Mapping suitable nesting habitat for marbled murrelets (*Brachyramphus marmoratus*) in the Santa Cruz Mountains

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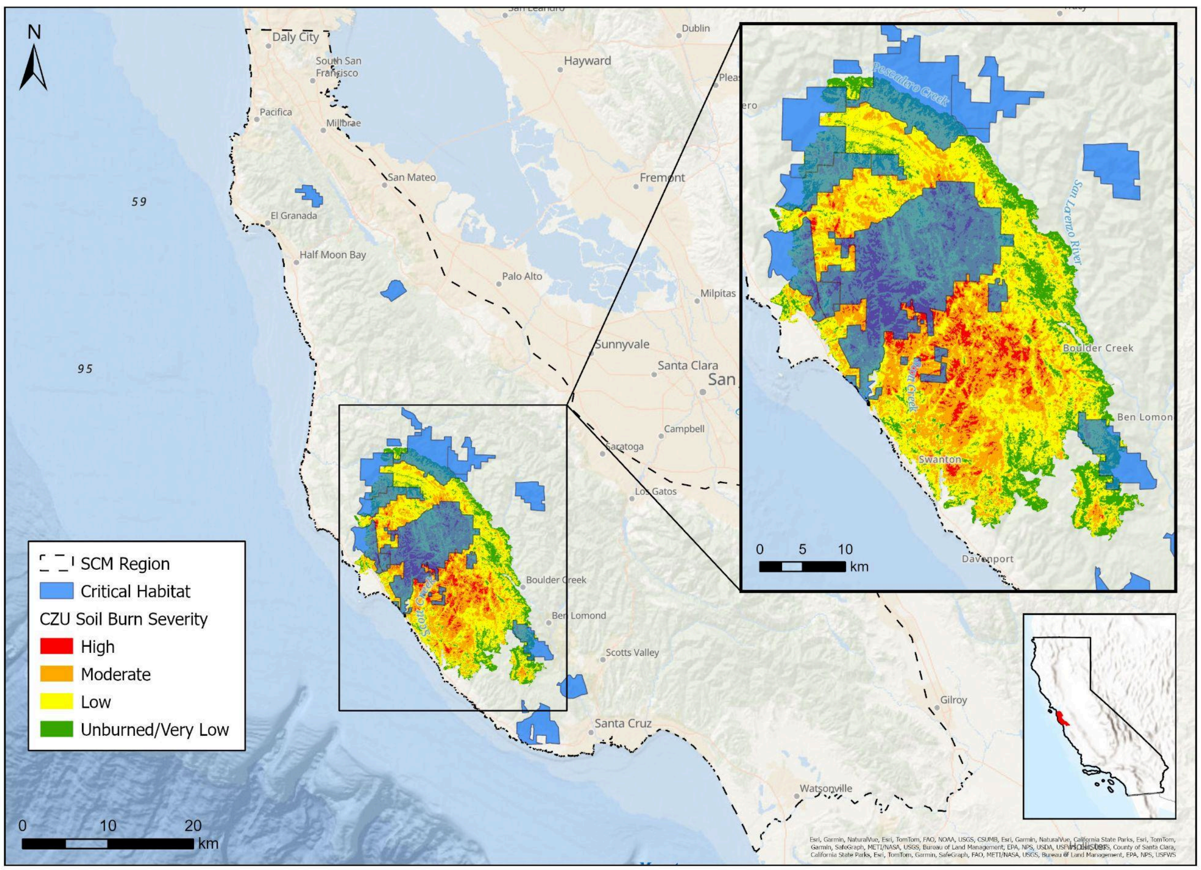
1. Introduction

Recovery and preservation of imperiled species are a major focus of conservation planning and one of the key conservation outcomes driving management actions. Among other reasons, practitioners and organizations often focus on single-species conservation because society can connect to them, they are the underlying ‘unit’ of biodiversity, it is generally easier to measure and monitor them than broader ‘ecosystem functionality’, and various human activities directly impact them (Bennett et al., 2015; Thomas-Walters & Raihani, 2016; Runge et al., 2019). Furthermore, focusing conservation efforts on a single species can indirectly protect other components of biodiversity. For example, the protection of umbrella species often benefits co-occurring species whose ecological niches fall within that of the umbrella species (Branton & Richardson, 2010; Runge et al., 2019). An avian species that is both imperiled and considered an umbrella species is the marbled murrelet (*Brachyramphus marmoratus*), a small seabird in the family Alcidae that forages at sea and nests on the large limbs of coastal old-growth forests. They spend most of their lives in near-shore marine environments, flying inland only to breed and nest in the tall canopies of coastal forests. Their at-sea distribution runs along the Pacific Coast from the Aleutian Islands and southern Alaska to southern California, and their breeding range extends from southern Alaska to central California (Halbert & Singer, 2017).

Primarily due to loss of habitat from logging and other anthropogenic pressures, the marbled murrelet was listed as “threatened” by the U.S. Fish and Wildlife Service (USFWS) under the Endangered Species Act in 1992 in California, Oregon, and Washington (Felis et al., 2022). Later that year, they were listed as “endangered” by the State of California under the California Endangered Species Act (Felis et al., 2022). The USFWS designated critical habitat for marbled murrelets in 1995 and then prepared a Federal Recovery Plan in 1997. This plan divided the breeding range of murrelets into six different conservation zones. Zone 6 includes the forested coastal habitats up to 24 km inland from San Francisco Bay to Point Sur in Monterey County, and the population of marbled murrelets in this zone nests primarily in the Santa Cruz Mountain (SCM) region (Baker et al., 2006) (Figure 2). The SCM population of murrelets has been declining due to a variety of factors, including but not limited to wildfire events, land use change limiting the distribution and availability of contiguous breeding habitat, and increased predation from predators like corvids (Felis et al., 2022; Valente et al., 2023). Marine surveying efforts off the Central California coast during the 2020 and 2021 breeding seasons estimated that the entire Zone 6 area had an abundance of “470 birds (95-percent confidence interval, 313–707 birds) in 2020 and 402 birds (95-percent confidence interval, 219–737 birds) in 2021” (Felis et al., 2022).

The 2020 CZU Lightning Complex wildfires burned more than 35,000 ha of forest land in Santa Cruz and San Mateo Counties (Potter, 2023). The majority of areas characterized by high burn severity fell within Big Basin Redwoods State Park (BBRSP), which is a known historic stronghold of suitable nesting trees for marbled murrelets (Hamer & Nelson, 1995; Baker et al., 2006; Potter, 2023). Figure 1 portrays the USFWS-designated critical habitat for murrelets overlaid with the CZU fire soil burn severity, showing the amount of critical habitat within BBRSP that burned severely during the fires. This geographically separated and endangered population of marbled murrelets was declining prior to these fires decimating their prime nesting habitat. These cumulative threats and recent losses emphasize a need to focus on the top conservation actions for murrelets' recovery in the Santa Cruz Mountains. A recommended strategy for murrelets in USFWS Zone 6 is to identify, protect, and restore key habitats that can serve as suitable nesting sites (Halbert & Singer, 2017). This project aims to help address this conservation goal through a series of objectives listed below.



Map by M. Pepperdine

Figure 1. CZU Lightning Complex burn severity overlaid with marbled murrelet critical habitat. Much of the USFWS-designated critical habitat was burned during these fires, especially regions of Big Basin Redwoods State Park which lies at the heart of the burn scar and map inset.

2. Objectives

As mentioned above, one of the top recommended conservation strategies for marbled murrelets in USFWS conservation Zone 6 is to identify, protect, and restore key habitats that can serve as suitable nesting sites (Halbert & Singer, 2017). The main goal of this project is to support USFWS Zone 6 conservation strategies and future recovery efforts for the imperiled murrelet population in the Santa Cruz Mountains (SCM) by helping in the identification and prioritization of suitable nesting habitats throughout this region. This will be achieved through the following objectives:

1. Employ a **science-based process** to inform habitat **preservation, conservation, and recovery** efforts for murrelets in the SCM.
2. Map and delineate the **occurrence probability** and geographical distribution of **suitable nesting habitat** using MaxEnt modeling, before and after the 2020 CZU Lighting Complex Fires.
3. **Prioritize county parcels** for future land acquisition and protection efforts, conservation easements with local land owners, and acoustic monitoring through a series of spatial overlays and intersections with the MaxEnt results and key data layers (e.g., post-fire suitable habitat, county parcels, and protected areas).

