. Decreased stand size corresponds to a change in land use and lost trees. The previously forested area appeared to be most predominantly replaced with developed land. The normalized difference vegetation index (NDVI) was calculated using the near-infrared bands of the same series of images. The NDVI values range from -1 to 1, with higher values indicative of healthier plants. The NDVI analysis (figure 14) demonstrated that the overall vegetative health of the stand did not decrease over the past 30 years, and remained moderately consistent. Specifically, there was no decrease correlated with below-average rainfall, in fact, there was a slight increase following the drought. This implies that the health of *pinus radiata* is not significantly affected by drought since the coastal fog belt provides sufficient moisture.

Terrain

To further understand the vulnerability and adaptive capacity of Pinus radiata in the future climate scenarios modeled with Maxent, we conducted a terrain analysis of the current distribution of trees. This analysis provides data on the terrain conditions that are ideal for *Pinus radiata*'s potential growth in future locations as the climate changes. Using ArcGIS Pro, terrain factors such as slope, elevation, aspect, and solar insolation per pixel were evaluated in the Cambria stand. A digital elevation model was clipped using Extract by Mask to the study area. Using the extracted DEM, hillshade rasters were produced for seasonal constants of incoming solar radiation, as well as an average hillshade raster to represent annual insolation. Slope and aspect were also calculated. Statistics were generated for all categorical variables.

This terrain analysis yielded insights into the optimal growing conditions of the Monterey Pine in the categories of elevation, insolation, slope, and aspect. For elevation, 100% of the area lies within the optimal growing range of sea level to 1000 feet (Mcdonald, P., & Laacke, R. J. (2018) (Figure 15). A majority of the area (~73%) had insolation values slightly above the yearly average for the nearby city of Morro Bay (values above 232.6 W/m^2), but still within yearly highs for Morro Bay (Solar Energy Local) (Figure 16). A significant majority of the area has gentle to moderate slopes (using a conservative classification of >20% as steep, 80% of the terrain is gentle or moderately sloping), which is *Pinus radiata*'s optimal range for growth (McDonald, P. and Laacke, R., 2018) (Figure 17). Most significantly in terms of climate change, the aspect analysis found that about a quarter of the stand has windward (north and northwest-facing) slopes (~26%), meaning that a significant portion of the terrain has potential for high fog exposure. Additionally, ecologists have observed that Pinus radiata grows almost exclusively on northern-facing slopes in the Cambria stand. Aggregating all northward slopes (including everything from northwest to northeast aspects), a third (~34%) of the terrain falls within this ideal ecological niche. In contrast, southern and leeward-facing slopes make up a majority of the area (35% for leeward and 42% for total southern) in which growth is poor due to higher sun exposure and lesser fog exposure (Figure 18) (Roy, D. F. (1966); Torregrosa, A., et al., 2016).

Overall, this analysis provides insights into the current vulnerability to climate changes in the species' current location. In the following management recommendations, we will demonstrate how this data can be used in both local conservation and assisted migration scenarios in the face of a changing climate.

SUGGESTED CLIMATE CHANGE ADAPTATION STRATEGIES AND MANAGEMENT RECOMMENDATIONS

Though there are multitude of conservation options for the Monterey pine that should be considered - including establishing and expanding protected areas, ex-situ genetic storage, and combating pathogens like pitch canker (Gundu et. al., 2014) - we highlight three options below, which show the most relevance in the face of climate change. These include two in-situ interventions (controlled burnings and quasi in-situ plantings) and one ex-situ intervention (assisted migration). Our in-situ management strategies will focus on increasing the resilience to and reducing climatic stress of the Monterey pine, while our ex-situ strategy aims to preserve the Monterey pine in the wild if severe habitat loss ensues.

Quasi In-Situ Plantings

Quasi in-situ plantings are a way of bringing more genetic diversity into a plant population. Specimens are selected from an off-site population and are then grown on-site or adjacent to the site being managed (Volis, 2010). Such transplants, if successful, add genetic diversity into the population which could increase resilience. In Cambria, for example, where historic fog and precipitation trends are expected to change, the injection of genes from ex-situ Monterey pine populations could increase the local adaptive capacity and resilience to water strain. Quasi in-situ plantings are a recommended intervention for all three California stands, whether under high or low threat from climate change.

A successful quasi in-situ planting starts with identifying a population that is locally adapted to the environmental conditions of the new site (Volis, 2017). Once selected, the initial translocation takes place and the specimens are planted in a closely matched habitat. The introduced population's size and its distance from the native population also determine its success in propagation among the existing stand (Volis et. al., 2010). After initial planting and maintenance, further observation and monitoring of growth and interactions is important for measuring the success of the initiative.

It is a relatively cheap management option. Funding is needed for sampling and specimen collection ex-situ and later for planting and caretaking in-situ or near in-situ, but after the trees have been shown to be able to sustain themselves free of human maintenance, little needs be done as they will propagate independently (Volis et. al., 2010).

Controlled Burnings

One of the biggest factors limiting the resilience of the Californian Monterey pine stocks is fire suppression. The Monterey pine is a fire-resistant tree that has adapted to low- and medium-intensity burns (Stephens et. al., 2004). However, since it is often located near or among human settlements some areas are put under fire suppression in order to prevent damage to nearby development. The Cambria stand, for example, has experienced fire suppression since 1860 (CCHD, 2017). This has increased the age of the stands, which makes them more vulnerable to pathogens and climate stress.

