CLIMATE CONSERVATION PRIORITIES:

USING MCDA TO IDENTIFY FUTURE REFUGE FOR THE JOSHUA TREE FOREST IN CALIFORNIA

by

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To the Mojave Desert, my inspiration

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Abbreviations

ACEC	Areas of critical environmental concern
BLM	Bureau of Land Management
CDFW	California Department of Fish and Wildlife
CESA	California Endangered Species Act
CMIP6	Coupled Model Intercomparison Project version 6
EPA	Environmental Protection Agency
GCMs	Global climate models
GHG	Greenhouse gas
GIS	Geographic information system
GIST	Geographic information science and technology
JTF	Joshua tree forest
MCDA	Multiple criteria decision analysis
MIROC	Model for Interdisciplinary Research on Climate
RCPs	Representative concentration pathways
SSI	Spatial Sciences Institute
SSPs	Shared socioeconomic pathways
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USNPS	United States National Park Service

Abstract

To address the current climate crisis, environmental scientists and resource managers need to understand climate change impacts to classify appropriate conservation priorities. Current conservation efforts must focus on our changing climate to ensure the survival of vulnerable keystone species and ecosystems. The Joshua tree, a member of the agave family, is of vital importance to the Mojave and Sonora ecosystems. These cacti are classified as a keystone species as many desert mammals, reptiles, and birds rely on these trees for food and shelter. The clustering of Joshua trees within the southwestern United States is defined in this project as the Joshua tree forest (JTF). Previous climate studies have verified that the JTF, located in southwestern California, is critically threatened under business-as-usual climate scenarios. Consequently, the future vulnerability of the Californian JTF must be examined to preserve this unique ecosystem that thrives nowhere else in the world. Climate refugia, as used in this project, are locations that could be a haven for current species. Through classified refugia, areas, where species may migrate due to climate change, were identified to support state conservation priorities. This project created a suitability model using weighted overlays of climate, environmental, and land use variables to identify a suitable range of JTF refugia. This research ultimately classified 704,160 square meters of suitable JTF refugia based on projected climate data (2041-2060). Suitable areas were then compared to the current Joshua tree distribution providing insight into future areas where species populations are stable and where species can migrate as climate changes.

Chapter 1 Introduction

To address the current climate crisis, environmental scientists need to understand climate change impacts to classify accurate conservation priorities. Various climate models and scenarios, such as the National Climate Assessment (NCA), provide high-level summaries of projected global climate changes (Wuebbles, Fahey, and Hibbard 2017). These global models provide a broad perspective of climate impacts that inform many climate adaptation efforts. Climate adaptation, and efforts to conserve current systems from climate change, are a priority of most environmental groups and government agencies. Standard climate adaptation practices, used by natural resource management to protect valued ecosystems, are categorized into transition, resilience, and resistance strategies. Resistance strategies, or climate refugia, focus on the preservation of historical structure, composition, and function of the ecosystem vulnerable to climate change (Morelli et. al 2022). Through classified refugia, areas, where species may migrate due to climate change, were identified to support state conservation priorities. The primary objective is to classify climate refugia using projected climate data for Joshua tree species (*Yucca brevifolia*) at the state level, via suitability analysis to inform precise conservation priorities.

Both spatial resolution and scale of analysis were optimized to preserve model resolution. Previous climate models have indicated changes across spatial and temporal scales with expected changes within the mean state and extremes that threaten ecosystems (Mahlstein and Knutti 2010). This has led to the development of several climate adaptation methods at varying scales, often used by natural resource management such as transition, resilience, and resistance strategies (Morelli et al. 2022). Conservation priorities at the state level should look at state models to inform adaptation strategies and the extent utilized in this research. Although the range of clustered Joshua trees is within several southwestern states, this project focused on the range residing in California. This allowed the use of state-specific data whose fine resolution helped propose precise Californian JTF refugia.

This research utilized multiple criteria decision analysis (MCDA) to leverage weighted overlay and combine climate, environmental, and land use variables to understand future JTF habitats. MCDA is a method of overlay that derives the behavior of a complex system, which takes explicit account of the system's key factors to produce a suitable surface. This type of suitability analysis commonly aids decision-makers in analyzing potential actions or alternatives (Greene et. al 2011). To create an appropriate suitability analysis, related works were examined to inform climate, environmental, and land use criteria. Through expert-informed weight importance, raster datasets were overlain. This analysis produced a range of suitable climate refugia for the Californian JTF that can be leveraged to inform precise conservation priorities.

1.1 Motivation

Climate change, the change in global weather patterns, includes unprecedented variations in global temperatures, precipitation trends, and ocean temperatures. These slow yet steadily increasing changes have drastically altered our planet's interconnected systems. According to the 2017 NCA version 4, thousands of studies conducted around the world have documented melting glaciers, diminishing snow cover, shrinking ice, rising sea level, and ocean acidification (Wuebbles, Fahey, and Hibbard 2017). These changes are projected to have lasting impacts on unique ecosystems, such as the JTF, as ecologically diverse areas are the most vulnerable to climate change. According to research focused on the disproportionate magnitude of climate change in the United States, various analysis of these highly impacted areas foresees dramatic shifts in temperature and precipitation trends (Gonzalez et al. 2018). This thesis looks to build on current climate analysis, utilized by spatial scientists, to explore climate impacts on a threatened ecosystem. Specifically, simulation analysis is performed to understand the complex relationships between future JTF distribution and projected climate shifts.

Efforts to conserve natural lands have been the priority of most environmental groups, who are tasked with the protection of valued ecosystems. To inform current policy global climate models (GCM) are used to ensure strategic foresight into future climate trends to implement effective climate adaptation planning and conservation strategies. Iwamura et al. (2013) put forth several global schemes to support decisions on where to invest funds which are crucial to impactful climate mitigation. These informative global schemes are often useful for federal funds, which distribute funds at a coarse scale. Thus, this research works to identify a localized scale to define suitable JTF climate refugia across California. Pinpointing JTF climate refugia at the state level ensures the protection of vulnerable ecosystems by informing conservation funding and policy statewide.

1.2 Joshua Tree Forest

The JTF is defined, in this study, as the clustering of Joshua trees (aka Yucca brevifolia) within the southwestern United States. Joshua trees grow on average 20 to 70 feet tall, evergreen, tree-like plants that are slow-growing and long-lived (Gucker 2006). These cacti span 4 western states, California, Arizona, Nevada, and Utah, and predominantly reside in Warm Desert and Mediterranean California regions of North America (see US EPA 2010). As shown in Figure 1, a large clustering of Joshua trees, recorded in iNaturalist, reside within southern California, particularly along the western border of the Mojave Basin and Range ecoregion.

Located in southeastern California the Mojave Basin and Range ecoregion provides a dry, subtropical desert climate, marked by hot summers and warm winters ideal for the

Californian JTF. The mean annual temperature in this ecoregion is approximately 5 degrees Celsius at high elevations, and 24 degrees Celsius in the lowest basins with annual precipitation of 167 millimeters (Wiken, Nava, and Griffith 2011). This area is also dominated by north-south trending mountains, broad basins, and alleys with long alluvial fans (EPA 2010). The characteristics of these regions support the Joshua tree life cycle and are currently home to the highest density of Joshua trees.

Figure 1. Current Joshua tree habitats (iNaturalist)

Figure 2 displays iNaturalist observation symbolized using dot density which provides a clearer view of the JTF population. Californian Joshua trees, as previously mentioned, predominantly reside in the Mojave Basin and Range ecoregion, marked by hot summers and warm winters ideal for the JTF. Figure 2 also shows the presence of Joshua trees in the Sonora Desert.

Adjacent to the Mojave Basin and Range is the Sonoran Desert which provides a similar dry subtropical desert climate, characterized by very hot summers and mild winters. With similar ranges in average temperatures and precipitation, this ecoregion has cyclical weather cycles with winter rainfall decreasing from west to east, while summer rainfall decreases from east to west (Wiken, Nava, and Griffith 2011). This also provides a home for some of the California Joshua Trees (Figure 2). However, this suitability analysis suggests a migration away from these ecoregions as temperatures increase and precipitations decrease.

Figure 2. Dot density within current JTF habitats

The Joshua tree, a member of the agave family, is of vital importance to the Mojave and Sonora ecosystems and is classified as a keystone species. These cacti are classified as a keystone species as many desert mammals, reptiles, and birds rely on these trees for food and shelter. Focused analysis of keystone species is an apparent practice in conservation efforts as it allows analysts to understand future distribution predictions, the influence of variables on species distribution, and suitability for future populations. These types of models can accurately use available data to assess the potential effects of climate change on well-studied local species while accounting for model uncertainty (Carroll 2010). This research identified statewide JTF refugia to account for changes in this keystone species distribution that can be devastating to unique Californian deserts.

It has become clear across many climate studies that Joshua trees have a slim chance of survival under business-as-usual scenarios. By 2099, under the highest emissions scenario forecast, the average annual temperature inside Joshua Tree National Park could increase by 8 degrees Fahrenheit suggesting it could eliminate nearly all suitable habitats for Joshua trees. (Rodgers 2021). Thus, as temperatures rise and precipitation decreases the distribution of the JTF change, as their life cycle is dependent on well-timed rains and freeze. It is crucial for current conservation efforts to define future refugia, while considering projected climate, to ensure the survival of this vulnerable keystone species.

1.3 Current Conservation Strategies

With the imminent threat of increasing temperatures, wildfires, and habitat loss, environmental agencies have evaluated and classified the threat levels of the Joshua tree species. The highest level of regulatory protection granted to the western Joshua Trees, based on the threat level, is CESA. The California Endangered Species Act (CESA) has prohibited the import, export, take, possession, purchase, or sale of western Joshua trees since 2020 (Bonham 2022). Joshua trees also received additional funds and protection under the Native Plant Protection Act, California Desert Native Plants Act, and California Environmental Quality Act (Bonham 2022).

Each required precise species analysis and research to provide actionable information to inform conservation funds and climate adaptation strategies.

1.3.1 Climate Adaptation Strategies

With the overwhelming research validating the increase of climate change impacts, standard conservation strategies were created to focus on climate adaptation. Climate adaptation, an effort to conserve current systems from climate change, is a priority of most environmental groups and government agencies. Standard climate adaptation practices, used by natural resource managers to protect valued ecosystems, include transition, resilience, and resistance strategies. Resistance strategies, or climate refugium, focus on the preservation of historical structure, composition, and function of the ecosystem vulnerable to climate change (Morelli 2022). Species-specific assessments, like the refugia model created in this project, predict responses of species and populations to changes in climate, allowing researchers to identify areas that will continue to have suitable climates for a given species into the future (Conservation Biology Institute 2023). This project identified refugia specific to where future Joshua tree populations are stable and possible areas of migration as climate changes.

Similar methods have been used at Joshua Tree National Park one of the densest regions of Joshua trees in California. Park managers have long foreseen the disappearance of their iconic tree and mitigated this through climate adaptation strategies. Specifically, Joshua Tree National Park climate plan emphasized the identification and protection of Joshua tree refugia, defined as areas of higher elevations and annual rainfall, within the park boundary (USNPS 2021). This resilient strategy provides land stewards with targets for focusing on protective management, giving desert biodiversity places to weather the future (Sweet et al. 2019). This research expanded on this work and defined statewide refugia to further understand the changes to the entirety of the Californian JTF.

1.3.2 Role of Global Climate Models

This project utilized projected climate data that provided strategic foresight to define climate refugia. As utilized by many environmental models' strategic foresight explores future conditions to inform current decisions appropriate for future challenges (Cook et al. 2014). These include projections and forecasts of alternative futures, commonly known as scenario planning. GCMs are a representation of possible climate futures based on several socioeconomic factors and often support decisions of where to invest vital conservation funds (Iwamura et al. 2013). For this reason, several GCMs were considered for this research as future climate conditions directly influence future JTF distribution.

To account for the most climate uncertainty this research utilized Shared Socioeconomic Pathways (SSPs) 8.5, or "worst case" climate scenario, in which no climate policy will be implemented. The Coupled Model Intercomparison Projects (CMIP6) produced the most recent standardized GCMs based on SSPs or possible climate futures. There are four SSPs categories (SSP 8.5, SSP 6, SSP 4.5, and SSP 2.6) each representing various futures based on different sets of population, economic growth, and other socioeconomic assumptions of future emissions scenarios (Hausfather 2019). Specifically, this project utilized SSP's 8.5 to represent the highest emissions baseline scenario to define JTF climate refugia.

Previous research suggests a range of GCM suitable for species distribution analysis, however, one specifically used in previous Joshua tree analyses is the Model for Interdisciplinary Research on Climate (MIROC). MIROC is one of over 40 physical GCMs, that is composed of atmosphere, land, and sea ice-ocean models (Hausfather 2019). A Joshua tree agent-based model, created by Sweet et al. (2019), leveraged MIROC as a means of involving large-scale spatial patterns. This large-scale analysis provided a better understanding of regional relationships between Joshua trees and global systems. A comparison of historical simulations and observational studies, suggests that MIROC successfully represents the transient global climate change and observes large-scale spatial patterns (Hajima et al 2020). Thus, MIROC SSP 8.5 is utilized in this research as it accounts for maximum climate uncertainty as well as large-scale spatial patterns.

1.4 Study Area

Nestled between the Little San Bernardino Mountains and Chuckwalla Mountains of southern California lies a unique forest of twisted spiky *Yucca brevifolia*, commonly known as Joshua trees. These cacti, although most associated with Southern California, span across 4 western states, California, Arizona, Nevada, and Utah, and predominantly reside in 2 ecoregions of North America, Warm Desert, and Mediterranean California (EPA 2010). Most of these trees are clustered at the southern end of California, across approximately 9 million acres of the Mojave, Sonora, and Colorado Deserts. This unique forest is a hub of rich biodiversity home to a delicate ecosystem dependent on timely warming and rainfall. It is these eco-regional boundaries where climate change may be more acute as temperature-precipitation gradients more drastically affect species composition and ecological relationships (Barrows et al. 2014). Thus, a localized study area was chosen to inform localized state policy and ensure the protection of the Californian JTF.

As shown in Figure 3, the study area chosen for this research is the state of California. Identified JTF climate refugia at the state level ensures the protection of vulnerable ecosystems by informing conservation funding and policy statewide.

Figure 3. Study area

California is situated along the southern coast of the Western United States, with many offshore islands and coastal lowlands, large alluvial valleys, forested mountain ranges, deserts, and aquatic habitats (Wiken, Nava, and Griffith 2011). The sprawling state is one of the most geographically and ecologically diverse regions in the world providing refuge for many species as climate changes.

1.5 Thesis Layout

The remainder of the document is divided into four remaining chapters. Chapter 2 is a review of related works that explore data availability, previous climate scenarios, and ideal analytical methods. Chapter 3 discusses data requirements and methods used to implement an accurate and precise suitability analysis. Results are then outlined in Chapter 4 followed by a discussion of results and limitations in Chapter 5. Ultimately, this research classified climate refugia, for the JTF in California, via suitability analysis to identify future conservation priorities.

Chapter 2 Related Work

This chapter outlines related works that have examined data availability and suitability analysis about Joshua trees. It is this discussion of previous models and analyses, that helped define an appropriate research design. The following research specific to Joshua trees also informed appropriate climate, environmental, and land use criteria.

2.1 Previous Joshua Tree Research

Although there is an expansive range of species distribution models that identify climate change impacts, Joshua tree-specific research is less abundant. The following section describes the research gathered to inform critical model criteria. These previous studies that identified future Joshua tree patterns include species assessments, vulnerability assessments, habitat suitability models, and agent-based modeling. All of which provided key insights to capture the complex interaction of variables that constrain a species' distribution (Barrows et al. 2014). This was a crucial step in this research and provided a framework for a precise criteria designation.

Effective suitability variables are primarily defined through expert knowledge, as precise criteria must be programmed into the model. It is common practice in authoritative distribution analysis to inform species requirements through various working groups and expert interviews. Unfortunately, because of the time constraints of this research only a literature review, described below, was conducted to collect and define species dynamics and needs.

2.1.1 Gathering Expert Knowledge

Criteria design is an essential component of MCDA and was considered carefully to ensure a useful and accurate suitability analysis. Criteria in this thesis, are variables that define a location suitable for the continued survival of the California JTF. Criteria in previous studies vary as each model is tailored to species-specific needs. For instance, suitability models used to identify solar wind farms, often consider the physical, distance from a road, the environment, the orientation of land, and climate criteria, average monthly temperature (Mierzwiak and Calka 2017). Similarly, previous Joshua tree studies, conducted by Greene et al. (2011) and Wanyama (2017), utilize an array of variables that not only represent the natural setting but other anthropogenic constraints as well. These included criteria that capture human impacts on the species such as developmental status, city boundaries, and land use. Therefore, the criteria utilized in this study are based on characteristics of suitable climate, environment, and land use needed for Joshua trees to prosper.

Several Joshua tree studies and species assessments were referenced to define the ideal location that encompassed suitable climate, environment, and land use. Specifically, 3 authoritative Joshua tree species assessments were reviewed to inform species needs, current distribution, and population stressors (Table 1).

Table 1. Joshua tree species assessments

Author	Year	Title	Annotation
Gucker	2006	*Yucca brevifolia*. Fire Effects Information System, [Online]	Species review includes information about plant species' biology, habitats, regeneration or reproductive processes, relationships with fire, and management considerations.
Sirchia, Hoffman, and Wilkening	2018	Joshua Tree Species Status Assessment	Species status assessment provides an analysis of the overall species viability and details the species' ecological requirements/resources needed for survival to evaluate current levels of population resilience.
Bonham	2022	Report to the Fish and Game Commission Status Review of Western Joshua Tress (Yucca brevifolia)	Status Review, based on the scientific information available to the California Department of Fish and Wildlife, on the western Joshua tree (*Yucca brevifolia*). This report serves as the basis that informed the California Fish and Game Commission to list the species as threatened under the California Endangered Species Act (CESA).

The first is a species review of the *Yucca brevifolia* and its wildfire impacts. This review provided information about physiological and environmental relationships specific to the Joshua tree (Gucker 2006). In 2018 a more specified species assessment was published by the US Fish and Wildlife Service, which provided a detailed analysis of the overall species viability (Sirchia, Hoffman, and Wilkening 2018). Its particular focus on the species' ecological requirements and resources needed for survival proved to be the most insightful for this research. This article was the main source that helped define variables and suitability classification. Finally, the most recent species review explored *Yucca brevifolia* with an emphasis on species survival and threats (Bonham 2022). This report verified species needs that informed model criteria.

A summary of resource needs, identified across species assessments, includes timed seasonal rainfall and temperatures, coupled with appropriate soils, and biodiversity. Figure 4, created by Sirchia, Hoffman, and Wilkening (2018), described the importance of these variables throughout the Joshua tree life cycle. Also verified by Gucker (2006) and Bonham (2022) climate variables are proven to be vital throughout the Joshua tree's life stages and are prioritized in this research (Figure 4). These criteria were also verified by similar Joshua tree studies (see, e.g., Sweet et al. 2019; Wilkening, Hoffmann, and Sirchia 2020; Barrows et al. 2014; and Cole et al. 2011), who define habitat quality, temperature, precipitation, and soil as important to the JTF population.

Resource Needs by Life-Stage

Life-Stage	Appropriate Seasonal Precipitation	Summer Precipitation	Adequate Soils	Seedbank	Nurse Plants	Minimum Temperatures < 4 C	Yucca Moths	Adequate Temperature Range	Rodents (Seed Dispersal/Cache)
Seeds/Seedlings (Less than 25 cm tall)	✓	✓	✓	✓	✓	✓		✓	✓
Juveniles (Non-flowering Individuals)	✓							✓	
Adults (Flowering Individuals)	✓						✓	✓	

Figure 4. Joshua tree needs (Sirchia 2019)

In addition to these criteria, anthropogenic variables were also considered in this research. Human development and activity have proven to be bounding features that constrain various species. These constraints are presumed stressors associated with habitat loss that influence JTF population dynamics (Sirchia, Hoffman, and Wilkening 2018). Land ownership and land cover were specifically explored as these designations represent conservation potential, areas that have limited habitat disturbance, intact ecosystems, and support more resilient local populations (Sirchia, Hoffman, and Wilkening 2018). Thus, both variables were utilized in this research to define land use constraints.

2.1.2 Climate Criteria

Effective suitability analysis was performed through well-defined climate criteria informed by species assessments and previous Joshua tree studies. The diverse areas, inhabited by Joshua trees, encompass various elevations resulting in variations in temperature ranges, and rainfall (Sirchia, Hoffman, and Wilkening 2018). Most studies agree that these cacti exhibit a high degree of flexibility showing resilience in fluctuating climate conditions. For this reason, these criteria were classified as wide ranges of suitable climates that represented appropriate climate regimes for the Californian JTF. A literature review, described below, was conducted to collect, and summarize crucial climate variables used in this model.

Precipitation and temperature are two of the most important variables for JTF survival. References described in the previous section verify that these resilient cacti can thrive in habitats characterized by wide variations in precipitation and temperature (Wilkening, Hoffmann, and Sirchia 2020). The consensus across Joshua tree research suggests long hot summers, mild winters, and overall low precipitation. Table 2 describes an overview of suitable precipitation and temperature criteria utilized in this analysis.

Table 2. Climate criteria

Criteria	Suitable Description
Mean summer temperatures (C°)	20 to 40, with mild temperatures being the most suitable
Mean winter temperatures (C°)	-11 to 3, a minimum of 4, with mild temperatures being the most suitable
Mean annual temperatures (C°)	-11 to 59, with mild temperatures being the most suitable
Mean summer precipitation (mm)	Wetter summers are ideal as it infers larger germination events.
Mean winter precipitation (mm)	Minimum of 82.4, with higher precipitation being the most suitable
Mean annual precipitation (mm)	80 to 740 with higher precipitation being the most suitable

Source: Sirchia (2018)

2.1.2.1 Annual temperature

Maximum average annual temperature, in degrees Celsius, is defined as a critical variable for vegetation distribution across ecological habitats. Sirchia, Hoffman, and Wilkening (2018), Broham (2022), Sweet et al. (2019), Gucker (2006), and Cole et al. 2011, agree that increased temperature may not directly affect Joshua tree physiological survival, but prolonged exposure to high temperatures could limit the distribution of the species. Specifically, an ambient temperature within the range of tolerance for this species is between -11 to 59 degrees Celsius (Sirchia, Hoffman, and Wilkening 2018). Although Joshua trees can live at a max temperature of 59 degrees Celsius, individual Joshua trees tend to maintain optimal photosynthetic activity within a range of more-mild temperatures (Wilkening, Hoffmann, and Sirchia 2020). For this reason, annual temperature criteria are defined as -11 to 59 degrees Celsius, with mild temperatures being the most suitable.

2.1.2.2 Seasonal temperature

As discussed previously, the survival of Joshua trees is highly dependent on the timing of necessary heat waves throughout the year. These periods of seasonal warming and cooling affect the overall germination of this species, limiting their extent across California. The absence of Joshua trees in the lowest and driest parts of the Mojave Desert can be credited to maximum summer and minimum winter temperatures (Wilkening, Hoffmann, and Sirchia 2020). Species assessment also correlates temperature and Joshua tree flowering and seed production, concluding that well-timed warming may positively affect Joshua tree reproduction (Broham 2022). Both Wilkening, Hoffmann, and Sirchia (2020) and Sirchia, Hoffman, and Wilkening (2018) propose an ideal mean summer temperature that ranges between 20 to 40 degrees Celsius. The need for short periods of cold temperatures in winter is also necessary for seed germination, with minimum winter temperatures ranging from -8.1 to 5.98 degrees Celsius that lead to optimal growth (Wilkening, Hoffmann, and Sirchia 2020). Sirchia, Hoffman, and Wilkening (2018) present a similar range of winter temperatures of -11 to 3 degrees Celsius min of 4 degrees Celsius. These seasonal climate ranges are considered by most references as ideal as Joshua trees, like most cacti are resilient to extreme heat waves and droughts. This supported the need for suitable winter and summer temperature criteria for this suitability model.

2.1.2.3 Annual precipitation

Maximum average annual precipitation in millimeters is also defined as a critical variable for vegetation distribution across ecological habitats. Sirchia, Hoffman, and Wilkening (2018), Broham (2022), Sweet et al. (2019), Gucker (2006), and Cole et al. (2011) all agree that adequate precipitation throughout the Joshua tree life cycle influences the germination and adulthood of these plants. Like suitable temperatures, suitable precipitation ranges widely for this resilient species. As defined by Wilkening, Hoffmann, and Sirchia (2020) and Sirchia, Hoffman, and Wilkening (2018) average annual rainfall between 80 and 740 millimeters is sufficient for Joshua tree seedlings and adults. However, with temperatures rising more precipitation is ideal for this species.

2.1.2.4 Seasonal precipitation

As previously mentioned, the Joshua tree's survival is dependent on the precise timing of sufficient rainfall. Residing in desert regions, Joshua trees are influenced by the magnitude and seasonality of precipitation, a principal driver of the ecosystems (Broham 2022). Both winter and summer rainfall contribute to the life cycle of these cacti which are discussed in detail by all species assessments. Summer precipitation is particularly important for Joshua tree reproduction, as wetter summers may result in larger germination events (Wilkening, Hoffmann, and Sirchia 2020). Unfortunately, the exact range of winter rainfall is not well defined in the previous research, as references only infer wetter summers positively impact Joshua tree distribution. Similarly, winter precipitation is prudent for seedling establishment as these cacti rely on a cool season marked by increased precipitation for survival. Increase winter showers are defined as most suitable with a min 82.4 millimeters of rainfall throughout the winter season (Sirchia, Hoffman, and Wilkening 2018). This research informed the seasonal precipitation constraints and suitability range of this model.

2.1.3 Environmental Criteria

Effective suitability analysis was performed through well-defined environmental criteria informed by species assessments and previous Joshua tree studies. The diverse areas, inhabited by Joshua trees, encompass various elevations, soil types, temperature ranges, rainfall amounts, and vegetation communities (Sirchia, Hoffman, and Wilkening 2018). Most studies agree that these cacti exhibit a high degree of flexibility showing resilience in a variety of environmental conditions. For this reason, environmental criteria, such as soil type, habitat quality, burn probability, geology, and topology were classified to represent appropriate environmental conditions for the Californian JTF. Table 3 describes an overview of suitable environmental criteria utilized in this analysis.

Table 3. Environmental criteria

Criteria	Description	Suitable Description
Aspect	The orientation of the land surface, an indicator of the amount of sunlight	Southwest/South/Southeast – maximum sun exposure
Elevation (ft)	Feet above/below sea level	1,600-6,600
Slope (%)	The degree of tilt of the land surface, indicative of water capacity and soil stability	flats, mesas, bajadas, and gentle slopes in the Mojave Desert [Flat (<1) and Gentle Slope (1-10)]
Soil	Sand content and drainage class	silts, loams, and/or sands described as fine, loose, well-drained, and/or gravelly
Geology	The superficial geologic units	Alluvia of igneous origin
Wildfire	Fire danger or the likely hood of wildfire damage associated with invasive vegetation	The likelihood of fires is described by the amount of burning fuel (invasive grasses)
Habitat Quality	Biodiversity representative of symbiotic relationships with the Yucca Moth, desert rodents, and other wildlife	Areas with an abundance of native species diversity and species richness

Source: Sirchia, Hoffman, and Wilkening (2018) verified by literature review

2.1.3.1 Aspect

Aspect, the compass direction of the downhill slope, is an indicator of sun exposure and soil temperature. A useful variable when considering vegetation suitability as plant life is dependent on the amount of daily sunlight. Sirchia, Hoffman, and Wilkening (2018), Wanyama (2017), Sweet et al. (2019), and Broham (2022) verify this as Joshua tree distribution is positively correlated with potential sun exposure. Aspect is also crucial to several abiotic factors that are important for plants, as it is often an indicator of soils, slopes, and ruggedness of terrain (Broham 2022). To account for the maximum sun exposure southwest/south/southeast facing sloped were defined as the most suitable.

2.1.3.2 Elevation

Topographical variables, such as elevation, are necessary to include as it is related to the amount of temperature and precipitation. This is true among current Joshua tree distribution as these cacti vary considerably throughout the Mojave Desert according to elevation, latitude, and precipitation patterns (Wilkening, Hoffmann, and Sirchia 2020). Species assessment concludes that the Joshua tree can inhabit a wide range of elevations. Gucker (2006), Sirchia, Hoffman, and Wilkening (2018), and Broham (2022) conclude that Joshua trees can occur at elevations ranging from 1,600-7,200 feet. However current distribution patterns speak to the elevational limits of Joshua trees where abundance increases with latitude in response to shifting climate patterns (Barrows and Murphy-Mariscal 2012). For this reason, studies infer that these cacti thrive at lower elevations and poorly at higher elevations.

2.1.3.3 Slope

Slope, or the degree of tilt, is indicative of water capacity and soil stability, another topological factor that influences vegetation distribution. Unanimously discussed across references, Sirchia, Hoffman, and Wilkening (2018), Wilkening, Hoffmann, and Sirchia (2020), Broham (2022), Gucker (2006), and Cole et al. (2011), Joshua trees are mostly found on gentle slopes of mesas, bajadas, and alluvial fans. Gentle slopes are described in percent slope in which flat is <1% slope and gentle slope of 1-10% slope (Thomas et al. 2004). These areas allow for ideal water retention and necessary soils for this plant. Thus, flatter surfaces are considered the most suitable for Joshua trees.

2.1.3.4 Soil

Soil, in this study, is characterized by two defining traits sand percentage and water drainage class. Previous studies identified dominant soils in Joshua tree habitats to be silts, loams, and/or sands described as fine, loose, well-drained, and/or gravelly (Gucker 2006). The highest densities of Joshua trees are mostly found on well-drained sandy to gravelly alluvial fans (Broham 2022). These gravelly sands provide the necessary space for Joshua tree root systems. Thus, like previous Joshua tree analysis by Sweet et al. (2019) and Barrows and Murphy-Mariscal (2012), high sand content and well drainage soils were classified as suitable.

2.1.3.5 Geology

The geological setting of land is defined in this research as a hard constraint. Informed by all species assessments alluvial units of igneous origin are unanimously the only suitable terrain for Joshua trees. Although these cacti can grow in a wide variety of environmental factors, alluvial soils are critical to Joshua tree survival and reproduction (Sirchia, Hoffman, and Wilkening 2018). Species assessments also verify that alluvial fans of igneous origin are the most suitable, with sedimentary units categorized as moderately suitable, and all other units as low.