3. Methods

3.1. Study area

The scope of this project is the Santa Cruz Mountains (SCM), a coastal redwood forest that extends from San Francisco to the Pajaro River (~119 km) and is part of the California Outer Coastal Range (Baker et al., 2006) (Figure 2). Elevation ranges from sea level to around 1,154 m in the SCM, and the forest in this region is dominated by coast redwood (*Sequoia sempervirens*) in the overstory with Douglas-fir (*Pseudotsuga menziesii*) also present to a lesser degree (Baker et al., 2006). Most of the original old-growth forest in this range was logged in the early 1900s, generally involving clear-cutting and leaving small pockets of inaccessible timber (Singer et al., 1991; Noss, 2000). In 2006 there was an estimated 4,100 ha of old-growth redwood forest remaining in the SCM primarily in state and county parks, but also dispersed in smaller parks and private property (Baker et al., 2006). However, a significant portion of this old-growth forest was situated in BBRSP which, as described above, burned severely in recent wildfires (Potter, 2023). There is also a significant area of late-successional and secondary old-growth forest distributed throughout the SCM, but a large portion of these regions were also burned severely (Baker et al., 2006; Potter, 2023). Climatic conditions in the SCM are fairly consistent but have some variation from west to east across ridgelines (Baker et al., 2006).

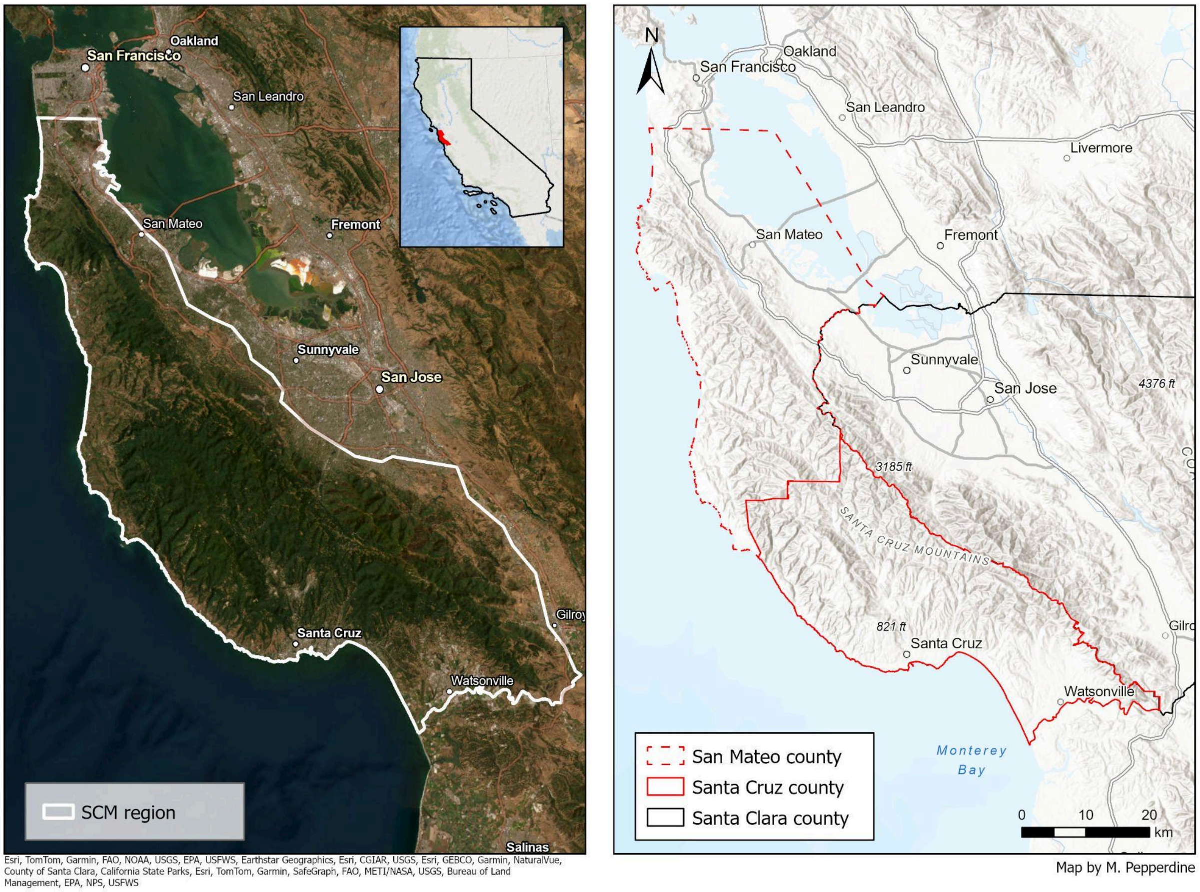


Figure 2. Project location. This analysis is focused on the Santa Cruz Mountain Region (left), which comprises Santa Cruz, San Mateo, and Santa Clara Counties (right).

3.2. Data description

All data used in this analysis is open-access and publicly available for download. See Table 5 in the appendix for a list and description of all datasets used in the analysis.

3.3. Data processing

This section outlines the processing of all data used for the MaxEnt modeling and development of the various species distribution models used to delineate suitable nesting habitats for murrelets in the SCM. Figure 3 shows all environmental predictor variables used in the analysis. Almost all of the data processing for this analysis was completed in RStudio (R v4.4.1), with a few steps completed in ArcGIS Pro v3.1.1. See Figure 8 in the appendix for a conceptual overview of data processing and analysis steps. All code used in the data processing and analysis is publicly accessible in the `mamu-conservation-scm` GitHub repository, which also includes detailed descriptions of the analyses completed in ArcGIS.

3.3.1. Occurrence data

All available occurrence records for marbled murrelets were downloaded from the Global Biodiversity Information Facility (GBIF) as a CSV file and then subset, filtered, and cleaned in RStudio. Only observations with geographical coordinates and those since 1990 were kept for the analysis. Because marbled murrelets are sea birds that spend most of their lives foraging in near-shore marine environments, coastal observations were abundant. These marine and near-shore observations were removed to only include terrestrial observations representing nesting site occurrences.

3.3.2. Forest structure & land cover

It is well-documented and known that the strongest predictor of murrelet nesting site selection and habitat suitability is canopy height and structural complexity (Hamer & Nelson, 1995; Baker et al., 2006; Hagar et al., 2018). A recent study by Cosgrove et al (2024) found that MaxEnt models using only one or two variables to reflect these conditions can predict murrelet occurrence with a high success rate. Two data sets were downloaded from Pacific Veg Map and used to represent different forest structure conditions in the SCM as environmental predictors in the MaxEnt modeling: a pre-CZU fire canopy height model (CHM) and a post-CZU fire CHM.

Pacific Veg Map provides a combined CHM for Santa Cruz and Santa Clara Counties and a separate CHM for San Mateo County. Both CHMs were downloaded at a native resolution of 3 ft and projected to the same coordinate reference system [NAD 1983 (2011) California Zone III]. They were then aggregated to a 45 ft resolution using bilinear interpolation for two main reasons: (1) to reflect the average canopy crown diameter of old-growth redwood and Douglas fir trees in the Central Coast, and (2) for processing and computing purposes. After ensuring both rasters were in the same CRS with the same resolution, they were merged to create one CHM extending across the entire extent of the SCM.

The post-fire CHM provided by Pacific Veg Map is also at a 3 ft resolution and only covers the delineated 2020 CZU Lightning Complex fire burn scar. This raster was also downloaded at its native resolution and then resampled to the extent, origin, and position of the processed pre-fire CHM described above using bilinear interpolation. The post-fire CHM was then merged on top of the pre-fire CHM ensuring that the post-fire values were preserved in areas of overlap. This generated the complete post-fire CHM raster layer that represents forest structure conditions and canopy heights across the SCM after the severe 2020 CZU wildfires and was used to transfer the pre-fire SDM to post-fire nesting suitability.

3.3.3. Topography

Elevation and aspect rasters were used to represent topographic conditions predicting locations of nesting sites for marbled murrelets, two variables that have also been shown to influence murrelet nesting site selection and habitat suitability (Hamer & Nelson, 1995; Baker et al., 2006). Elevation data was downloaded from Pacific Veg Map and then used to generate an aspect raster. Similar to the forest structure data provided by Pacific Veg Map, they offer one digital elevation model (DEM) that covers both Santa Cruz and Santa Clara Counties, and another that covers only San Mateo County. These layers were downloaded at a resolution of 3 ft and then processed following the same methodology outlined for the CHMs to generate one DEM covering the full extent of the SCM region at a resolution of 45 ft. This DEM was then used to generate an aspect raster in ArcGIS Pro v.3.1.1 with the Aspect Spatial Analyst tool.