Furthermore, there are worries that Monterey pines in Cambria will be replaced by the coast live oak. The coast live oak normally coexists in the understory of the Monterey pine and presents no threat to it under normal circumstances. But if climatic conditions deteriorate, the Monterey pines could be out-competed, unable to give way to a new individual that would take its place. This threat may be remediable with a controlled fire. While the Monterey pine is fire-adapted, the coast live oak is not. A controlled burn, therefore, could keep the coast live oak at bay and at the same time rejuvenate the Monterey pine population (Stephens et al., 2004).

Controlled burns are an affordable and effective method for fomenting resilience and encouraging expression of genetic diversity. Thousands are held in the United States every year. Based on size, location, and permitting the cost can vary wildly, but the most expensive cost only a few thousand dollars (Quinn-Davidson et. al., 2019). In the short term, it is not a recurring measure - one burn of the right intensity is sufficient for a regenerative event to take place.

The biggest barrier to implementing a prescribed burn is not cost, but human pushback. The stands in Cambria and Monterey are so entangled among human development that gaining local support for a controlled burn would be extremely difficult. In Cambria, since the pines snake through houses and other infrastructure, a controlled burn that covers the whole stand would simply be impossible. A larger fire that clearly delimits the undeveloped stand from the parts intertwined with the community would be a possibility, but due to the proximity to the town, greater safety measures would be required which would raise the cost.

Controlled burnings, then, may be a management method better suited for less developed areas. Though it may be impractical in Cambria and parts of the Monterey stand, in the more isolated parts of the latter stand in the less developed Ano Nuevo stand controlled burnings may have a better chance of being carried out.

Assisted Migration

Assisted migration is generally considered a last-case resort for plant conservation (McLachlan et. al., 2007). Unlike reintroduction in historic ranges, assisted migration calls for the translocation of the species into a non-native habitat. But depending on the direction that climate change takes along the Central Coast, the Monterey pine may find itself under such threat in its native habitats that assisted migration may become necessary.

Assisted migration is a difficult task to implement successfully (Diallo, 2023). The introduction of one species into a non-native location could present a host of problems for the ecosystem already found there. For example, the introduced species could find itself competing for the niche of a preexisting species, disturbing the ecological balance on which the ecosystem hangs. We highly recommend that significant resources be invested into ecological studies of the transplant environment and the Monterey pine, including into modeling possible scenarios. This could elucidate any uncertain or yet-to-be-uncovered factors at play in the introduction, helping to preclude a failed attempt or providing evidence that would recommend altering the course of implementation (McLachlan et. al., 2007).

In the case that studies and modeling recommend moving forward, it is crucial that the translocated plants be sufficiently genetically diverse. If there is limited genetic variability, there is a higher chance of a failed introduction. A broader gene pool gives expression to more phenotypic variations, which a smaller introduced population may lack (Schemske et. al., 1994). Even if some of the specimens fail to take off, there is a greater possibility that some will have more fitness and successfully establish themselves.

But it remains to be seen if assisted migration will even be necessary. Though by 2100 the Cambria stand is expected to fall outside of the ideal range for Monterey pines and face significant climatic and non-climatic threats, the Monterey and Ano Nuevo stands will remain in better climatic conditions. The extirpation of the Cambria stand would be unfortunate, but the survival of the two other stands would not justify the need for assisted migration. But we should not take this measure off the table yet. As noted previously, coastal fog coverage is the most important factor encouraging Monterey pine growth. Yet a dearth of coastal fog data, specifically predictions of its future extent, means we must be open to altering long-term conservation decisions. If coverage were to drop significantly among all three California stands, assisted migration may be the only option to sustain the Monterey pine in the wild.

Selecting Optimal Sites for Planting

Both assisted migration and in-situ plantings require a framework to determine which sites are optimal for planting. The best way to do this is by combining more than one analysis. By overlaying a terrain analysis with a predicted range analysis, we can provide comprehensive and accurate suggestions for ideal planting sites.

Our terrain analysis of the Cambria stand highlights four factors in selecting sites for Monterey pine planting: an elevation below one thousand feet; a gentle to moderate slope; a north- or coast-facing aspect; and high year-round insolation. These conditions can be viewed as parameters for future locations of Monterey pine conservation, whether locally or through assisted migration. For example, under an extreme climate scenario in which suitable habitat shrinks and shifts northward, pinpointing a region that meets the terrain criteria and falls within the future suitable habitat will be crucial for our proposed conservation methods. Furthermore, efforts to monitor local changes in the distribution of the Monterey pine in areas near the Cambria stand would be greatly aided by considering these terrain elements.

CONCLUSIONS

- The Monterey pine is predicted to come under greater threat in the next century. Climatic changes will place further stress on its fragile populations that have already had to cope with non-climatic pressures such as human development and pathogens like pitch canker.
- The California climate is expected to warm in the coming years and average precipitation is expected to increase. Predictions for coastal fog cover are fewer and less certain, with some experts suggesting increases and others reductions. Seeing as coastal fog cover is perhaps the most important factor in determining Monterey pine growth and distribution, we suggest investing more resources in researching its dynamics along the California coast.
- Maxent modeling proposes that by 2100, the predicted ideal range of the Monterey pine is expected to retract, especially along the southernmost end of its distribution near the Cambria stand.
- Terrain analyses highlighted four key factors that influence the site selection of the Monterey pine: high insolation, elevations less than one thousand feet, gentle to moderate slopes, and north- and coast-facing slopes. This has relevance in choosing locations for future planting initiatives and can be used alongside suitable range predictions to that end.
- Key management recommendations include quasi in-situ plantings, controlled burnings, and assisted migration. Quasi in-situ plantings and controlled burnings will increase real genetic diversity and rejuvenate aged stands, respectively, while assisted migration is a more drastic measure recommended in case of severe drops in habitat suitability due to climate change.

