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Sea Level Rise’s Impact on Island Vegetation: Coiba National Park

by

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Class of 2020

A thesis submitted to the
faculty of Wesleyan University
in partial fulfillment of the requirements for the
Degree of Bachelor of Arts
with Departmental Honors in Earth and Environmental Science

Middletown, Connecticut April, 2020

Acknowledgments:

Thank you, Prof. Kim Diver, for your mentorship and all the advice you have given me throughout the past months. Your guidance has been invaluable, and your calm perspective has been great for my sanity. I really appreciate the time and concern you have put into helping me.

Thank you, Prof. Marty Gilmore and Prof. Helen Poulos, for offering me your time, letting me pester you with questions and most importantly for reading this paper. A big thank you to Alicia Ibáñez of the Smithsonian Tropical Research Institute, as well, whose work has informed so much of this project and who took the time to write down to which vegetation types each of 1,035 plant species on the islands belong for this project.

Thank you to all of my other professors and friends at Wesleyan who have taught me so much and really shaped how I see the world. I am so glad that I have had the opportunity to work with all of you.

And last, but most certainly not least, thank you to my family for giving me the support and encouragement I have needed to get me this far in life. You all have been so great to me, and I love you all so much!

Abstract:

In the face of a warming climate and a rising ocean, island ecosystems are expected to change in the coming years. Classical island biogeography relates species richness as a function of island size and extinction/migration patterns largely controlled by isolation. Using sea level rise predictions, this study applies island biogeography theory to estimate the decline of plant species richness on the Coiba Islands, a Panamanian National Park off the southwestern coast of the country. An ASTER digital elevation model (DEM) represents the island at present day and was modified to describe the islands at 1 meter of sea level rise with a new hightide at 3 meters and at 3 extreme sea level events (4 meters, 6 meters and 9 meters). Historic shoreline changes were compared to inform the likelihood of projected sea level rise inundation. The present-day vegetation captured by Sentinel-2 was divided into eight vegetation types: mature forest, secondary forest, pioneer forest, fields, cork oak groves, mangroves, dry coastal forest and beach vegetation. The sea level maps and vegetation maps were overlaid to determine the area lost by each vegetation type, representing a scenario in which species do not migrate before being inundated. This estimate of species loss is compared to the predictions made by regressions between island configuration metrics and diversity metrics. In making these predictions, this study aims to be a starting point for further research on the islands' vulnerabilities to sea level rise and climate change more generally. Ultimately, this study puts theory to work for real world conservation planning, as people prepare to respond to the climate to which our emissions have already committed us.

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Chapter 1. Introduction

As the ocean rises, coastal communities, both human and non-human are displaced. The objective of my thesis is to investigate impacts of plant community displacement in an archipelago with high conservation importance, Coiba National Park in the Republic of Panama. Past work in the field of island biogeography has found a relationship between island morphology – namely size and isolation – and the diversity of lifeforms living on the island. By establishing the details of that relationship in Coiba National Park, this study is an initial effort at predicting specific changes to biodiversity caused by changes in island morphology brought about by sea level rise. Knowledge of the degree of species loss, paired with maps of potential flooding will produce better estimates of which plant species and communities are at risk.

Thinking about these islands in the context of their changing ocean, it is important to first identify the major forces of coastal change. These are isostatic land movement, sea level rise and tides/storm surges. Climate-related sea level rise is largely controlled by ocean volume changes and land-based ice melt which will be unevenly distributed. The former is created by thermal expansion, and uneven redistribution of temperature, salinity and atmospheric pressure, while the latter is caused by changes in snow fall and annual temperatures. In the recent Intergovernmental Panel on Climate Change (IPCC) special report of “Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities,” the authors outline the most recent projections for climate change-induced sea level rise over the next century and beyond. The authors also outlined some of the potential risks created by sea level rise, namely, permanent submergence of land, more coastal flooding, increased coastal erosion, loss and change of ecosystems, salinization and decreased drainage (Oppenheimer et al., 2019). All of these outcomes have the potential to change the ecosystems of Coiba National Park, but the most important to this study is the permanent and storm-related flooding and its impact on plant communities.

In order to investigate plant community displacement due to sea level rise, I first determined the changes to island shape and size brought about by sea level rise and extreme sea level events (storm surges). Then using the predictions of future morphologies, I examined changes in vegetation communities. More specifically, I attempt to identify which vegetation communities will be most at risk, and how these vegetation losses change the overall diversity of habitats. I expect that higher sea levels will reduce the size and increase the isolation of each island, potentially submerging a few islands. Coastal vegetation communities should lose more area and therefore, more species, which will diminish the overall plant species richness of smaller islands to a greater extent than large islands.

Early island biogeography theory predicts that the biodiversity of an isolated community is in a dynamic equilibrium determined by the size and degree of isolation of that community which control extinction and immigration (MacArthur and Wilson, 1967). Later research has repeatedly found that habitat heterogeneity influences species richness and distribution separately from island size (Baldi et al., 2008; Shen et al., 2009; van der Werff, 1983). These differing frameworks are not incompatible. Kadmon and Allouche (2007) combined the models by explaining island biodiversity as the sum of the diversity of the island’s habitat types. These habitat types can host distinct species communities whose size are determined by habitat area, immigration, mortality and reproduction. Then, to predict changes in the biodiversity of these islands, it is necessary to know the change in total area available, the degree of isolation and the heterogeneity of each island and vegetation type. If strong correlations can be found between these metrics and species richness, then the regressions derived from those metrics should be able to capture the number of species that future islands can support.

Chapter 2. Study Area

2.1 Recent Political History

Culturally, the Coiba Islands hold many titles. Coiba, the largest island, was once a penal colony for serious criminals and Manuel Noriega's political prisoners between 1919 and 2002 (Mayson, 2005). In 1991, towards the end of Coiba's life as a penal colony, the islands and surrounding waters were first set aside for conservation by a resolution passed by the National Resource Institute (INRENARE) (Ibáñez, 2011), and is now managed by Panama's National Environmental Authority (ANAM). The resolution was politically weak, but fear of criminals kept most people away from the islands. The prisoners were forced to work long days clearing the forest and cultivating food, enough to feed Panama's penal and public health systems. However, the agricultural impact was minor and most of the island's mature forests remained intact. In 2004, the area was upgraded to full national park status by the Panamanian government with support from local conservation agencies, and then designated a World Heritage Site in 2005 by UNESCO (Ibáñez, 2011; Mayson, 2005; Steinitz et al. 2005). These designations ushered in a new era of policing on Coiba, now aimed at controlling outsiders' access rather than keeping in insiders.

The 38 protected islands earned these protections for their importance along migratory routes, their mature forests and their high levels of bird, mammal and plant endemism. As such, fishing around and construction on the islands are limited, catering mostly to artisanal fishermen and tourists hoping to catch glances at the beautiful wildlife. UNESCO and the International Union for Conservation of Nature (IUCN) deem illegal fishing, introduced species, eco-tourism development and climate change as the major threats to the Coiba National Park (CNP) islands. In the early 2000s, when the park's status was being debated, hotel-developers argued for more development on the islands to boost the economy and address concerns about the lack of opportunities for economic growth in the coastal communities adjacent to the park which were particularly poor; however, this idea was politically unpopular and eventually abandoned (Steinitz et al., 2005). CNP is managed by a team of Panamanian's from a variety of fields in close partnership with ANAM. The park's first management plan was drafted the Spanish Agency for International Cooperation, and then updated in 2006 by a team from the Smithsonian Tropical Research Institute (). Still, the IUCN lists Coiba National Park and its zone of marine protection as a place of significant concern due to weak enforcement of current regulations, legal problems around the Coiba Fund and a lack of planning for the marine protection zone and for protecting the biosecurity of the islands. The ICUN does not account for the effects of climate change but does acknowledge that observations of landslips on steep island shores are evidence that bad storms and sea level rise could further harm the islands (IUCN, 2017). In their most recent meeting in November of 2019, the Coiba National Park Board of Directors made decisions that addressed some of the management concerns (República, 2019).

2.2 Importance for Conservation

The islands host biodiverse communities that serve as a sanctuary for mainland species, a stopping point for migratory species and home for several endemic species. The CNP islands share many species in common with the mainland, such as crested eagles and scarlet macaws. As Panamanians develop more land for human use, threatened species populations are being buffered from local extinction thanks to the islands' habitat protections (UNESCO, 2020). The islands' relatively undisturbed beach vegetation harbors a number of rare species (Ibáñez, 2011).

The Park is within the Tropical Eastern Pacific Marine Corridor. As such, the marine biodiversity in the region is impressive with the islands located along the migratory routes of many tropical eastern Pacific turtles, sharks, pelagic fish, and marine mammals (UNESCO, 2020). Furthermore, its high-quality marine habitats harbor migrating and residential fish populations. While conditions in the eastern Pacific are not favorable for coral reefs and many of the reefs in this region are small and species-poor, Panama's coasts are home to 91% of eastern Pacific reefs and Coiba National Park protects a significant portion of that including several endemic corals (Cortes, 1997; Claudino-Sales, 2018).

The success of conservation at Coiba National Park has benefits beyond the ecosystems being supported. In 2005, Steinitz et al. modeled the economic and ecological impacts of different management scenarios for CNP. They concluded that the economic benefits of tourism in the region is linked to the conservation of species and ecosystems on the island, because islands' appeal to tourists is rooted in its cultural and ecological richness. Furthermore, CNP serves as both an important study site for natural sciences and an important educational center (UNESCO, 2020; Claudino-Sales, 2018).