3.3.4. Distance to rivers & ocean

Another strong predictor of suitable habitat and nest site selection for murrelets is the proximity of potential nesting trees to perennial or intermittent streams (Baker et al., 2006). This is because murrelets are known to use riparian corridors as flyways when moving inland from near-shore environments to nest (Baker et al., 2006). This data layer was created through a series of geospatial analyses in ArcGIS Pro and RStudio. First, a blank set of grid cells at a resolution of 100 ft was generated across the entire SCM region. The Euclidean distance (m) from each grid's centroid to the nearest intermittent or perennial stream in the SCM was then calculated. The National Hydrography Dataset (NHD) was used to represent intermittent (*fcode 46003*) and perennial (*fcode 46006*) streams across the SCM. These grids were then rasterized, preserving the distance to the nearest stream feature, and resampled to the extent, origin, and resolution of the CHM raster using bilinear interpolation. This resulted in a 45 ft resolution raster covering the entire SCM that represents the Euclidean distance from each grid cell's centroid to the nearest intermittent or perennial stream delineated by the NHD.

Murrelets are also thought to nest in closer proximity to the coast because they exert less energy to reach nesting trees and have closer access to their foraging grounds while breeding (Baker et al., 2006). The same methodology outlined above was used to generate a distance to ocean layer, creating a 45 ft resolution raster across the entire SCM representing the Euclidean distance from each grid cell's centroid to the Pacific Ocean.

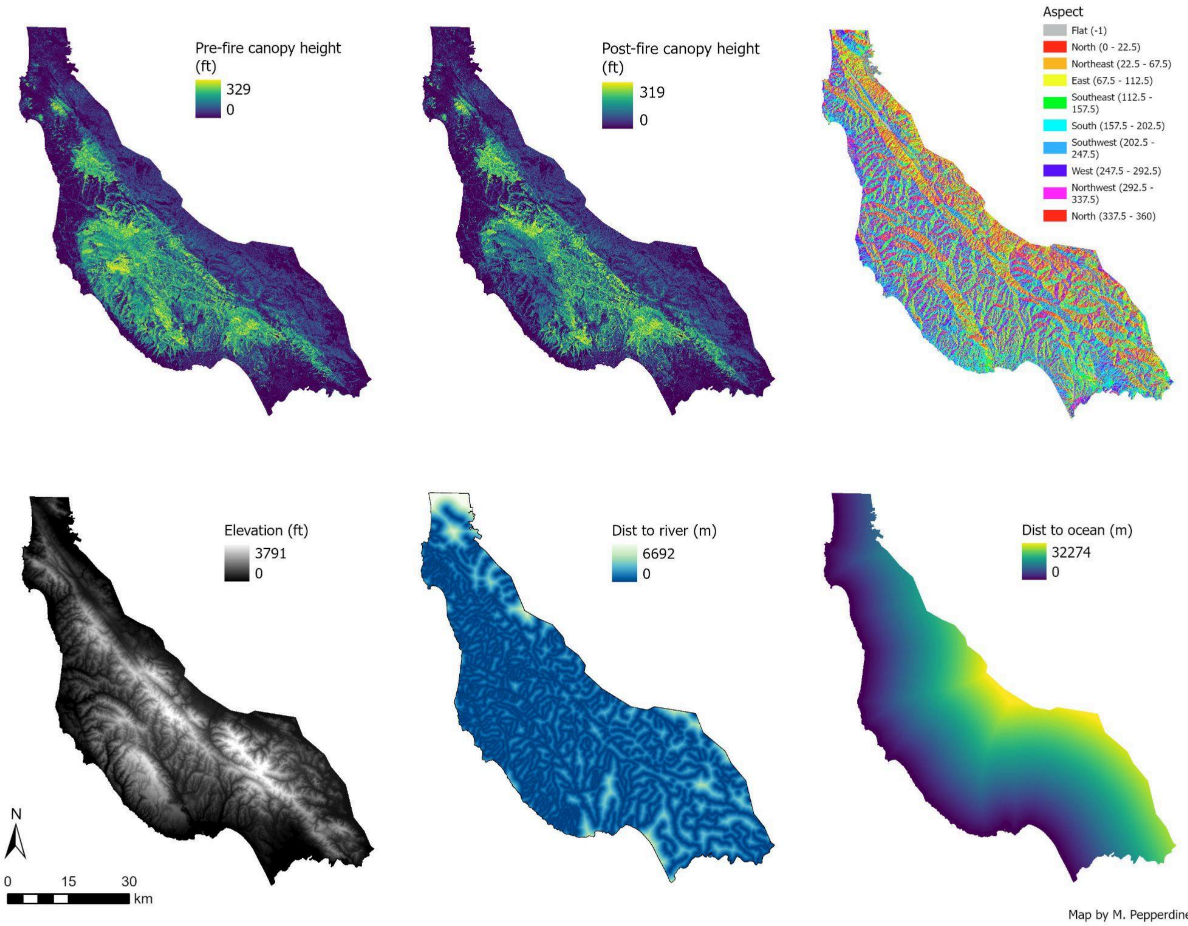


Figure 3. Environmental predictor variables used in the MaxEnt modeling.

3.4. Data analysis

3.4.1. Occurrence distribution & habitat suitability modeling

A maximum entropy (MaxEnt) model was used to predict the occurrence probability distribution of marbled murrelets and their suitable nesting habitat in the SCM region based on the key vegetation and topographic variables described above. MaxEnt is a commonly used species distribution model that predicts distribution based on presence-only records and environmental predictor variables (Jayakody et al., 2024). This approach is especially useful when a user does not have access to certain locations to know definitively where a species was absent (Cosgrove et al., 2024).

MaxEnt models are recommended as an appropriate habitat suitability modeling method when working with presence-only data and relatively low sample sizes, which is commonly the case with endangered species (Cosgrove et al., 2024). See Figure 3 and Table 1 for all predictor variables used in the analysis. The selection of these variables was informed primarily by Baker et al. (2006), Hagar et al. (2018), Valente et al. (2023), and Cosgrove et al. (2024) who modeled suitable nesting habitats and characterized known nesting site conditions for murrelets. MaxEnt models were created for three scenarios:

1. [Pre-fire]. Before the 2020 CZU Lightning Complex Fires with occurrence data from GBIF between the years 1990-2020.
2. [Pre-fire]. Before the 2020 CZU Lightning Complex Fires with occurrence data from the USFWS with 19 scientific grade known nesting site observations recorded by wildlife biologists working in Santa Cruz County. Given the small sample size, this model was generated solely for exploratory purposes and not used to transfer to post-fire conditions or in the land prioritization analysis.
3. [Post-fire]. After the 2020 CZU Lightning Complex Fires by transferring the best pre-fire model to post-fire vegetation structure conditions. Because a significant portion of key murrelet nesting habitat in the SCM was burned during these fires, it's crucial to delineate suitable nesting locations that fall outside of the high-severity burn scars.

MaxEnt was applied using the R package Wallace (v2.1.1), an R-based GUI application that offers a simple, reproducible approach for ecological modeling and niche/distribution modeling analyses (Kass et al., 2022). Because of RAM limitations when running Wallace with very fine-resolution predictor variables, the SDMs were generated in RStudio outside of Wallace's GUI with minor changes to the baseline session code. This code is also available in the project's publicly accessible GitHub repository.

Spatial partitioning was used to partition the occurrence data with a 75:25 (training:testing) split and generation of 10,000 background points. As a machine learning technique, MaxEnt can make internal decisions about variable selection and model fit; however, model complexity and geographic predictions are still greatly affected by external decisions with these models (James et al., 2013). MaxEnt software leveraged by Wallace gives users the ability to impact model complexity through two key factors: feature classes and the regularization multiplier. When using the maxnet algorithm in MaxEnt to model the probability of presence, 4 feature classes (or functions) can be chosen: linear (L), quadratic (Q), hinge (H), product (P), or some combination of these. The selection of these feature classes affects the flexibility of modeled responses; they determine the shape of modeled relationships across environmental space and influence model complexity (Kass et al., 2023). The regularization multiplier penalizes model complexity with higher values, leading to simpler models with fewer variables. For this study, four feature class combinations were used based on the characteristics of the predictor variables: L, LQ, H, LQH. Regularization multipliers from 1-2 were used for the runs, generating 8 models in total.

Table 1. Environmental predictor variables used in the Maxent modeling.