2.1.3.6 Wildfire

Wildfire criteria are defined as the probability of burn or the likelihood of intensive or frequent wildfires. As temperatures rise wildfire risk has expanded throughout California. In the past, fires were rare in desert settings however because of the establishment of invasive species, like red brome and cheatgrass, fires have become more frequent and more severe (Gucker 2006). Species assessments anticipate an increase in wildfires based on models that account for invasive annual grass potential or the likely hood of fire based on the amount of fuel (Sirchia, Hoffman, and Wilkening 2018). Thus, the Joshua tree fire regime is characterized by changes to fuel structure and subsequent fire behavior. This was observed in recent Joshua tree habitats as approximately 2.5 percent of the species were impacted by wildfires resulting in lowered species abundance (Broham 2022). Thus, the presence of higher invasive vegetation is categorized as areas of low suitability as they are more likely to burn.

2.1.3.7 Habitat quality

Habitat quality is indicative of areas with rich biodiversity that Joshua trees rely on for reproduction and seed dispersal. The role of pollinators and rodents is discussed across Joshua tree studies as rodents support seed dispersal and insects support pollination (Sirchia, Hoffman, and Wilkening 2018). It is clear across previous research that biodiversity, the abundance of native species, ensures the critical convergence of ecological events. For instance, optimal Joshua tree reproduction currently relies on pollination from moths and seed dispersal/caching by rodents (Wilkening, Hoffmann, and Sirchia 2020). These relationships between desert natives such as the Yucca moths, deer mice, kangaroo rats, and white-tailed antelope squirrels, are captured in this criterion as the degree of biodiversity (Cole et al. 2011). This research identified suitable habitat quality, as areas of higher biodiversity.

2.1.4 Land Use Criteria (Conservation Potential)

Land use criteria were utilized in this project as hard constraints that limited Joshua tree distribution due to human development and management. These constraints represented the accessibility to implement conservation strategies and species limitations due to human development. The 2019 Joshua tree species assessment explicitly defines these variables as a reflection of conservation potential, or the means of establishing funds and implementation (Sirchia, Hoffman, and Wilkening 2018). For this reason, land use criteria, such as surface management and land cover, were classified to represent the maximum conservation potential for the Californian JTF. Table 4 describes an overview of suitable environmental criteria utilized in this analysis.

Table 4. Land use criteria

Criteria	Description	Suitable Description
Surface Management	Landownership as defined by the Bureau of Land Management	Federal agencies, state, and other environmental communities that adopted laws and ordinances that protect Joshua trees (NPS, BLM, ST, USFS, etc.)
Land Cover	Standardized National Land Cover Classifications, defined by vegetation type, development density, and agricultural use.	Areas that provide limited habitat distribution and support resiliency in the local population (Deciduous Forest, Developed, Open Space, Evergreen Forest, Grassland/Herbaceous, Mixed Forest, Shrub/Shrub, etc.)

Source: Sirchia, Hoffman, and Wilkening (2018) verified by literature review

2.1.4.1 Surface management

Surface Management is a standardized land classification scheme that speaks to the land ownership of a particular area. Land ownership provides insight into the ability to supply funds and implement climate adaptation strategies. Management areas of high conservation potential are defined as areas within the National Park Service (NPS), BLM's Areas of Critical Environmental Concern (ACEC), and other wilderness designations (Sirchia, Hoffman, and Wilkening 2018). These represent protected natural lands that adopted a policy that potentially protects Joshua trees. For this reason, land ownership of the associated lands, federal agencies, state, and other open space communities are defined as suitable in this research.

2.1.4.2 Land cover

Land cover, like surface management, is a standardized land classification scheme that represents vegetation type, development, and agricultural use. The land cover speaks to the areas that provide limited habitat disruption and supports resiliency in the local population. Land cover classes that provide the most suitable habitat for Joshua trees include Deciduous Forest, Developed, Open Space, Evergreen Forest, Grassland/Herbaceous, Mixed Forest, and

Shrub/Shrub (Sirchia, Hoffman, and Wilkening 2018). As these areas provide natural open spaces with suitable vegetation.

2.2 Suitability Analysis

Multi-Criteria Decision Analysis (MCDA) is a geospatial technique used to select a suitable location for various environmental and economic problems. The flexibility of this method allows the analyst to assign importance to variables by defining various weights based on suitability (Mitchelle 2012). This type of suitability analysis considers a variety of criteria, or characteristics of an ideal location, which can be tailored to produce a multitude of suitability scenarios. The suitability model conducted takes advantage of the analytical flexibility of MCDA by incorporating 16 unique climate, environment, and land use criteria. Resulting in a wide range of climate refugia that could be used to inform conservation strategies for the JTF.

2.2.1 Weighted Overlays

A weighted overlay is a geospatial tool used to combine multiple data layers to produce a summation of all layers to the final output. This method of analysis is commonly utilized to define a range of suitable locations. Particularly useful to evaluate alternative scenarios by altering the relative importance of the various criteria (Mitchelle 2012). This methodology is less computational and can be useful when seeking a specific solution or value (Esri 2020). The ArcGIS Pros weighted overlay tool was used to produce a suitable surface on which conservation strategies should be focused to ensure the longevity of the JTF.

2.2.2 Weights

The assignment of weights, or importance, associated with each criterion was a crucial step in this research. A few methods utilized in previous research were considered to ensure accurate weighted assignments. For example, a suitability model created in 2017 utilized an analytical hierarchy process, a pairwise comparison of criteria used to assign criteria importance in maize productivity (Wanyama 2017). Although this method permitted a hierarchical structure for criteria based on psychological observations it was limited by aggregational bias as criteria with more sub-categories were prioritized (Ishizaka and Labib 2011). For this reason, this research assigned weights based on expert opinion derived from the literature review.

Climate conditions are the most impactful factors that influence the Joshua tree population and survival. Summer maximums and winter minimums in both temperature and precipitation patterns are explicitly described as constraints to current Joshua tree populations (Sirchia, Hoffman, and Wilkening 2018). The significant importance of precipitation is substantiated by several other studies, Gucker (2006) and Wilkening, Hoffmann, and Sirchia (2020), as timely showers are indicative of sustained reproductive cycles. Species assessments also specified that annual and summer rainfall is necessary for cacti to absorb the water immediately as well as replenish underground moisture for drier seasons (Broham 2022). Thus, precipitation is weighted the highest, with higher importance assigned to summer precipitation. Whereas, temperature is weighted second highest, with higher importance assigned to annual and winter temperatures.

Similarly, environmental variable weights were defined based on discussions in the literature review. The most important variables discussed in detail across references include habitat quality and wildfire regimes. These factors are attributed, by species assessments, as the largest threat facing Joshua tree habitat as wildfire, drought, and habitat loss may affect the resiliency of the species (Sirchia, Hoffman, and Wilkening 2018). For this reason, habitat quality and burn probability were assigned the highest weight of all the environmental variables.

Topological variables, elevation ranked highest, are also considered important to Joshua tree physiology as it is correlated with precipitation and temperature patterns. Altogether this research informed the assigned weight scheme, in which precipitation variables were weighted highest followed by temperature, wildfire, habitat quality, and topological data.

2.3 Ideal Location

To summarize the ideal location for the Joshua tree is defined as protected areas of land, among alluvial fan deposits of igneous origin, across biodiverse regions of gravelly well-drained soil. Topologically these cacti prefer lower elevation ranges of gentle slopes and high sun exposure. As well as thrive in areas with moderately hot summers, cold winters, annual summer showers, and relatively wet winters.

Although the culmination of all these factors is important for the Joshua tree life cycle, climate variables are assigned the highest importance. Summer precipitation weighed the highest, followed by annual and winter precipitation. Second, are temperatures with higher importance assigned to annual and winter temperatures. Environmental factors, which include habitat quality, burn probability, and elevation were assigned the next highest weight.

Chapter 3 Methods

This chapter describes the analytical strategies and methods performed to identify suitable climate refugia for the Californian JTF. The following sections provide a detailed description of ontology, data, and tools utilized in this research, chosen based on the topics discussed in Chapter 2. Multi-Criteria Decision Analysis (MCDA) via weighted overlay was performed to select a suitable location for climate refugia across the study area.

3.1 Research Design

The research design was created based on the literature review discussed in Chapter 2. The overall workflow, shown in Figure 5, shows the broad steps performed to produce a suitable surface. First, an ideal Joshua tree habitat was defined, followed by data acquisition. A total of 9 datasets were collected to represent 3 categories of 16 criteria all informed by previous studies. This data was then calibration through hard constraints and reclassification. Before overlay, hard constraints were applied first using surface management, land cover, and geology data to identify areas with high conservation potential. All data layers were clipped to this intermediate result and projected State Plane Coordinate System (SPCS), NAD 1983 California (Teale) Albers (Meters). Next, all data were reclassified into a suitability scale using equal intervals with several precipitation and topological constraints applied. Equal intervals were used to assign suitability due to a lack of expert knowledge and to avoid unnecessary bias. Finally, several weighted overlays were then performed to create sub-models or suitability surfaces that combined climate and environmental variables.

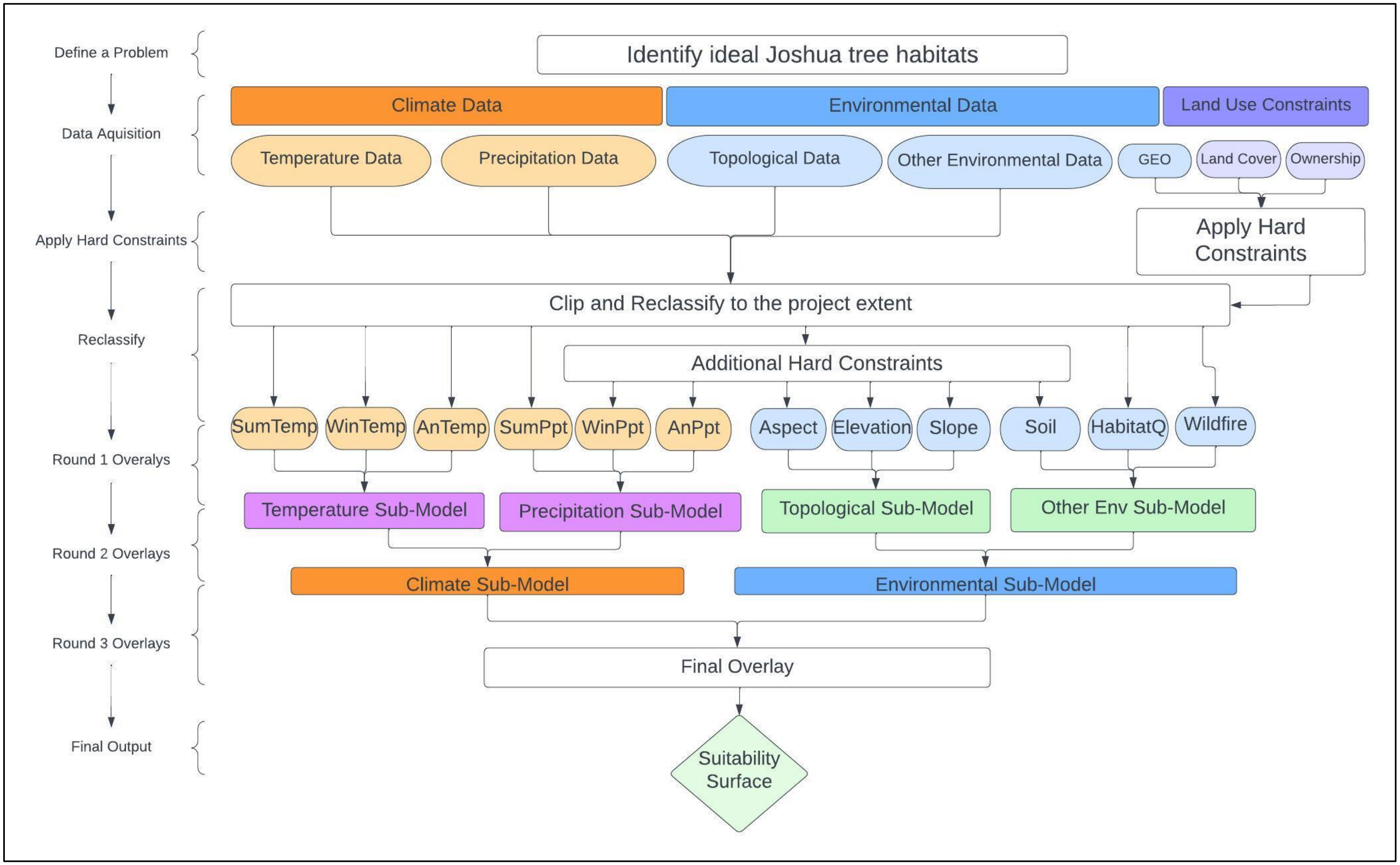

Figure 5. Overlay workflow

3.2 Data Overview

Data needs are centered around climate, environmental, and land use variables that play a key role in the JTF ecosystem. The data presented in Table 5 were collected to represent the necessary ecological, climatological, and topological variables crucial for Joshua tree survival. Each dataset was acquired from an open data source of various authoritative agencies.

Table 5. Data table

Category	Variable	Year	Source	Title	Description
Environmental	Soil	2023	USDA	Gridded Soil Survey Geographic (gSSURGO) Database	Derived from national, regional, and statewide resource planning and analysis of soil data. Provides standardized drainage and sand percentage.
	Slope/Aspect/Elevation	2022	Esri	Ground Surface Elevation – 30m	Combined 1 arc-second DEM datasets from the USGS's 3D Program, provide numeric values representing ground surface heights, based on a digital terrain model.
	Geology	2009	USGS	California Geologic Map Dataset	California-specific geologic datasets that provide geologic units and structural features with lithology, age, and data structure.
	Wildfire	2020	USDA	Wildfire Risk to Communities: Burn Probability (or Wildfire Likelihood)	Datasets of landscape-wide annual burn probability (or wildfire likelihood) for the United States, based on vegetation and wildland fuels data from LANDFIRE 2014 (version 1.4.0).

	Habitat quality	2018	CDFW	Species Biodiversity – Areas of critical environmental	A summary of species biodiversity in California based on species occurrence and distribution information (includes amphibians, aquatic macroinvertebrates, birds, fish, mammals, plants, and reptiles). Areas are ranked (1-5) according to native species richness, rare species richness, and irreplaceability.
Climate	Projected temperature	2020	WorldClim	CMIP6 Future climate data (degrees Celsius)	WorldClim v2 is a downscaled 20-year summary of monthly projected climate datasets (2041 -2060) from CMIP6. Includes projected temperature and precipitation of Model for Interdisciplinary Research on Climate (MIROC), SSP 8.5.
	Projected precipitation	2020	WorldClim	CMIP6 Future climate data (millimeter)	
Land use	Land cover	2015	USGS	USA NLCD Land Cover	Displays land cover for the United States based on 20 classifications, derived from vegetation type, development density, and agricultural use.
	Surface Management	2022	BLM	CA BLM National Surface Management Agency Area Polygons	Depicts land management agencies and land ownership in the United States.

3.2.1 Overall Data Preparation

The various raw datasets underwent similar preparation that included data projection clipping, and reclassification. First, each dataset was projected to the State Plane Coordinate System (SPCS), NAD 1983 California (Teale) Albers (Meters). This California-specific projection is recommended for all statewide analyses by the California Department of Fish and Wildlife (CDFW) to minimize distortion and capture regional patterns (Patterson 2018). Next, the data underwent recalibration to ensure consistent data type, raster format, resolution, 30 meters or 900 meters, and scale, ranked based on suitability. The following section describes in detail all data characteristics and preparation procedures performed before overlay.

3.2.2 Climate Data

As discussed in previous sections Joshua trees thrive in areas with moderately hot summers, cold winters, annual summer showers, and relatively wet winters. For this reason, projected monthly and annual climate datasets were utilized to represent crucial climate variables.

WorldClim v2 is a downscaled 20-year summary of monthly projected climate data from CMIP6. The downloaded Geotiff files represent projected temperature and precipitation in 2041-2060 derived from MIROC worst-case scenario, SSP 8.5. Monthly values of maximum temperature and precipitation are displayed at 900-meter resolution across the entire study area (Table 6).

Table 6. Climate data description

Criteria	Resolution	Format	Extent	Data description
Mean summer temperatures (C°)	900m	raster	global	Averaged maximum mean monthly temperature of July, August, and September 2041-2060
Mean winter temperatures (C°)	900m	raster	global	Averaged maximum mean monthly temperature of January, February, and March 2041-2060
Mean annual temperatures (C°)	900m	raster	global	The maximum annual mean temperature of 2041-2060
Mean summer precipitation (mm)	900m	raster	global	Averaged maximum mean monthly precipitation of July, August, and September 2041-2060
Mean winter precipitation (mm)	900m	raster	global	Averaged maximum mean monthly precipitation of January, February, and March 2041-2060
Mean annual precipitation (mm)	900m	raster	global	Maximum annual mean precipitation of 2041-2060

Source: WorldClim v2 2020

All monthly and annual rasters were projected using a standardized 900m snap raster to ensure a precise overlay. The raster calculator tool was then used to create all seasonal variables by averaging the monthly means of the associated months. Summer precipitation and temperature for example were derived from the maximum average July, August, and September precipitation and temperature. Similarly, winter precipitation and temperature were derived from WorldClim winter months, which include January, February, and March.

3.2.3 Environmental Data

As discussed in Chapter 2, the ideal environment for the Joshua tree is defined as protected areas of land, among alluvial fan deposits of igneous origin, across biodiverse regions of gravelly well-drained soil. Topologically these cacti prefer lower elevation ranges of gentle slopes and high sun exposure. Table 7 describes the various datasets utilized to represent all important environmental criteria.

Table 7. Environmental data description

Criterion	Resolution	Format	Extent	Data description
Aspect	30m	Raster	USA	Created from the surface parameter tool in ArcGIS Pro using Esri's 2022 Ground Surface Elevation
Elevation	30m	Raster	USA	Created from Esri's 2022 Ground Surface Elevation
Slope	30m	Raster	USA	Created from the surface parameter tool in ArcGIS Pro using Esri's 2022 Ground Surface Elevation
Soil	10m	Raster	USA	Created from the 2020 gSSURGO database using the soil data development toolbox in ArcGIS Pro
Geology	1:750,000	Vector	CA	Created from the 2016 California geologic map
Wildfire	30m	Raster	CA	Created from the Wildfire Risk to Communities: Burn Probability (or Wildfire Likelihood) raster
Habitat Quality	2.5 square mile hexagon grid	Vector	CA	Created from the 2018 CDFW Species Biodiversity – Areas of Conservation Emphasis (ACE) [ds2769] dataset

The 2022 Ground Surface Elevation dataset is a mosaic of 3DEP 1 arc-second geotiffs from the USGS's 3D Program. This nationwide dataset was accessed from Esri's Living Atlas as 30m raster files. It provided an elevational surface, or numeric values of ground surface heights, for the entire project area (Esri 2022). The surface parameter tool, in ArcGIS Pro, was then utilized to create an aspect and slope surface from this dataset.

The USDA 2023 Gridded Soil Survey Geographic (gSSURGO) Database is derived from national, regional, and statewide resource planning and analysis of soil data. This data was used to represent two soil characteristics: sand percentage and water drainage class. Soil maps were produced by the soil data development toolbox which joined gSSURGO vector and tabular data. Sand percentage and drainage class maps were then projected and clipped to the intermediate result, using a 30m snap raster. Unfortunately, this data is incomplete in areas where detailed soil survey maps are not available, despite this gSSURGO is the most recent and complete soil data for California.

The USGS 2016 California Geologic Map Dataset was utilized to represent the geologic constraints of this project. This California-specific dataset provided geologic units and structural features with lithology, age, and data structure. (USGS 2016). The data was downloaded from the USGS online spatial data portal as a vector file. The shapefile was dissolved, converted a to raster format, and finally clipped to the project extent to create a finalized geologic surface.

The USDA 2020 Wildfire Risk to Communities: Spatial datasets of landscape-wide wildfire risk components for the United States; Burn Probability (or Wildfire Likelihood) was utilized to represent wildfire criteria. This wildfire constraint is defined as the probability of burn or the likelihood of intensive or frequent wildfires based on fuel structure. Based on vegetation and wildland fuels data from LANDFIRE 2014 (version 1.4.0) this raster file presents the annual probability of wildfire burning in a specific location (USDA 2020). The data was projected and clipped to the intermediate results, areas of high conservation potential, using a 30m snap raster.

The 2018 CDFW Species Biodiversity - Areas of Conservation Emphasis (ACE) [ds2769] dataset is a summary of the best available information on species biodiversity in California. This dataset is based on species occurrence and distribution information for amphibians, aquatic macroinvertebrates, birds, fish, mammals, plants, and reptiles. ACE biodiversity rankings (1-5) are a combination of overall native species diversity, rare species richness, and irreplaceability. The vector data was projected and converted to raster format using a 30m snap raster.

3.2.4 Land Use Data

As described in Chapter 2, these variables are hard constraints that identify conservation potential or area with means of establishing conservation funds and implementation. To ensure the accessibility of climate adaptation, land use, and management are represented using two land management datasets. Table 8 describes the various datasets utilized to represent all important land use criteria.

Table 8. Land Use data description

Criteria	Resolution	Format	Extent	Data description
Surface Management	1:500,000 scale	vector	USA	Created from BLM Surface management. Federal or state lands, based on Admin Agency Code, were extracted
Land Cover	30m	raster	USA	Created from USA NLCD Land Cover. Deciduous Forest, Developed, Open Space, Evergreen Forest, Grassland/Herbaceous, Mixed Forest, Shrub/Shrub were extracted

Source: Data Acquisition

The BLM 2022 Surface Management Agency dataset displays land ownership and land management agencies for the entire United States. Surface Management is a standardized land classification scheme that correlates the ability to supply funds and implement climate adaptation strategies. This data was projected and clipped to the California boundary creating surface management across the project area.

The 2015 USA National Land Cover Database displays land cover for the entire United States. This land management scheme was based on 20 classifications, derived from vegetation type, development density, and agricultural use. This data was projected and clipped to the California boundary creating land cover across the project area.

3.3 Hard Constraints

Hard constraints were applied to surface management, land cover, and geology. Federal or state lands were extracted from surface management data that define areas that can provide adequate conservation funds and plans. These include environmental agencies such as the National Park Service (NPS), the Department of Defense, the Bureau of Land Management, the National Landscape Conservation System, State (ST), Forest Service (FS), United States Forest Service (USFS), and Bureau Indian Affairs (BIA). Figure 6 shows these regions of suitable surface management extracted from the overall dataset as areas that provide increased conservation potential.

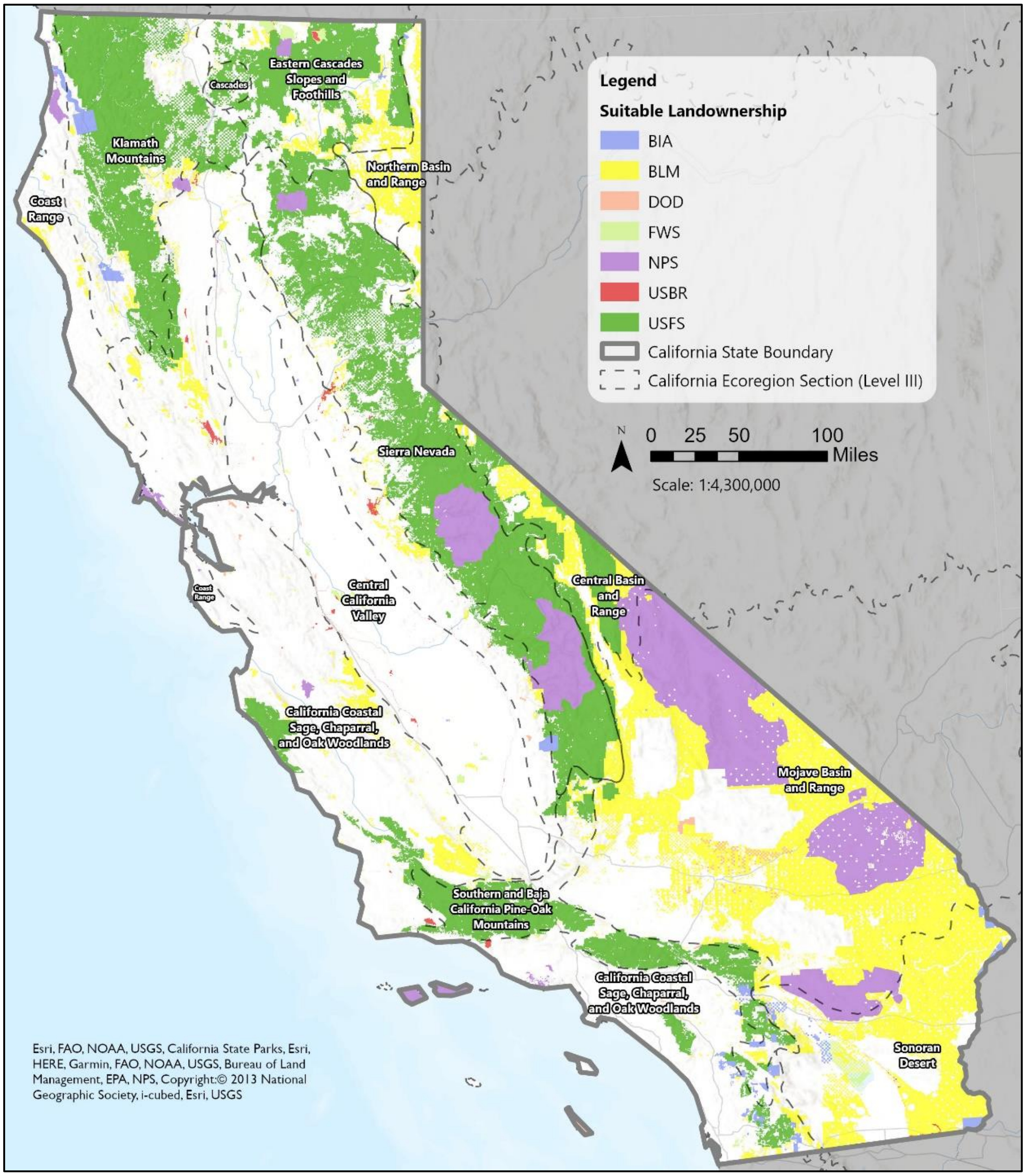

Figure 6. Suitable surface management

Land cover with wilderness designation was then extracted from NLCD. These wilderness areas provide Joshua trees with limited habitat disruption and support resilient local populations. These areas include Deciduous Forest, Developed, Open Space, Evergreen Forest, Grassland/Herbaceous, Mixed Forest, and Shrub/Shrub. Figure 7 shows areas of suitable land cover that extracted from the overall dataset as areas that provide increased conservation potential.

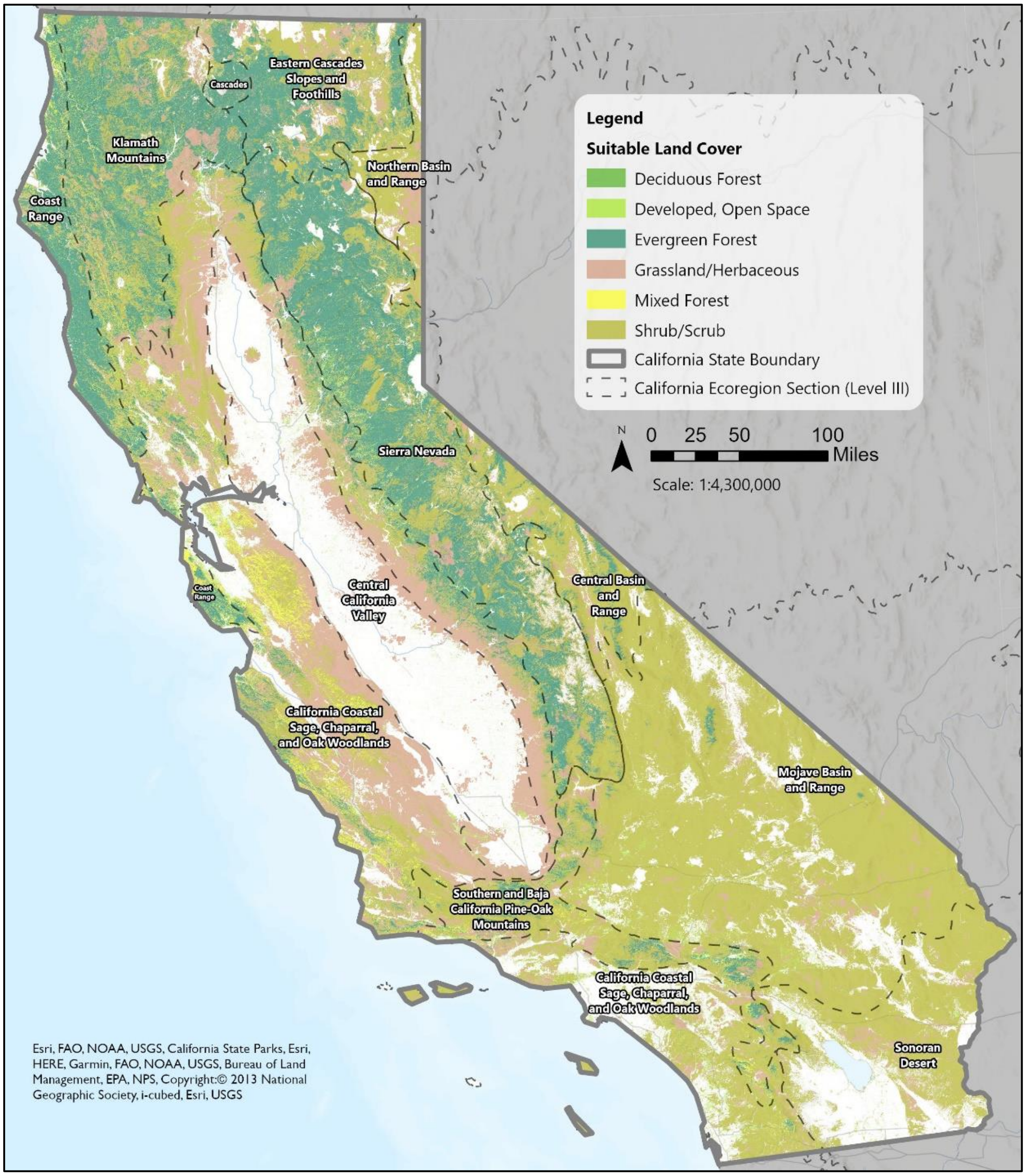

Figure 7. Suitable land cover

Finally, alluvial units were extracted from the geologic dataset based on unit link codes or geologic descriptions (Figure 8). These units include Alluvial sediments; Eolian sediments;

Eolian sediments; Playa sediments; (UnitLinkCode: CAQ;0, CATv2;0, CATv16;0, CATv15;0, CATR1;0, CAQv7;0, CAQs2;0, CAQPOc;0, CAQ;0). Figure 8 shows regions of suitable geology extracted and used in conjunction with land use criteria to apply hard constraints.