Figures and Appendices

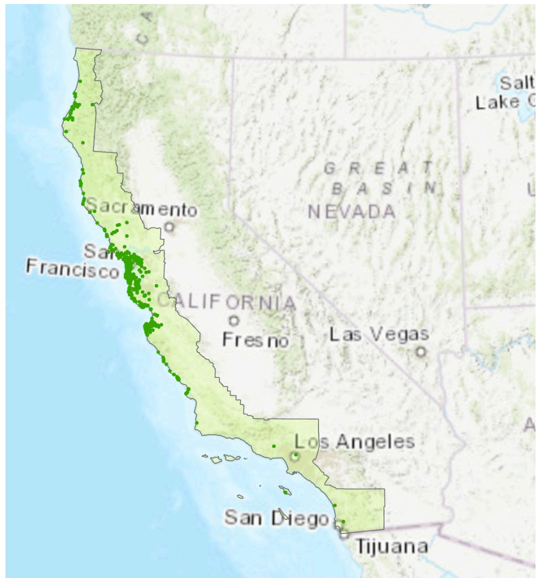

Figure 2: Distribution of Pinus radiata

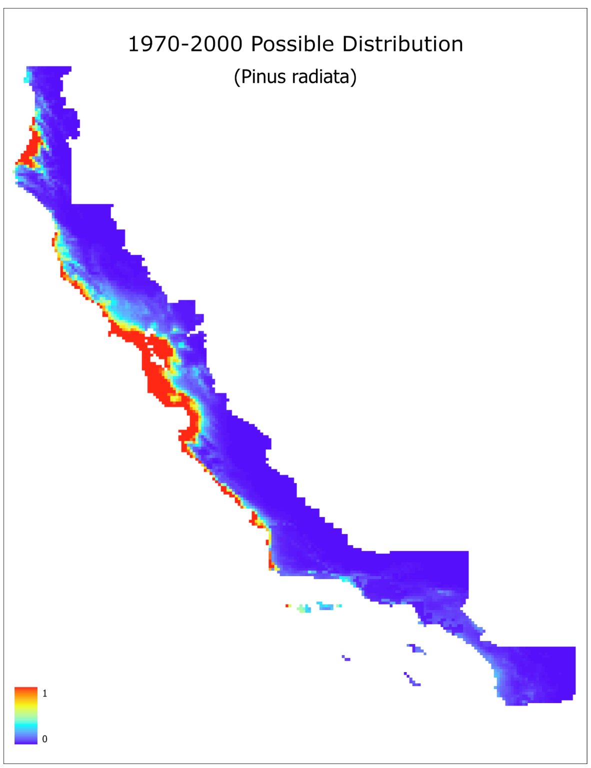

Figure 3: Suitability Score (1970-2000)

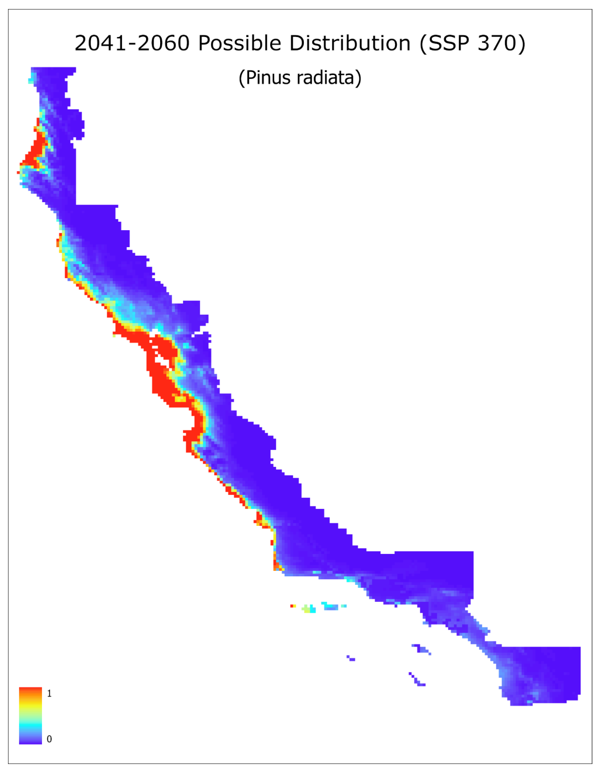

Figure 4: Suitability Score under SSP3-7.0 (2041-2060)