Number	Predictor Variable
1	Distance to river (m)
2	Distance to ocean (m)
3	Elevation (ft)
4	Aspect
5	Pre-fire canopy height model (ft)
6	Post-fire canopy height model (ft)

To assess the tested models, model validation statistics of area under the curve (AUC) and Akaike information criterion (AIC) scores were used. AUC ranges from 0 to 1 and assesses the accuracy with which a model can determine presences compared to random prediction. AUC values less than 0.5 imply a model is worse than random, 0.5 that the prediction is random, and 1 implies perfect prediction. When true negative/absence data does not exist, major complications for interpreting AUC scores exist (Lobo et al., 2008; Peterson et al., 2008); however, they can still provide relative indicators of performance. AIC is a common model evaluation metric for regression-based techniques with lower scores representing more optimal candidate models, and it penalizes complex models while also rewarding those with a high likelihood to find the best balance between complexity and fit (Burnham & Anderson, 2004). Response curves for the best-performing model were used to visualize the relationship between environmental predictors. After identifying the best model to predict occurrences between 1990-2020 under pre-fire vegetation conditions, the model was transferred to the post-fire forest canopy height conditions to examine the impact of the wildfires on the species' occurrence probability and locations of suitable habitat.

3.4.2. Land protection prioritization

After generating the various SDMs using MaxEnt, these results were used alongside other spatial data to prioritize various county parcels for protection to further conservation and recovery efforts for murrelets. The probability of occurrence rasters for both pre- and post-CZU fire conditions were reclassified to create pre- and post-fire habitat suitability models, with areas above 0.7 representing suitable habitat and below 0.7 unsuitable. The post-fire habitat suitability layer served as the basis for the land prioritization analysis. To assess changes in terrestrial habitat suitability for murrelets across the SCM, these rasters were differenced, subtracting the pre-fire habitat suitability layer from the post-fire. This generated a new layer to represent areas throughout the Santa Cruz Mountains that either gained (1), lost (-1), or had no change (0) in nesting habitat suitability.

Expert opinion informed a series of spatial overlays and geometric intersections to identify county parcels throughout Santa Cruz, San Mateo, and Santa Clara that should be prioritized for habitat protection. Using the California Protected Areas Database (CPAD), the amount of post-fire suitable habitat on all county parcels and on each *unprotected* county parcel throughout the SCM was calculated to identify those with the highest proportion of suitable nesting trees. Post-fire suitable habitat was calculated for both all county parcels and only unprotected parcels to inform different future research and conservation actions. For example, terrestrial surveying efforts should be focused on any areas throughout the SCM region with suitable habitat, whereas land acquisition efforts to increase the protected network for this species should only be focused on unprotected parcels.

4. Results

4.1. MaxEnt occurrence probability

Multiple iterations and combinations of feature class and regularization multiplier parameters were tested to identify the best-performing model. The model with the LQH feature combination and 1 regularization multiplier had the second-highest AUC and lowest AIC score, and was selected as the 'best model' to predict the occurrence probability of murrelets throughout the Santa Cruz Mountains. See Table 2 below for key AUC and AIC scores for each of the 8 models generated with MaxEnt. Figure 4 (A/B) shows the 45-ft resolution probability of occurrence rasters for the selected model with pre-fire occurrence data and vegetation conditions, and Figure 4 (C/D) shows the transfer of this model to the post-fire forest structure.

Table 2. Evaluation of AUC and AIC scores for all MaxEnt models generated.

Model	auc.train	auc.val.avg	AICc	Δ AIC
fc.L_rm.1	0.916	0.916	6631.272	122.261
fc.LQ_rm.1	0.938	0.938	6526.421	17.409

fc.H_rm.1	0.948	0.942	6519.862	10.850
fc.LQH_rm.1	**0.946**	**0.942**	**6509.012**	**0**
fc.L_rm.2	0.916	0.916	6634.152	125.140
fc.LQ_rm.2	0.937	0.936	6545.064	36.052
fc.H_rm.2	0.944	0.939	6561.53	52.518
fc.LQH_rm.2	0.944	0.940	6527.728	18.716

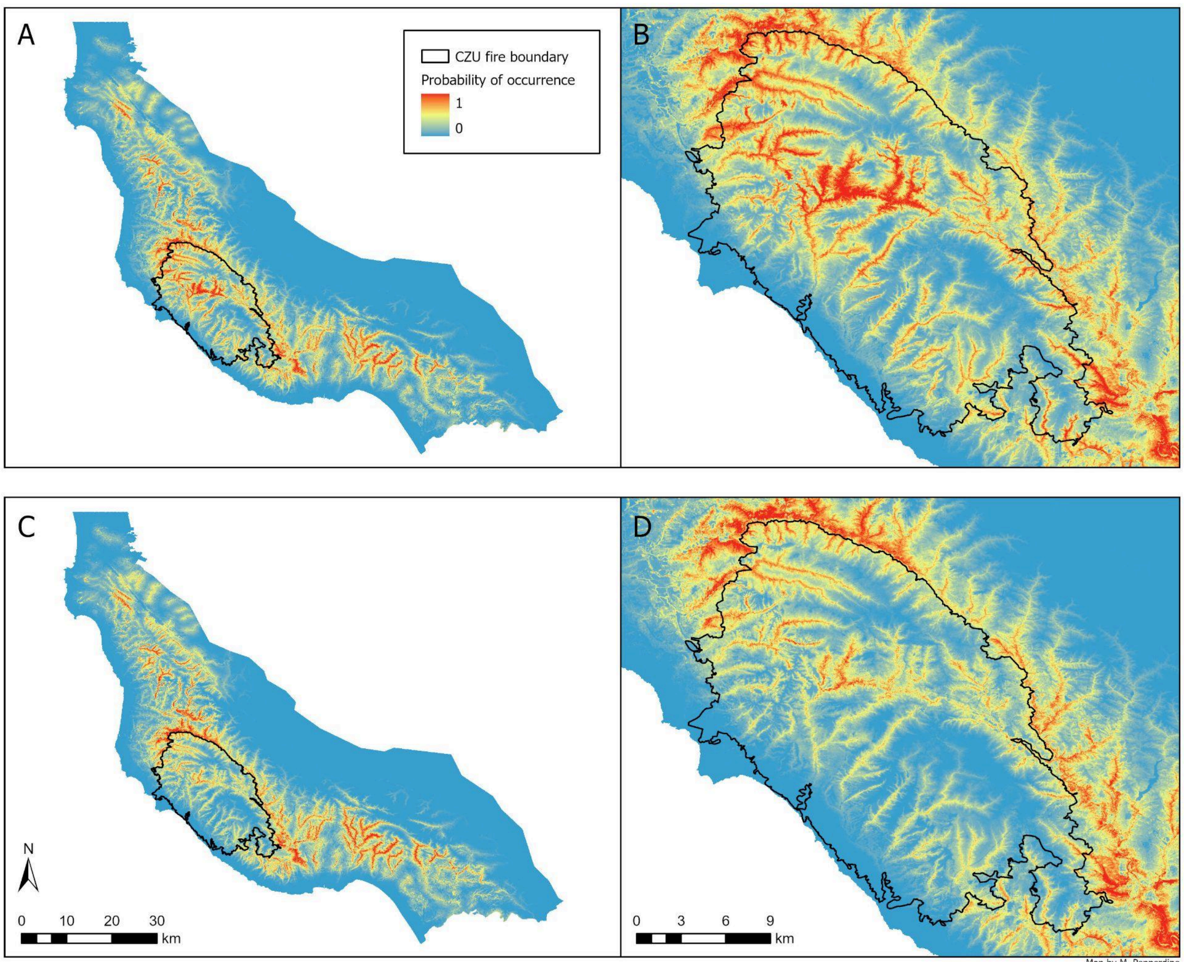


Figure 4. Marbled murrelet probability of occurrence throughout the Santa Cruz Mountains using predictions from the best performing MaxEnt model (fc.LQH_rm.1). The top maps (A/B) show the model generated with pre-fire occurrence data and vegetation conditions, and the bottom maps (C/D) show the predictions of this model transferred to the post-fire forest structure conditions. Looking within the boundaries of the CZU Lightning Complex Fire burn scar, delineated by the black line, it is evident that a significant area of suitable habitat was lost.

Figure 9 in the appendix shows the response curves for each environmental predictor generated from the best-performing model. These show that murrelet probability of occurrence in the SCM was the highest in west and southwest-facing slopes, very tall canopies, lower elevations, distances between 7 to 12 km from the Pacific Ocean, and closer proximities to intermittent and perennial streams.