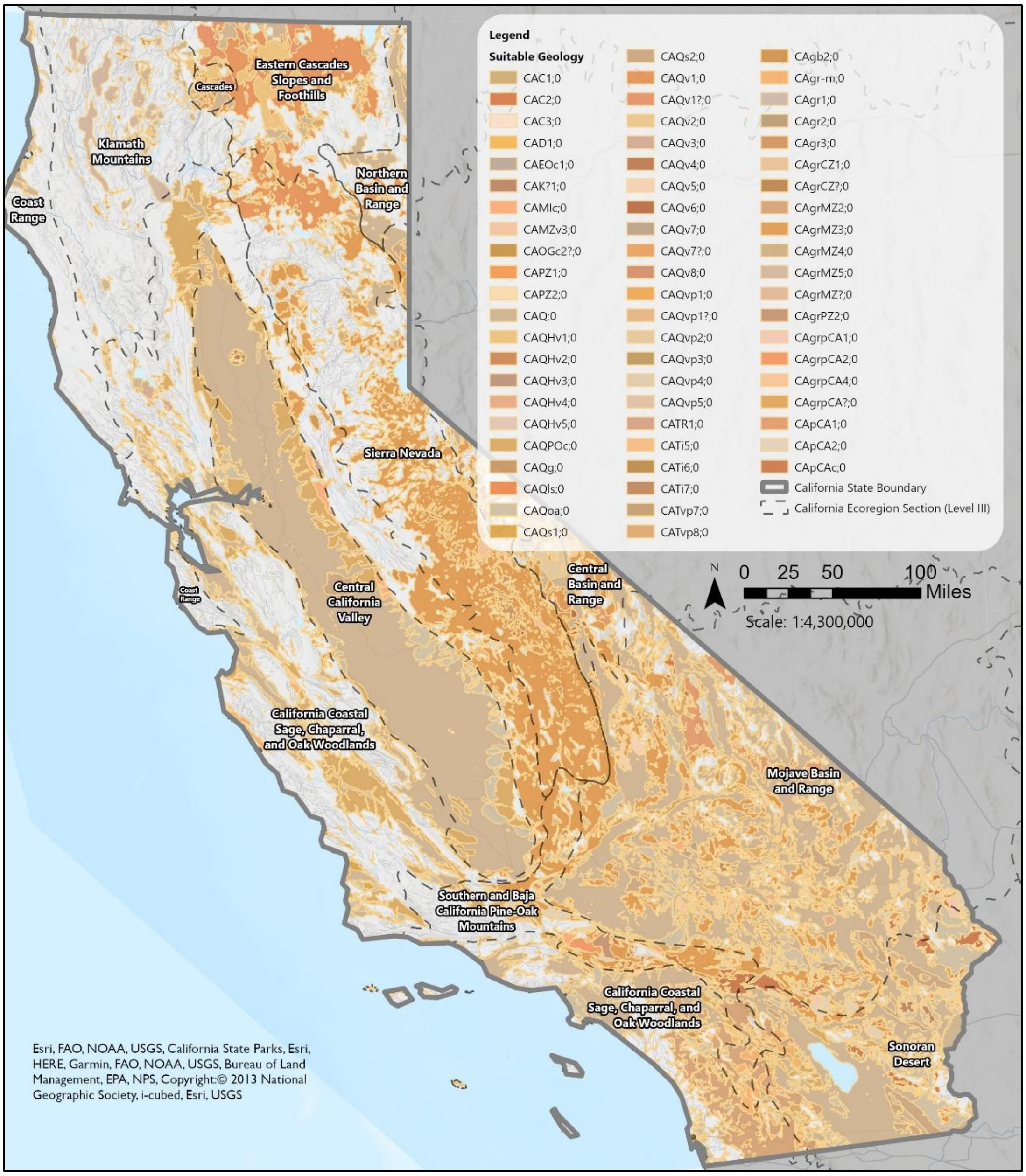

Figure 8. Suitable geology

To capture the overlaps of all three criteria the count overlapping feature tool was used to combine surface management, land use, and geology (Figure 5-8). The overlapping polygons were then dissolved into this intermediate result, as shown in Figure 9. These areas of conservation potential, shown in blue, were used as hard constraints to narrow down the remaining data (Figure 9).

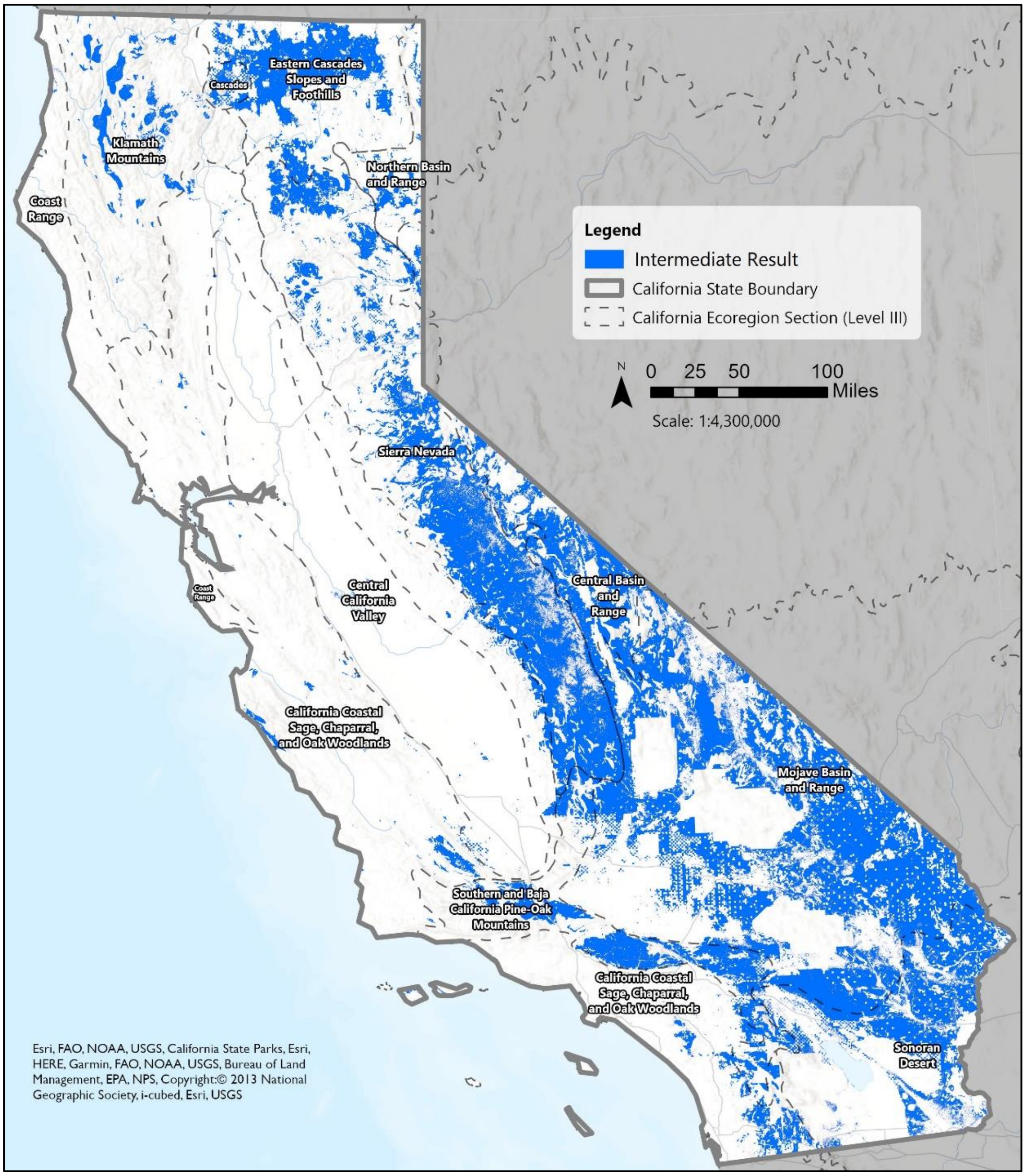

Figure 9. Applied hard constraints

3.4 Data Reclassification

To ensure meaningful overlays, each source layer was reclassified into a standardized suitability scale. The relative suitability scale used for this project was a simple interval scale of 1-5, (1 is less suitable and 5 is most suitable). This allows for a consistent measure of values, allowing all the datasets to mathematically combine into meaningful results (Greene et al. 2011). As part of the reclassification process, all data outside of the suitability range, as defined for each criterion in the literature, were removed from the analysis as not suitable. These non-suitable areas were removed from data layers in the reclassification stage and defined as no data. The remaining data was reclassified using equal intervals, given the lack of previous literature utilizing MCDA and specifics for Joshua tree habitat. Equal intervals were used to avoid model bias when classifying as other methods, such as the Jenks method, could introduce unnecessary bias.

3.4.1 Reclassification of Climate Data

All climate variables were reclassified into the simple suitability scale 1-5, as determined in the literature review in Chapter 2. Reclassification using equal intervals was used, given the lack of previous literature. In addition, all data outside of the suitable range were removed from the analysis as not suitable (hard constraint).

The ideal mean summer temperature for Joshua trees ranges from 20 to 40 degrees Celsius, with mild temperatures assigned as the most suitable. However, currently, projected temperatures are suspected to be outside of Joshua tree needs, shown in Table 9. Suitability is assigned to the data outside this ideal range as the literature review suggests species resiliency to summer heat waves. Categories were created from equal intervals with higher suitability assigned at lower temperatures (Table 9).

Table 9. Reclassified mean summer temperature

Mean Summer Temperature (°C)	Suitability Scale
96.0 -113.3	1 (least suitable)
97.0-84.0	2
85.0-72.0	3
62.0-73.0	4
62.0-39.8	5 (most suitable)

Figure 10 displays the combined temperature of summer months provided by WorldClim v2. This data represents the projected mean summer temperature in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

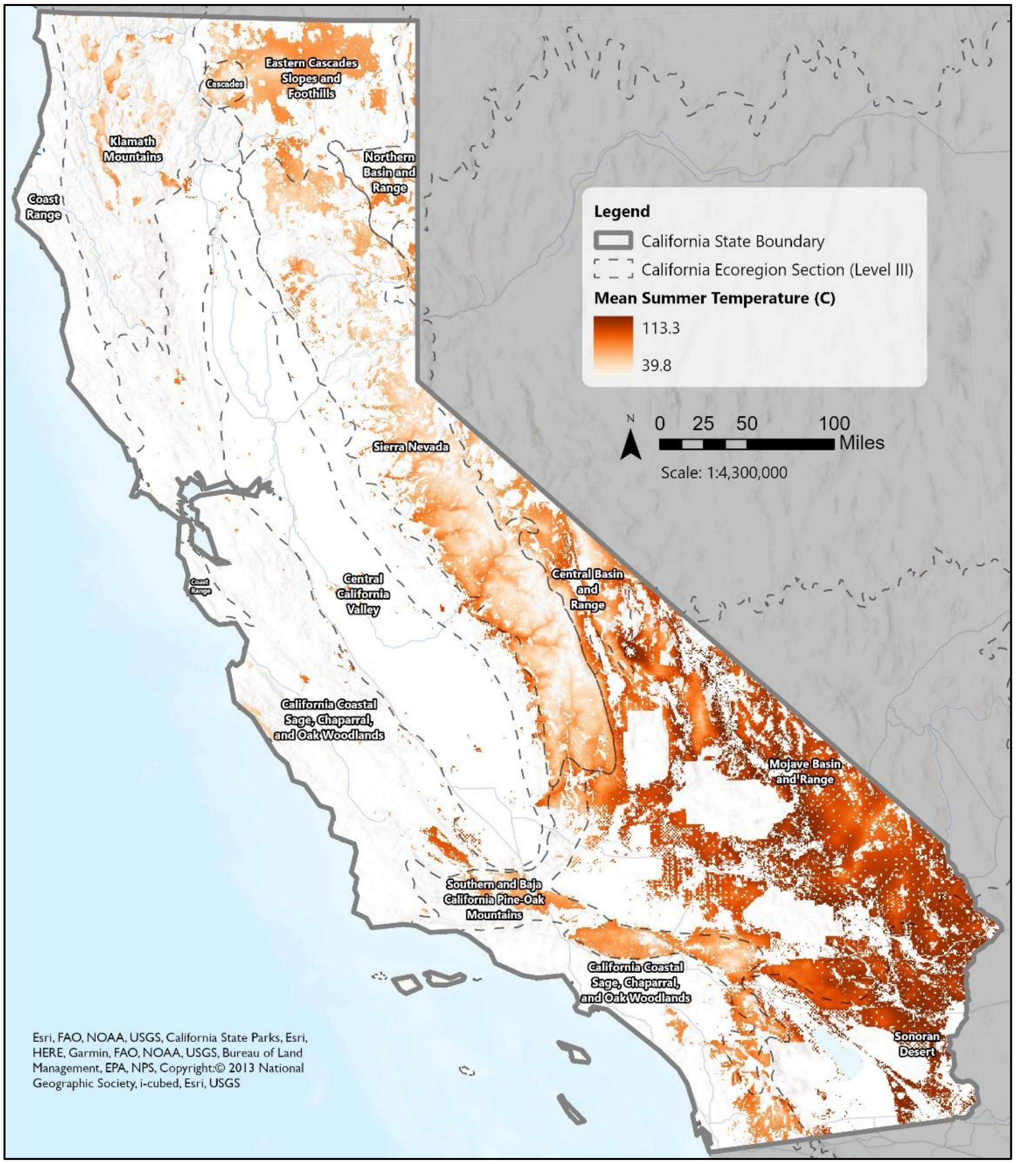

Figure 10. Raw mean summer temperature (WorldClim 2020)

Projected summer temperatures, of 39.8 - 113.3 degrees Celsius, were reclassified into equal intervals with higher suitability assigned at lower temperatures (Table 9). Figure 11 shows the reclassified WorldClim v2 data that represents suitable summer temperatures.

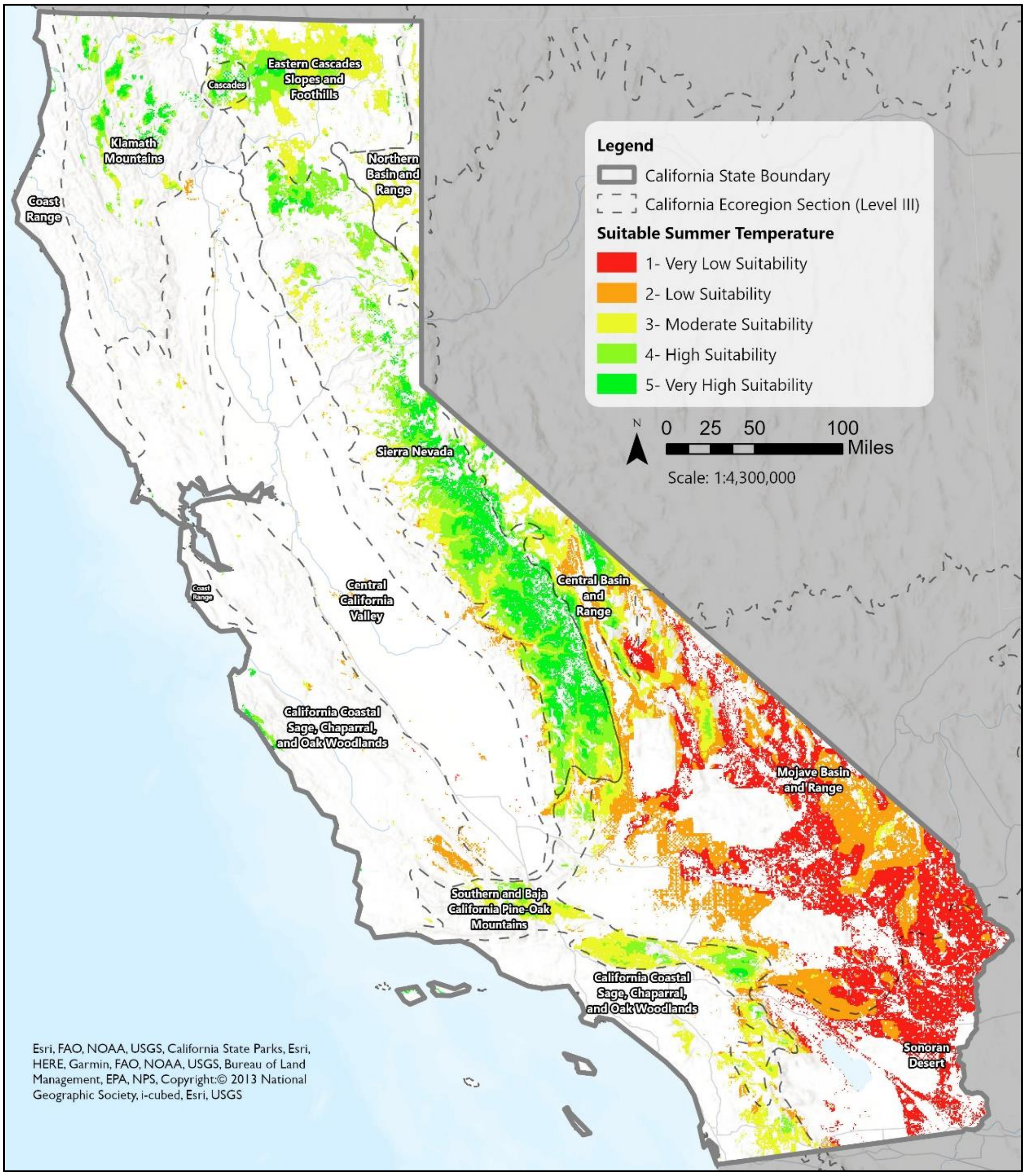

Figure 11. Reclassified mean summer temperature

The ideal mean winter temperature ranges from -11 to 3 degrees Celsius, min of 4 degrees Celsius. Like summer temperature, data outside this ideal range was not removed as Joshua trees are resilient to extreme temperatures. Categories were created using equal intervals with higher suitability assigned at lower temperatures (Table 10).

Table 10. Reclassified mean winter temperature

Mean Winter Temperature (°C)	Suitability Scale
48.840- 63.1333	1 (least suitable)
38.960 - 48.840	2
28.230 - 38.960	3
17.820 - 28.230	4
-2.50 - 17.820	5 (most suitable)

Figure 12 displays the combined temperature of winter months provided by WorldClim v2. This data represents the projected mean winter temperature in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

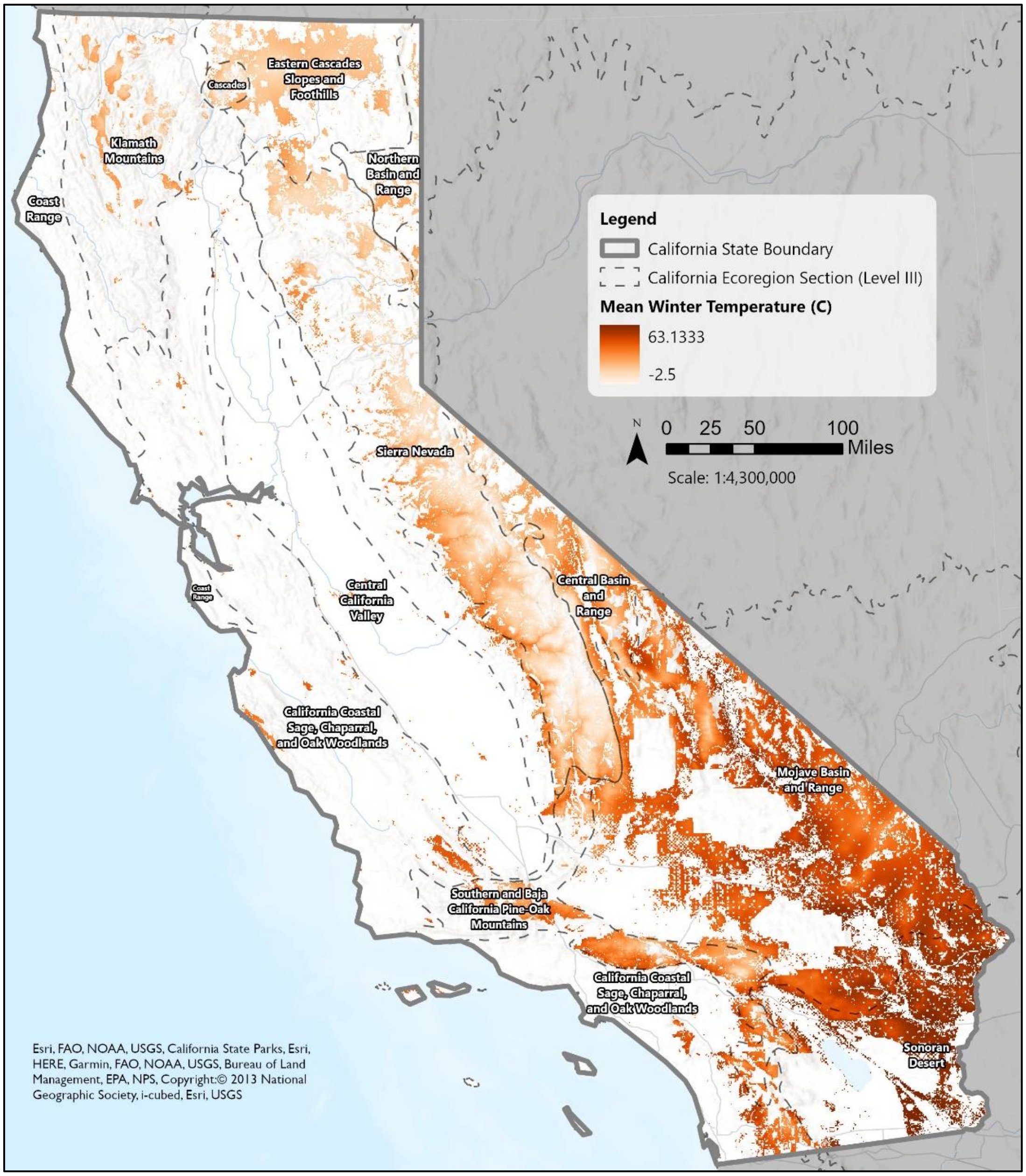

Figure 12. Mean winter temperature (WorldClim 2020)

Projected winter temperatures, of -2.5 - 63.1333 degrees Celsius, were reclassified into equal intervals with higher suitability assigned at lower temperatures (Table 10). Figure 13 shows the reclassified WorldClim v2 data that represents suitable winter temperatures.

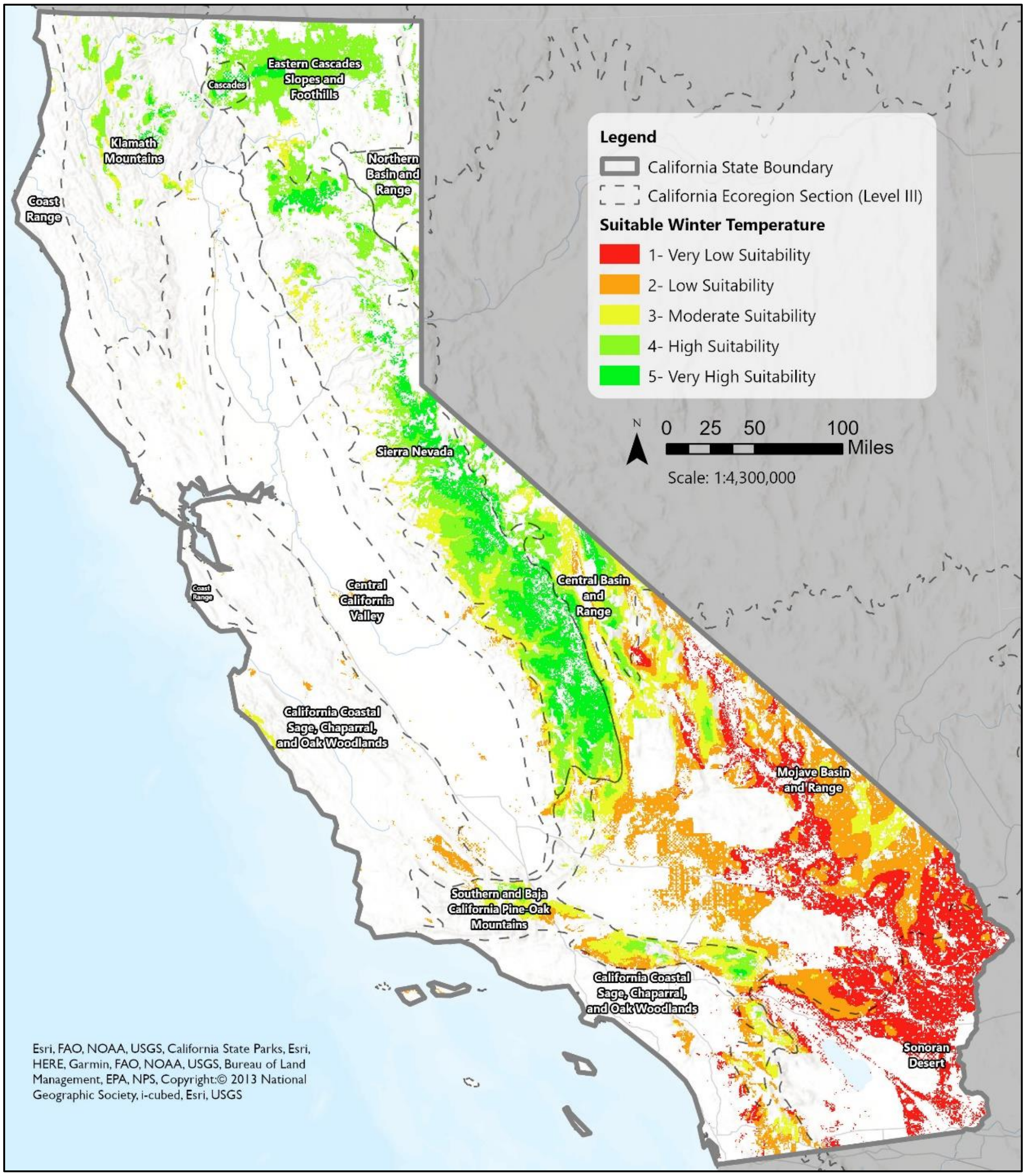

Figure 13. Reclassified mean winter temperature

The ideal mean annual temperature ranges from 11 to 59 degrees Celsius with the mild temperatures assigned as the most suitable. Data outside this ideal range were not removed because of the resiliency of Joshua trees to the extreme temperatures. Categories were created from equal intervals with higher suitability assigned at lower temperatures (Table 11).

Table 11. Reclassified mean annual temperature

Mean Annual Temperature (°C)	Suitability Scale
22.1 - 27.6	1 (least suitable)
16.6 - 22.1	2
11.1 - 16.6	3
5.6 - 11.1	4
0.1 - 5.6	5 (most suitable)

Figure 14 displays the raw annual temperature provided by WorldClim v2. This data represents the projected mean annual temperature in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

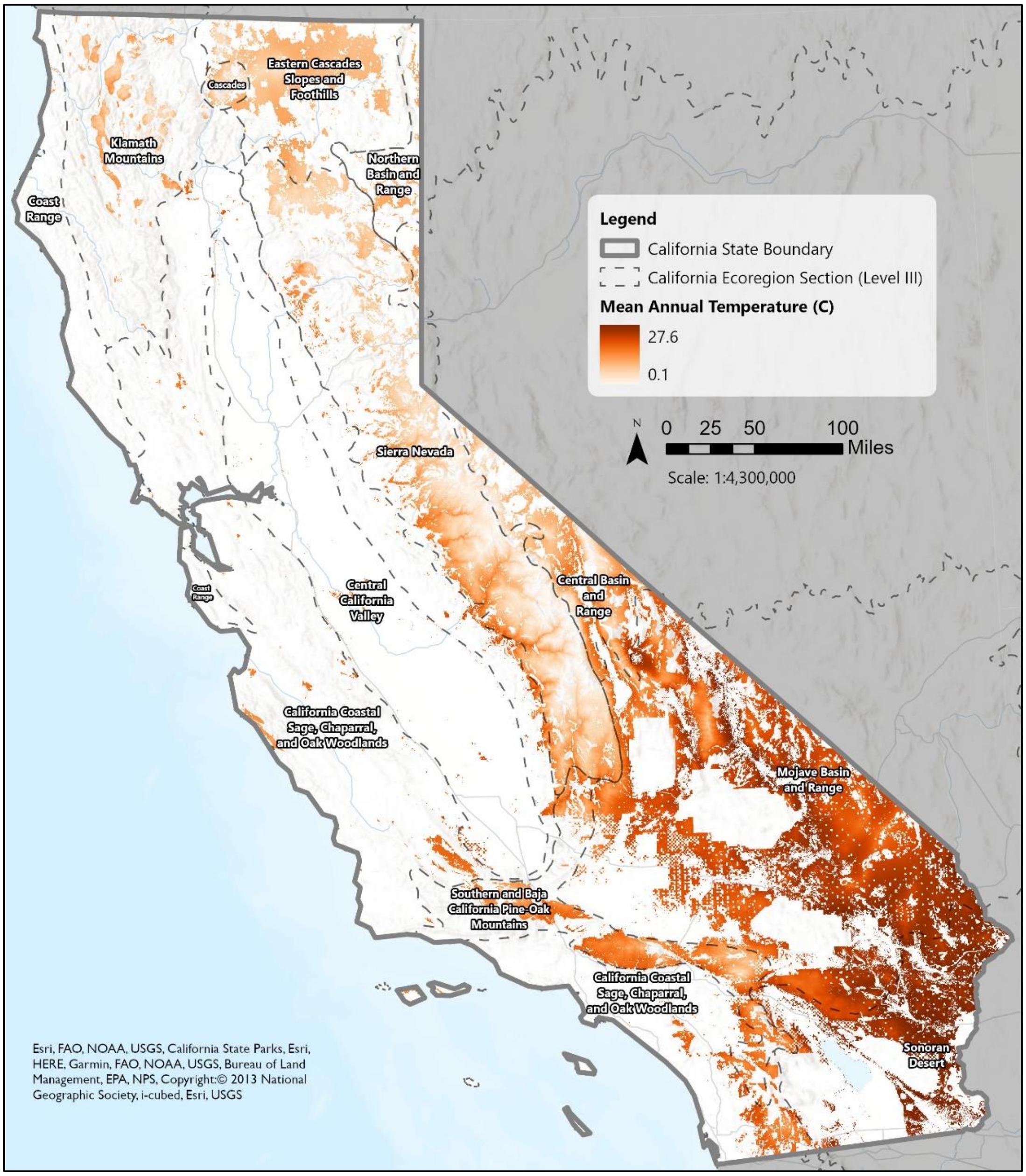

Figure 14. Mean annual temperature (WorldClim 2020)

Projected annual temperatures, of 0.1 – 27.6 degrees Celsius, were reclassified into equal intervals with higher suitability assigned at lower temperatures (Table 11). Figure 15 shows the reclassified WorldClim v2 data that represents suitable annual temperatures.