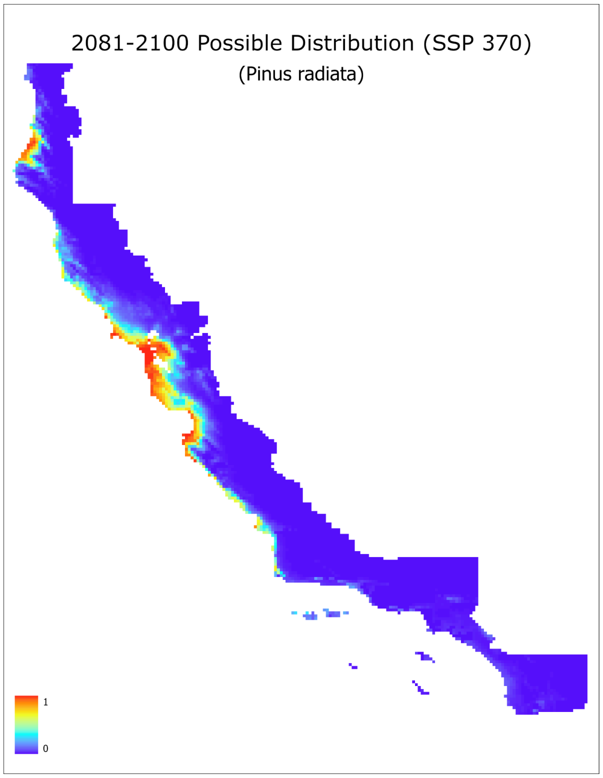

Figure 5: Suitability Score under SSP3-7.0 (2081-2100)

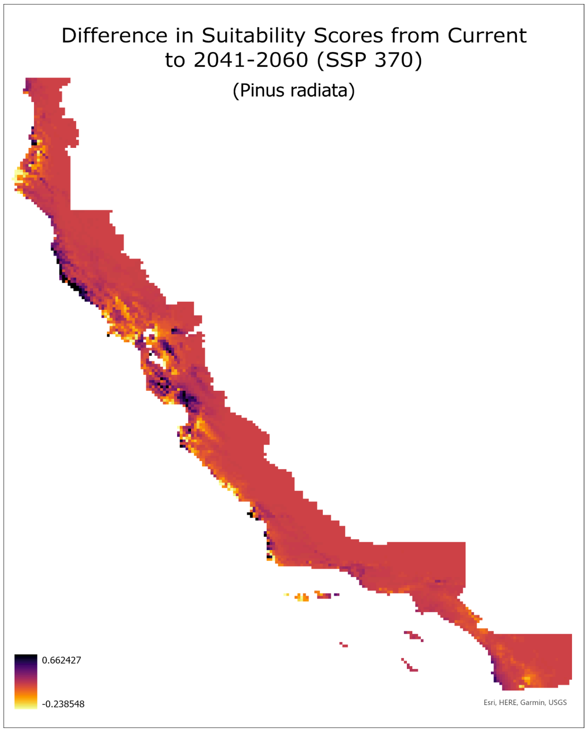

Figure 6: Difference in Suitability under SSP3-7.0 (2041-2060)

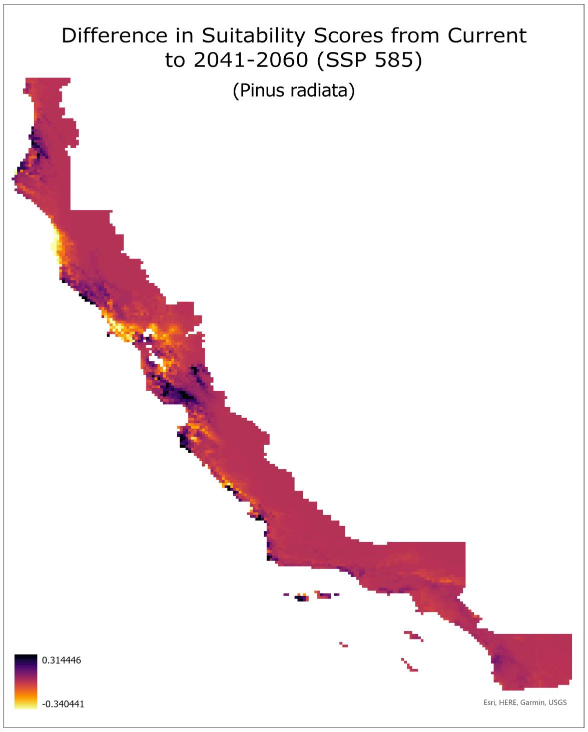

Figure 7: Difference in Suitability under SSP5-8.5 (2041-2060)

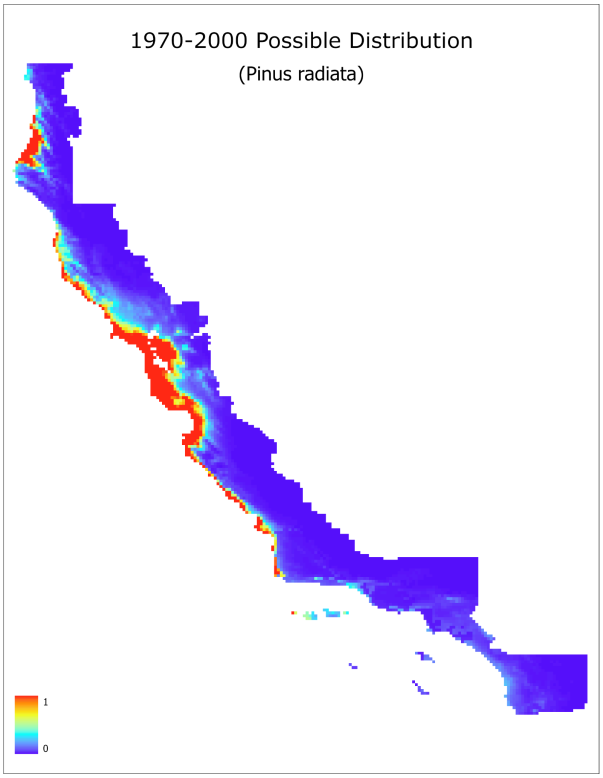

Figure 8: Suitability Score (1970-2000)