4.2. Habitat suitability

Figure 5 shows the pre- and post-fire habitat suitability models for marbled murrelets across the Santa Cruz Mountains, and the results from differencing these two layers. These models were derived by reclassifying the MaxEnt SDMs in Figure 4 above. The pre-fire suitability model was subtracted from the post-fire model, allowing for the identification of regions that lost (-1), gained (1), or did not change (0) the amount of suitable habitat present.

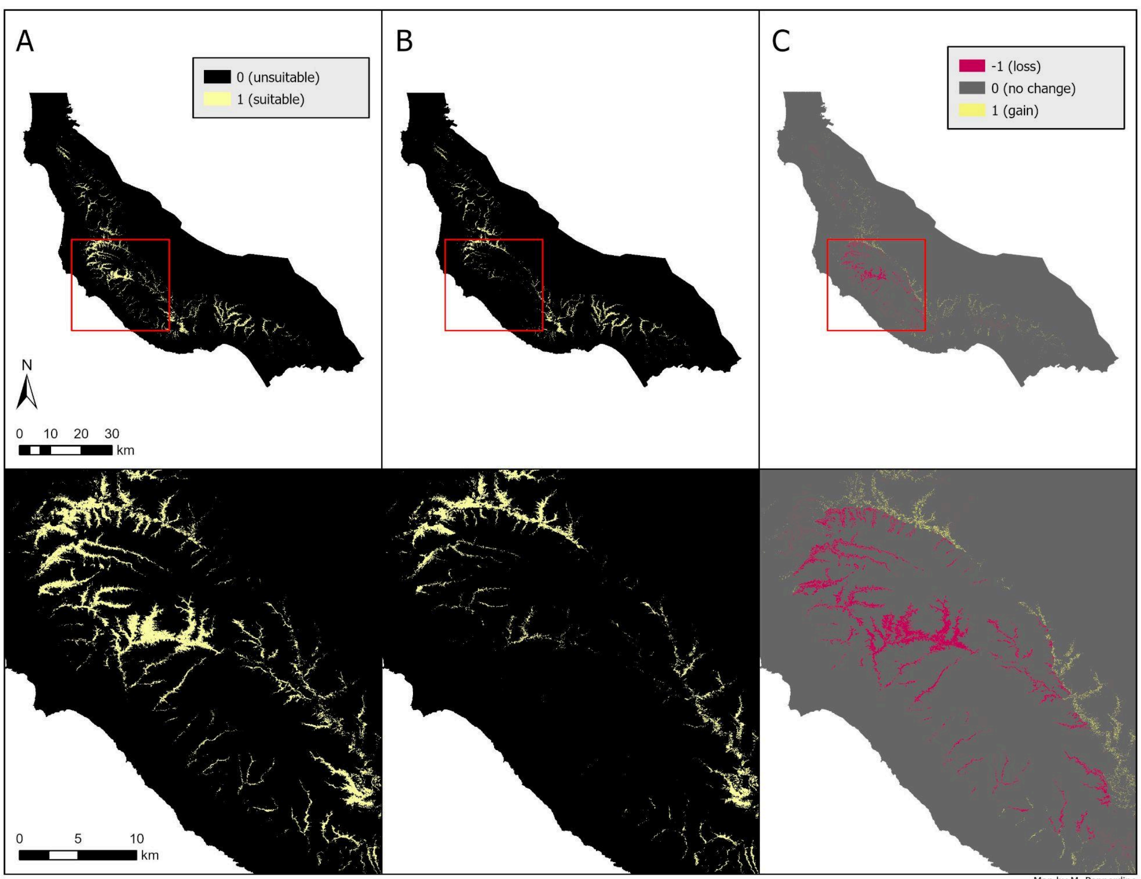


Figure 5. Habitat suitability models for marbled murrelets under pre-fire (A) and post-fie (B) vegetation structure conditions. The differences between these models (C) show areas that gained, lost, or did not change suitability for nesting habitat due to the CZU fires.

4.3. Land prioritization

Table 3 shows the results of the land prioritization analysis with the top 10 *protected or unprotected* county parcels (i.e., all county parcels) across the SCM region with the greatest area of suitable habitat within their boundaries. Table 4 shows the top 10 *unprotected* county parcels with the greatest area. Figure 6 displays the area (ha) of suitable habitat within each of these parcels, and Figure 7 shows their location across the SCM. Only one of the identified unprotected county parcels (APN 083320070) was in the top 10 of any county parcels.

Table 3. Top 10 *protected or unprotected* county parcels in the SCM region with the greatest area (ha) of suitable habitat for marbled murrelets within their boundary.

APN	Suitable habitat (ha)	Address	County
10501125	464.61	0 Nisene Marks Sp	Santa Cruz
06143102	217.04	2591 Graham Hill Rd, Santa Cruz , 95060	Santa Cruz
085150080	118.10	N/A	San Mateo
084130120	84.99	N/A	San Mateo
09919102	83.55	0 Nisene Marks Sp	Santa Cruz
083340020	82.16	N/A	San Mateo
083320070	77.11	45 Jones Gulch Rd, La Honda, CA 94021	San Mateo
083271020	75.19	N/A	San Mateo
09835101	66.88	N/A	Santa Cruz
085080020	65.57	9000 Portola State Park Rd, La Honda, CA 94020	San Mateo

Table 4. Top 10 *unprotected* county parcels in the SCM region with the greatest area (ha) of suitable habitat for marbled murrelets within their boundary.

APN	Suitable habitat (ha)	Address	County
083320070	77.11	45 Jones Gulch Rd, La Honda, CA 94021	San Mateo
10502108	51.10	N/A	Santa Cruz

067350020	42.51	N/A	San Mateo
072280060	41.82	N/A	San Mateo
084141010	41.48	N/A	San Mateo
09914101	35.14	N/A	Santa Cruz
088070020	34.88	N/A	San Mateo
081140010	29.30	N/A	San Mateo
082090030	26.84	N/A	San Mateo
083300010	26.59	N/A	San Mateo

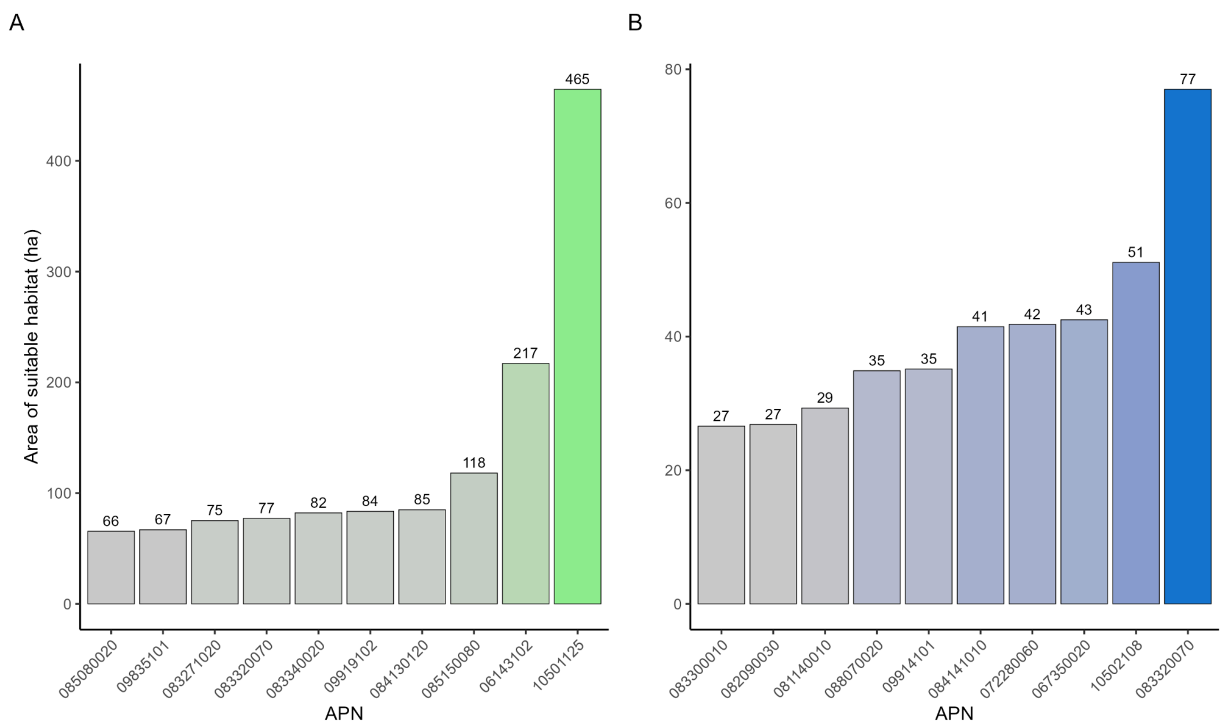


Figure 6. County parcels in the SCM region that have the greatest area (ha) of suitable habitat for marbled murrelets within their boundary. (A) Shows the results when considering all county parcels in the SCM region, whether protected or unprotected. (B) Shows the results of only unprotected county parcels. The unprotected parcel with the highest area of suitable habitat (083320070) was also in the top 10 of all parcels in the SCM region whether protected or unprotected. Protected status was determined using the California Protected Areas Database (CPAD).