2.3 Geological and Climactic Context

The study area is centered on Coiba Island and the other islands of the Coiba National Park in the Gulf of Chirqui but extends eastward to Cebaco Island and several smaller islands in between. These islands outside the park were limited to areas visited by Ibáñez and Diver in 2012 and only those that are larger than 6 pixels (5,400m^2). These select islands outside the park were included because species information for these islands exists and they provide a wider dataset for establishing patterns between island morphology and diversity. These easterly islands will serve as points of comparison and be used to understand the regional relationships between island size and biodiversity. In total, 31 islands are included in this study with 20 inside the park and 11 outside. Of the islands within CNP, Coiba Island is the largest at 50,364 ha. Archipelagoes within CNP include the islands around Coiba, the Canales de Afuera islands, and the Contreras island cluster (Figure 1). Montuosa Island was not included because it was not captured in the same satellite images as the other islands. Sampled islands outside of CNP include islands within the Canales de Tierra archipelago just east of the Canales de Afuera islands, and the Cebaco archipelago which sits in the Gulf of Montijo in its own zone of special management (Figure 1).

This study focuses on sea level rise (SLR), accounting for tides and extreme sea level events, but ignores isostatic movement because there is insufficient data. The study area sits on the Caribbean Plate, near the triple juncture of the Nazca, Cocos and Caribbean Plates. Split from northwest to southeast by a fault, the western side of Coiba was created from volcanism over the Galapagos hotspot during the Cretaceous, which moved east, collided with Central America and was augmented by additional volcanism in the north and east and marine sedimentation in the south (Ibáñez, 2011). The fault running through Coiba may still be active, but I was unable to find any data or literature about its recent activity.

Gunnar Roden studied sea level changes on both coasts of mainland Panama between 1909 and 1962, and attributed rising annual sea levels to land subsidence due to a lack of correlation with any changes in climatological data. On the pacific side, at Balboa, Roden recorded an 8.5 ± 1.5 cm rise in sea level and a 7.1 ± 2 cm rise on the Caribbean side at Cristobal over 53 years (Roden, 1967). While there are long term records of sea level at both Balboa and Cristobal, there are no such records publicly available for the study area islands, nor can the historic isostatic movements of the mainland be extrapolated to the offshore islands. Therefore, I do not consider isostatic movement in this study.

Climate change is expected to increase the frequency of intense storms and the intensity of frequent storms. CNP is positioned within the Intertropical Convergence Zone (ITCZ) where converging trade winds produce seasonal thunderstorms, giving the region distinct wet and dry seasons. Thunderstorms originating in the ITCZ become hurricanes after leaving the ITCZ (Graham et al., 2006). According to the NOAA Hurricane Tracker historical hurricane path data, eight hurricanes have passed within 200 nautical miles of Coiba Island in the past 155 years, most of which dissipated to tropical depressions within that search area. These storms came from the tropical North Atlantic and North Pacific. The most recent storm was Tropical Depression Dalia which came in July of 2019 and is the only 1 of the 8 to come from the Pacific Ocean. Dalia, however, did not get as close as Hurricane Martha that crossed Panama to come within 120 km of Coiba Island (NOAA Historical Hurricane Tracks). As such, Coiba Island has historically enjoyed a somewhat sheltered position in the Pacific, but the future may be different. Already, the closest tide gauge at Balboa, Panama shows that 3-meter storm surges are common (Oppenheimer et al., 2019). By testing a range of potential extreme sea levels, I hope to capture the full extent of potential inundation.

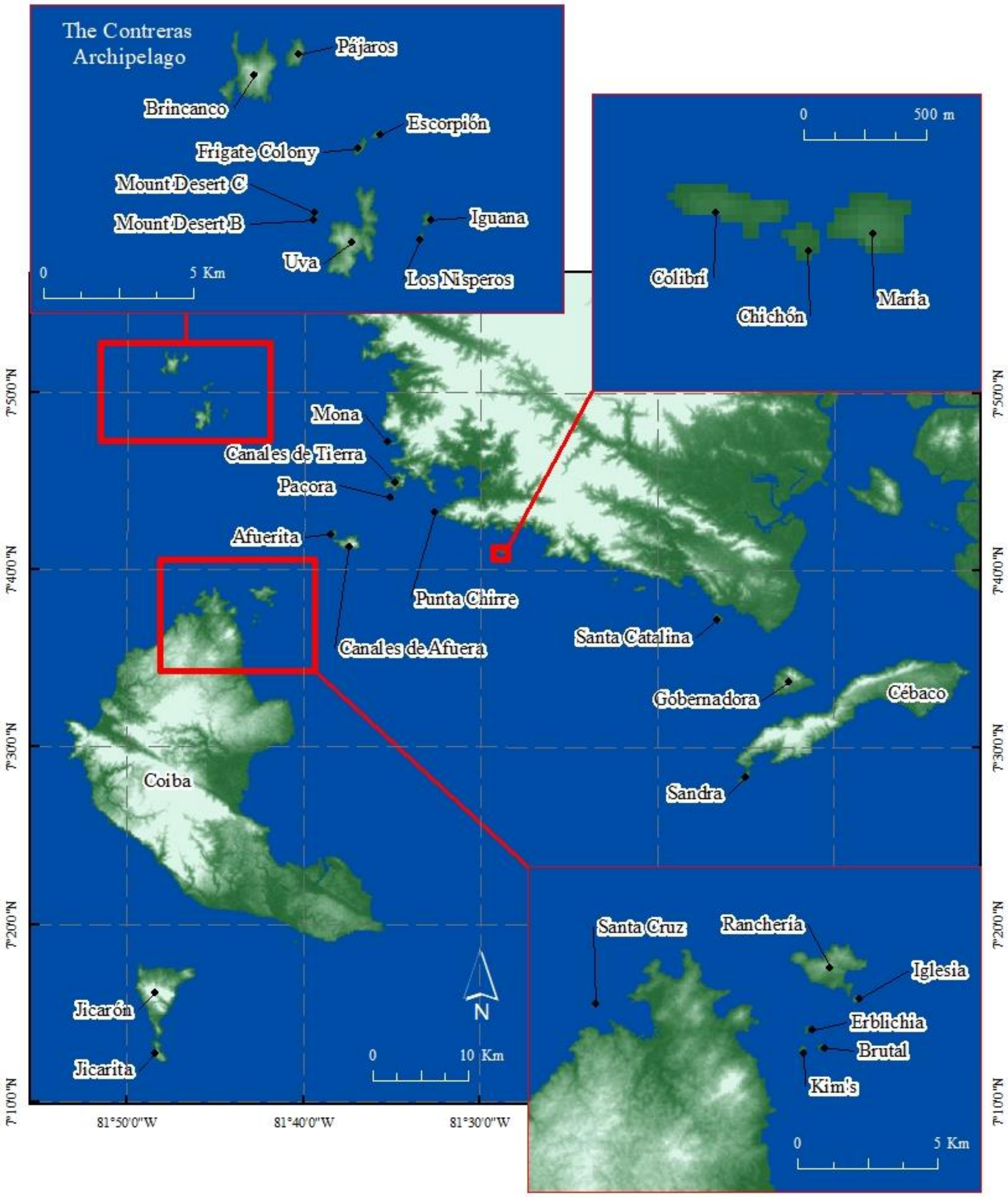


Figure 1. The study area for this project is depicted above. The Aster GDEM provides the basemap with elevations above sea level increasing along the green to white gradient. The names for each island are those used by Ibáñez and Diver (unpublished manuscript).

2.4 Island Vegetation

In a vegetation map (hereafter referred to as the 2009 Vegetation Map) published by ANAM in 2009 made with 2006 ASTER imagery (Ibáñez, 2011; Autoridad Nacional del Ambiente, 2009), it is possible to identify mature tropical rainforests, secondary forests, pioneer forests, cork oak groves, coastal dry forests, fields, mangroves, beaches, and human-made structure across CNP and the surrounding islands. Mature forests are by the most common vegetation on Coiba Island and throughout the park. These forests are rough 10,000 years old and are defined by their dense canopy cover, vertically stratification, and late successional species such as *Calophyllum longifolium*, *Tetragastris panamensis*, *Carapa guianensis, Prioria copifera*, *Couratari guianensis*, *Manilkara staminodella*, *Parinari chocoensis* and *Csipourea elliptica* in the north as well as *Eschweilera* spp., *Terminalia amazonia* and *Podocarpus guatemalensis* in the west. Many of the plant species found in these mature forests are endemic to the island or are no longer common on the mainland (Ibáñez, 2011).

Prioria copifera, commonly known as "cativo" is one of two dominant species in notable "catival" stands. Covering 300 hectares in the 2009 map, these stands of *Prioria copifera* and *Peltogyne purpurea* have grown up to 50 meters tall and as wide as 1 meter in diameter. While catival is distinct in species composition from other parts of the mature forest on Coiba Island, I do not distinguished catival from mature forest in the new vegetation map, because it is not visually distinct in satellite imagery. Gallery forests are also included within the mature forest category, because the 2009 Vegetation Map does not distinguish between those two categories, which have distinct species composition, but look similar from space. Gallery forests are generally found along rivers and in ravines (Ibáñez, 2011).