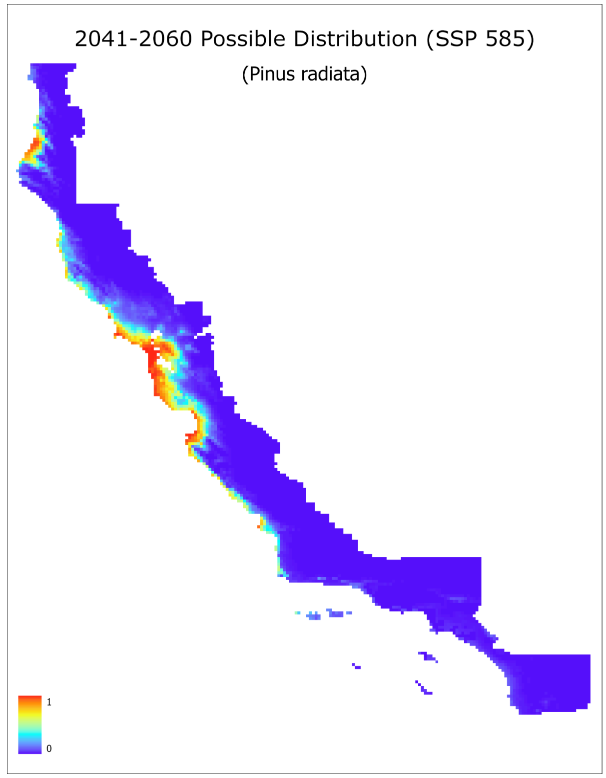

Figure 9: Suitability Score under SSP5-8.5 (2041-2060)

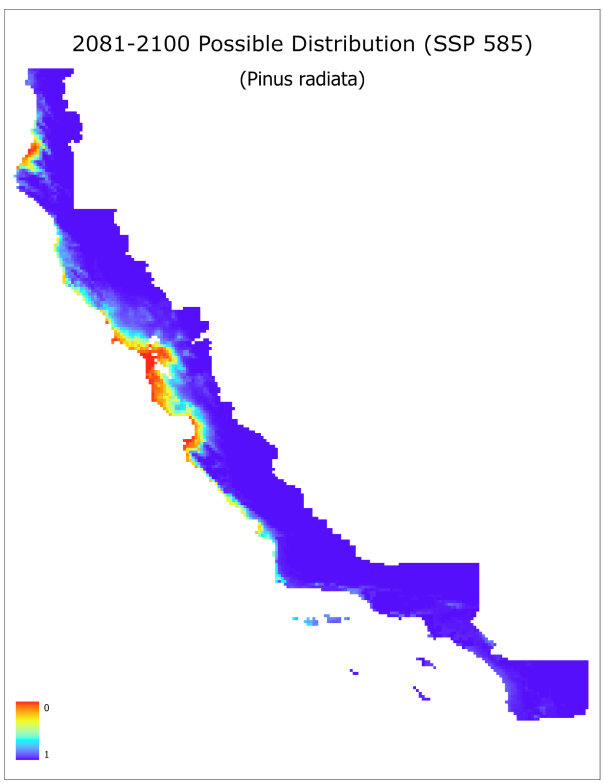

Figure 10: Suitability Score under SSP5-8.5 (2081-2100)

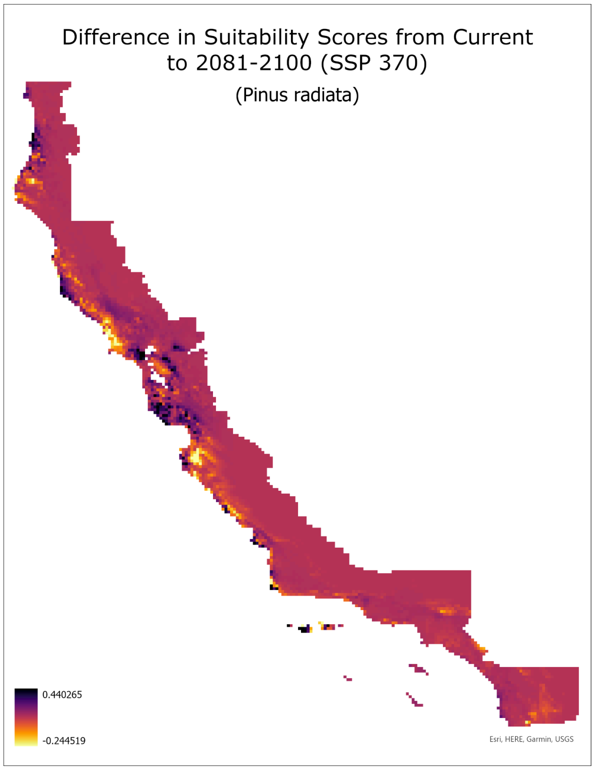

Figure 11: Difference in Suitability under SSP3-7.0 (2081-2100)