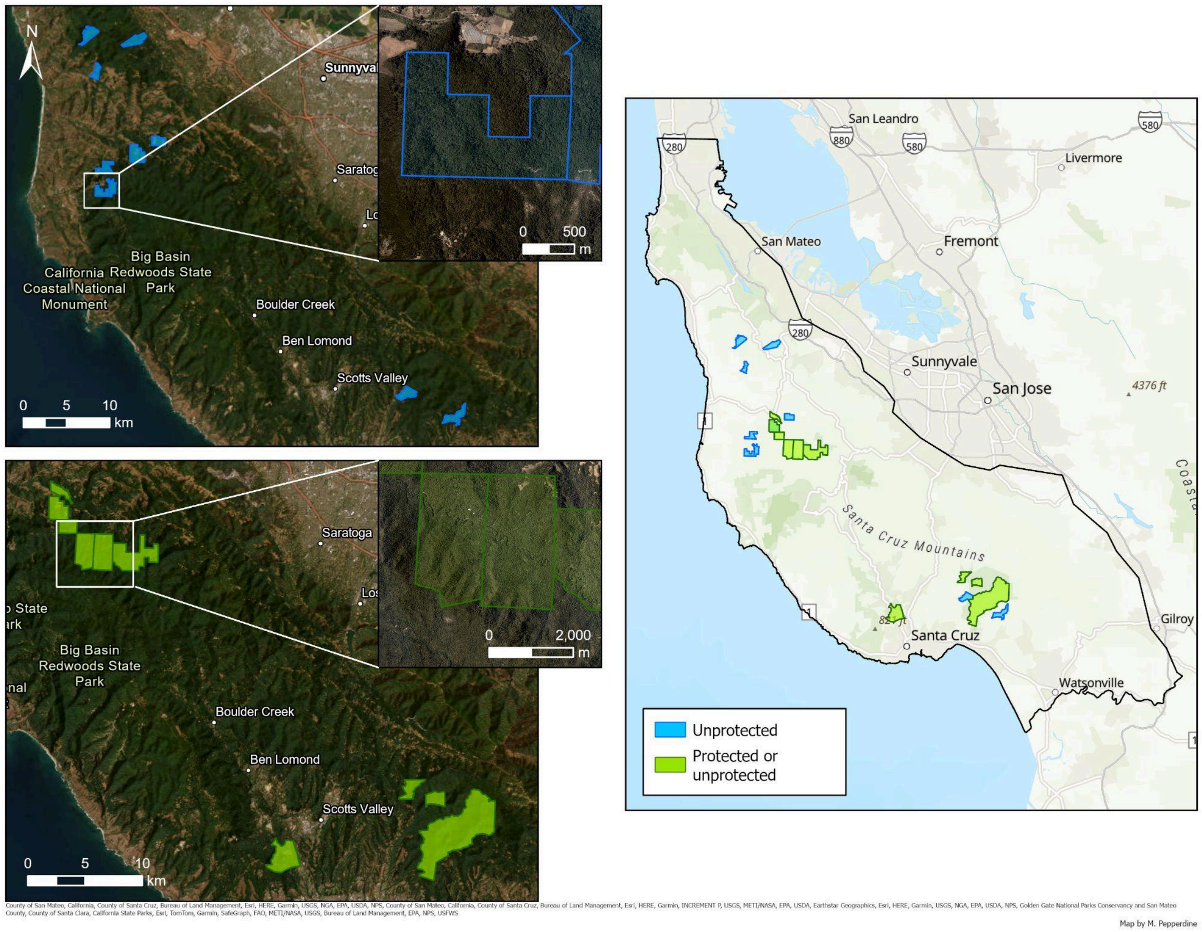


Figure 7. Protected or unprotected county parcels (green) and only unprotected county parcels (blue) in the SCM with the largest area of suitable marbled murrelet habitat within their boundaries.

5. Conclusions

5.1. Discussion & conservation implications

This project aimed to inform one of the top conservation actions for marbled murrelets' recovery in the SCM which is to identify, protect, and restore key habitats that can serve as suitable nesting sites (Halbert & Singer, 2017). Listed as an endangered species in California in the early 1990s, this southernmost, isolated breeding population of murrelets has been declining steadily over the past decades (Felis et al., 2022). Already known to some degree, given the severity of the 2020 CZU Lightning Complex fires, this analysis highlights and quantifies how destructive recent wildfires were to critical nesting habitat for the SCM population of marbled murrelets.

Big Basin Redwoods State Park (BBRSP) was a well-known and documented 'nesting stronghold' for these birds (Hamer et al., 1995; Baker et al., 2006). The majority of the known suitable nesting trees for murrelets in the SCM resided in BBRSP (Hamer et al., 1995; Baker et al., 2006); however, situated at the heart of the CZU burn scar, this region burned severely and decimated crucial nesting sites the already declining SCM population of murrelets have depended on. This habitat loss highlights a need to identify regions outside of BBRSP that could serve as suitable nesting locations for murrelets, and prioritize these locations for future land acquisition efforts, conservation easements with private landowners, and acoustic monitoring and radar surveying efforts (Halbert & Singer, 2017).

This analysis employed MaxEnt to map the occurrence probability distribution and model suitable nesting locations for murrelets in the SCM region at a 45-ft resolution. The primary distribution model was generated with pre-CZU fire occurrence, vegetation, and topographic data, and then transferred to post-CZU fire forest structure conditions. With only 5 main environmental predictor variables, the top MaxEnt model was able to predict murrelet occurrence at a high performance rate. It found that murrelet probability of occurrence in the SCM region is highest in tall canopies and trees, west and southwest-facing slopes, lower elevations, closer proximity to streams, and distances between 7 to 12 km from the coast. These findings align with other studies that have used MaxEnt or similar approaches to model and characterize suitable nesting habitats (Hamer et al., 1995; Baker et al., 2006; Cosgrove et al., 2024).

The continuous predictions of occurrence produced by MaxEnt are particularly useful for habitat assessment, reserve design, and habitat identification (Halbert & Singer, 2017). They were reclassified to represent areas of suitable and unsuitable habitat, which were then used to quantify which protected and unprotected county parcels throughout the SCM have the greatest area of suitable habitat within their boundaries under post-fire vegetation conditions. The county parcels identified in Table 3, Table 4, Figure 6, and Figure 7 should be considered for future management and research actions described further below. These results emphasize the decimation of nesting trees throughout the CZU burn scar; however, they also highlight other unburned regions throughout the SCM that may possess suitable habitats. Various locations throughout the Pescadero Creek Watershed (e.g., Portola Redwoods State Park, San Mateo Memorial County Park, Sam McDonald County Park) directly north of the prime habitats burned in the CZU fires still exhibit forest structure conditions reflective of suitable nesting trees. There are also significant patches of suitable habitat towards the southern end of the SCM region in Henry Cowell Redwoods State Park, the Soquel Demonstration State Forest, and the Forest of Nisene Marks State Park. While these regions aren't historically frequented areas by murrelets (Hamer et al., 1995; Baker et al., 2006), they possess characteristics of suitable nesting habitat that may play crucial roles in the species' persistence throughout the SCM.

5.2. Limitations

The biggest limitation and shortcoming of this analysis is the occurrence data that was used. GBIF is an international network and data infrastructure that's managed by a variety of stakeholders to provide open access data to all types of life on Earth. It seeks to harness the participation and passion of citizen scientists while setting various data collection and organization standards. Occurrence data makes up the core of data available on GBIF, providing a variety of information and evidence of the occurrences of different species at a particular place on a specified date. Some of the variables *required* to be attached to each record, informed by Darwin Core data standards, include the following: occurrence ID, basis of record, scientific name, and event date (GBIF, 2024).