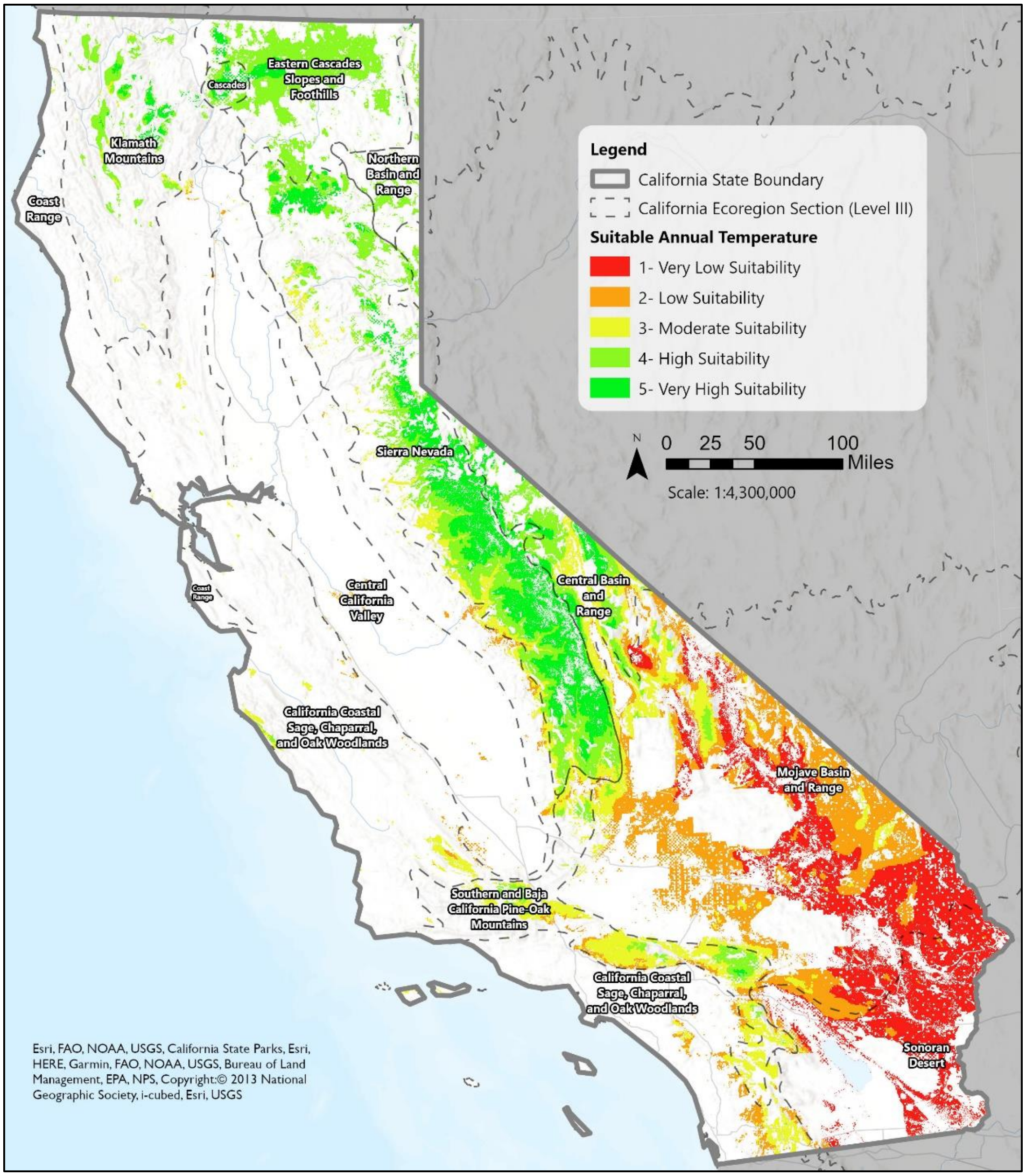

Figure 15. Reclassified mean annual temperature

Unfortunately, the exact range of suitable summer rainfall is not well documented, however, wetter summers positively impact Joshua tree distribution. Categories were created from equal intervals with higher suitability assigned at higher precipitation (Table 12).

Table 12. Reclassified mean summer precipitation

Mean Summer Precipitation (mm)	Suitability Scale
3 - 20	1 (least suitable)
20 - 32	2
32 - 44	3
44 - 60	4
60 - 108	5 (most suitable)

Figure 16 displays the combined monthly precipitation of the summer months provided by WorldClim v2. This data represents projected mean summer precipitation in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

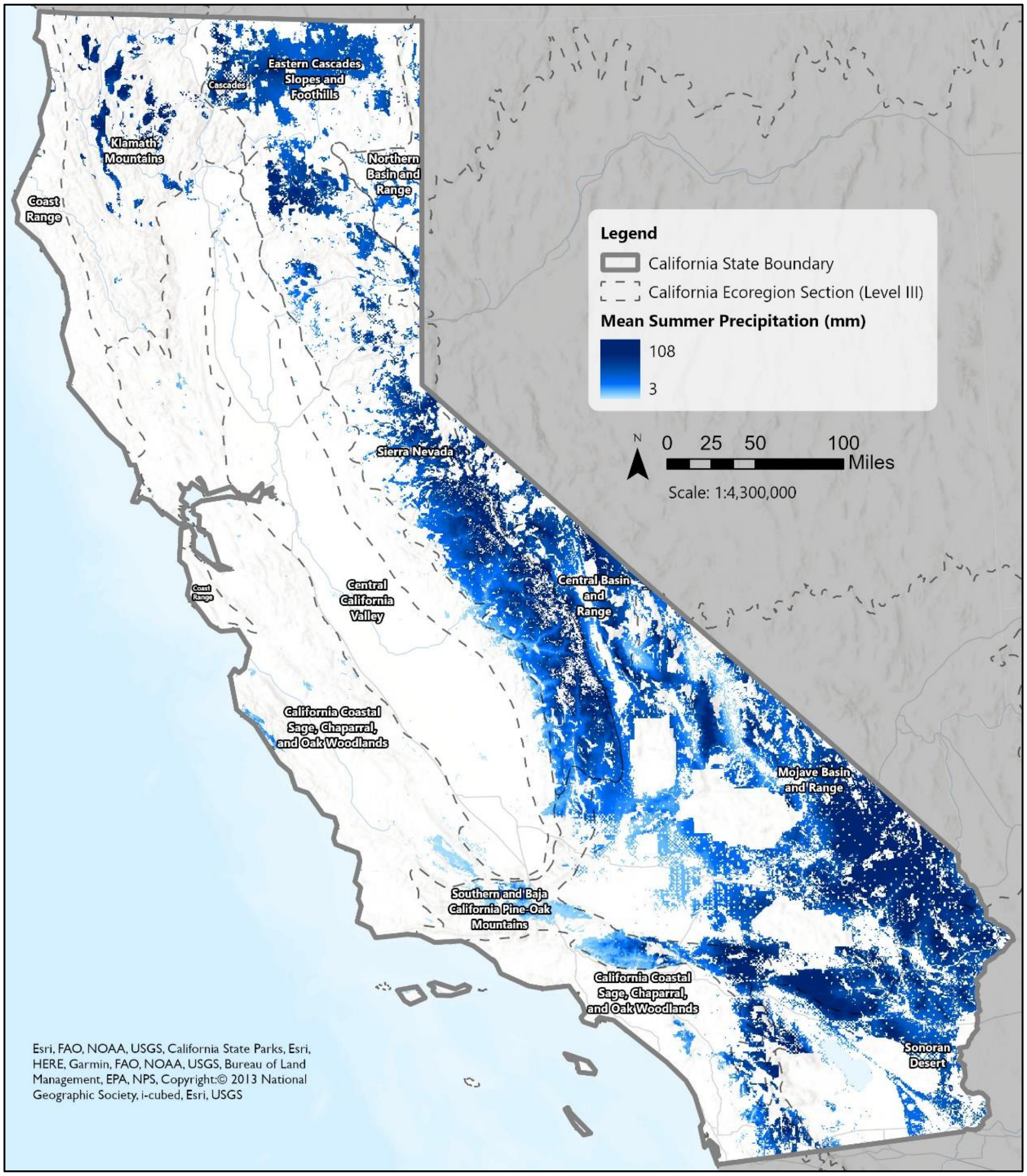

Figure 16. Mean summer precipitation (WorldClim 2020)

Projected summer precipitation, of 3 – 108 millimeters, was reclassified into equal intervals with higher suitability assigned at higher precipitation (Table 12). Figure 17 shows the reclassified WorldClim v2 data that represents suitable summer precipitation.

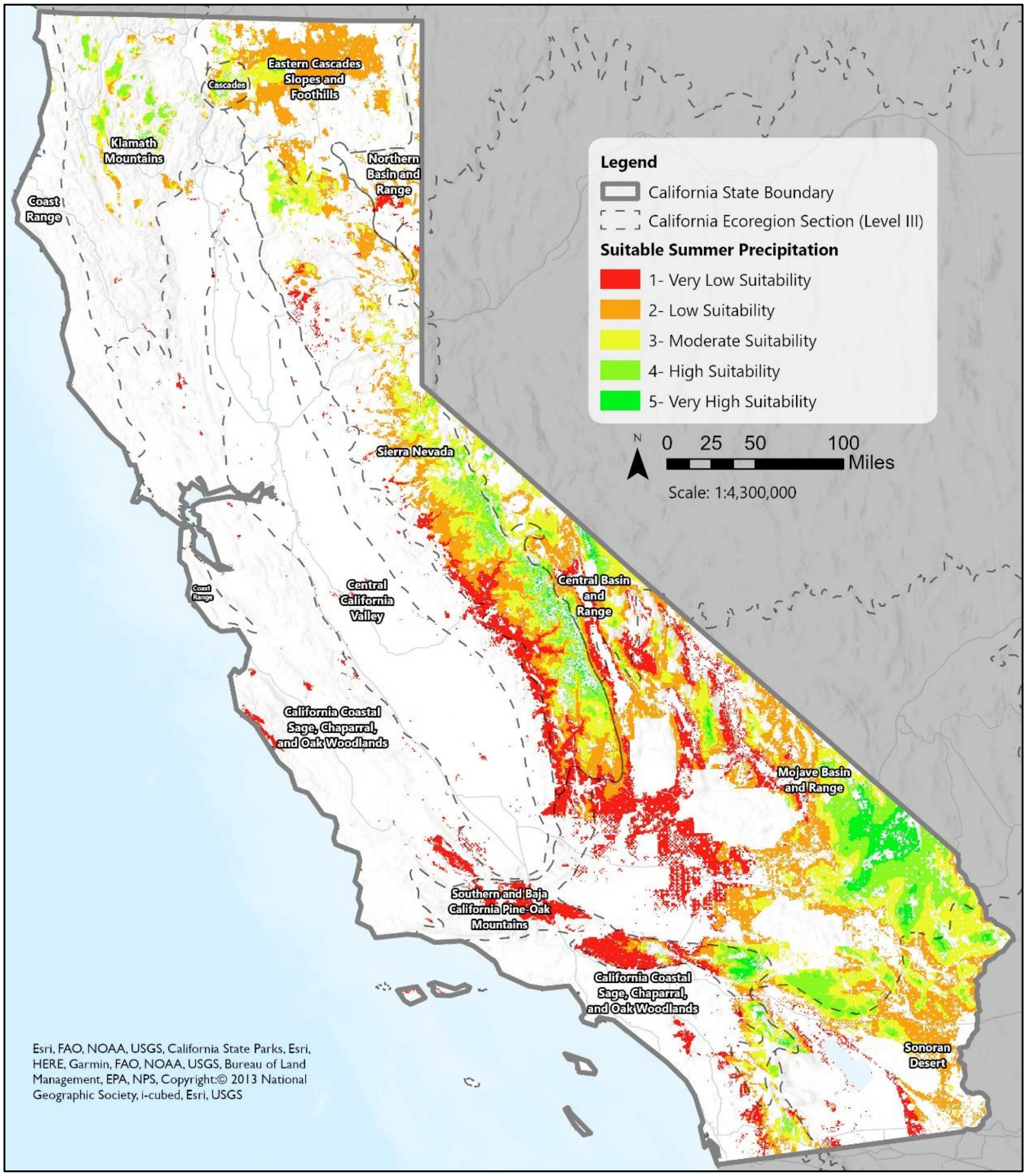

Figure 17. Reclassified mean summer precipitation

The minimum winter precipitation is identified as 82.4 millimeters with wetter winters positively impacting Joshua tree distribution. All data below 80 millimeters were removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data. The remaining data were reclassified from equal intervals with higher suitability assigned to higher precipitation (Table 13).

Table 13. Reclassified mean winter precipitation

Mean Winter Precipitation (mm)	Suitability Scale
16-81	Not suitable (hard constraint)
81-155	1 (least suitable)
155-237	2
237-327	3
327-444	4
444-741	5 (most suitable)

Figure 18 displays the combined mean monthly precipitation of the winter months provided by WorldClim v2. This data represents projected mean winter precipitation in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

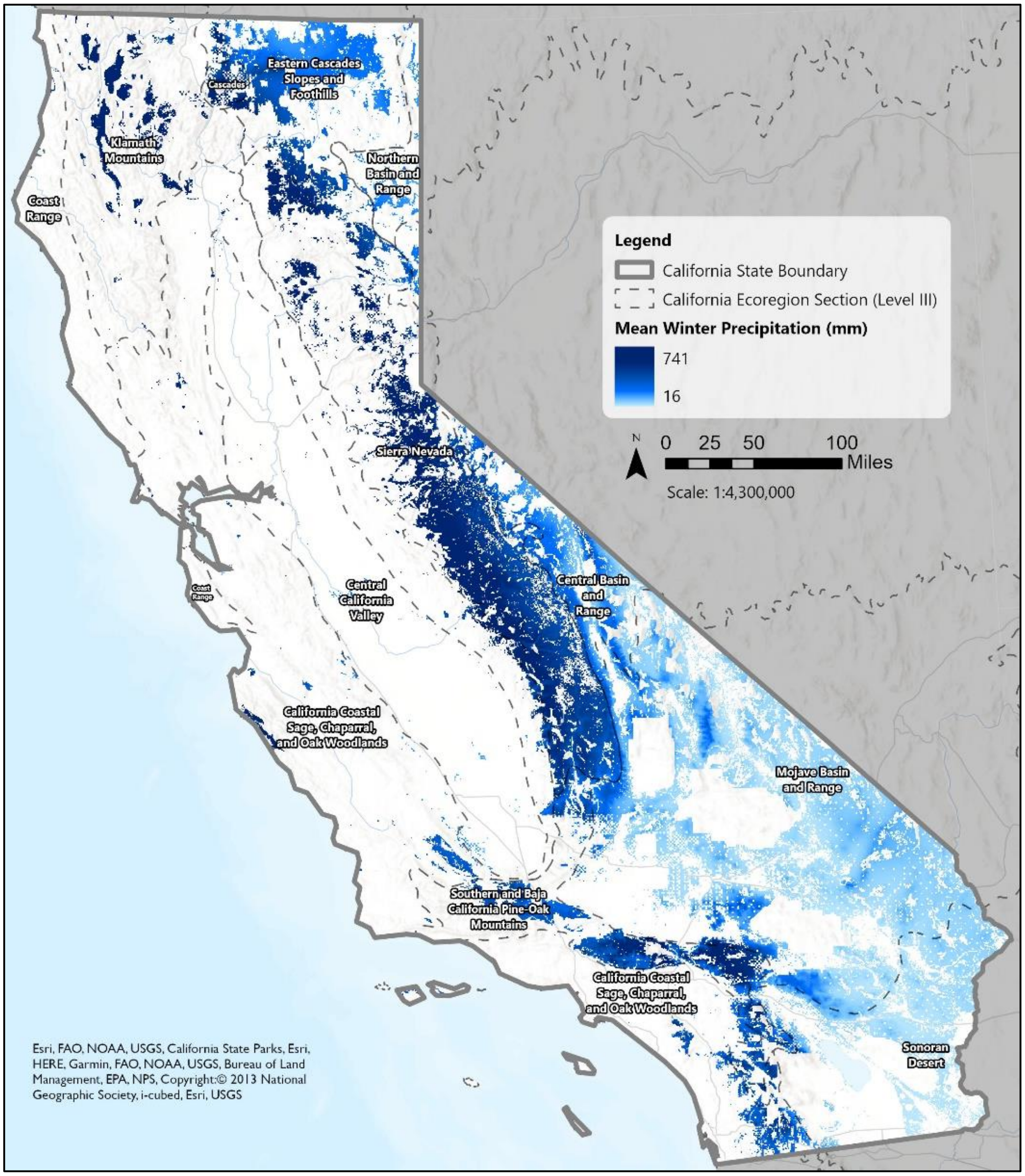

Figure 18. Mean winter precipitation (WorldClim 2020)

Projected winter precipitation, of 16 – 741 millimeters, was reclassified into equal intervals with higher suitability assigned at higher precipitation (Table 13). All data below 80 millimeters were removed from the analysis as not suitable (hard constraint). Figure 19 shows the reclassified WorldClim v2 data that represents suitable winter precipitation.

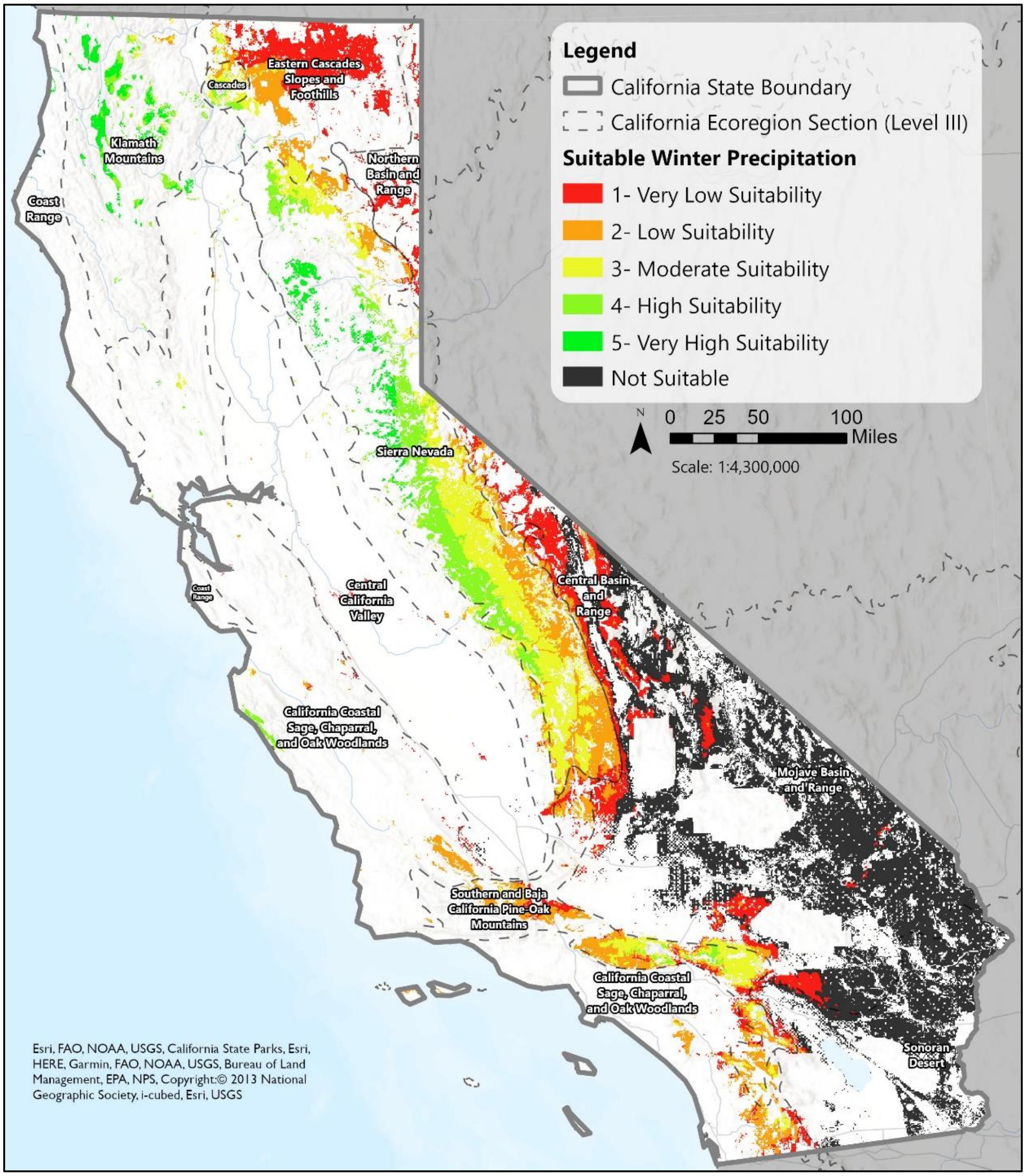

Figure 19. Reclassified mean winter precipitation

The ideal mean annual precipitation ranges from 80 and 740 millimeters with higher precipitation positively influencing Joshua tree reproduction. All data outside this range was removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data. Categories within this range were created from equal intervals with higher suitability assigned at higher precipitations (Table 14).

Table 14. Reclassified mean annual precipitation

Mean Annual Precipitation (mm)	Suitability Scale
54-80	Not suitable (hard constraint)
80 - 175	1 (least suitable)
176 - 306	2
306 - 463	3
463 - 612	4
612 - 751	5 (most suitable)
751-2007	Not suitable (hard constraint)

Figure 20 displays the raw mean annual precipitation provided by WorldClim v2. This data represents projected mean annual precipitation in 2041-2060 according to the MIROC worst-case scenario, SSP 8.5.

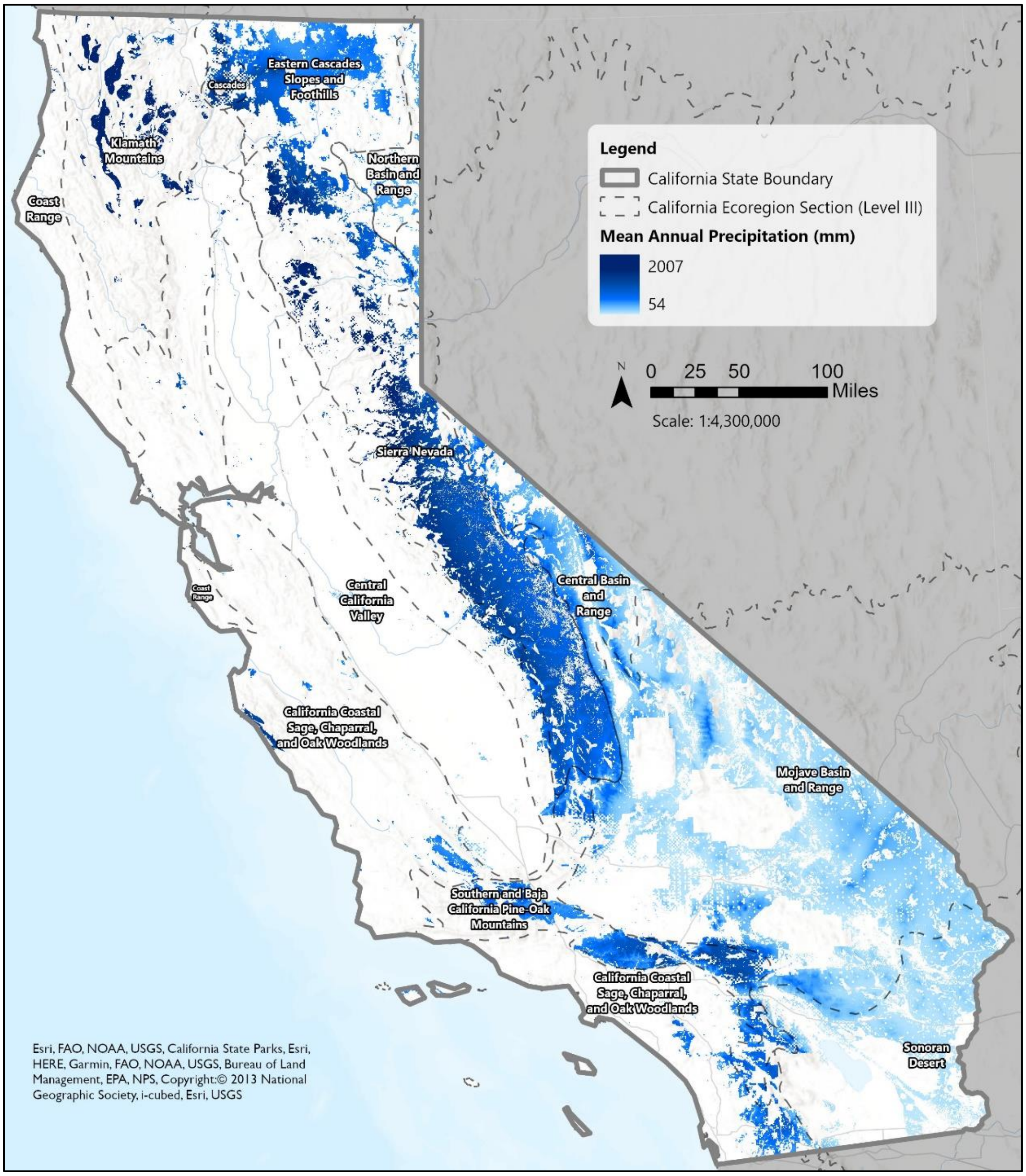

Figure 20. Mean annual precipitation (WorldClim 2020)

Projected annual precipitation, ranging from 54 – 2007 millimeters, was reclassified into equal intervals with higher suitability assigned at higher precipitation (Table 14). All data outside the ideal range, mentioned previously, were removed from the analysis as not suitable (hard constraint). Figure 21 shows the reclassified WorldClim v2 data that represents suitable annual precipitation.

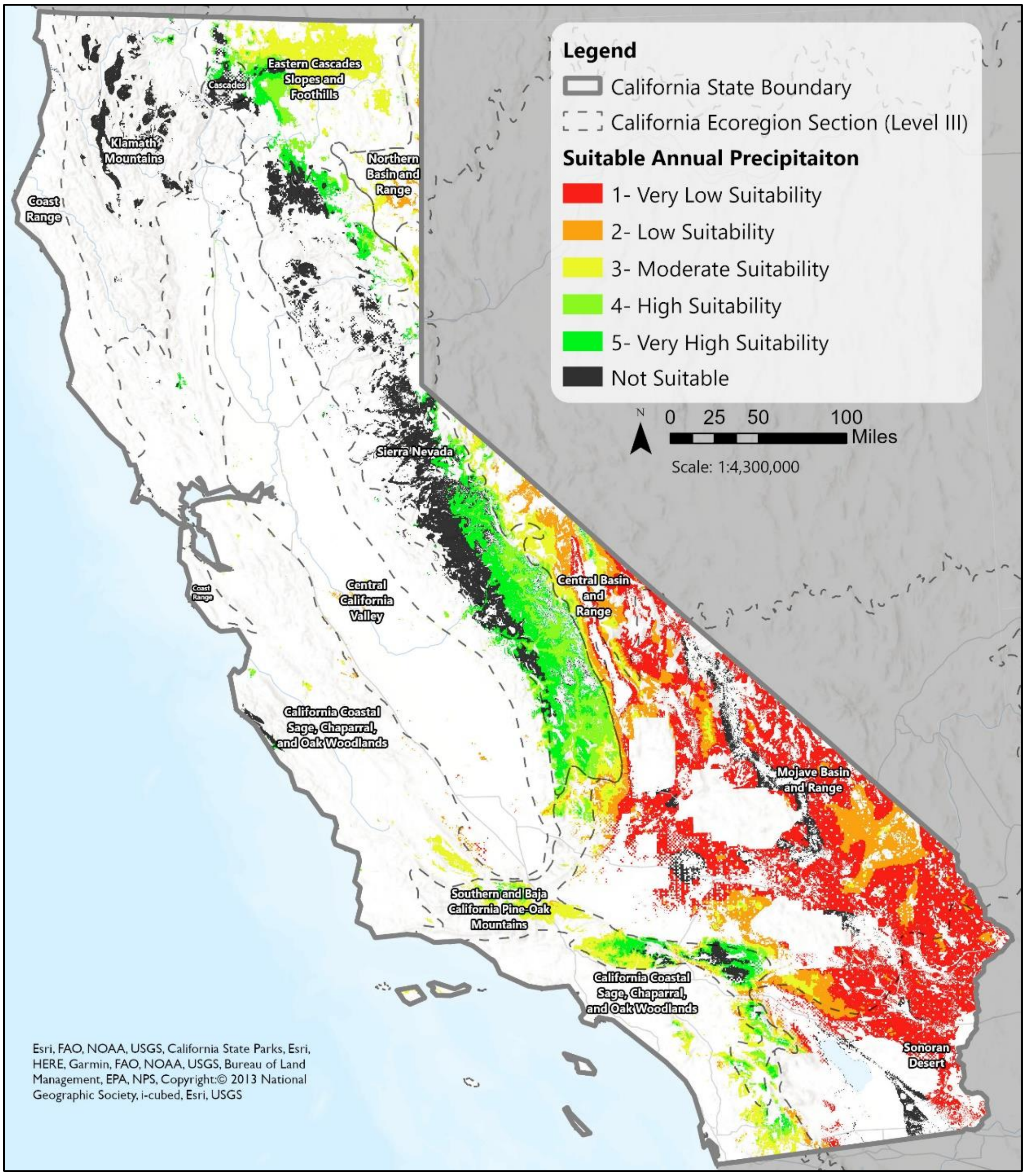

Figure 21. Reclassified annual precipitation

3.4.2 Reclassification of Environmental Data

All environmental variables were reclassified into the simple suitability scale, 1-5, 5 being the most suitable, as determined by the literature review in Chapter 2. In addition, all data outside of the suitable range were removed from the analysis as not suitable (hard constraint).