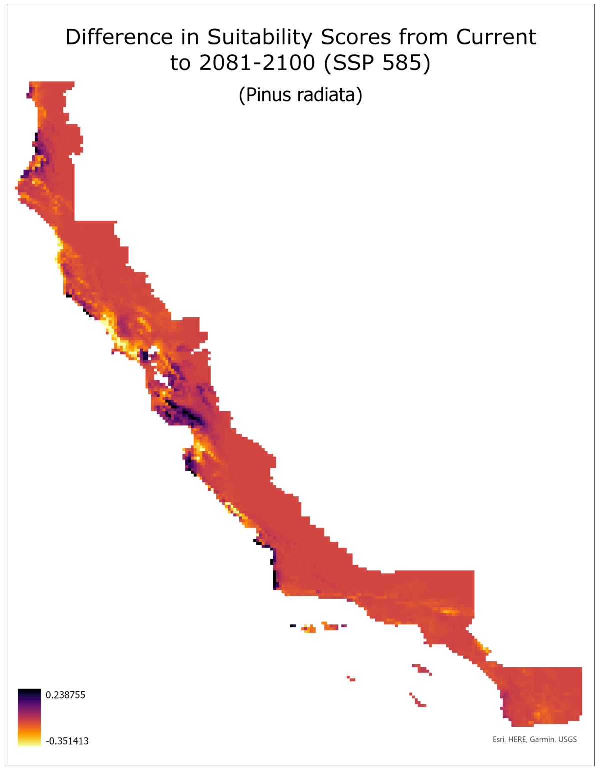

Figure 12: Difference in Suitability under SSP5-8.5 (2081-2100)

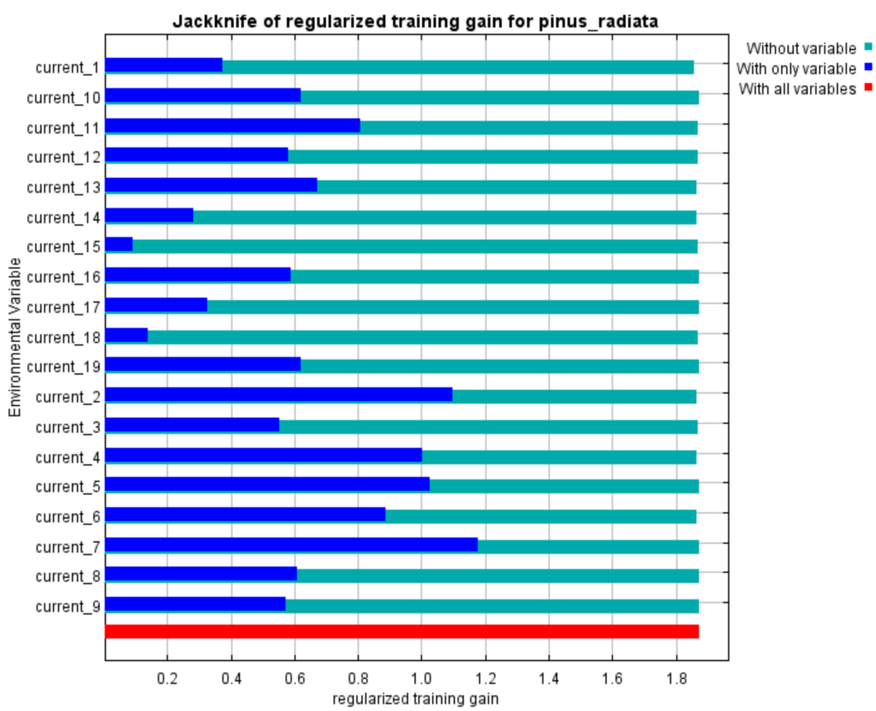

Figure 13: Jackknife Analysis from 1970-2000 Model

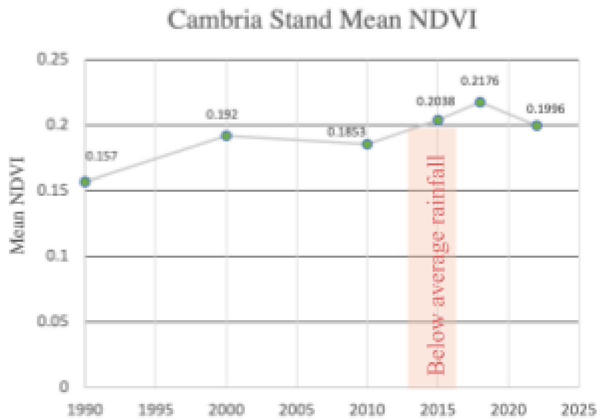

Figure 14: Mean Normalized Difference Vegetation Index over a 30 year period

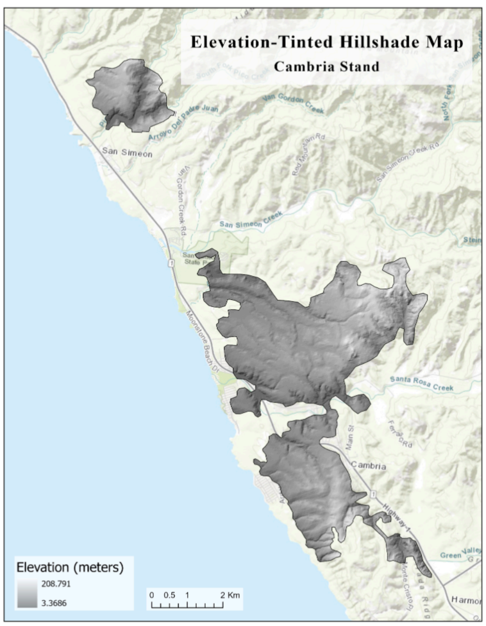

Figure 15: Elevation in Cambria Stand.