Despite these baseline requirements for occurrence data, GBIF records are still subject to shortcomings, the main being human error. GBIF occurrence records are often human observations, and there is no way to confirm with 100% confidence that these records are correct. Due to their small body size, dense forested nesting habitat, cryptic plumage, crepuscular activity, fast flight speed, and secretive behavior near nests, marbled murrelets are an especially elusive species with which terrestrial occurrence and nesting data are extremely hard to obtain (Hamer et al., 1995). This analysis modeled suitable nesting habitats, and because murrelets only fly inland to nest, we assumed that all inland and terrestrial occurrence data were of nesting locations or in close proximity to them. Although there is no way to confirm that all of these occurrences were truly within nesting sites and trees, the results of the SDMs, habitat suitability reclassification, and impact of the CZU fires on both of these are reflective of what one would expect given murrelet ecology and known nest sites from previous studies (Baker et al., 2006; Hagar et al., 2018; Cosgrove et al., 2024).

Another potential shortcoming of this analysis is the classification of suitable habitat by reclassifying the MaxEnt modeled probability of occurrence. We defined suitable habitat by selecting an occurrence probability threshold with which any values under it were deemed unsuitable, and any values over as suitable. This study set that threshold at 0.7; therefore, locations in the SCM that modeled murrelet probability of occurrence greater than or equal to 0.7 were classified as suitable habitat, and those below it as unsuitable habitat (Figure 5). This is a fairly high threshold value to use and was chosen because murrelets have very specific nesting site requirements (Baker et al., 2006). It was selected somewhat arbitrarily, and slightly different threshold values would skew the distribution of regions characterized as suitable habitats. It is extremely important to realize that the maps and quantifications of suitable habitats produced in this project are only estimations. There are likely under or over-estimates of the area of suitable habitat in regions throughout the SCM; however, while all models are inherently wrong, they can still provide valuable information and insights.

5.3. Future recommendations

This analysis delineated areas in the SCM that are likely to exhibit characteristics of suitable nesting habitat and have a high occurrence probability for murrelets under pre- and post-CZU fire forest conditions. It also quantified which protected and unprotected county parcels throughout the SCM have the greatest area of post-fire suitable habitat within their boundaries. This kind of project helps to lay the foundation for future research and conservation initiatives in the SCM to further the conservation and preservation of an imperiled murrelet population. Here are some recommended next steps, research, and management actions:

1. *Ground truth the results*: as the British statistician George Box wrote, "All models are wrong, some are useful". The results of this analysis in the priority parcels listed above and larger patches of forest identified as suitable nesting habitats must be ground-truthed with fieldwork. Wildlife biologists should confirm that the locations isolated with modeling in this analysis have enough structural complexity, canopy openings, and other suitable conditions for murrelets to nest in.
2. *Conduct terrestrial surveying*: after ground truthing the results and confirming the priority locations identified may serve as suitable nesting sites, these results can be used to inform audio recording and radar surveying efforts. More reliable occurrence data would not only provide greater insight into the current state of the SCM population of breeding murrelets but also foster the development of more robust studies similar to this one. These kinds of efforts should be focused on all parcels, whether protected or unprotected.
3. *Protect key parcels & suitable habitat*: after ground truthing results in the priority parcels listed above and larger patches of forest identified as suitable nesting habitat, agencies and organizations involved in Zone 6 murrelet conservation should work to protect locations vital to murrelet persistence. Land acquisition and other conservation efforts (e.g., conservation easements) should be focused on unprotected or privately owned parcels with large amounts of key habitat.
4. *Employ a more commonly used land prioritization methodology*: in the future, this kind of analysis could benefit greatly from a more robust land prioritization approach such as Marxan or `*prioritizr*`. This would allow for the incorporation of cost-weighted prioritization and other key components of reserve design that were not captured in this analysis.

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7. Appendix

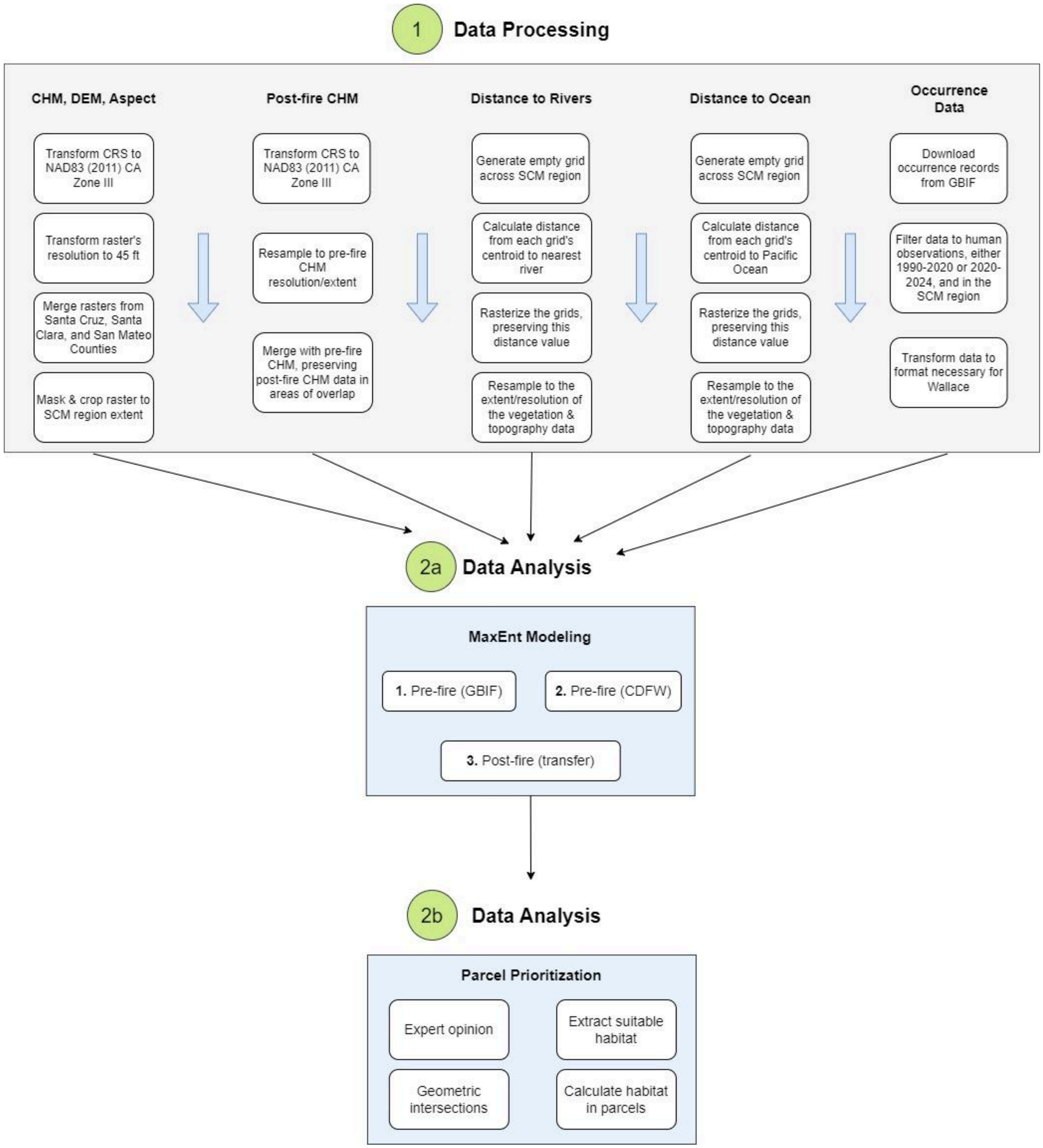

Figure 8. Conceptual outline of data processing and analysis for the project.