The ideal aspect is defined as Southwest/South/Southeast facing sloped indicative of maximum sun exposure, whereas moderate suitability was assigned to flat, east, and west-facing slopes (Table 15). North-facing areas were assigned as not suitable and removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data.

Table 15. Reclassified aspect

Aspect	Suitability Scale
N/A	1 (least suitable)
Flat (-1)	2
East (67.5 - 112.5)	3
West (247.5 - 292.5)	4
Southeast (112.5 - 157.5) \South (157.5 - 202.5)\Southwest (202.5 - 247.5)	5 (most suitable)
Northwest (292.5 - 337.5) /North (0 - 22.5) and North (337.5 - 360)/Northeast (22.5 - 67.5)	Not Suitable (hard constraint)

Figure 22 displays aspect data derived from the 2022 Ground Surface Elevation dataset. This data represents the compass direction of the downhill slope and is an indicator of sun exposure and soil temperature.

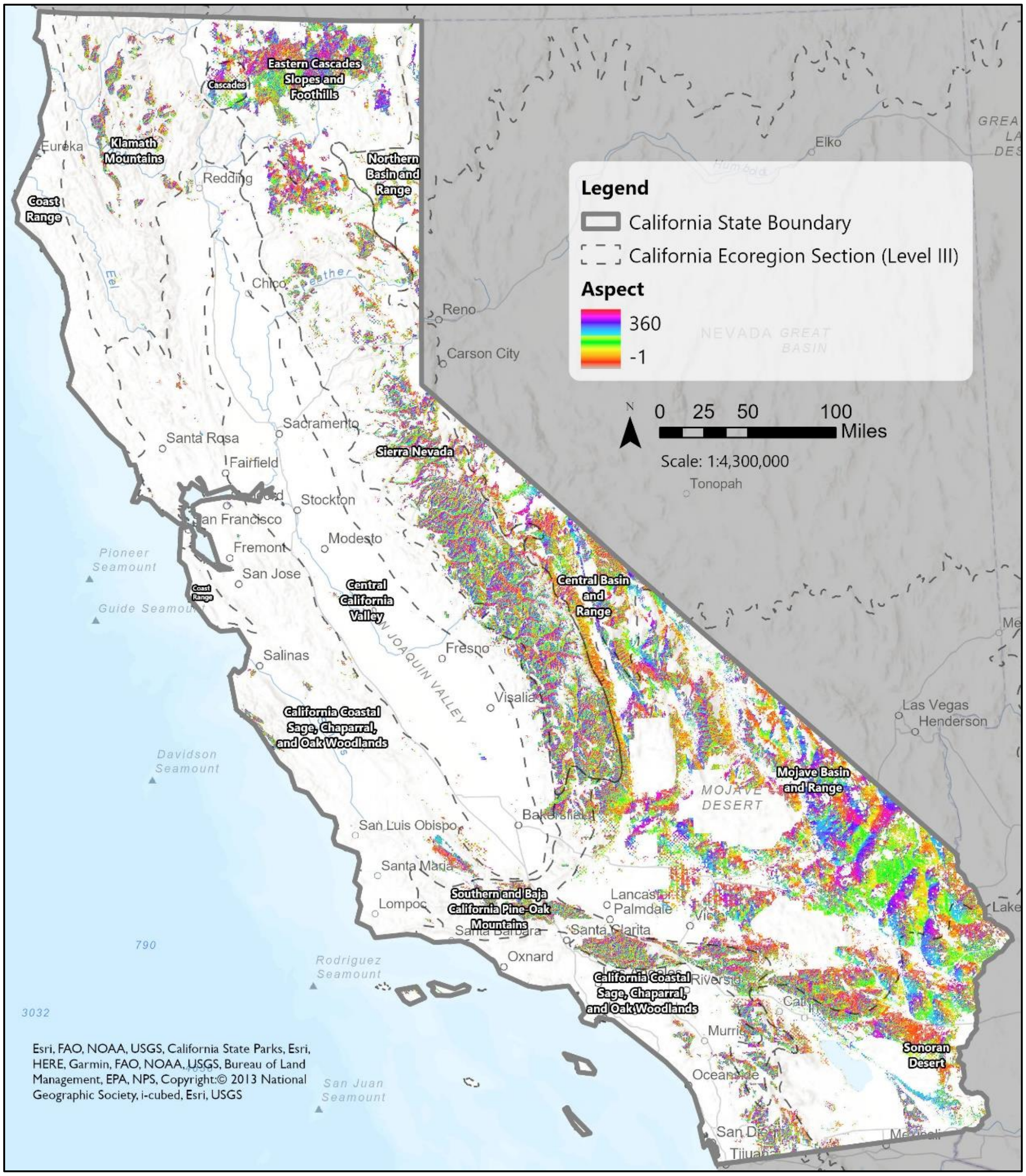

Figure 22. Aspect (Esri 2022)

Aspects, of -1 – 360, were reclassified into equal intervals with higher suitability assigned to Southwest/South/Southeast facing sloped indicative of maximum sun exposure (Table 15). North-facing areas were assigned as not suitable and removed from the analysis as not suitable (hard constraint). Figure 23 shows the reclassified data that represents suitable aspects.

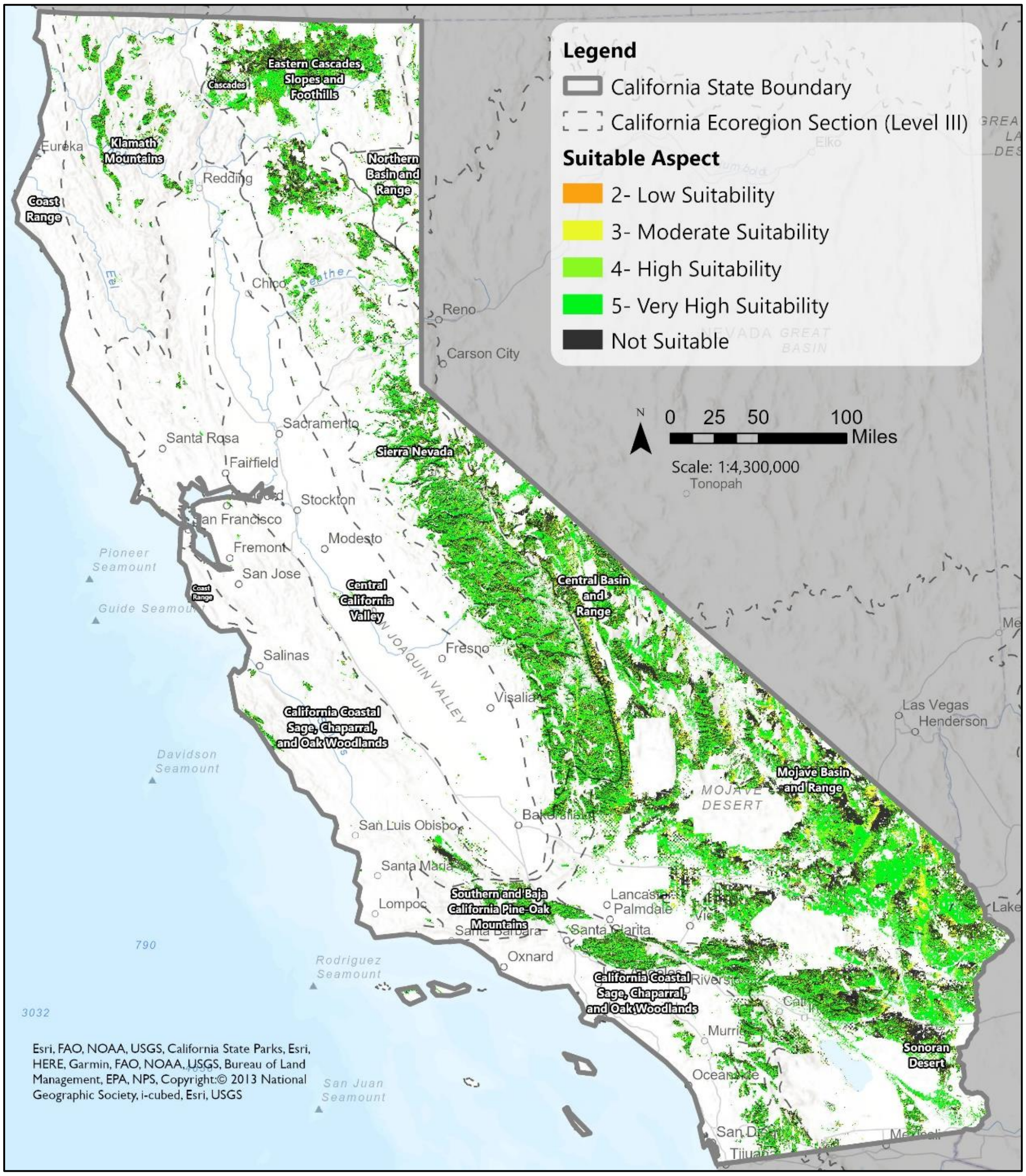

Figure 23. Reclassified aspect

Ideal elevation ranges from 1,600-7,200 feet, with higher elevation corresponding to lower suitability. Categories within this range were created from equal intervals with higher suitability assigned at lower elevations (Table 16). In addition, all data below the ideal range were removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data.

Table 16. Reclassified elevation

Elevation (feet)	Suitability Scale
3,520.00-4,397.87	1 (least suitable)
3,040.00-3,520.00	2
2,560.00-3,040.00	3
2,080.00-2,560.00	4
1,600.00-2,080.00	5 (most suitable)
-85.5587-1,600.00	Not suitable (hard constraint)

Figure 24 displays the raw 2022 Ground Surface Elevation dataset. This data represents the elevation within the project area and is an indicator of certain climate regimes.

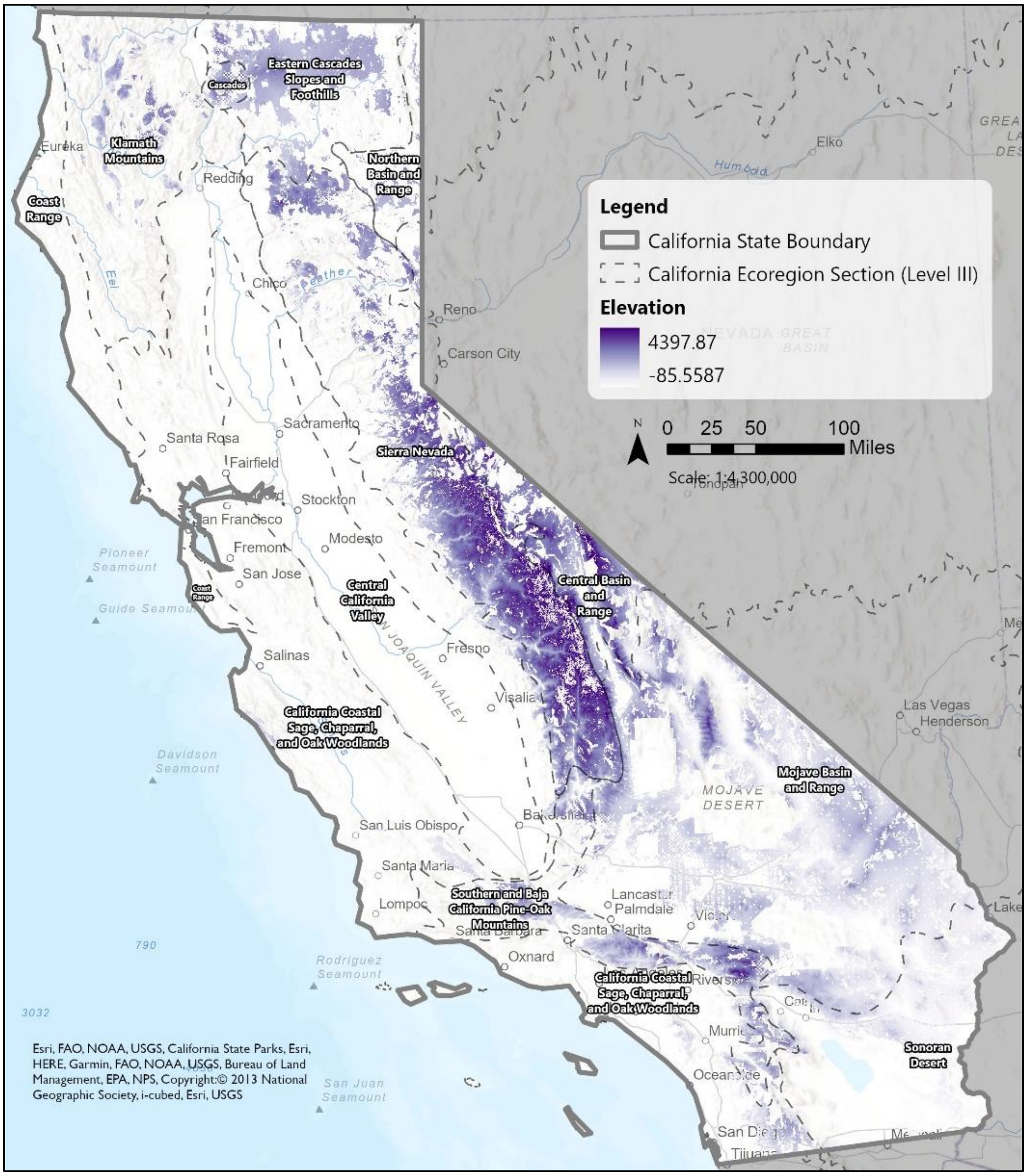

Figure 24. Elevation (Esri 2022)

Elevations, of -85.5587 – 4397.87 feet, were reclassified into equal intervals with higher suitability assigned to lower elevations (Table 16). In addition, all data below the ideal range were removed from the analysis as not suitable (hard constraint). Figure 25 shows the reclassified data that represents suitable elevation.

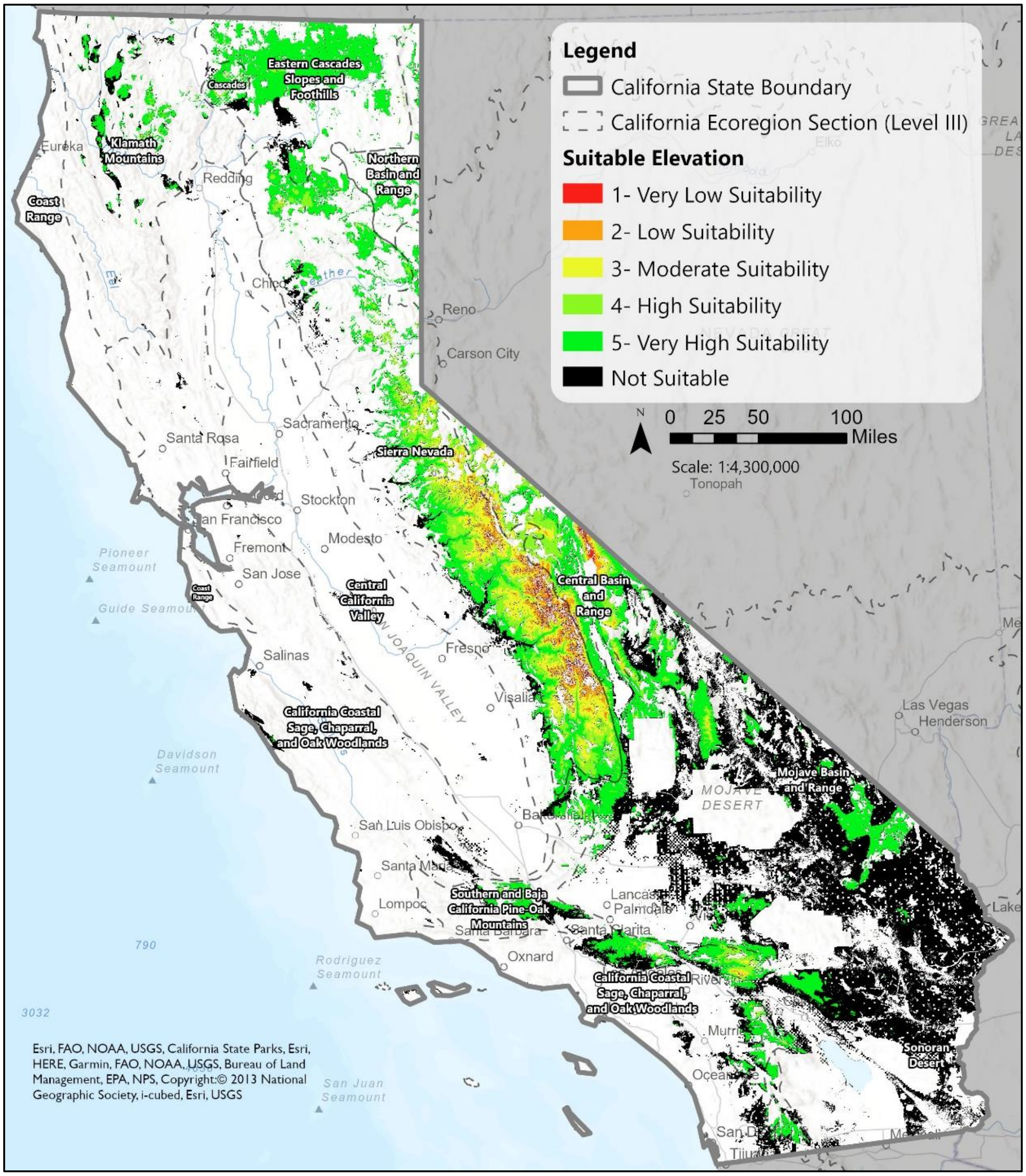

Figure 25. Reclassified elevation

The ideal slope, for Joshua tree ranges from flat (<1%) to gentle slopes (1-10%). Categories within this range were created from equal intervals with higher suitability assigned at flatter slopes (Table 17). In addition, all data outside of the ideal range were removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data.

Table 17. Reclassified slope

Slope (%)	Suitability Scale
85-11	Not suitable (hard constraint)
11-10	1 (least suitable)
10- 8	2
8- 6	3
6- 4	4
4- 2	5 (most suitable)
1-2	Not suitable (hard constraint)

Figure 26 displays the slope derived from the 2022 Ground Surface Elevation dataset. This data represents the degree of tilt of the land surface and is indicative of water capacity and soil stability.

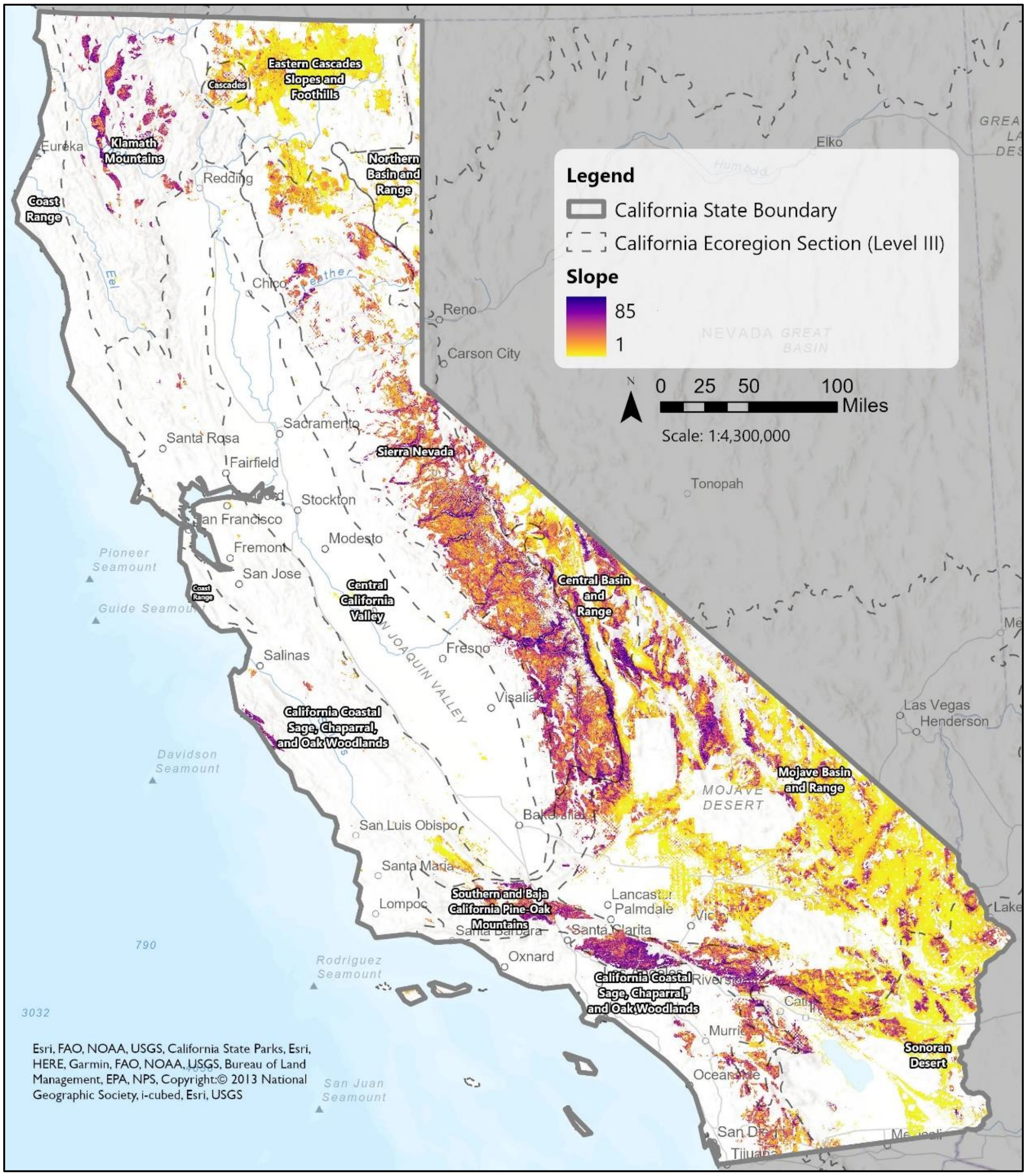

Figure 26. Slope (Esri 2022)

Slopes, of 1 – 85 percent, were reclassified into equal intervals with higher suitability assigned to flatter slopes (Table 17). In addition, all data >11, were removed from the analysis as not suitable (hard constraint). Figure 27 shows the reclassified data that represents a suitable slope.

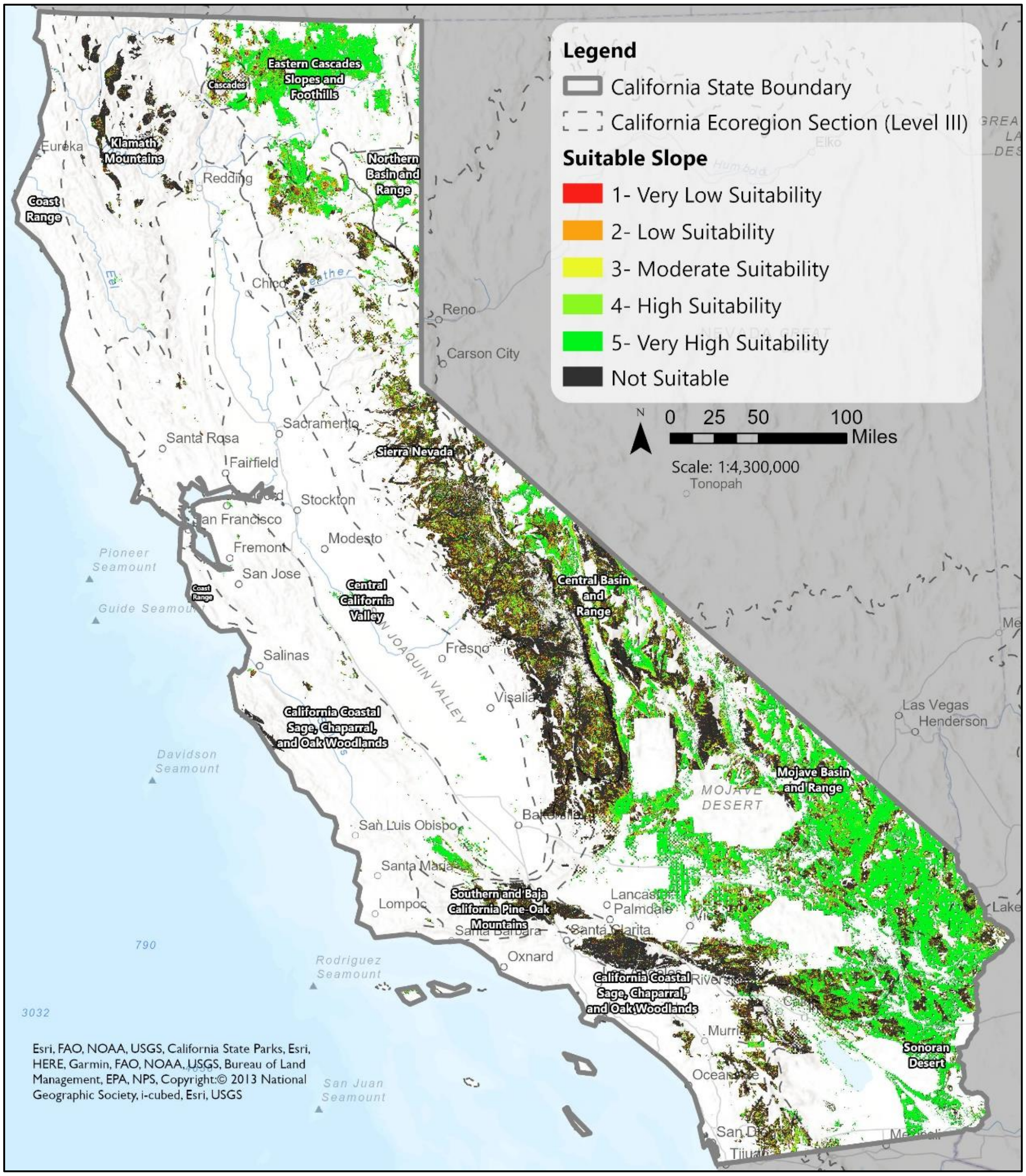

Figure 27. Reclassified slope

Suitable soils are defined as silts, loams, and/or sands with fine, loose, well-drained, or gravelly characteristics. High sand content and water drainage were assigned higher suitability (Table 18). Categories created from gSSURGO's standardized soil survey were used to define high sand percentage and drainage class (Table 18). In addition, poorly drained, very poorly drained, and subaqueous soils are assigned as not suitable and removed from the analysis as not suitable (hard constraint). These non-suitable areas were removed from data layers in the reclassification stage and re-defined as no data.

Table 18. Reclassified sand percentage and water drainage

Sand Percentage (%)	Water Drainage	Suitability Scale
N/A	Poorly drained, very poorly drained, and Subaqueous	Not suitable (hard constraint)
0.3-20.3	Somewhat poorly drained	1 (least suitable)
20.3 - 40.2	Moderately well drained	2
40.2- 60.1	Well drained	3
60.1- 80.1	Somewhat excessively drained	4
80.1- 100	Excessively drained	5 (most suitable)

Figure 28 displays soil classified by drainage class derived from gSSURGO 2023. This data represents the degree of water retention in a particular soil, indicative of water capacity and soil stability.

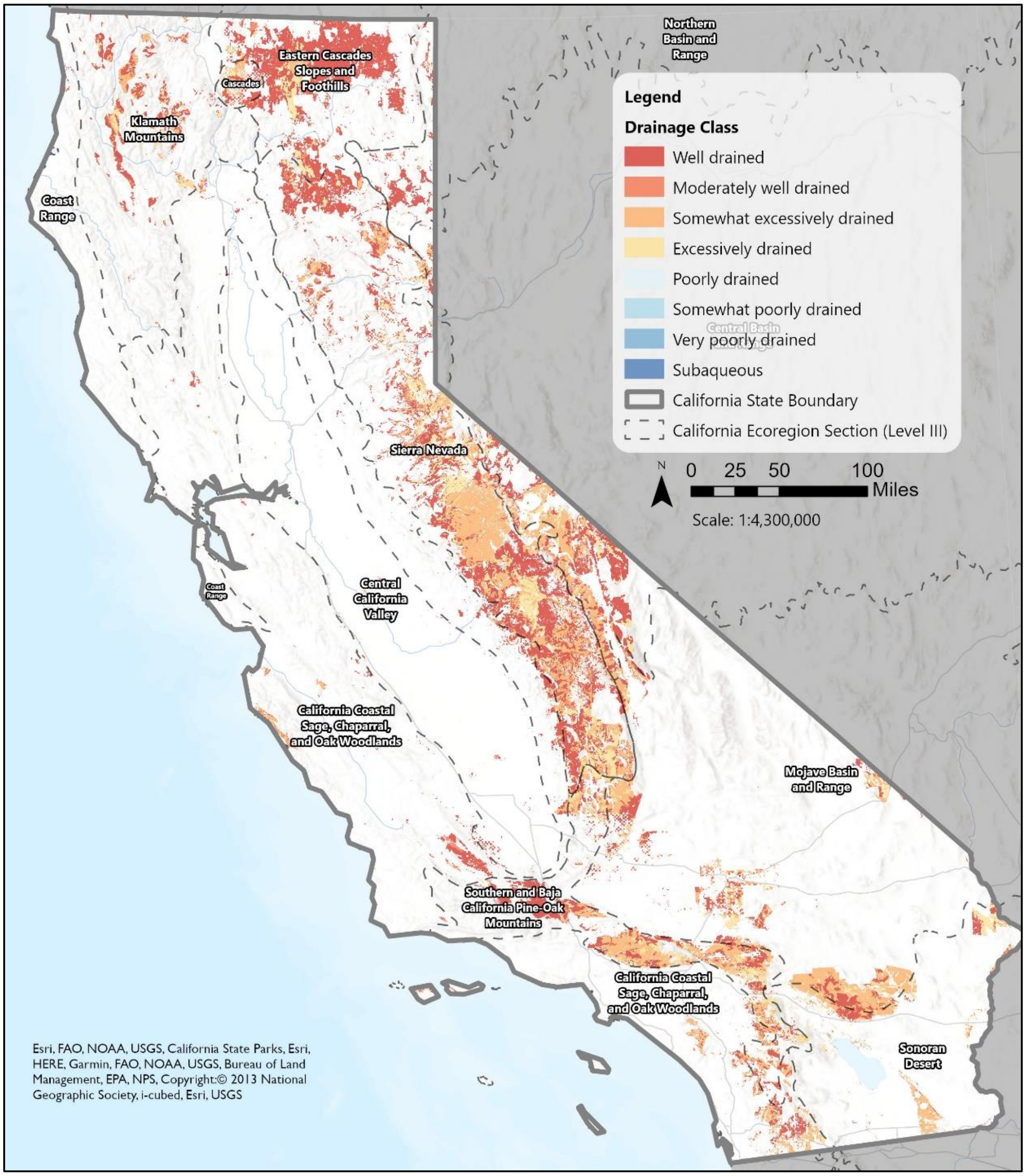

Figure 28. Drainage class (gSSURGO 2023)

Drainage classes, from somewhat poorly drained and extensively well-drained, were reclassified with higher drainage assigned the highest suitability (Table 18). Whereas poorly drained, very poorly drained, and subaqueous soils are assigned as not suitable and removed from the analysis as not suitable (hard constraint). Figure 29 shows the reclassified data that represents a suitable drainage class.