As defined by the Panama Forest Codes (Mamoní Valley Preserve, 2019), secondary and pioneer forests on the islands inhabit places where large sections of mature forest have been fully or partially cleared. The two vegetation types differ from each other in age and species composition. Pioneer forests are younger and dominated by dense herbaceous plants, vines and shrubs. Secondary forests are slightly older and dominated by shrubs and early-successional trees. On Coiba Island, the secondary forests are largely the result of selective logging by companies in the 1970s and 80s and prisoners for the duration of the penal colony. As a result, the secondary forests have a similar vertical structure to that of the mature forests, but only non-commercially viable species dominate. The pioneer forests cover much of the land fully cleared for the penal colony and its farms, as well as for logging camps all of which has been abandoned. The distribution of species within the pioneer forests across the island is dependent on time and previous use. Some of the land cleared by prisoners was used for grazing cattle, cows and buffalo, some of whom remain on the island, having been abandoned when the prison shut down. These semi-wild bovine animals continue to graze old pastures, preventing the establishment of pioneer or secondary forests (Ibáñez, 2011).

Coiba Island’s coasts are lined with mangroves, cork oak groves, dry forests and beaches. According to the 2009 map, the park’s mangroves are located at the mouths of many of the island’s rivers, including the Joro River, the San Juan River and the Santa Cruz River, and in the lowlands of Boca Grande and Barco Quebrado in the south. *Rhizophora mangle* is one of the more common mangrove species on the island, particularly in the southern Boca Grande and Barco Quebrado. *R. mangle* is joined by *Rhizophora racemosa*, both of which have a high salinity tolerance. Species like *Avicennia germinans* and *Laguncularia racemosa* have a lower tolerance to salinity and occupy smaller areas with fresher water. The mouth of the Santa Cruz River has a unique mangrove stand dominated by *Pelliciera rhizophorae*. Living among the mangrove trees, is the mangrove fern (*Acrostichum aureum*) which extends its range into the cork oak groves, dominated by *Mora oleifera*. A species only found on the Pacific coast of Central America and northern South America, M. oleifera is considered a threatened species by the International Union for Conservation of Nature and Natural Resources (Duke, 2008). CNP's cork oak groves are affected by tidal waters, but to a lesser extent than the mangroves. These stands usually act as a transition zone between coastal habitats and the mature forest interior. The 2009 Vegetation Map depicts dry coastal beaches along the rocky western coast of Coiba Island. These coastal forests are found on steep slopes, where soils are thinner. Unlike the mature forests further inland, the dry forest is not able to depend on soil water reserves to last through the dry season and must shed their leaves annually. Also winding along the edges of the island, beaches are an important interface between terrestrial and marine life. Tourists, sea turtles and scarlet macaws are drawn to them alike, the latter two being endangered and in need of habitat protection. While sea turtles nest in the sand, scarlet macaws alight in the trees, eating fruits. The CNP islands have some of the least disturbed beach vegetation in Panama and harbor several rare plant species (Ibáñez, 2011).

Chapter 3. Methods

3.1 Data Sources

I used the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) to derive elevations for Coiba National Park. ASTER is a satellite-based sensor that provides high-resolution images of Earth in 14 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The ASTER GDEM has a horizontal resolution of 30 m and a vertical resolution of 1 m. While LiDAR is able to image landscapes at high horizontal resolution and vertical accuracy (Gesch, 2009), there are no known, publicly available LiDAR datasets for this region. CNP falls within one panel of the ASTER GDEM. The shorelines of each island were defined by the ASTER Waterbodies Database (data collected between 2000-2013) with additional modifications based on the Sentinel-2 land cover classification. Sentinel-2 consists of paired satellites that collect high-resolution, multispectral images. This Sentinel-2 data was captured March 14, 2019 and has 13 bands of which 4 have 10 m resolution, 6 have 20 m resolution and 3 have 60 m resolution. All bands were resized all have 30 m resolution.

3.2 Sea Level Rise and Extreme Sea Level Events

I loosely based the SLR predictions on the scenarios created by the IPCC (Oppenheimer et al., 2019), but I rounded to the nearest meter to fit the resolution of the ASTER GDEM. The scenarios include 1 m, 3 m, 4 m, 6 m and 9 m of SLR. Under Representational Concentration Pathway 2.6 (RCP2.6) in which "stringent mitigation" policies that limit global temperature rise to less than 2º, the IPCC expects to see regional mean sea level (RMSL) increase 0.2 m by mid-century and 0.3

m by the end of the century for CNP's part of the Pacific (2019). In that same report, the authors also predicted a 0.2 m RMSL rise by mid-century and 0.7 m by the end of the century if policies are driven by current economics (RCP8.5; Oppenheimer et al., 2019).

Limited by the vertical resolution of the ASTER GDEM, the 1 m SLR scenario represents a future world in which little was done to fight climate change and RMSL rise is slightly worse than expected by the end of the century. I added an extra 2 m hightide zone to this scenario based on averages of tide data from Balboa, Panama. The 4 m, 6 m and 9 m SLR scenarios represent extreme sea level events (storm surges, etc.). In the recent past, Balboa has seen 3 m extreme sea level events regularly, and the worst storm surges are only a few centimeters higher (IPCC, 2019). In the IPCC's RCP2.6 projections, extreme sea levels over 3 m will become common occurrences at Balboa, while in RCP8.5 projections, the storm surges could get up to 4 m or more above mean sea level. Without tidal gauge data for the islands, it is hard to know how these values compare. The islands may be at greater or lower risk. If they are at higher risk, the 6 m and 9 m scenarios should capture the worst cases. For each scenario, I queried the areas of inundation from the GDEM of each island using attribute queries in ArcGIS Desktop version 10.7.1 (Environmental Systems Research Institute, Redlands, California). These raster selections were converted to points. Non-contiguous points were deleted, and the remaining points were converted back into a raster with cell sizes equal to the original raster.

3.3 Vegetation Communities and Calculations of Diversity

The vegetation distribution map used in the analyses (hereafter referred to as the 2020 Vegetation Map) is based on the 2019 Sentinel-2 imagery and the 2009

Vegetation Map. It has been over a decade since ANAM created their vegetation map. Much can change in 10 years, so a new vegetation map was needed for this study; however, without time to travel to CNP and run field experiments, this study is limited to satellite image analyses.

Identifying plants to the species level solely from remotely sensed imagery is difficult is difficult to unfeasible, but it is possible to categorize the landscape based on changes in the average values of layered wavelengths. Dulanjalee (unpublished manuscript) used Landsat imagery and the Maximum Likelihood Classifier process in ENVI (Exelis Visual Information Solutions, Boulder Colorado) to distinguish between forest and non-forest land types in the Amazon Rainforest. I based the vegetation classification methodology used in this thesis on Dulanjalee's work.

In ENVI version 5.4, I resampled the Sentinel-2 bands to a lower resolution so that all the spectral data had a resolution of 10m. Then I created Regions of Interest (ROIs) for each vegetation type based on the location of each of these vegetation communities in 2006 and the visual clues provided by the true color Sentinel-2 imagery. Next, I ran the band statistics for each vegetation type's ROI to find the average values of each spectral band (Figure 2). Of the 13 bands in the scene, none had unique averages for every ROI vegetation type, but every ROI had unique values for at least 4 different bands. Mature forest has the most overlap in band averages (9), while cork oak groves and mangroves have the least (3 each). These ROIs were then fed into the Maximum Likelihood Classifier, which was set to assign each square to the most likely vegetation type based on bands with distinct values for at least 8 of the 10 ROIs: band 6 (740nm), band 7 (783nm), band 8a (865nm), band 9 (940nm), band 11 (1610nm) and band 12 (2190nm). Bands 6, 7, 8a, 11, and 12 originally had 20 m resolution and band 9 had 60 m resolution. The resulting Classification raster map was then exported to ArcGIS Desktop, where it was converted to a colormap.

By overlaying the new vegetation map with areas that may be inundated, it is possible to identify what proportion of each vegetation type would be lost if that vegetation type is unable to migrate inland. Species will likely be able to migrate to some degree, so this measure of loss should capture a worst-case scenario and real losses will likely be less severe. The effect of these worst-case scenario losses on