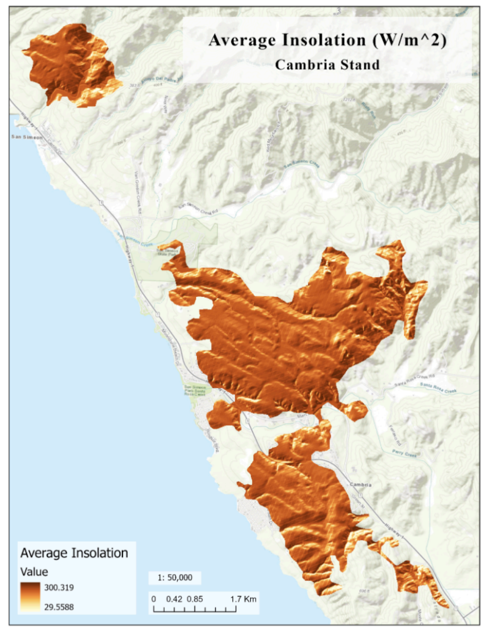

Figure 16. Insolation in Cambria Stand.

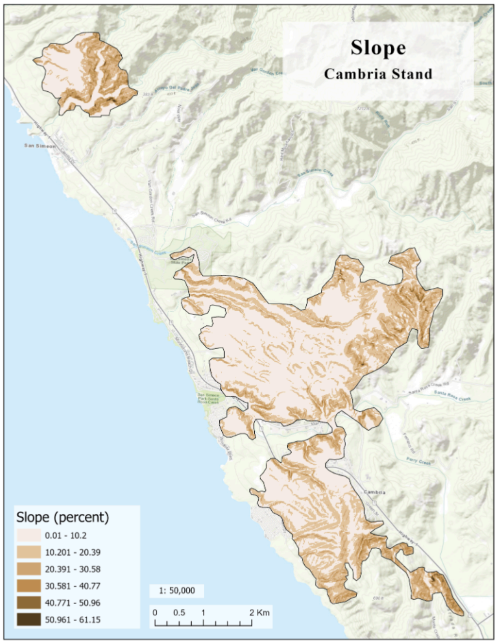

Figure 17. Slope in Cambria Stand.

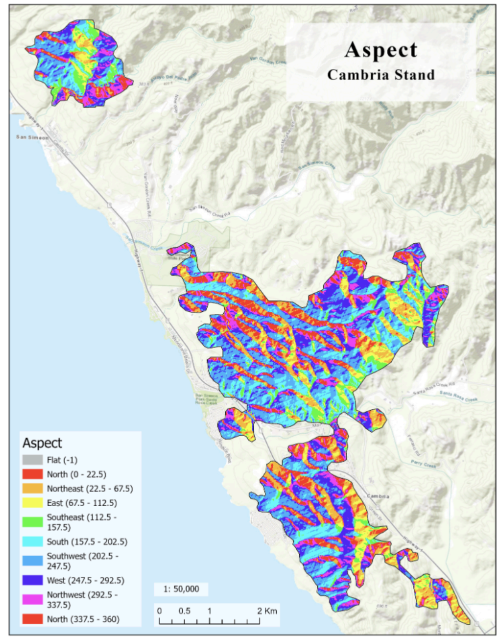

Figure 18. Aspect in Cambria Stand.

REFERENCES

Diallo, M., Mayeur, A., Vaissière, AC., Colas, B. (2023). The relevance of plant translocation as a conservation tool in France. *Plant Ecol, 224*, pp. 777–790 . https://doi.org/10.1007/s11258-023-01295-4

(CCHD), C. C. S. D. C. C. C. H. D. (2017). Multi-Jurisdictional Hazard Mitigation Plan for Cambria Community Services and Cambria Community Healthcare Districts. http://cambriaforestcommittee.org/wpcontent/uploads/2017/09/Cambria.MJHMP_.Master.pdf.

Fischer, D. T., Still, C. J., Ebert, C. M., Baguskas, S. A., & Park Williams, A. (2016). Fog drip maintains dry season ecological function in a California coastal pine forest. *Ecosphere*, *7*(6), e01364.

Fischer, D. T., Still, C. J., & Williams, A. P. (2009). Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species. *Journal of Biogeography*, *36*(4), 783–799.

Gundu, E., Adia, J.E.(2014). Conservation Methods of Endangered Species. *Journal of Research in Forestry, Wildlife, and Environment, 6*(2).

Hartoyo, A. P. P., Pamoengkas, P., Mudzaky, R. H., Khairunnisa, S., Ramadhi, A., Munawir, A., Komarudin, K., Hidayati, S., & Sunkar, A. (2022). Estimation of vegetation cover changes using normalized difference vegetation index (Ndvi) in Mount Halimun Salak National Park, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1109*(1), 012068. https://doi.org/10.1088/1755-1315/1109/1/012068

Hausfather, Z. (2021). CMIP6: The next generation of climate models explained. Carbon Brief. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/.