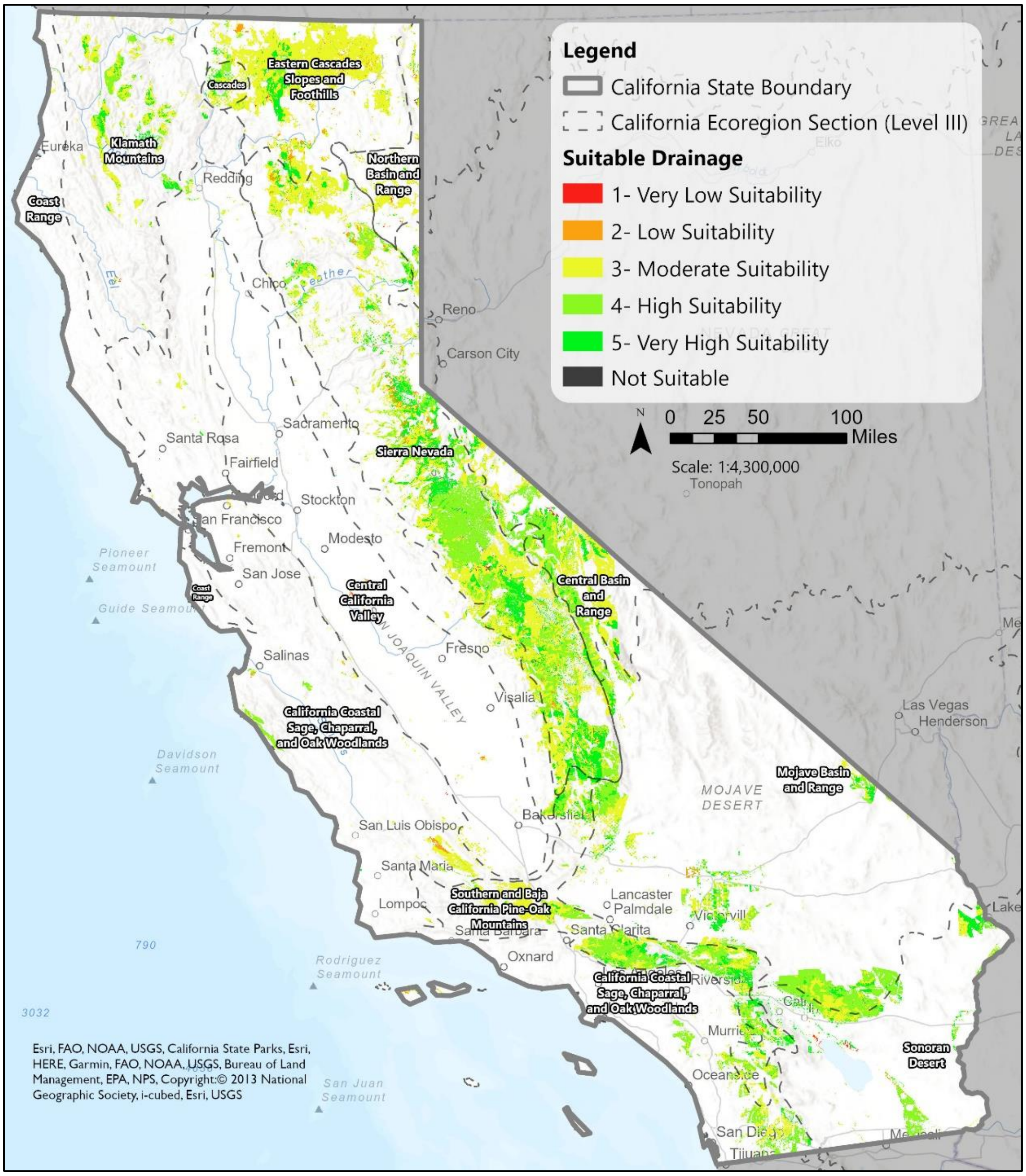

Figure 29. Reclassified drainage class

Figure 30 displays soil classified by sand percentage derived from gSSURGO 2023. This data represents the degree of sand present in a particular soil and is indicative of soil texture and stability.

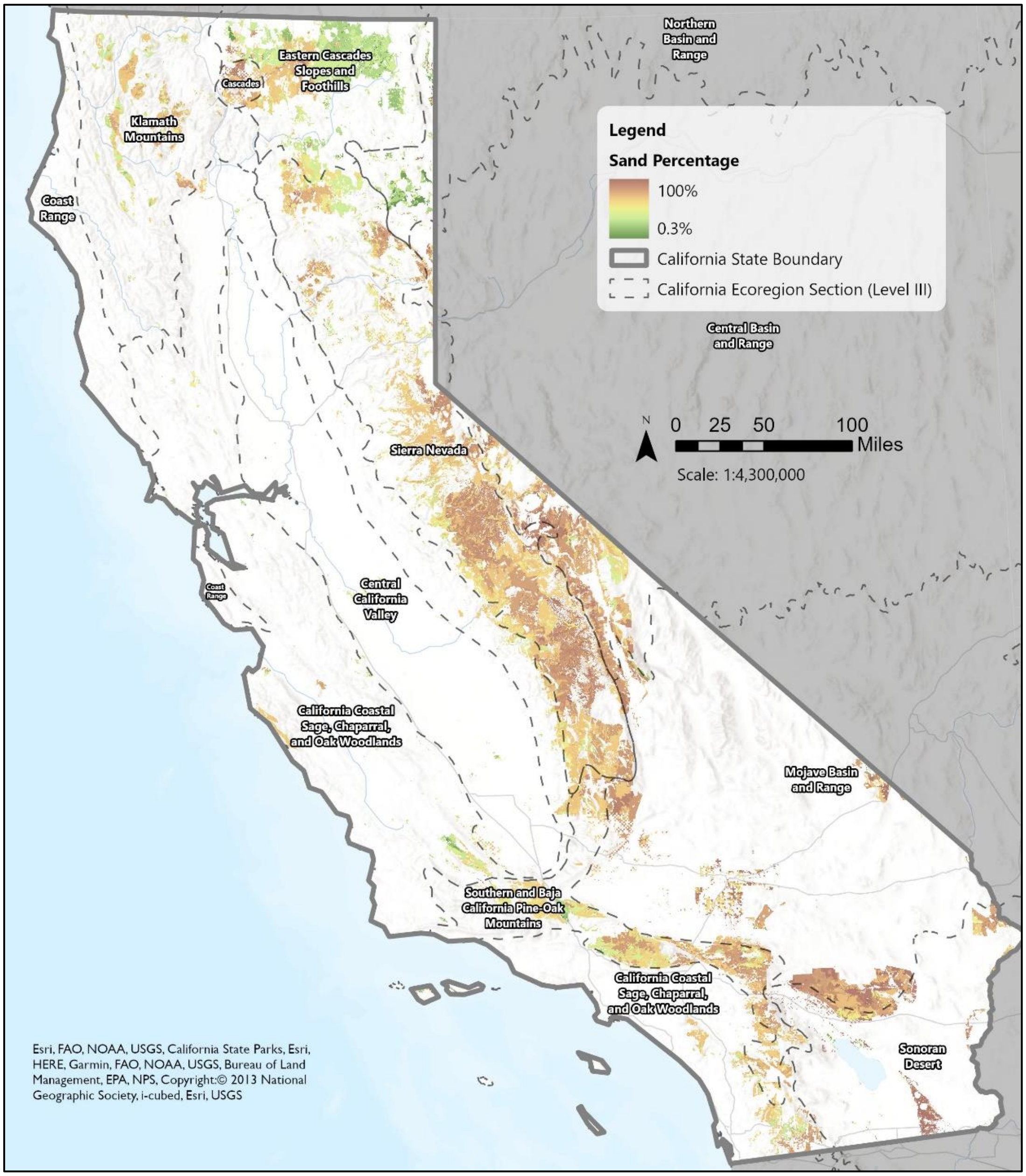

Figure 30. Sand percentage (gSSURGO 2023)

Sand percentages, ranging from 0.3 – 100 percent, were reclassified with higher suitability assigned to higher sand content (Table 18). Figure 31 shows the reclassified data that represents suitable sand percentages.

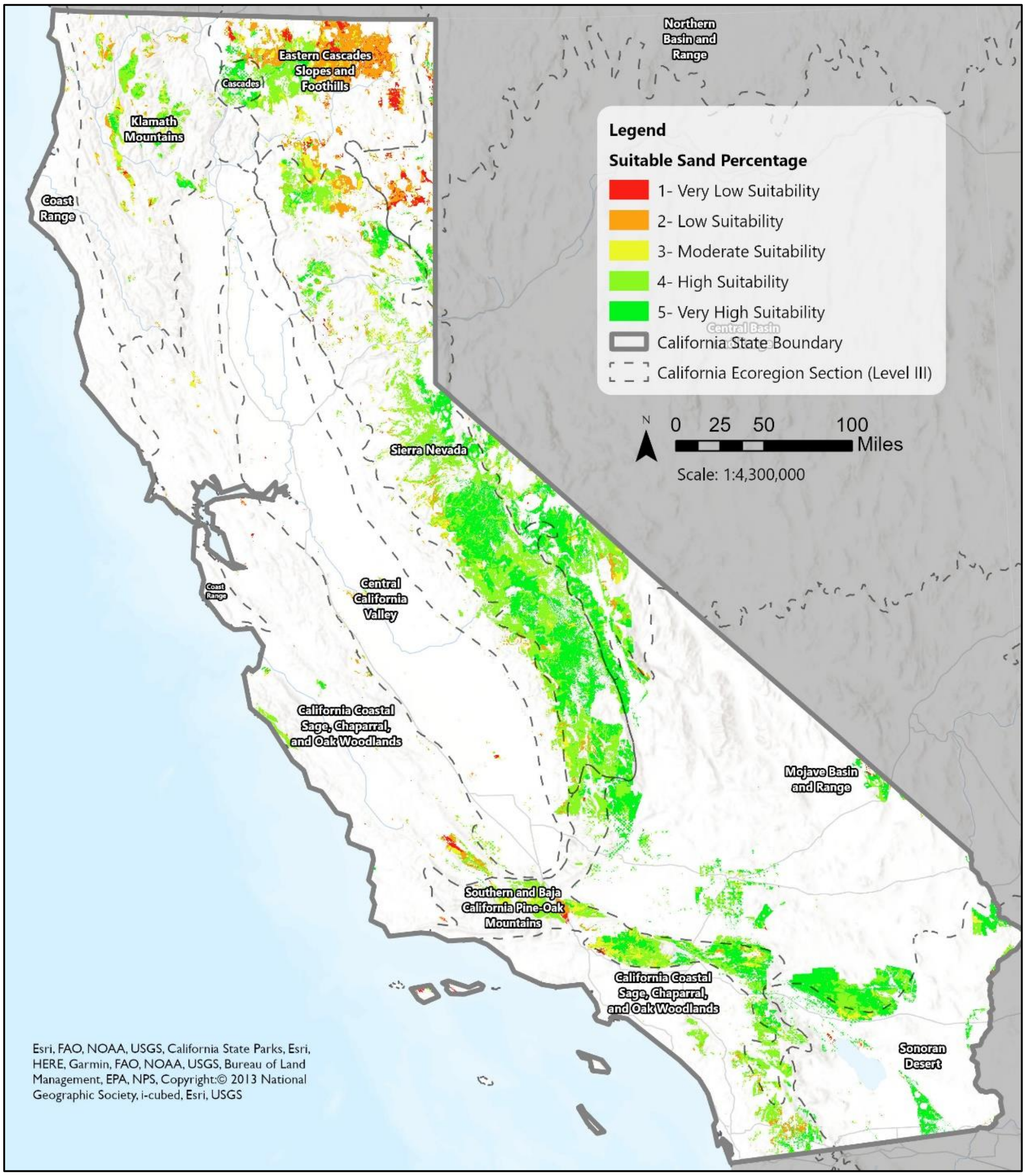

Figure 31. Reclassified sand percentage

The increased likelihood of fires, described by the amount of burning fuel (invasive grasses), is assigned low suitability. Categories, created from equal intervals were utilized, with higher suitability assigned to areas with lower burn probability (Table 19).

Table 19. Reclassified burn probability

Burn probability	Suitability Scale
0.043 - 0.091	1 (least suitable)
0.024- 0.043	2
0.012 - 0.024	3
0.004 - 0.012	4
0.001 - 0.004	5 (most suitable)

Figure 32 displays the raw burn probability provided by the 2020 Wildfire Risk to Communities Dataset. This data represents the wildfire risk indicative of vegetation and wildland fuel within the project area.

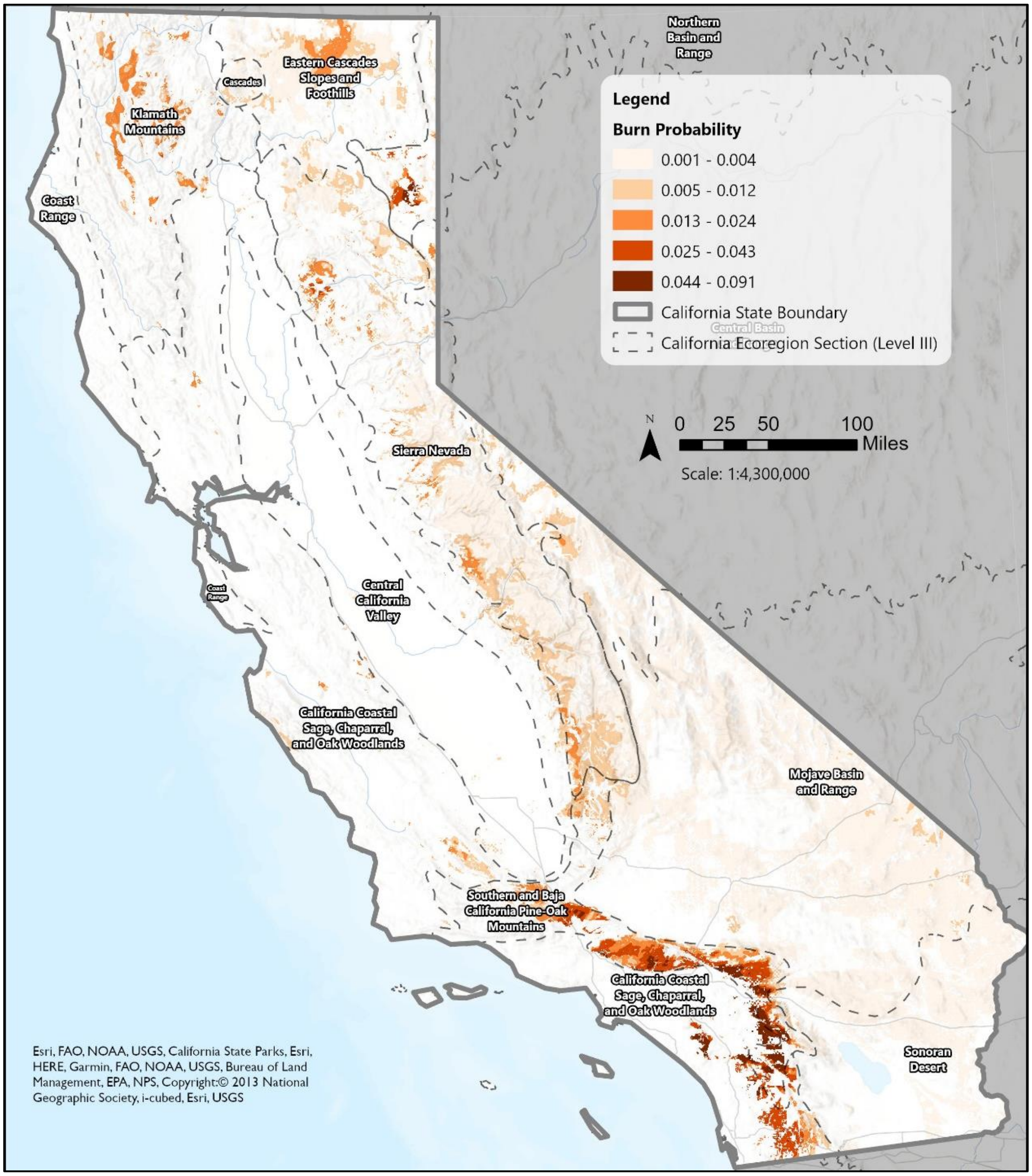

Figure 32. Burn probability (USDA 2020)

Burn probability, ranging from 0.001 – 0.091, was reclassified with higher suitability assigned to lower wildfire risk (Table 19). Figure 33 shows the reclassified data that represents suitable burn probability, or areas with limited burn fuel.

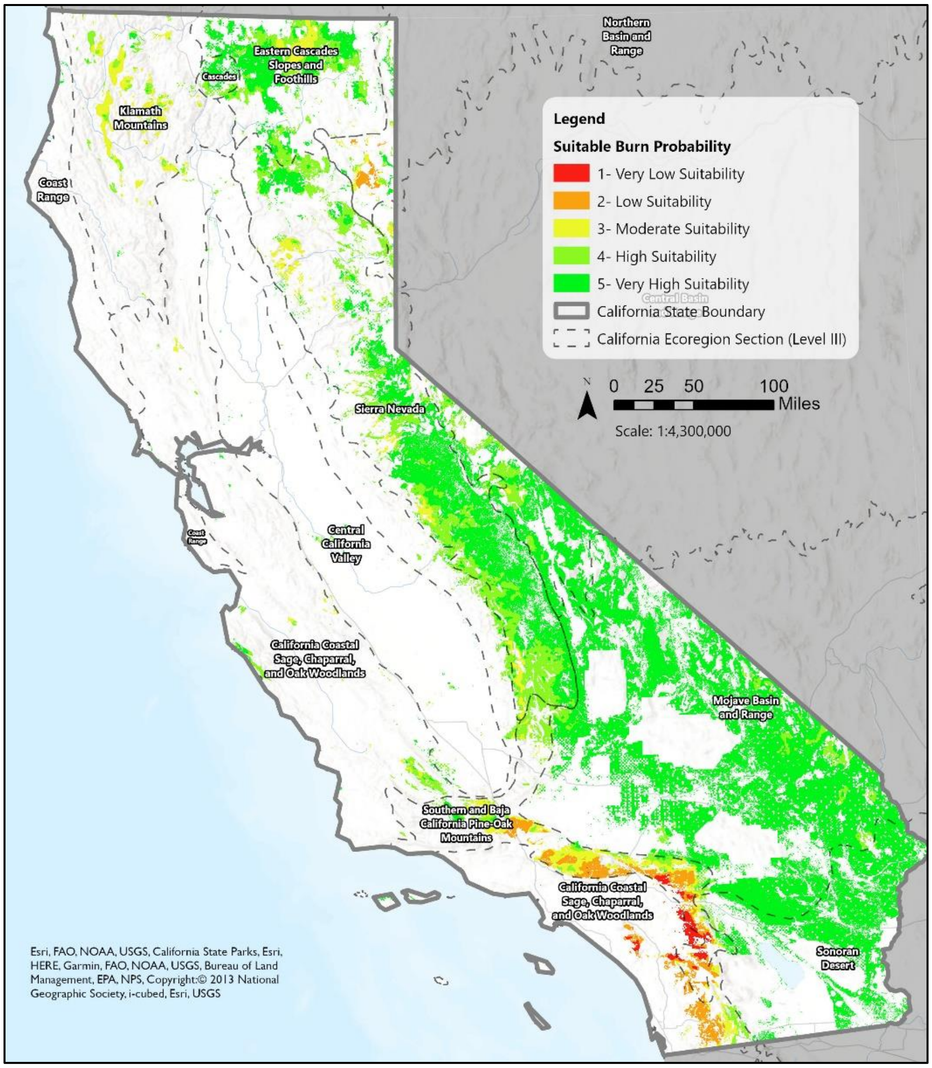

Figure 33. Reclassified burn probability

Areas of high biodiversity, defined by CDFW as areas with native species richness, are considered the most suitable. Suitability is assigned to mirror ACE rankings with areas ranked 5 having the most biodiversity (Table 20).

Table 20. Classified habitat quality

Biodiversity Rank	Suitability Scale
1	1 (least suitable)
2	2
3	3
4	4
5	5 (most suitable)

Figure 34 displays habitat quality provided by the 2018 Species Biodiversity dataset. This data represents a summary of species biodiversity in California based on species occurrence and distribution information.

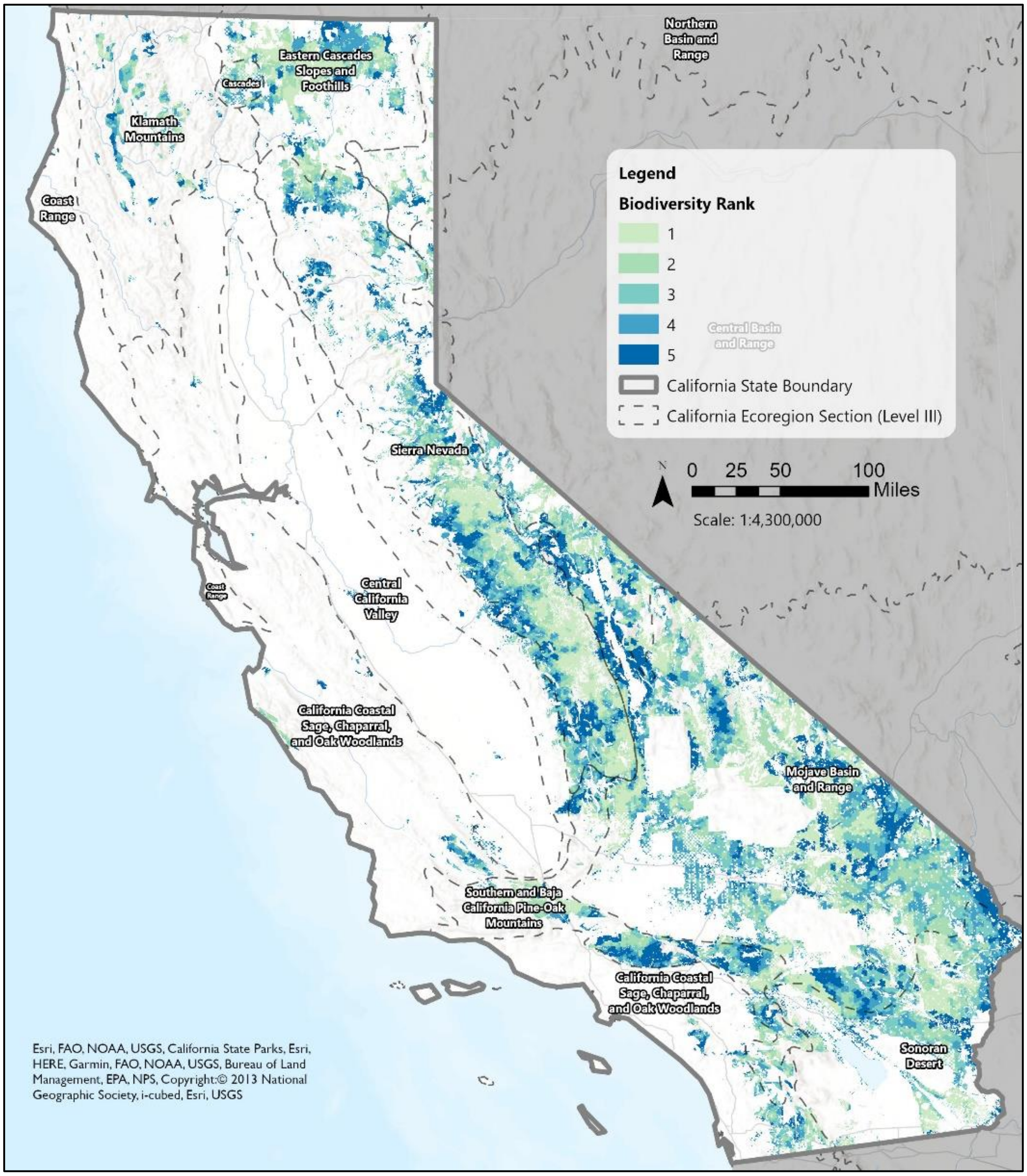

Figure 34. Habitat quality (CDFW 2018)

Habitat quality, ranging on a scale of 1 (low species diversity) to 5 (high species diversity), was reclassified with higher suitability assigned to areas of higher biodiversity (Table 20). Figure 35 shows the reclassified data that represents suitable habitat quality.

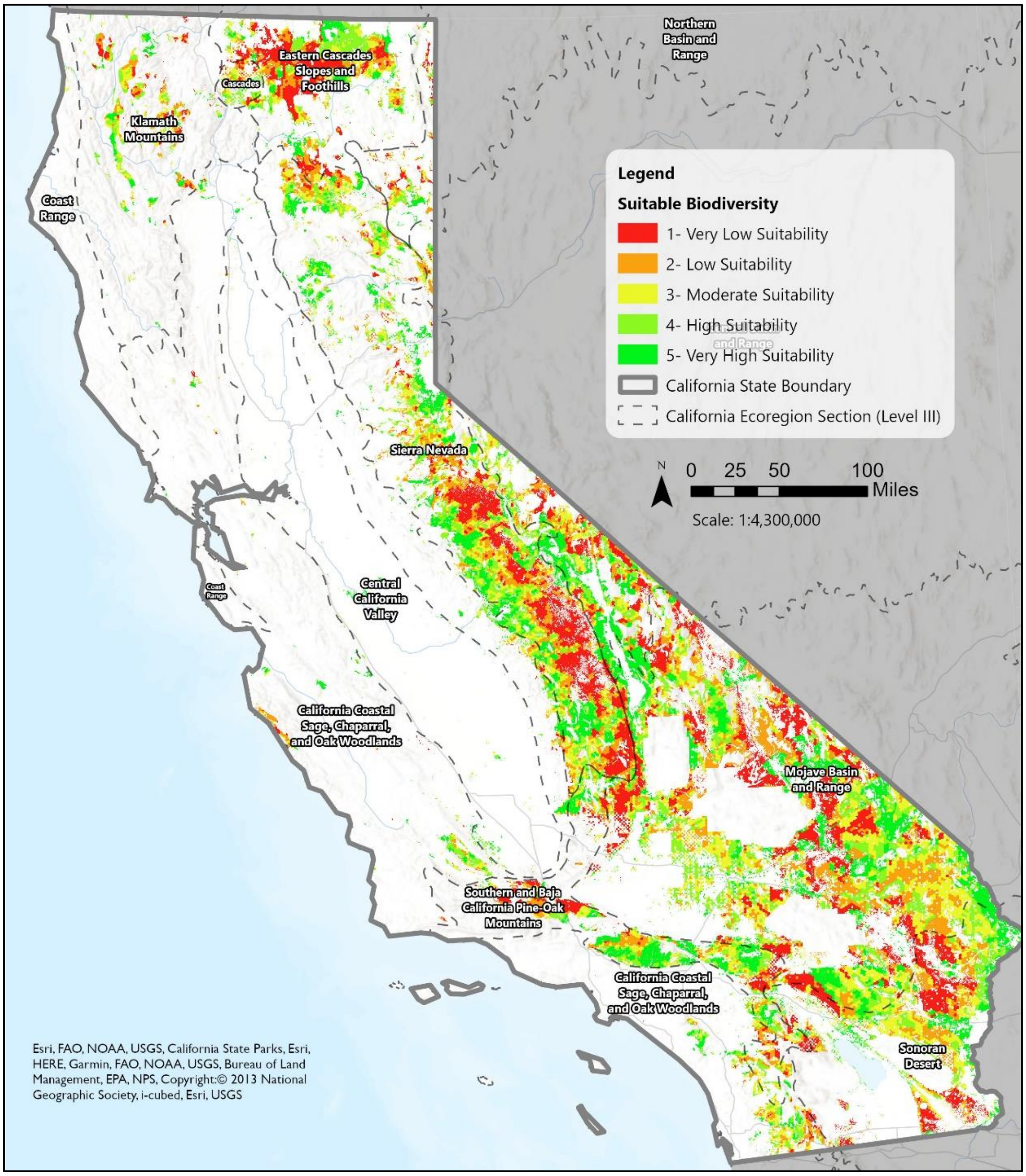

Figure 35. Reclassified habitat quality

3.5 Creation of Sub-Models

Following reclassification several weighted overlays were performed to meaningly combined all 16 criteria. Specifically, 3 rounds of weighted overlays created intermediate sub-models of climate and environmental variables. This method of overlay allowed the author to meaningfully assign weights and ensure accurate results. As mentioned previously hard constraints were first applied followed by reclassification.

3.5.1 Hard Constraints

Hard constraints were first applied to surface management, land cover, and geology as described in the previous section. The extract data tool was used to capture the suitable locations overlapped by all 3 criteria. To extrude the overlapping areas the count overlapping feature tool was used and dissolved was leveraged to create intermediate results, as shown in Figure 5.

3.5.2 Climate Sub-Models

As previously described, seasonal temperature and precipitation were created using a raster calculator to create mean summer/winter temperature and precipitation rasters. These along with annual temperature and precipitations were reclassified and masked to intermediate results. Two preliminary overlays (overlay 1) were performed, to produce the temperature sub-model and precipitation sub-model, with weights defined by the literature review in Chapter 2 (Table 21). The resulting 900m outputs were then combined in a second weighted overlay (overlay 2) using a 30m snap raster. This produced a 30m climate sub-model representative of a suitable climate within the project area.

Table 21. Climate sub-models

Sub-model	Criteria	Overlay 1 Weights	Overlay 2 Weights
Temperature	Mean summer temperatures	20%	40%
	Mean winter temperatures	40%	
	Mean annual temperatures	40%	
Precipitation	Mean summer precipitation	50%	60%
	Mean winter precipitation	25%	
	Mean annual precipitation	25%	

3.5.3 Environmental Sub-Models

As previously described, environmental criteria were preprocessed and reclassified to intermediate results. These calibrated datasets were then analyzed with two rounds of overlays. Two preliminary overlays (overlay 1) were performed, to produce a topological sub-model and other environmental sub-model, with weights defined by the literature review in Chapter 2 (Table 22). The resulting 30m sub-models were then combined in a second weighted overlay (overlay 2) using a 30m snap raster. This produced a 30m environmental sub-model, representative of a suitable environment within the project area.