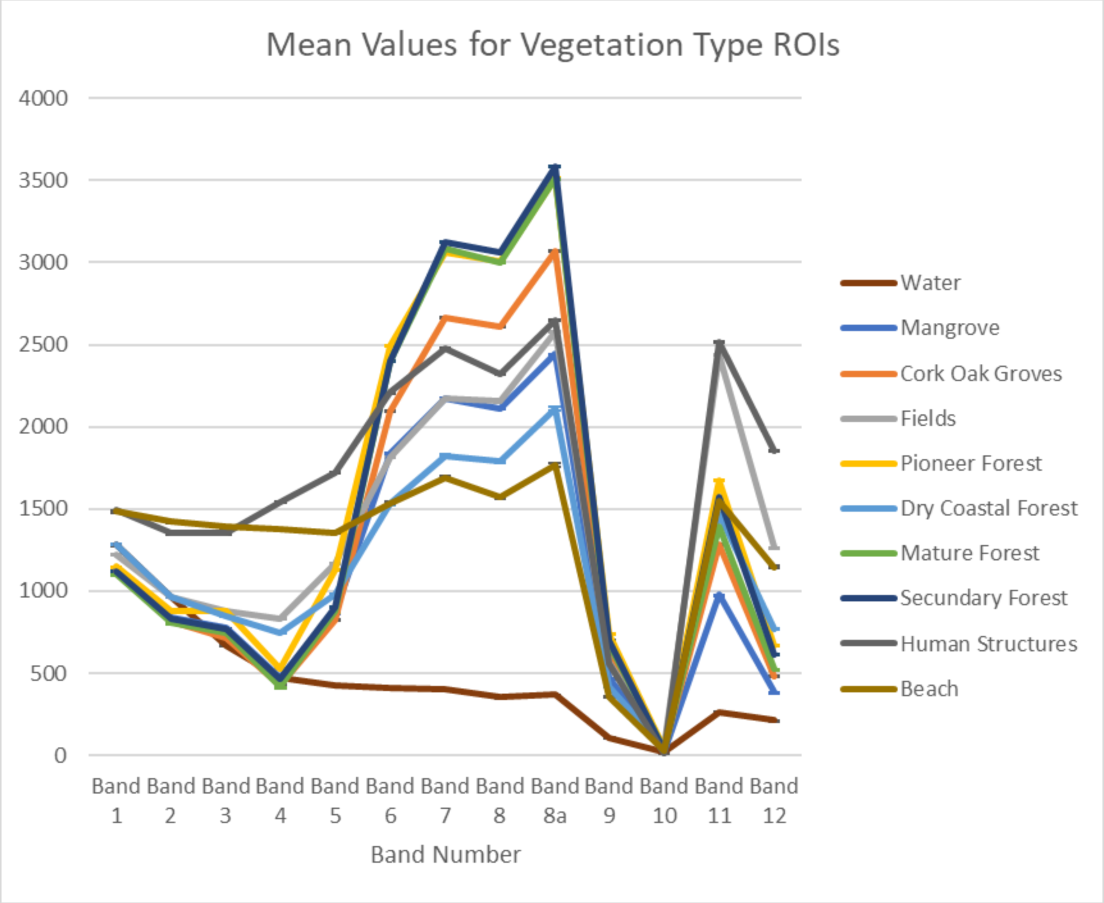


Figure 2. The mean values for the 13 Sentinel-2 bands are graphed for each land cover ROI. Standard error bars were added to each point to determine whether or not different land covers had distinct mean values. Only bands 6, 7, 8a 11 and 12 were used to classify the Sentinel-2 image.

community diversity is quantified as patch richness, patch density, edge density, Simpson's Diversity and Shannon's Diversity using Fragstats version 4.2 (University of Massachusetts Landscape Ecology Lab, Amherst, Massachusetts).

The Maximum Likelihood Classifier was used again to recreate Coiba Island's historic shorelines based on ASTER images from 2002 and 2010. Both images are from January of their respective years and have close to 0% cloud cover. The 2010 image has an estimated tide level of 2.06m above Mean Lower Low Water while the 2002 image is estimated around 2.04m, based on tide data from Puerto Armuelles and Balboa, Panama. The 2002 image cuts off Coiba Island's western-most peninsula but covers the vast majority of the island. Again, ROIs were made for the ocean areas and land areas. These ROIs were limited to the areas where both images' extents overlapped, so that the same two ROIs could be used to classify both years. The resulting map was converted to a vector and then a shapefile and exported to ArGIS. The ROIs were used to train three of the 15 m resolution VNIR bands to classify each pixel as land or ocean using the Maximum Likelihood Classifier.

Island size, isolation and habitat heterogeneity are all potential predictors of plant species richness in CNP. To understand which of these factors best predict variations in species richness, the new vegetation maps for each island were then fed into Fragstats to quantify the size, isolation and heterogeneity of the vegetation types and the islands. Total area (TA) of each island and vegetation type are the primary metrics of island size, while Euclidean Nearest Neighbor (ENN) measures the isolation of a patch of vegetation from similar patches on the same island. Isolation is also measured as the proportion of land within a 10,000 m and 25,000 m buffer zone around each island. Historically, island isolation has been measured by distances to the mainland and steppingstone islands, but recent work by Diver (2008) and Weigelt and Kreft (2013) found that the buffer method is a better predictor of species richness.

Habitat heterogeneity is quantified by island elevation range (ER), patch richness (PR), patch density (PD), edge density (ED), contrast-weighted edge density (CWED), Shannon’s Diversity Index (SHDI) and Simpson’s Diversity Index (SIDI). ER is the only direct measure of the variation in environmental conditions that control plant species distribution. The other metrics describe the heterogeneity of conditions on each island by assuming that changes in plant dominance describe changing environmental conditions. While measuring the number of distinct vegetation communities on the island (PR) begins to measure the number of species present, PR and PD make it possible to see the effects of the rate of change of environmental conditions on species diversity. The Shannon and Simpson diversity indices put the heterogeneity in terms of information and probability. CWED, like ED, measures the length of patch edge per area unit, but unlike ED, CWED only keeps a portion of each boundary based on the degree of contrast between the bordering patches. In this way, patches that are similar to each other are counted less. Similarity was quantified as the number of species two patch types share, proportionate to their combined total species. This species data, including species richness for both the islands and each vegetation type come from field data collected between the late 1990s and 2012 (Ibáñez, 2001; Ibáñez and Diver, 2012).

Correlations between these metrics and species richness were investigated in RStudio version 1.2.1335-1 (Boston, Massachusetts) using linear regressions. Regressions with p-values less than 0.001 were considered significant and regressions with R^2 values greater than 0.6 were considered strong. A Shapiro-Wilk test was used to verify the normal distribution of the residuals with p-values less than 0.05 rejected.

Chapter 4 Results

4.1 Changes to Island Morphology

From January of 2002 to January of 2010, Coiba Island's beaches appear to have accumulated area based on the classifications of ASTER imagery at a tide level of 2 m (Appendix 1). This result is based on only two observations and needs further investigation, because there are few satellite images of the island taken on clear days at the same tide level.

Only six islands are expected to be inundated by 1 m of SLR, half of which are in CNP (Table 1). The two largest islands, Coiba and Cebaco, lose the most land in this scenario and none of the smallest islands are affected. With 3m of SLR, ten more islands begin to lose land. Of these ten islands, only Sandra is not a part of CNP. In SLR4m, 68% of all the islands and 85% of the CNP islands are flooded. By SLR6m, all islands are inundated to some extent, except Iglesia which finally loses 6% of its total area in SLR9m. The only island expected to be fully submerged in Mount Desert C in the SLR9m scenario. Coiba Island loses the most land in every scenario; however, the inundated land is a small proportion of the island's total area, only losing 4% of its total area in SLR9m.

Table 1. Area Lost by Each Island in Each of the SLR Scenarios

Island Name	Current Area (m^2)	Max Elev (m)	Area Lost (m^2):				
			1 m SLR	3 m SLR	4 m SLR	6 m SLR	9 m SLR
Afuerita	270,054	82	0	0	941	6,586	16,937
Brincanco	2,157,611	173	941	14,114	25,406	67,749	174,077
Brutal	27,288	21	0	0	941	4,705	14,115
C. Afuera	2,351,448	221	0	0	4,705	26,347	66,808
C. Tierra	1,978,830	152	0	0	0	14,115	59,281
Cebaco	79,486,285	356	53,634	96,918	222,065	670,901	1,427,429
Chichon	11,291	19	0	0	0	1,881	3,763
Coiba	503,636,148	403	85,627	780,993	1,656,082	5,934,607	18,541,531
Colibri	47,989	35	0	0	0	1,882	5,646
Erblichia	39,520	22	0	941	941	11,291	19,760
Escorpion	45,166	48	0	0	0	941	4,705
Frigate	111,974	51	0	941	941	4,705	11,292
Gobernadora	7,776,998	207	5,645	7,527	19,760	56,457	127,029
Iglesia	47,989	62	0	0	0	0	2,823
Iguana	77,158	44	0	941	2,823	7,527	13.173
Jicarita	1,319,220	199	0	9,410	19,760	80,922	161,845
Jicaron	20,166,384	399	3,587	104,269	207,774	495,707	1,017,937
Kim’s island	38,579	41	0	0	941	1,882	6,587
Los Nisperos	24,465	28	0	941	941	1,882	6,587
Maria	48,930	44	0	0	0	1,882	4,705
Mona	73,395	62	0	0	0	2,823	6,587
Mt. Desert B	5,646	13	0	0	0	1,882	3,764
Mt. Desert C	11,291	8	0	940	3,763	8,468	11,291
Pacora	34,815	36	0	0	0	941	1,882
Pajaros	396,142	108	0	941	3,764	21,642	35,756
Punta Chirre	29,170	30	0	0	0	2,823	3,764
Rancheria	2,342,980	124	0	5,646	12,233	41,403	98,801
Sandra	198,542	41	0	5,646	8,469	26,347	52,694
S. Catalina	331,216	56	5,645	11,291	16,937	39,520	69,630
S. Cruz	15,996	22	0	0	941	2,823	5,646
Uva	2,409,787	160	0	1,882	5,645	30,110	91,272

4.2 Direct Losses of Vegetation Communities

Every island supports both beach vegetation and dry coastal forest (Figure 3). The least common vegetation types are cork oak groves and fields which are only found on 11 islands, the former found primarily on islands within the park. Every other land cover is found on at least half of the 31 islands. Nine of the park islands have human-made structures. Every island with fields also has pioneer forest and every island that has pioneer forest has secondary forest. Santa Catalina is the only island where secondary and pioneer forests exist without mature forest, but there are 9 islands on which mature forest grows without any secondary forest pioneer forest or fields.

There are 8 islands on the newly derived 2020 Vegetation Map that support all 8 vegetation types and human-made structures: Brincanco, Canales de Tierra, Cebaco, Coiba, Gobernadora, Jicarita, Jicaron and Uva. These islands are all in the top 10 largest islands of the study group. Canales de Afuera, Rancheria and Pajaros have all land cover types, except for fields, and are the 6th, 7th and 11th largest islands, respectively. Seven islands are composed of mature forest, dry coastal forest, mangroves and beaches. Colibri and Maria islands are similar to those seven, but have buildings, while Mona and Escorpion are similar, but have secondary forest. The four smallest islands (Santa Cruz, Mt Desert B and C, and Chichon) are comprised of dry coastal forest and beaches, exclusively. Lastly, Afuerita, Frigate Colony, Iguana, Sandra and Santa Cruz have unique combinations of the 9 land covers.