Langridge, R., et al (2018). Central Coast Region Report.

Looney, C. E., Stewart, J. A. E., & Wood, K. E. A. (2023). Mixed-provenance plantings and climatic transfer-distance affect the early growth of knobcone-monterey hybrid pine, a fire-resilient alternative for reforestation. *New Forests*.

Mcdonald, P., & Laacke, R. J. (2018). Pinus radiata D. Don Monterey Pine. https://www.semanticscholar.org/paper/Pinus-radiata-D-%2C-Don-Monterey-Pine-Pinaceae-Pine-Mcdonald-Laacke/a062c8da6010fb1e440288461a24eaa0680decb7

McLachlan, J. S., Hellmann, J. J., & Schwartz, M. W. (2007). A Framework for Debate of Assisted Migration in an Era of Climate Change. *Conservation Biology*, *21*(2), 297–302. http://www.jstor.org/stable/4620812

Millar, C. I. (1998). Reconsidering the conservation of Monterey pine. *Fremontia*, 26(3), 12-16.

Millar, C. I. (2000). Evolution and biogeography of Pinus radiata, with a proposed revision of its quaternary history. *New Zealand Journal of Forestry Science* 29(3):335-365.

O'Brien, M. J., O'Hara, K. L., Erbilgin, N., & Wood, D. L. (2007). Overstory and shrub effects on natural regeneration processes in native Pinus radiata stands. *Forest Ecology and Management*, *240*(1), 178–185.

Phillips, S. J. (2009). A Brief Tutorial on Maxent. Network of Conservation Educators and Practitioners, Center for Biodiversity and Conservation, American Museum of Natural History. Lessons in Conservation, Vol. 3, pp. 108-135.

Quinn-Davidson, L., Stackhouse, J. (2019). Burning by the Day: Why cost/acre is not a good metric for prescribed fire. *Grasslands.*

Reynolds, G. J., Gordon, T. R., & McRoberts, N. (2019). Projecting Monterey Pine (Pinus radiata) Populations over Time in the Presence of Various Representations of Pitch

Canker Disease, Caused by Fusarium circinatum. *Forests*, *10*(5), Article 5.

Rogers, D. (2004). In situ genetic conservation of a naturally restricted and commercially widespread species, Pinus radiata. *Forest Ecology and Management, 197*, Issues 1–3, pp. 311-322. https://doi.org/10.1016/j.foreco.2004.05.022.

Roy, D. F. (1966). Silvical Characteristics of Monterey Pine (Pinus Radiata D. Don). Pacific Southwest Forest and Range Experiment Station, *Forest Service - U.S. Department of Agriculture*.

Sawaske, S. R., & Freyberg, D. L. (2015). Fog, fog drip, and streamflow in the Santa Cruz Mountains of the California Coast Range. *Ecohydrology*, *8*(4), 695–713.

Schemske, D. W., Husband, B. C., Ruckelshaus, M. H., Goodwillie, C., Parker, I. M., & Bishop, J. G. (1994). Evaluating Approaches to the Conservation of Rare and Endangered Plants. *Ecology*, *75*(3), 585–606. https://doi.org/10.2307/1941718

Seager, R., Neelin, D., Simpson, I., Liu, H., Henderson, N., Shaw, T., Kushnir, Y., Ting, M., & Cook, B. (2014). Dynamical and Thermodynamical Causes of Large-Scale Changes in the Hydrological Cycle over North America in Response to Global Warming. *Journal of Climate*, *27*(20), 7921–7948.

Stephens, S. L., Piirto, D. D., & Caramagno, D. F. (2004). Fire Regimes and Resultant Forest Structure in the Native Año Nuevo Monterey Pine (Pinus radiata) Forest, California. *The American Midland Naturalist*, *152*(1), 25–36.

Still, C. J., Foster, P. N., & Schneider, S. H. (1999). Simulating the effects of climate change on tropical montane cloud forests. *Nature*, *398*(6728), Article 6728.

Storer, A. J., Bonello, P., Gordon, T. R., & Wood, D. L. (1999). Evidence of Resistance to the Pitch Canker Pathogen (Fusarium circinatum) in Native Stands of Monterey Pine (Pinus radiata). *Forest Science*, *45*(4), 500–505.

Solar Energy Local. Solar energy and solar power in Morro Bay, CA. Retrieved December 11, 2023, from https://www.solarenergylocal.com/states/california/morro-bay/

Torregrosa, A., Combs, C., & Peters, J. (2016). GOES‐derived fog and low cloud indices for coastal north and central California ecological analyses. *Earth and Space Science*, *3*(2), 46–67. https://doi.org/10.1002/2015EA000119

Volis, S., Blecher, M. (2010). Quasi in situ: a bridge between ex situ and in situ conservation of plants. *Biodivers Conserv* **19**, 2441–2454. https://doi.org/10.1007/s10531-010-9849-2

Volis S. (2017). Complementarities of two existing intermediate conservation approaches. Plant Divers. 39(6):379-382. doi: 10.1016/j.pld.2017.10.005. PMID: 30159532; PMCID: PMC6112325.

Williams, A. P., Still, C. J., Fischer, D. T., & Leavitt, S. W. (2008). The influence of summertime fog and overcast clouds on the growth of a coastal Californian pine: A tree-ring study. *Oecologia*, *156*(3), 601–611.