Table 22. Environmental overlay weights

Sub-model	Criteria	Overlay 1 Weights	Overlay 2 Weights
Topological	Aspect	20%	40%
	Slope	20%	
	Elevation	60%	
Other	Soil (Percent Sand) - Low due to missing data	5%	60%
	Soil (Drainage Class) - Low due to missing data	5%	
	Wildfire	40%	
	Habitat	50%	

3.6 Final Model

A final overlay was performed to combine the 30m environmental and 30m climate sub-models. These areas of suitable climate and environment were overlaid with climate weighted the highest, informed by the literature review in Chapter 2 (Table 23). This final overlay produced a final suitability surface representative of potential climate refugia for JTF across California.

Table 23. Final overlay weights

Sub-model	Criteria	Weights
Final Overlay	30m Suitable Environment	25%
	30m Suitable Climate	75%

Chapter 4 Results

The following chapter details the results of the suitability analysis performed for this thesis. The workflow and research design, discussed in Chapter 3, was utilized to produce two overlay outputs that are representative of the suitable climate and environment described in this Chapter. Lastly, this chapter presents the final suitability surface that represents JTF refugia across California.

4.1 Weighted Overlay Results

The following section details the two overlay outputs that represent a suitable climate and environment accommodating Joshua trees in the coming decades. As described in Chapter 3, climate overlays used WorldClim's 900m resolution and the second used a 30m resolution to represent the various environmental data.

4.1.1 Climate Overlay Results

Two preliminary overlays were performed, which created a temperature and precipitation sub-model, with weights defined by the literature review in Chapter 2.

Suitable precipitation, highlighted in the precipitation sub-model, covers 48,679,200 square meters of the study area (Figure 36). These suitable areas include 0.7% ranked as very high, 13.9% as high, and 37.6% as moderate suitability. Suitability is absent in the southeastern area of the study area, which narrowed suitable locations around the northeastern, central, and southern coast of California. As well as the westernmost edge of the inland desert region, the historic habitat of JTF.

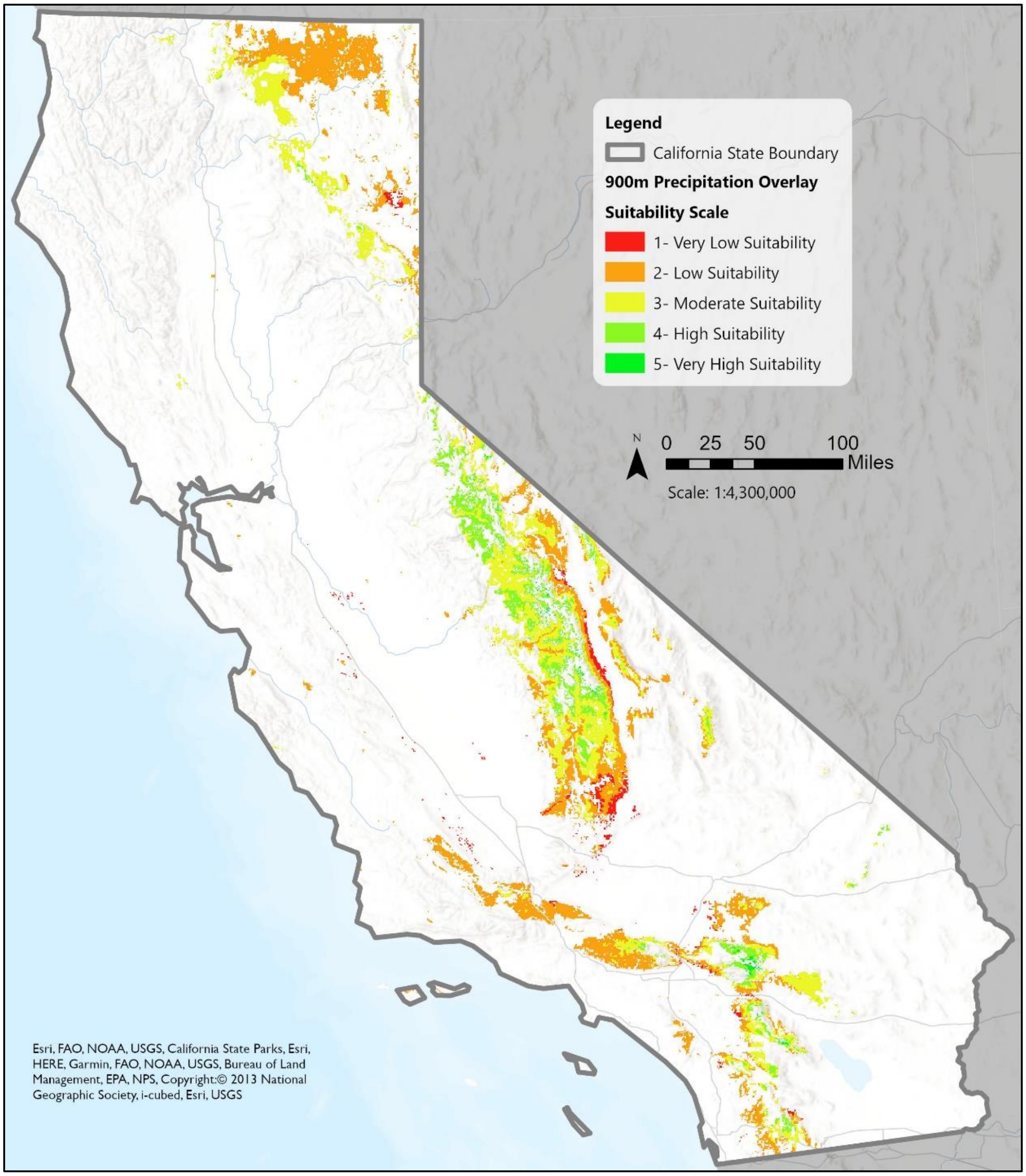

Figure 36. Precipitation sub-model

The suitable temperature, highlighted in the temperature sub-model, expands 118,315,800 square meters of the study area (Figure 37). These suitable areas include 12.7% ranked as very high suitability, 25.9% as high suitability, and 18.7% as moderate suitability.

These highly ranked areas are located in northeast and central California, with pockets of moderate suitability in the inland desert region and the southern coast.

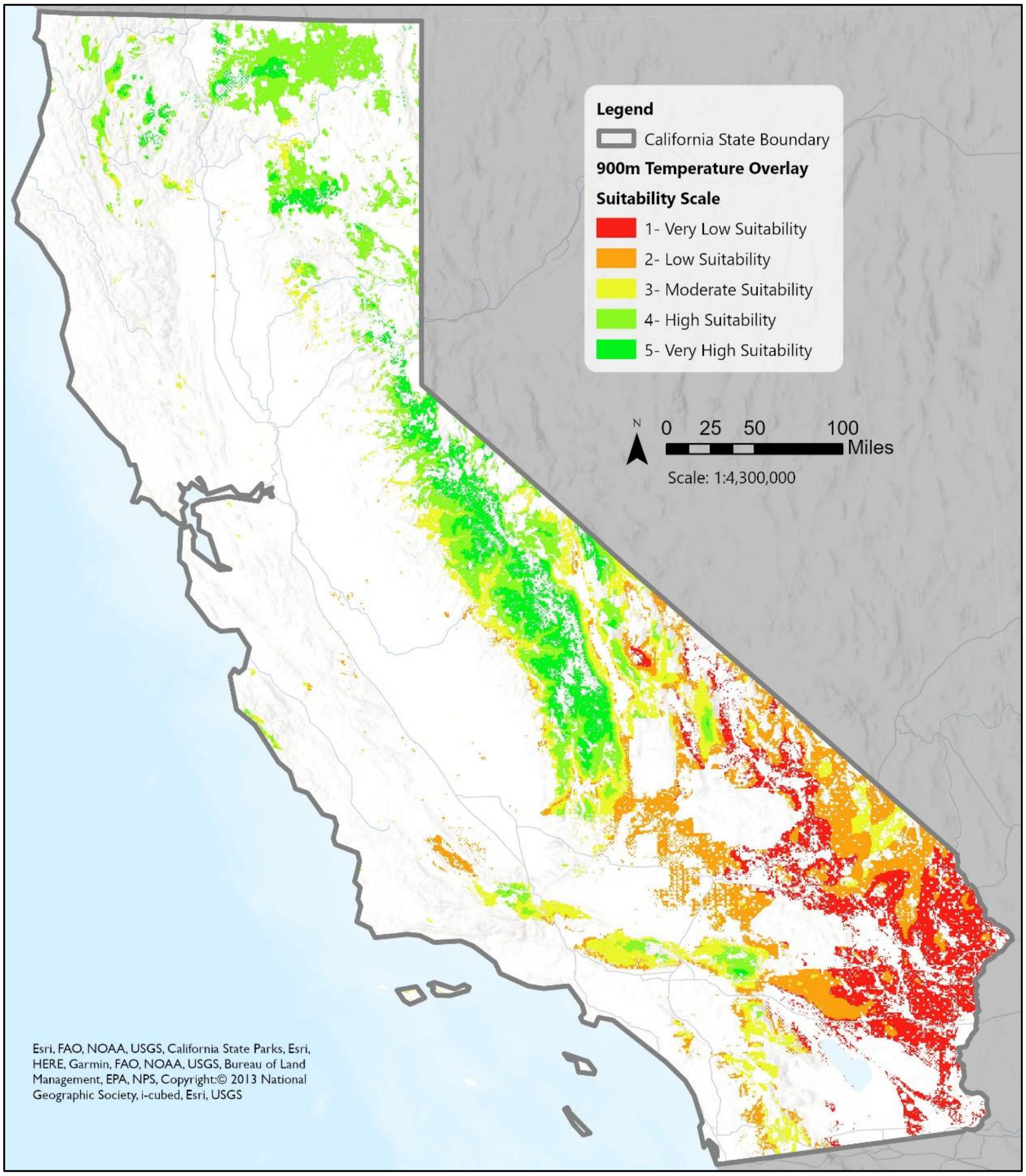

Figure 37. Temperature sub-model

The two 900m outputs, discussed above, were then combined in a second weighted overlay with a 30m snap raster. This step produced a 30m climate sub-model within the intermediate result. Figure 38 shows the expanse of approximately 1,622,640 square meters of suitable climate with approximately 0.7% ranked as very high suitability, 23.6% as high suitability, and 49.8% as moderate suitability. As mentioned previously precipitation limited the project extent which narrowed the suitable climate locations around the northeastern, central, and south coast of California.

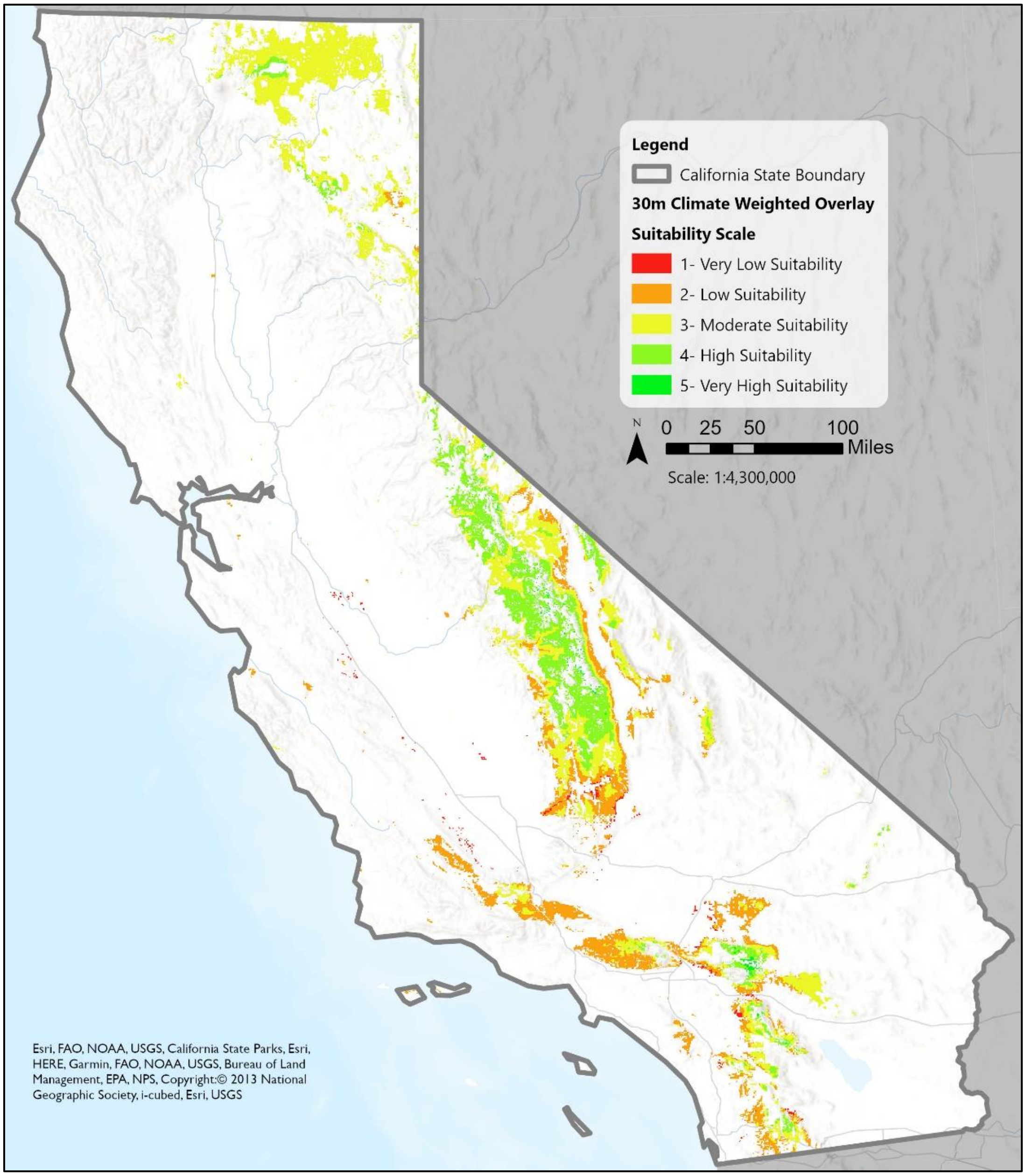

Figure 38. Overall climate suitability

4.1.2 Environmental Overlay Results

Like the climate sub-models, two preliminary environmental overlays were performed, to create topological and other environmental sub-models based on weights defined by the literature review in Chapter 2.

The other environmental sub-model produced suitability expanding approximately 18,822,559,040 square meters of the study area with 12.9% ranked as very high suitability, 36.9% as high suitability, and 43.2% as moderate suitability (Figure 39). These highly ranked areas are clustered in northeastern and central California, with pockets of moderate suitability in the inland desert region and the southern coast.

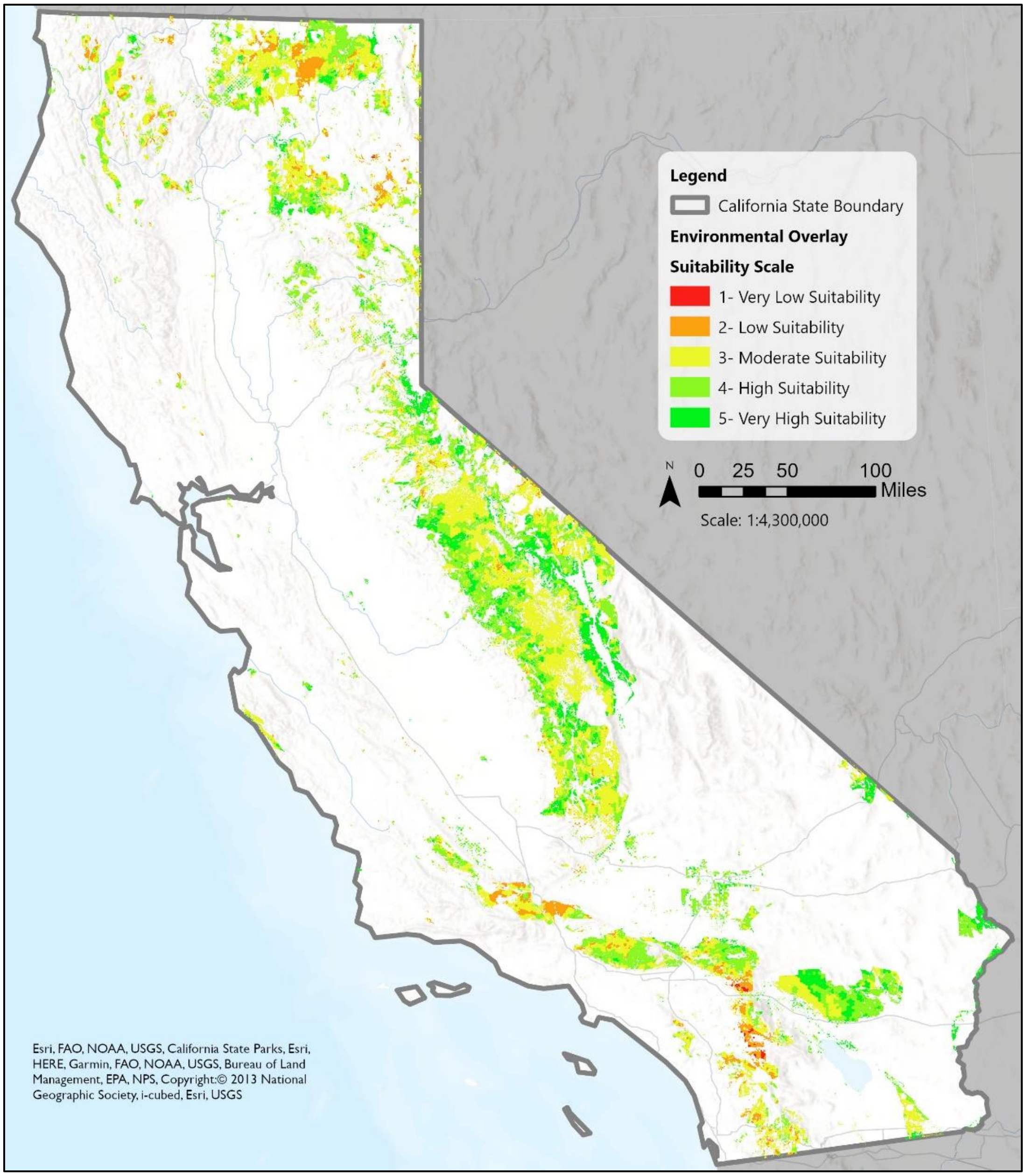

Figure 39. Environmental sub-model

Suitable topological areas, highlighted in the topological sub-model, expand 704,160 square meters of the study area with approximately 0.7% ranked as very high suitability, 18.2% as high suitability, and 55.8% as moderate suitability (Figure 40). Suitable locations are found throughout the study area specifically around the northeastern, central, and southern coast of California but are limited in the southeastern regions.

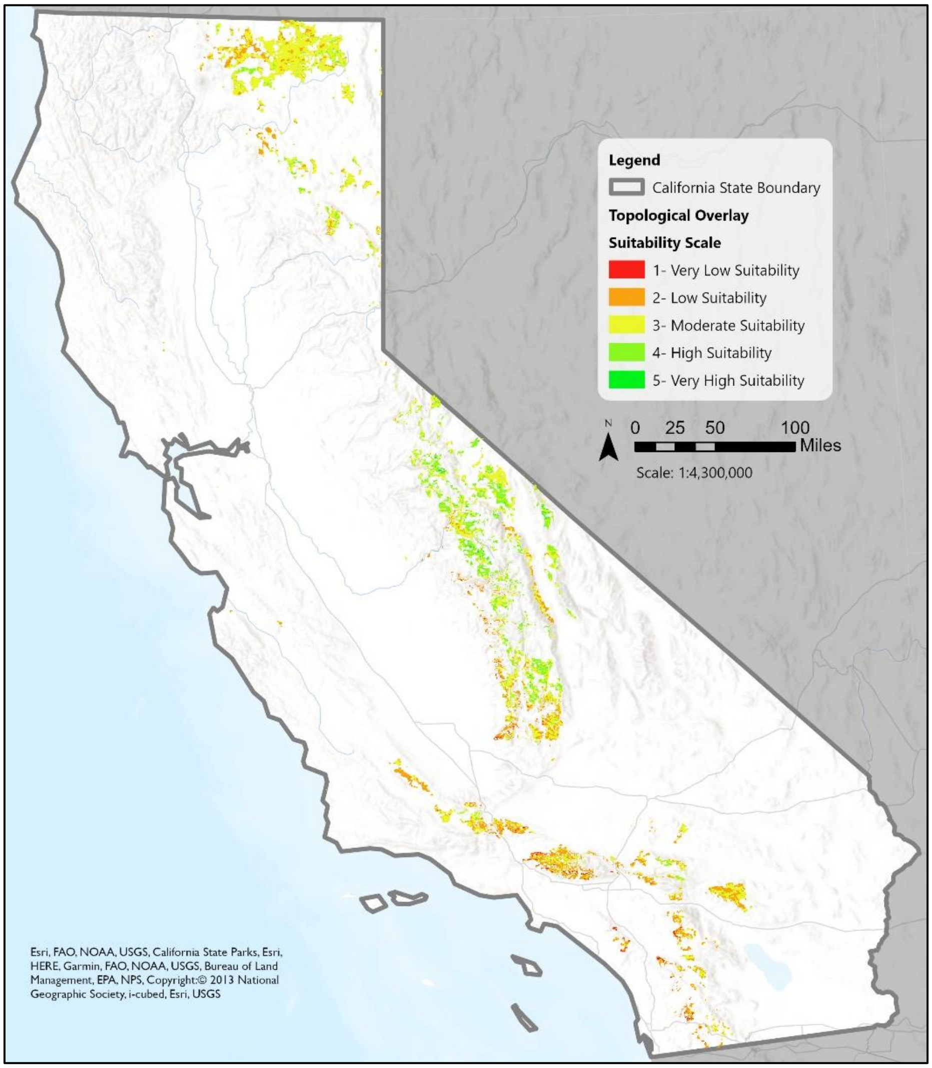

Figure 40. Topological sub-model

The resulting 30m outputs, described above, were then combined in a second weighted overlay which produced a 30m environmental suitability surface within the project extent This step produced a 30m environmental suitability surface within the project extent. Figure 41 shows the expanse of approximately 704,160 square meters of suitable climate with approximately 2.2% ranked as very high suitability, 29.8% as high suitability, and 57.1% as moderate suitability. This narrowed suitability around the northeastern, central, and southern coast of California.

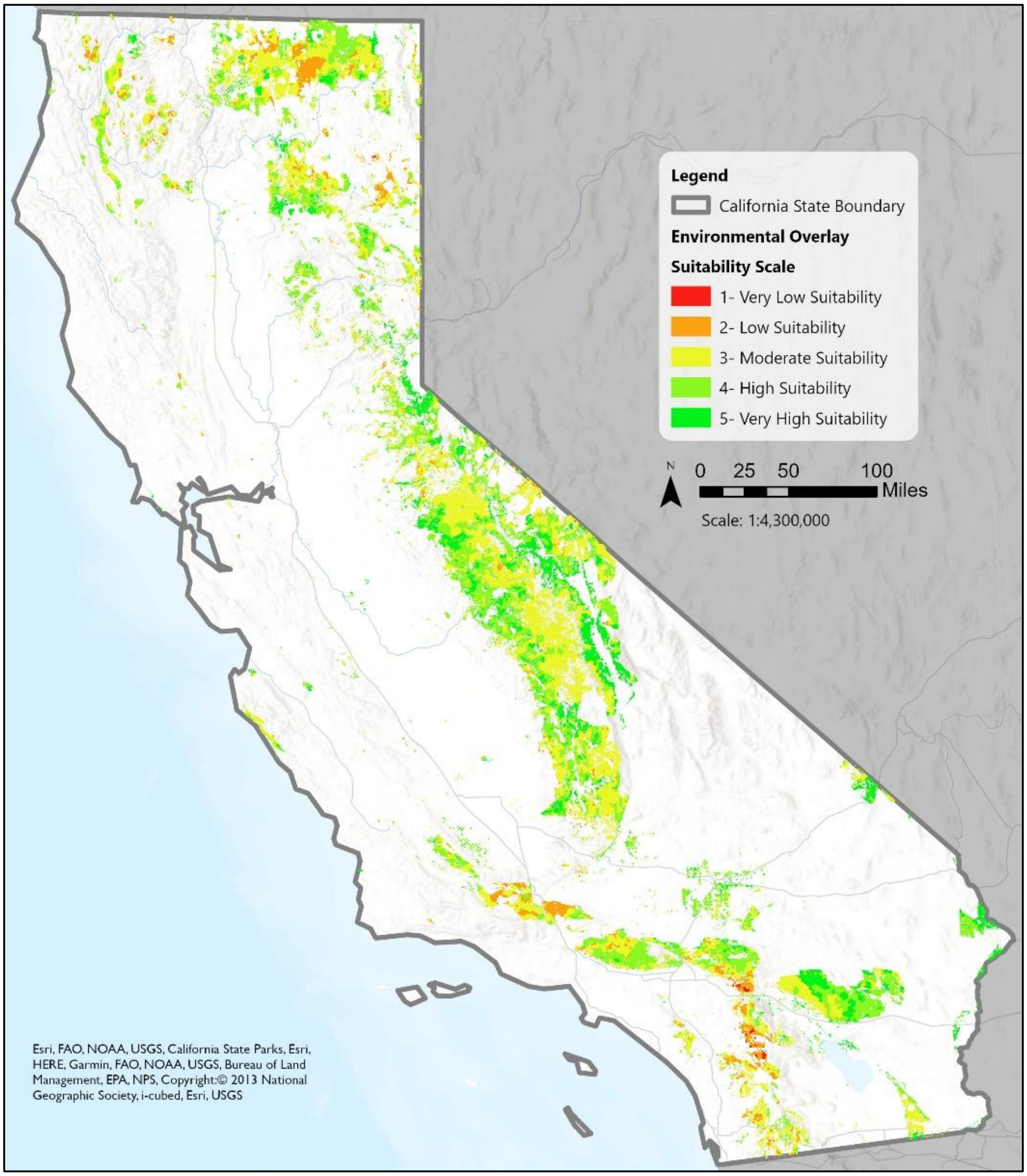

Figure 41. Overall environmental suitability

4.1.3 Final Overlay Results

A final overlay was performed to combine the 30m environmental submodel and 30m climate sub-model. A final raster output was produced representative of potential climate refugia for JTF. Figure 42 shows climate refugia expanding 704,160 square meters of the study area with approximately 0.18% ranked as very high suitability, 20.67% as high suitability, and 61.27% as moderate suitability. These highly ranked areas are clustered in 3 distinct areas, the first in the northeastern region, the second located in the central region, and the third between the south coast and inland desert region (Figure 42).

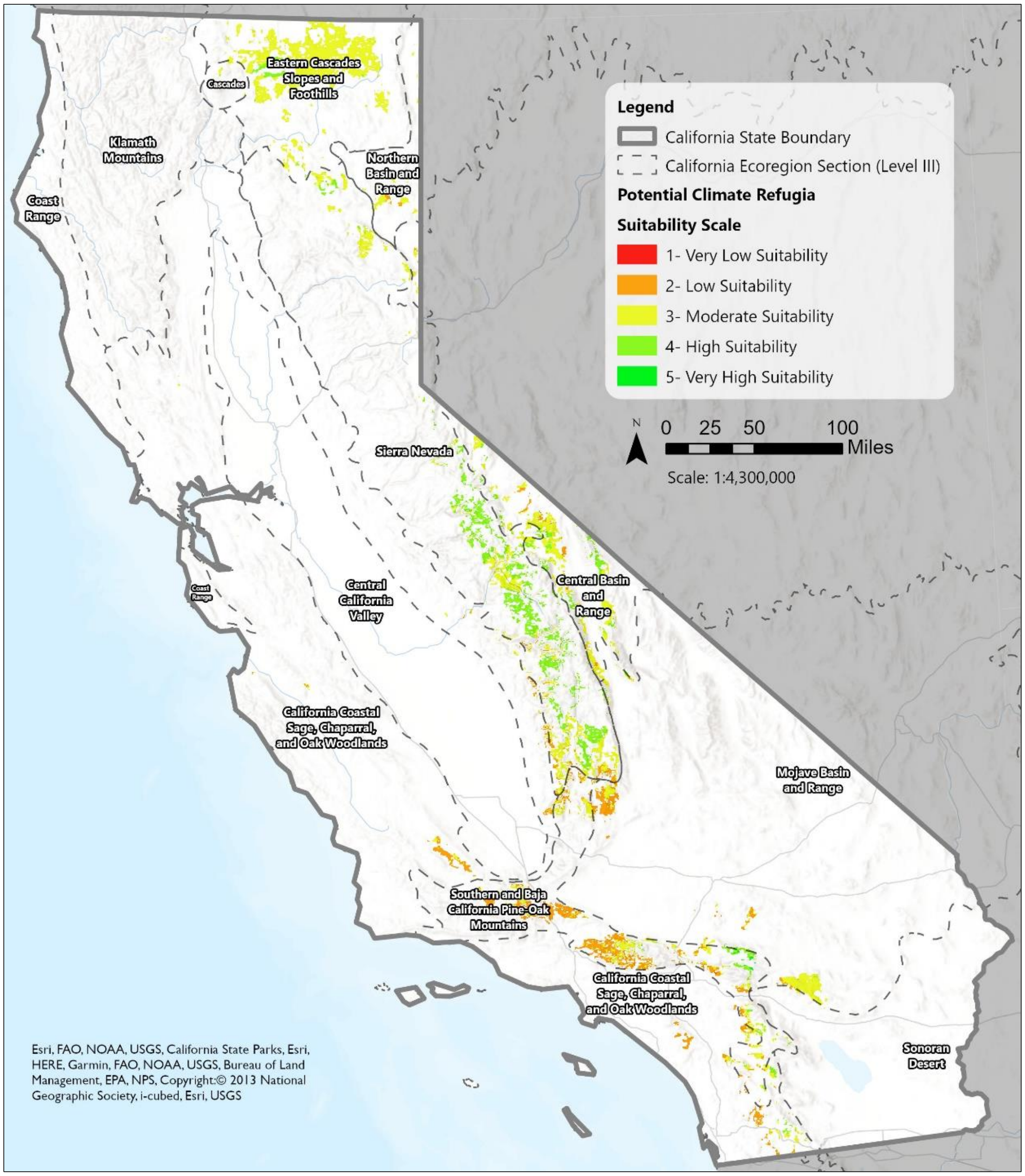

Figure 42. Final suitability surface

4.2 JTF Refugia in California

Examining these JTF refugia more closely, three distinct areas encompass suitable environments and climates within the study area. The first is located in the northeastern region, the second is located within the central region, and the third is between the south coast and inland desert regions of California. The following sections describe these areas in detail.