Comparing the 2009 Vegetation Map to the newly derived 2020 Vegetation Map, there is strong agreement between the two about the location of mangroves on Coiba Island; although the new map suggests that there are mangroves at Hermosa Beach not previously mapped and classifies some of the 2009 mangroves near Santa Cruz as beach (Figure 3). The new map likely overestimates the distribution of cork oak forests which is usually restricted to coastal areas as a transition zone between coastal habitats and mature forests but is drawn as dispersed patches among the interior mature forest. The mature forest that, in 2009, blanked the interior of the island is encroached upon by secondary forest and cork oak groves in the new map. The secondary forest also occupies spots that were classified as pioneer forest and fields at Hermosa Beach, the San Juan Valley, Boca Grande and Barco Quebrado in 2009. Likewise, around Esquina Point, pioneer forest occupies land previous classified as fields, which cover less land in the new map.

On Jicarón, mature forest still dominates the center of the island with patches of dry coastal forest around the edges, while Jicarita is mostly dry coastal forest. However, both islands have more secondary forests than in the 2009 map, and none of their northern pioneer forest. North of Coiba Island, Rancheria Island is still dominated by mature forests with some pioneer forest and a few fields, but now also encroached upon by secondary forests. In 2009, an extensive swamp forest was mapped in the southern portion of the island, just north of the runway. Swamp forest was not included in the new classification because of its small area and its association with species found in cork oak, dry coastal forest and mangrove vegetation; however, none of those three vegetation types are assigned to Rancheria.

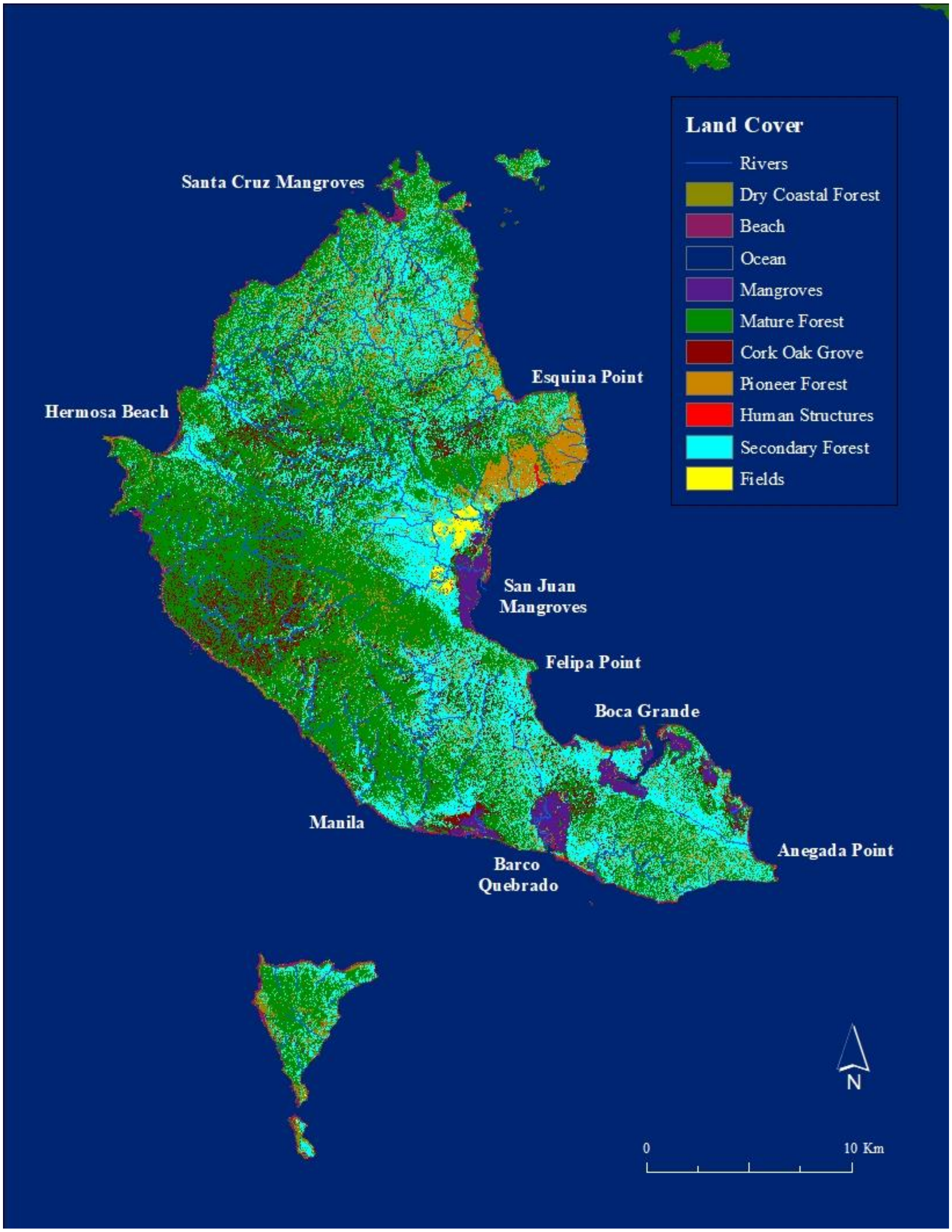


Figure 3. The distribution of different vegetation types on present day Coiba, Jicarita, Jicarón, Rancheria Islands based on Sentinel 2 imagery.

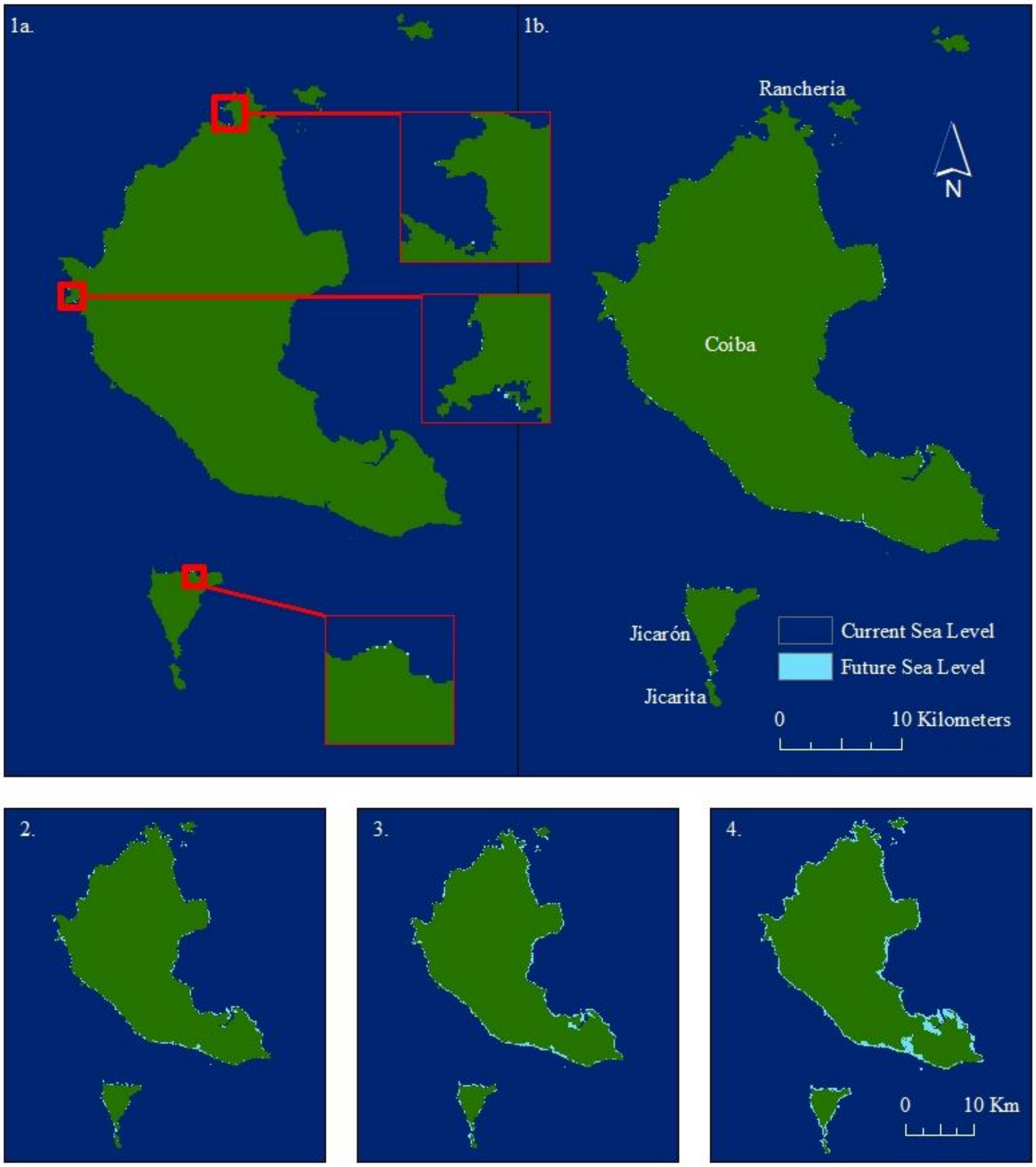


Figure 4. Sea Level Rise scenarios for Coiba, Rancheria, Jicaron and Jicarita islands are shown above. In scene 1, areas inundated at a new average sea level 1 meter above the current average (a) and at the new hightide 3 meters above the current average (b). In scenes 2-4, extreme sea level events take water up to 4 meters above the current average sea level, 6 meters above current average and 9 meters above current average.