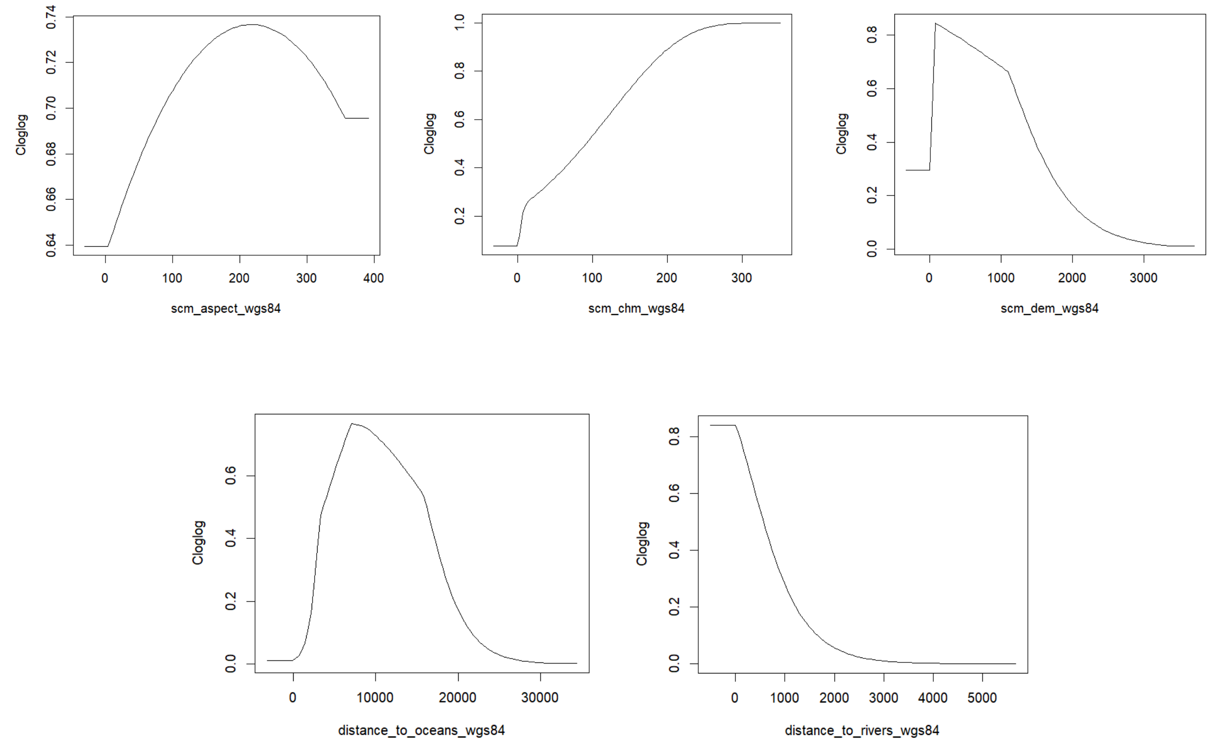

Figure 9. Response curves for environmental predictors used in the MaxEnt modeling. Aspect, canopy height (CHM) (ft), and elevation (DEM) (ft) are shown on top with the Euclidean distance to the ocean (m) and nearest rivers (m) on the bottom. The y-axis values (‘cloglog’) range from 0-1 and represent the approximate probability of occurrence for murrelets given the associated environmental conditions on the x-axis. Therefore, a higher value indicates more suitable conditions.

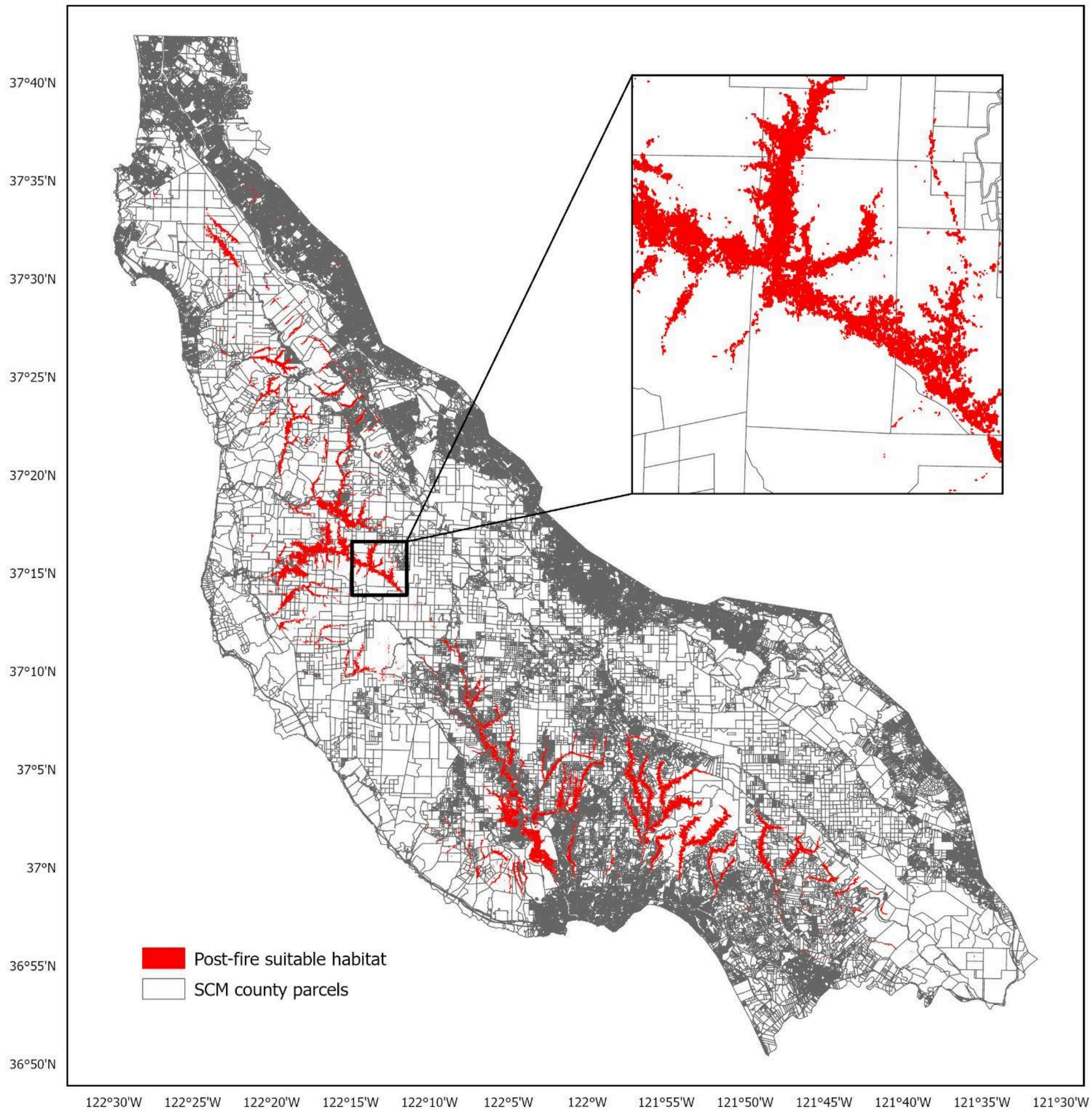

Figure 10. Post-CZU fire modeled suitable nesting habitat for marbled murrelets overlaid with all county parcels in the Santa Cruz Mountain region. In the land prioritization analysis, the area of post-fire suitable habitat within each parcel was calculated to determine parcels where conservation actions and surveying efforts should be focused.

Table 5. Description of key datasets used in the analysis.

Description	Source	Year(s)	Data type	Native Resolution	Project Relationship
Occurrence data (1); terrestrial occurrence records of marbled murrelets in the SCM region.	GBIF	1990 - 2020	CSV	N/A	MaxEnt
Occurrence data (2); known nesting trees and occurrences of murrelets in the SCM region.	CDFW	2007	Shapefile (.shp)	N/A	MaxEnt
Canopy height model (pre-CZU fire); represents above-ground height of vegetation and trees across the entire SCM.	Pacific Veg Map	2020	Raster (.tif)	3 ft	MaxEnt
Canopy height model (post-CZU fire); represents above-ground height of vegetation and trees across the entire SCM following the 2020 CZU wildfire.	Pacific Veg Map	2021	Raster (.tif)	3 ft	MaxEnt
CZU fire canopy damage map; woody canopy damage (% burned) as a result of the 2020 CZU fire in San Mateo and Santa Cruz County.	Pacific Veg Map	2022	Vector (.shp)	N/A	Land Prioritization
Fine-scale vegetation; 121-class vegetation map showing vegetation types across the entire SCM region.	Pacific Veg Map	2020	Vector (.shp)	N/A	MaxEnt
Aspect; downslope direction of the maximum rate of change in elevation value from each cell to its neighbors in the SCM.	Pacific Veg Map	2020	Raster (.tif)	3 ft	MaxEnt
Digital elevation model; elevation above sea level in the SCM.	Pacific Veg Map	2020	Raster (.tif)	3 ft	MaxEnt
Protected areas; lands that are owned in fee and protected for open space purposes, ranging from our largest National Forests and Parks to neighborhood pocket parks.	California Protected Areas Database (CPAD)	2024	Vector (.shp)	N/A	Land Prioritization