4.2.1 Area 1: Northeastern California

Area 1, as shown in Figure 43, is in the northeast corner of California. The suitable locations identified herein are situated predominantly within three EPA-recognized ecoregions: Eastern Cascades Slopes and Foothills, Northern/Central Basin and Range, and Sierra Nevada (see US EPA 2010). Low to moderate suitability dominates this area as this relatively small cluster of suitability resides in a continental climate with greater temperature extremes in the warm summers and less precipitation. The highest suitability in this area is focused within the northwestern region of the Eastern Cascades Slopes and Foothills (Figure 43).

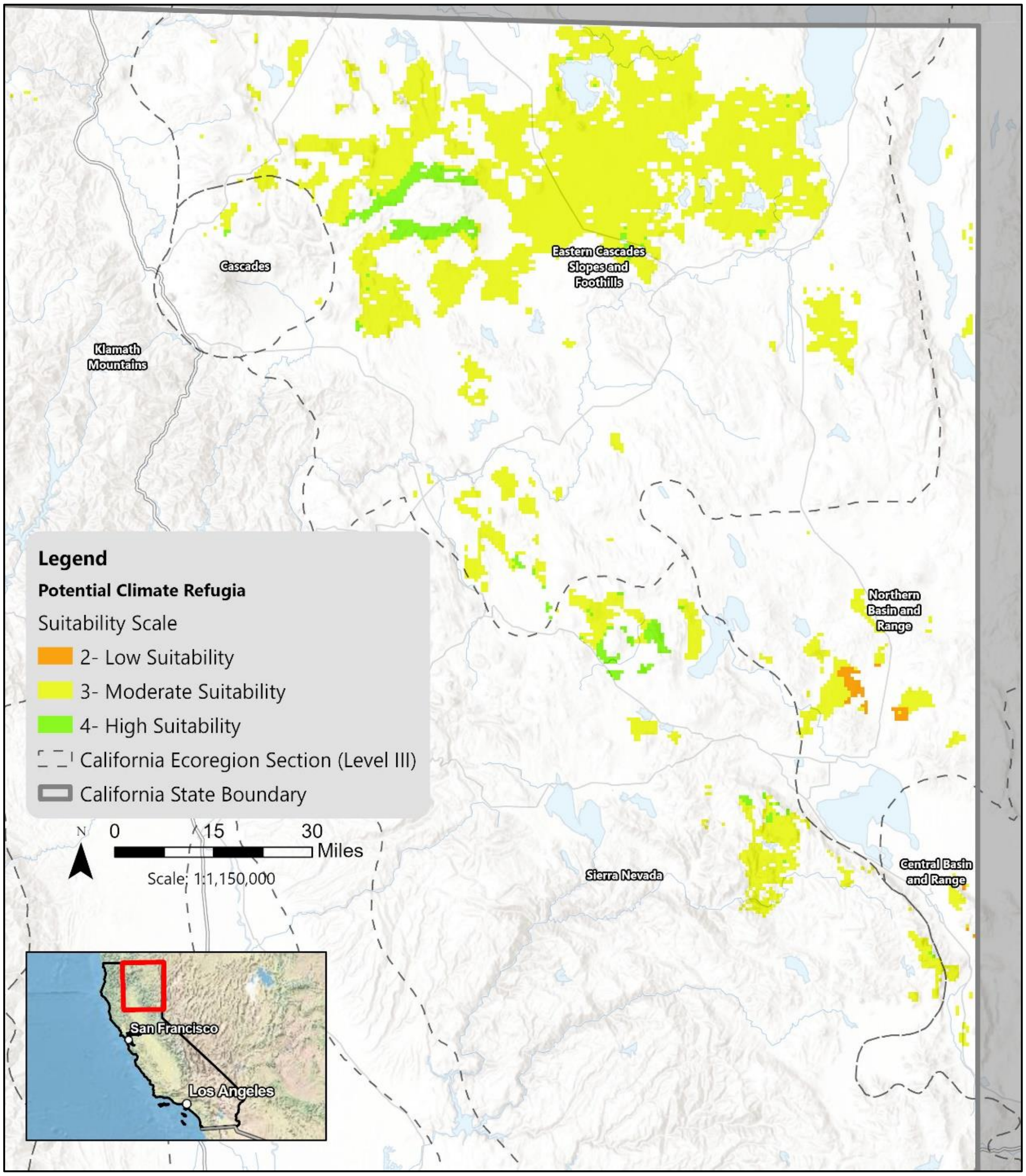

Figure 43. Area 1: Northeastern California

Potential JTF refugia are identified within the Cascade Mountains of northern California, predominantly in the Easter Cascades Slopes and Foothills ecoregion (see US EPA 2010). This ecoregion is characterized by its continental climate with greater temperature extremes in the warm summers and less precipitation. Gently steeply sloping mountains including volcanic cones and buttes dominate much of this region (Wiken, Nava, and Griffith 2011). All northern California ecoregions identified as suitable in this analysis, although not typically associated with desert habitats, may provide the necessary mild summers and wet winters in the coming decades. However, this seems most unlikely as this location encompasses the lowest suitability of this analysis.

4.2.2 Area 2: Central California

Area 2, as shown in Figure 44, reveals suitable locations clustered in the central region of California. These locations fall predominantly within two EPA-recognized ecoregions Mojave/Central Basin and Range, and Sierra Nevada ecoregions (see EPA 2010). The entire spectrum of suitability is present in this region with the lowest suitability at the borders of the Sierra Nevada ecoregion. High to very high suitability dominates this area with clustering within the Central Basin and Range ecoregion.

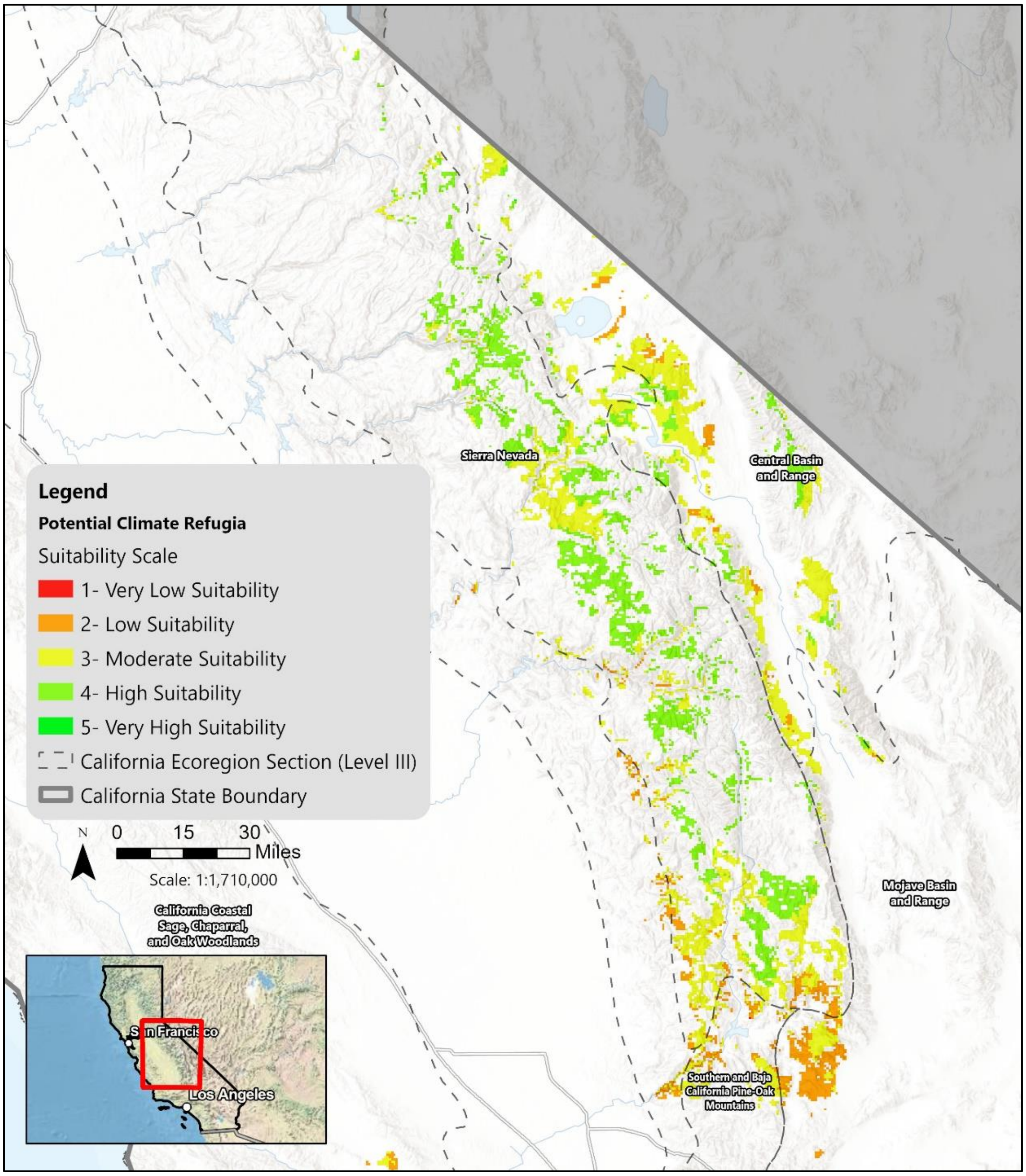

Figure 44. Area 2: Central California

Located in the Great Basin of California, the Central Basin and Range ecoregion is defined as an area of a hotter and drier climate with milder temperatures than the Mojave Basin and Range and Sonoran Desert ecoregions to the south. This ecoregion is also characterized by a wide range of temperatures and precipitation. With north-south trending ranges, basins, playas, salt flats, low terraces, and dunes often bordered by long gently sloping alluvial fans (Wiken, Nava, and Griffith 2011). Similarly, as climate change creates a more hostile climate for JTF the mild temperatures of the Central Basin and Range could provide refuge for these cacti.

The Sierra Nevada ecoregion, according to the EPA, expands to the high north-south mountain range of eastern California. The defining feature of this ecoregion is a severe to mild mid-latitude climate with extreme variability in elevation. Alongside mild to hot dry summers and cool to cold wet winters (Wiken, Nava, and Griffith 2011). The Sierra Nevada ecoregion is currently dominated by conifer forests which historically thrive in the mild summers and cold wet winters. However, as temperatures and precipitation are altered so does the distribution of these forests leaving space for more resilient species. This is verified by previous ecological research which conclude that the Sierra Nevada's conifer forests had, on average, shifted about 112 feet higher in elevation providing space for new species (Shao 2023). The most suitable temperature range for the conifers has shifted leaving an estimated 11 percent of today's conifer forest in the Sierra Nevada mismatched to its current climate conditions (Shao 2023). Thus, as climate changes previously hostile environments for Joshua trees, such as the Sierra Nevada ecoregion, may provide the necessary climate and environment in the coming decades.

4.2.3 Area 3: Southeastern California

Area 3, as shown in Figure 45, is found in southeastern California. These suitable locations lay predominantly within one of the EPA-recognized ecoregions, Southern and Baja California Pine Oak Mountains (see EPA 2010). The entire spectrum of suitability is present in this region with the highest suitability along the borders of the Southern and Baja California Pine Oak Mountains, Sonora, Mojave Basin, and Range, and California Coastal Sage, Chaparral, and

Oak Woodlands ecoregions (see EPA 2010). Low suitability dominates the eastern and western edges of the Southern and Baja California Pine Oak Mountains.

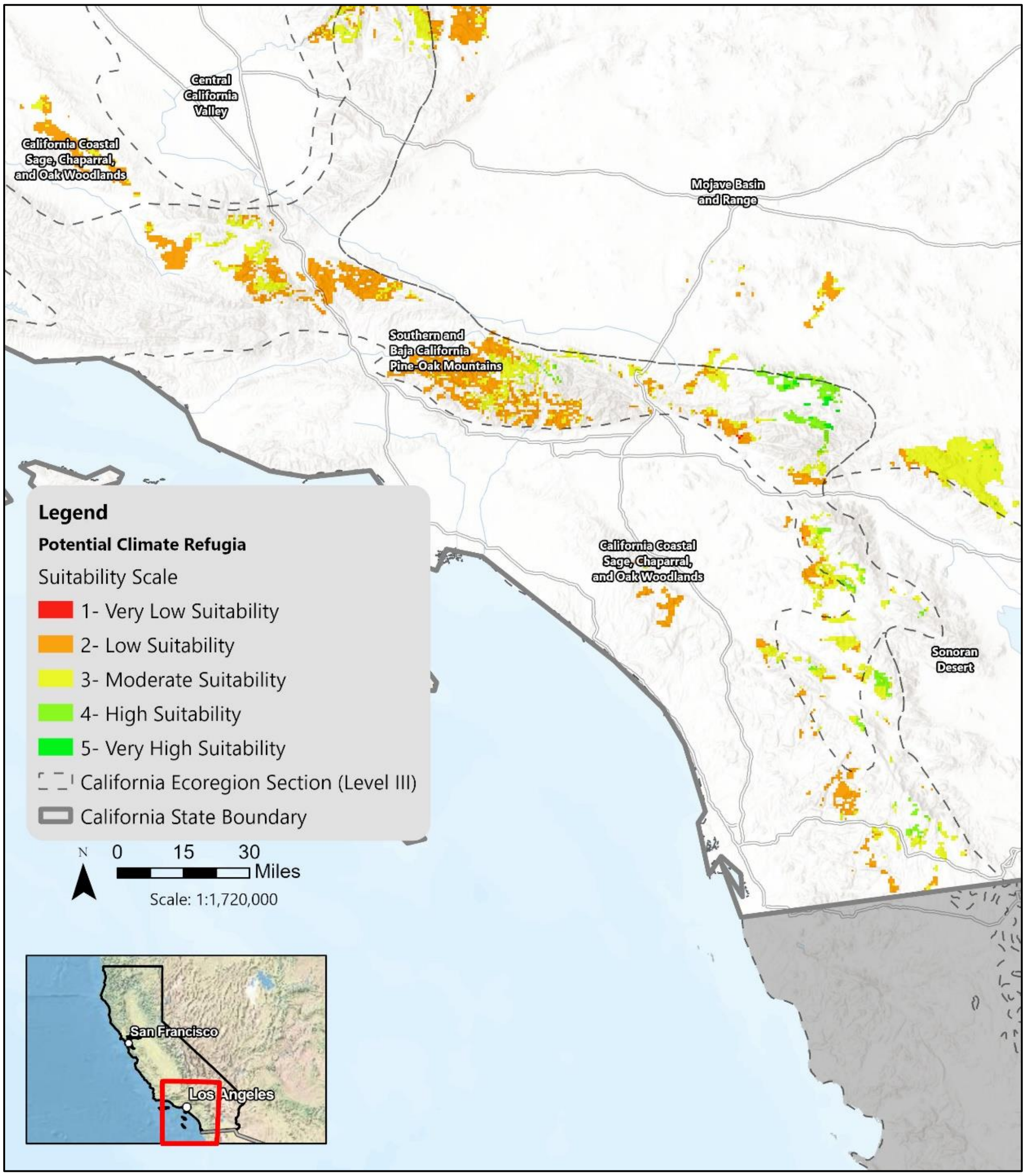

Figure 45. Area 3: Southeastern California

As recognized by the EPA, the Southern and Baja California Pine Oak Mountains ecoregions include the highland areas of southern California made up of the Transverse Range, such as the Santa Ynez, San Gabriel, San Bernardino, and Peninsular Range mountains. Currently, this ecoregion has a mild mid-latitude Mediterranean and desert climate characterized by long, hot dry summers and mild, slightly wet winters (Wiken, Nava, and Griffith 2011). These high-sloped areas with narrow valleys of colluvium and alluvium are not typical to Joshua tree habitats however provide a moderately suitable habitat according to this analysis (Wiken, Nava, and Griffith 2011). The analysis suggests a migration to the northwest toward this ecoregion that may provide the necessary climate needs as climate changes.

Chapter 5 Discussion

The following chapter discusses the findings presented in Chapter 4. The results of the suitability analysis indicate the shift in future Joshua tree habitats away from the current Joshua tree distribution. The overall result of this suitability analysis suggests a migration of JTF habitats, away from its current ecoregion, northwest to other non-typical ecosystems as climate changes. As previously described, the current JTF spans across the Mojave Basin and Range and Sonoran Desert ecosystems. Areas 1, 2, and 3, as shown in Figure 25-27, are potential future Joshua tree habitats in the south-central region of California within the Mojave/Central Basin and Range, Sierra Nevada, and Baja California Pine Oak Mountains ecoregions (EPA 2010). These locations of high suitability speak to a possible species migration toward less hostile climates. Accuracy of analysis if verified by historical analysis and currently proposed refugia of these resilient cacti. Finally, limitations and future research is discussed to improve current conservation methods.

5.1 Migration to the North

The projected shift northward identified in this analysis speaks to a cyclical habitat pattern historically seen in Joshua trees. As previously discussed, changes to global climate systems pressure wildlife and vegetation to move to higher elevations or toward polar latitudes to stay in climate zones for which they have historically adapted (Shao 2023). The same can be said of these cacti in previous climate warmings; for example, 11,700 years ago the range of Joshua trees decreased, leaving only the populations near what had been its northernmost limit (Cole et al. 2011). The results of this suitability analysis suggest a similar outcome. As shown in Figure 46, this can be deduced by comparing suitable Area 3, in southeastern California, with current iNaturalist observations. The suitability surface shows projected habitats in 2041-2060 along the northwestern boundary of the Mojave Basin and Range ecosystem. This indicates climate adaptation strategies should consider the historical shift of Joshua trees northward to ensure species survival.

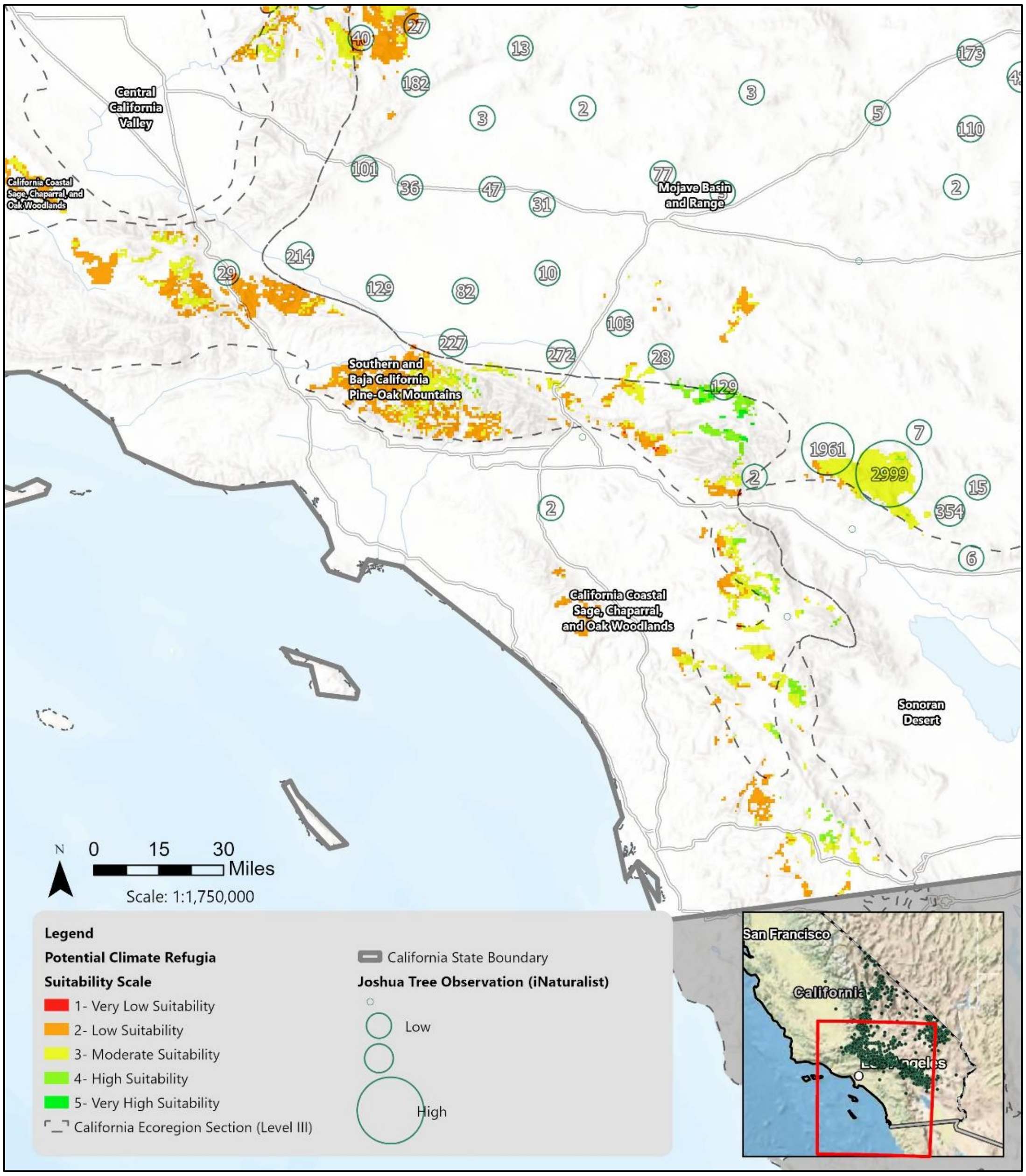

Figure 46. Suitability surface and current Joshua tree distribution

Other scholars make similar projections. Joshua tree refugia through the end of the 21st century are projected as higher elevations, north-facing slopes, canyons, or ravines that capture and hold water, and cool air drainages (Sweet et al. 2019). The 2018 Joshua Tree Species Assessment whose analysis concludes that in terms of species-level effects, the range of Joshua Trees could shift to more northern areas or to higher elevations where temperatures are more accommodating to species needs (Sirchia, Hoffman, and Wilkening 2018). For this reason, resource managers should prioritize the northern boundaries and higher elevations of current Joshua tree habitats when defining climate refugia. This will capture the shifting of suitable climates for California JTF as the climate continues to change.

5.2 Limitations

Suitability analysis using weighted overlay is ideal for this research as it considers multiple criteria of varying weight to create a tailored suitability surface. However, the customization of this analysis comes with its limitations in the form of cross-scale inference and uncertainty. Uncertainty is also introduced because of the limited availability of relevant knowledge and data.

Ultimately, this research provides a projection of suitability at the population and not at the individual scale. This introduces cross-scale inferencing, wherein the analyst assumes that correlations observed for aggregates can be transferred to the individual (Goodchild 2011). Consequently, this analysis only provides actionable information at the regional level. Specifically, the scale of this analysis, 900m, utilized in this analysis provides a confident estimate to inform only regional conservation strategies. Like other species distribution models, findings demonstrate what is occurring and may occur in a broad sense, as well as provide actionable data (Sweet 2019). While this suitability analysis projected locations in California where the future climate may be accommodating to JTF, it cannot infer how or when this species will respond to this shift.

Uncertainty in species distribution modeling is an inevitable part of spatial analysis and can impact the confidence of the result. This is common across this analysis as the uncertainty of results could mean that a species' exposure to climate change is either higher or lower than models predict (Bonham 2022). This is most likely a result of the modifiable areal unit problem, the uncertainty created by any level of areal aggregation and scale that impacts the results of any given spatial analysis (Goodchild 2011). Overlay methods often involve the aggregation of data points and analysis of different attributes of the same location, creating variability in criteria/data ontology. Specifically, this analysis aggregates data at inconsistent resolutions because of data availability**.**

As described in Chapter 3, nine datasets were utilized to represent the criteria that define suitable JTF habitats. All data, to ensure accuracy, was acquired from authoritative sources through open data platforms. Data availability, however, still played a role in the models' limitations. Specifically, the USDA 2023 Gridded Soil Survey Geographic (gSSURGO) Database, derived from resource planning and analysis of soil data, was incomplete for this study. As shown in Figure 28, soil data within the project extent, shown in black, contained large gaps in the Mojave Basin and Range ecoregion. Unfortunately, this data is incomplete in areas where detailed soil survey maps are not available. Despite this, gSSURGO is the most recent and complete soil data for California. Although contributing slightly to model bias, the author believes these data gaps do not significantly impact the results because the areas that suffered from gSSURGO gaps were largely removed and winnowed out of the workflow before the final stages as they were deemed unsuitable due to precipitation levels. Thus, the hard constraints within the reclassification process shrank away from these data gaps (Figure 47).

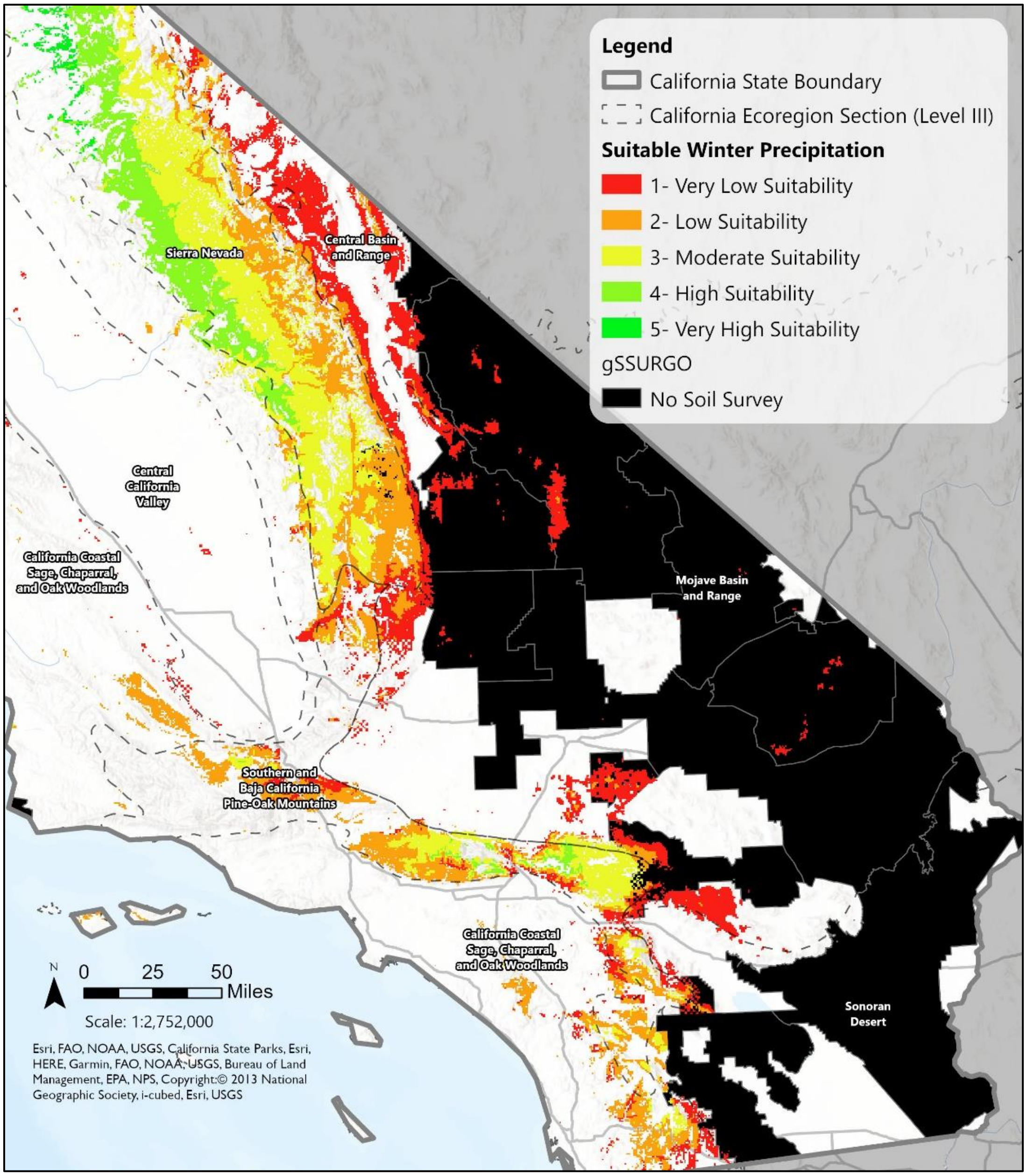

Figure 47. Soil data incompleteness

Reclassification and assignment of weights, associated with each criterion was a crucial step in this research and was informed solely based on expert knowledge. Like data availability, the limited availability of expert knowledge on which to draw may limit the model's performance. As discussed in Chapter 2, only a handful of analyses exist that contained the detail necessary to inform model specification. For example, equal intervals were utilized to reclassify because of a lack of detail about Joshua Tree's needs. However, this method of reclassification avoided unnecessary bias that might have been introduced using other data-specific methods.

To ensure an accurate suitability analysis, uncertainty was mitigated by defining criteria solely through expert knowledge from authoritative sources. This proves to be an effective method used by similar research in which species predictions of JTF are difficult to determine without a large degree of speculation even with the best information currently available (Sirchia, Hoffman, and Wilkening 2018). Therefore, the authors believe the JTF refugia defined in this project are accurate projections of suitability shortly for this key species.

5.3 Future Research and Policy

To create a more precise suitability model, future research should gather expert knowledge from expert interviews and working groups. Expert knowledge gathered from biologists, botanists, and ecologists would capture species' needs more accurately which would flow through from model design to results. Incorporating a temporal scale could also provide dimensionality to this analysis, by analyzing suitability across various 20-year summaries (2021-2040, 241-2060, 2061-2080, 2081-2100). Exploring JTF refugia across time would produce insight into the rate at which Joshua tree populations are migrating northwards. Lastly, this research could be a stepping stone to a larger scale of analysis focused on a smaller project area.

In conclusion, this suitability analysis suggests a migration away from current ecoregions (Mojave Basin/Range and Sonoran Desert) as temperatures increase and precipitation levels decrease. Joshua tree habitats in 2041-2060 are projected to reside in the south-central region of California within the Mojave/Central Basin and Range, Sierra Nevada, and Baja California Pine Oak Mountains ecoregions. Climate adaptation actions defined by resource management should prioritize the northwestern edges of current climate refugia as JTF habitats shift to northern areas of higher elevations where climates are more accommodating to species' needs.

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