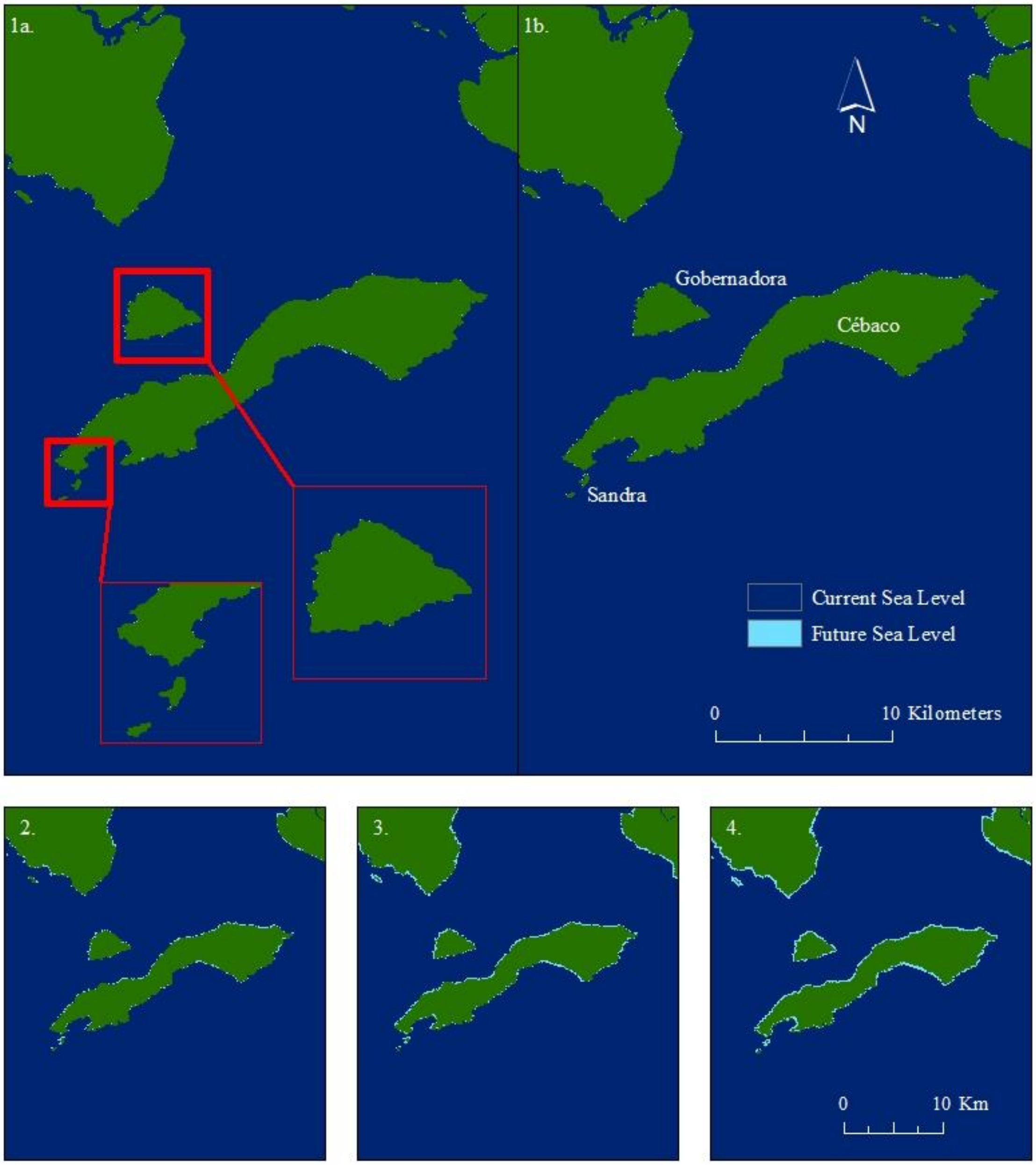


Figure 5. Sea Level Rise scenarios for Cebaco, Gobernadora and Sandra islands are shown above. In scene 1, areas inundated at a new average sea level 1 meter above the current average (a) and at the new hightide 3 meters above the current average (b). In scenes 2-4, extreme sea level events take water up to 4 meters above the current average sea level, 6 meters above current average and 9 meters above current average.

Beaches make up 86% of the land flooded at sea levels 1 meter above current sea level (Table 2). With increasing water levels, beaches make up an ever-smaller proportion of the flooded areas. With 6 m or 9 m extreme sea level events, beaches are 54 or 33%, respectively, of the land flooded across all the islands. For the milder three scenarios, dry coastal forests are the second most flooded lands, making up 9-10% of the flooded area. As extreme sea level events flood inland, mangroves become the second most flooded land cover, accounting for 17% of land lost in the 6 m SLR and 31% in the 9 m SLR scenario across all the islands (Appendix 2 and 3). Up to 10% of all human structures could be flooded. All other vegetation types lose a small fraction of their total area. Fields and cork oak groves are the most protected from flooding.

On Coiba Island, 1 meter of SLR covers 77,162 m^2 of beach, and 4,705 m^2 of dry forest (Table 3). Most of this lost land is located on the western side of the island. At the new hightide, an additional 350,052 m^2 of beaches are inundated, covering 5% of the island's beaches in total. Meanwhile, 2% of human structures go under. At this point, secondary forests and pioneer forests begin to be flooded as well.

If Coiba Island is hit by an extreme sea level event that raises the sea level an additional meter above the new hightide, a total of 1,197,893m^2 of currently exposed land will be inundated. In such an event, 15% of current beaches will be flooded along with 4% of human structures, and 2% of dry forests. Beaches and dry coastal forest are the two hardest hit vegetation types until SLR6m, when the area lost by mangroves exceeds that lost by dry forest. In this scenario, beach flooding rises to

Table 2. Study Region Inundation

Vegetation Type	Flooded Area on All Islands									
	1m SLR		3m (new hightide)		4m (ESL event)		6m (ESL event)		9m (ESL event)	
	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type
Mature Forest	941	0.0003	8,469	0.0029	26,348	0.0092	232,427	0.0808	1,098,147	0.4610
Secondary Forest	0	0	4,705	0.0030	4,705	0.0030	159,970	0.1025	1,139,551	0.7300
Coastal Dry Forest	15,997	0.0534	71,516	0.2386	166,557	0.5557	667,169	2.2260	1,981,746	6.6120
Mangroves	941	0.0051	28,230	0.1524	89,395	0.4827	903,360	4.8780	5,071,049	27.3831
Fields	0	0	0	0	941	0.0014	14,115	0.2705	93,159	1.7851
Pioneer Forest	0	0	941	0.0014	941	0.0046	33,876	0.0516	328,409	0.5006
Cork Oak Groves	0	0	0	0	1,882	0.0046	5,646	0.0138	200,433	0.4911
Beach	136,445	0.9846	614,473	4.4340	1,260,940	9.0989	289,0752	20.8596	5,279,951	38.1001
Human Structures	3764	0.0478	47,050	0.5974	111,979	1.4219	399,925	5.0783	800,791	10.1685
Total	158,088		775,384		1,663,688		5,307,240		15,993,236	

25%, human structures to 18%, mangroves to 5%, and dry forests to 6%. Further sea level rise to 9m would inundate 591,570m^2 of the island, with mangroves losing the most land. An extreme event like this would flood 59% of beaches, 40% of human structures, 34% of mangroves, 23% of fields, 21% of dry forest, 2% of secondary forest (Appendix 2).

Table 3. Coiba Island Inundation

Vegetation Type	**Flooded Area on Coiba Island**					
	1m SLR		3m (new hightide)		4m (ESL event)	
	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type
Mature Forest	941	0.0004	4,705	0.0019	19,761	0.0082
Secondary Forest	0	0	4,705	0.0034	4,705	0.0034
Coastal Dry Forest	4,705	0.0562	47,991	0.5729	109,156	1.303
Mangroves	941	0.0056	26,348	0.1574	85,631	0.5116
Fields	0	0	0	0	941	0.0298
Pioneer Forest	0	0	941	0.002	941	0.002
Cork Oak Groves	0	0	0	0	1,882	0
Beach	77,162	0.9148	427,214	5.0653	885,481	10.4987
Human Structures	1,882	0.1021	35,758	1.9397	89,395	4.8494
Total	85,631		547,662		1,197,893	

Vegetation Type	**Flooded Area on Coiba Island**			
	6m (ESL event)		9m (ESL event)	
	Area (m2)	% of Veg. Type	Area (m2)	% of Veg. Type
Mature Forest	192,905	0.0799	1,098,147	0.4549
Secondary Forest	138,327	0.1006	1,006,870	0.7328
Coastal Dry Forest	485,556	5.7965	1,475,488	17.614
Mangroves	885,481	5.2903	4,987,300	29.797
Fields	11,292	0.3575	80,926	2.5626
Pioneer Forest	28,230	0.0609	299,238	0.6461
Cork Oak Groves	5,646	0.0141	197,610	0.4942
Beach	2,131,365	25.2705	3,818,578	45.275
Human Structures	333,114	18.0704	653,995	35.4773
Total	4,211,916		13,618,152	

Coiba is one of three islands where cork oak groves will be directly impacted by any of the SLR scenarios. On Brincanco and Cebaco, 9 m of SLR will inundate 941 m^2 (2% of vegetation type) and 1,882 m^2 (0.3% of vegetation type) of cork oak, respectively (Appendix 2). On Coiba, loss of cork oaks starts at 4 m of SLR with 1,882 m^2 lost and increases to 197,610 m^2 (0.5% of vegetation type) with SLR9m. Overall, cork oak groves will experience the least amount of flooding of all the vegetation communities.

On the other 7 islands that host all land covers, beaches and dry coastal forests are generally the hardest hit by each SLR scenario, with a few exceptions in SLR6m and SLR9m (Appendix 2). Canales de Tierra is unaffected by the SLR scenarios until SLR6m, at which point it losses beach (2,823 m^2), mature forest (1,882 m^2) and fields (941 m^2) to roughly the same degree. Other vegetation types are flooded at SLR9m of this island, but beaches and mature forests lose the most area. The same is true for Brincanco and Uva at SLR9m.

The 4 small islands that host beaches and dry coastal forest split their land 50-50 or 60-40 between the two categories. On Santa Cruz, where beaches are slightly dominant, dry forests are inundated first and in a greater proportion; however, on Chichon, where beaches are also dominant, the island consistently losses more beach area than dry forest. The Mt. Desert islands also show a similar rates of inundation for both land types.

Mount Desert C is predicted to be completely submerged and Iguana Island is the only island predicted to lose an entire vegetation type in the SLR9m scenario. If an extreme sea level event creates a swell 9 m higher meters higher than the current sea level, it should cover the 941 m^2 of fields present on Iguana Island and all of the beaches and dry forest on Mount Desert C.

4.3 Changes to Overall Island Habitat Diversity

Total island area, elevation range and species richness distributions are skewed by large outliers. I created normal residuals for their regressions by taking the natural log of all three metrics. After this transformation a significant species-area relationship was found ($R^2 = 0.73$, p-value < 0.001, Figure 6) as well as between elevation range and species richness ($R^2 = 0.78$, p-value < 0.001, Figure 7). Total island area explains 88% of the variation in elevation range (p-value < 0.001), but of the two, only elevation has a statistically significant relationship with patch richness ($R^2 = 0.84$). Patch richness also has a statistically significant (p-value < 0.001) relationship to species richness ($R^2 = 0.65$, Figure 8), as does patch density ($R^2 = 0.44$) and edge density ($R^2 = 0.55$). There is a significant, but weak positive trend between mean ENN and the patch richness on each island. Island isolation (Buf10 and Buf25) is not a statistically significant predictor of any of the variables in the study, including species richness.

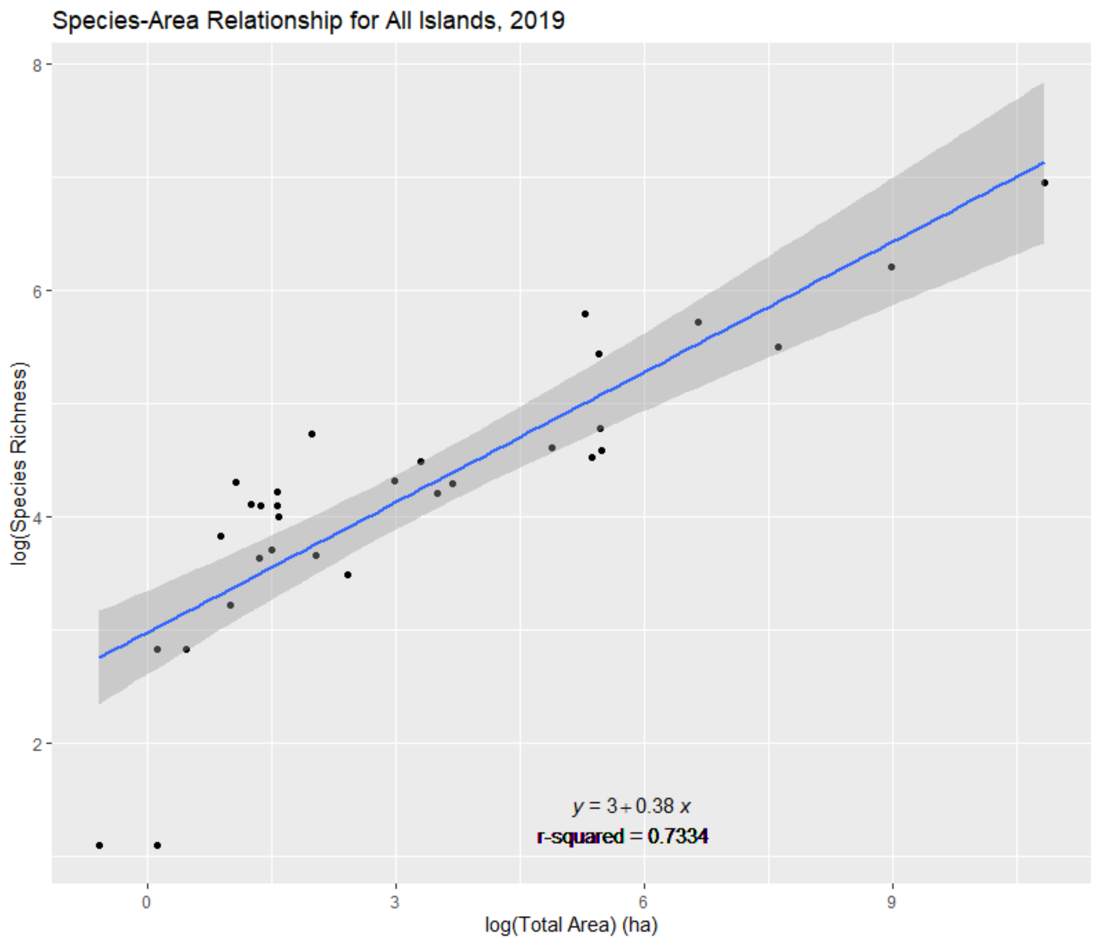


Figure 6. Species richness is plotted against total area (ha) in log-log space, illustrating the species-area relationship for the study islands. A linear regression line of these variables (blue) is plotted with a 95% confidence interval (dark grey).

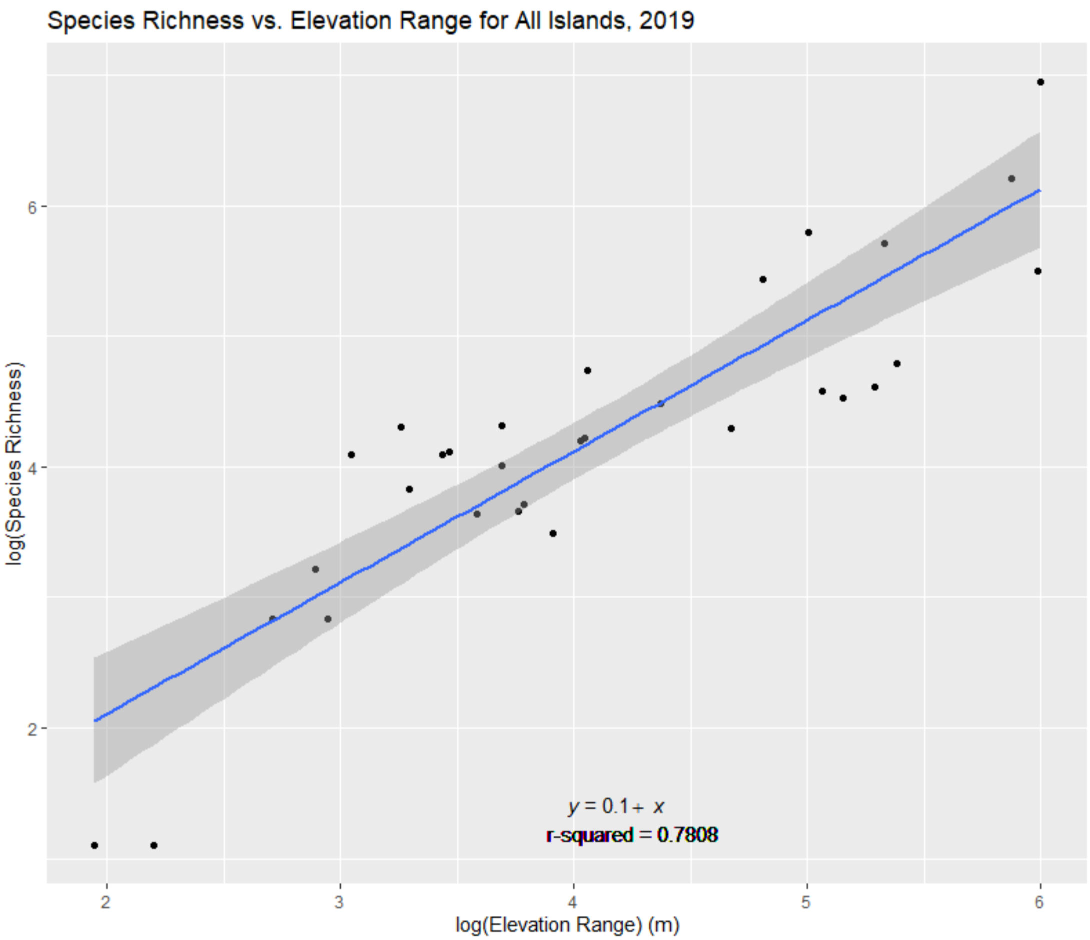


Figure 7. Species richness is plotted against elevation range (m) with a linear regression line (blue) in log-log space for each island as of 2019. The dark gray area represents at 95% confidence interval for the regression line.

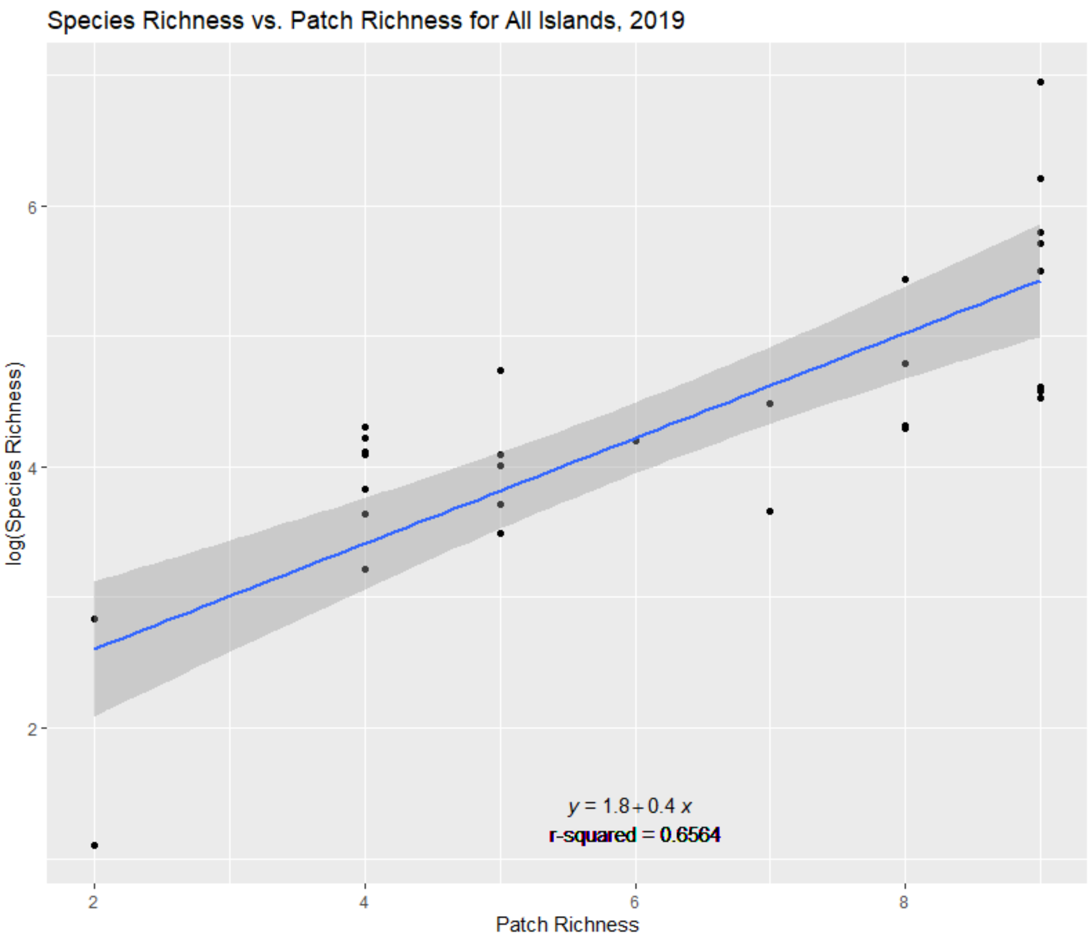


Figure 8. Species richness is plotted against patch richness (number of vegetation types per island) for all the islands as of 2019. A linear regression (blue) is plotted with a 95% confidence interval (dark grey).

After considering that correlations between elevation range, island size, patch richness and species richness, I chose to use elevation range to predict future species richness, because it has the strongest correlation with SR and theoretically describes both island size and environmental heterogeneity. A linear regression for elevation range and species richness in log-log space produced Equation 1:

$y = e^{0.1 + \ln(x)}$

where y is equal to the SR and x is equal to elevation range. The resulting SR predictions yield species losses for most of the islands but estimate a higher species richness than measured by Ibáñez’s field work for 12 of the islands (Figure 9-11). As a result, Equation 1 predicts an average loss of 70.5 species across 7 inundated islands from an average loss of 1 m of elevation under SLR1m with Coiba expected to lose 600.7 species and Brincanco expected to gain 97 species. The average species loss is lower for the other 4 scenarios. Under SLR3m through SLR9m, the average loss per inundated island is 25.1 species, 22.4 species, 22.7 species and 25.7 species. Each of these scenarios respectively lose an average of 2 m, 3 m, 4 m, and 6 m of elevation, per inundated island. In SLR6m and SLR9m, all islands show a reduction in elevation range. The changes in species richness predicted by modeled changes in elevation range are smaller for islands that plot closer to the regression line. Coiba and Cebaco are both mountainous islands, but Coiba’s SR falls father above the regression line than that of Cebaco and they are respectively predicted to lose 600.7 species and 104.7 species with a 1 m change in elevation range. Flat, species-poor islands like Mount Desert B and C that fall below the regression line are both predicted to be able to support 6 more species than they currently do, even with a 1 m loss of elevation.

Given that Equation 1 predicts considerably higher species richness counts for the current elevation of some islands than the species inventory data support while also predicting considerably lower species counts for others, I calculated the difference between SR under the SLR scenarios and the new baseline for current conditions created by Equation 1. This calculation should capture the rate of species loss over a progression of SLR, even if the actual number of species supported by a given island is different from actuality. The average change in species for the inundated islands with 1 m of SLR is a loss of 1.1 species. In SLR scenarios 3 through 9, the inundated islands are expected to lose 2.3 species, 2.8 species, 4 species and 7 species on average. In this case, average species lost is in a nearly 1:1 ratio with average elevation lost. The current measured SR smaller islands tend to follow this ratio more closely than large islands.

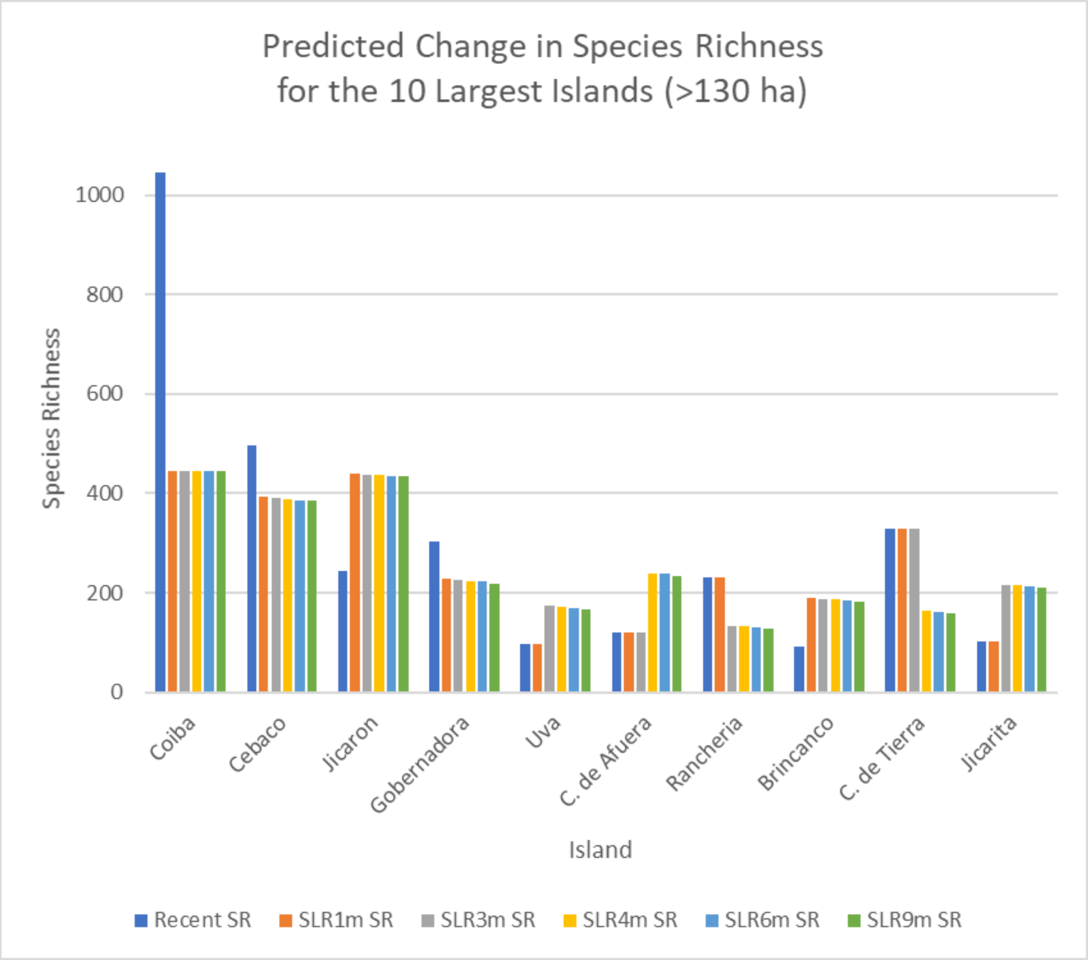


Figure 9. The known SR (dark blue) is plotted next to the predicted SR for each of the SLR scenarios for the 10 largest islands in the study group. The islands are listed from largest to smallest.

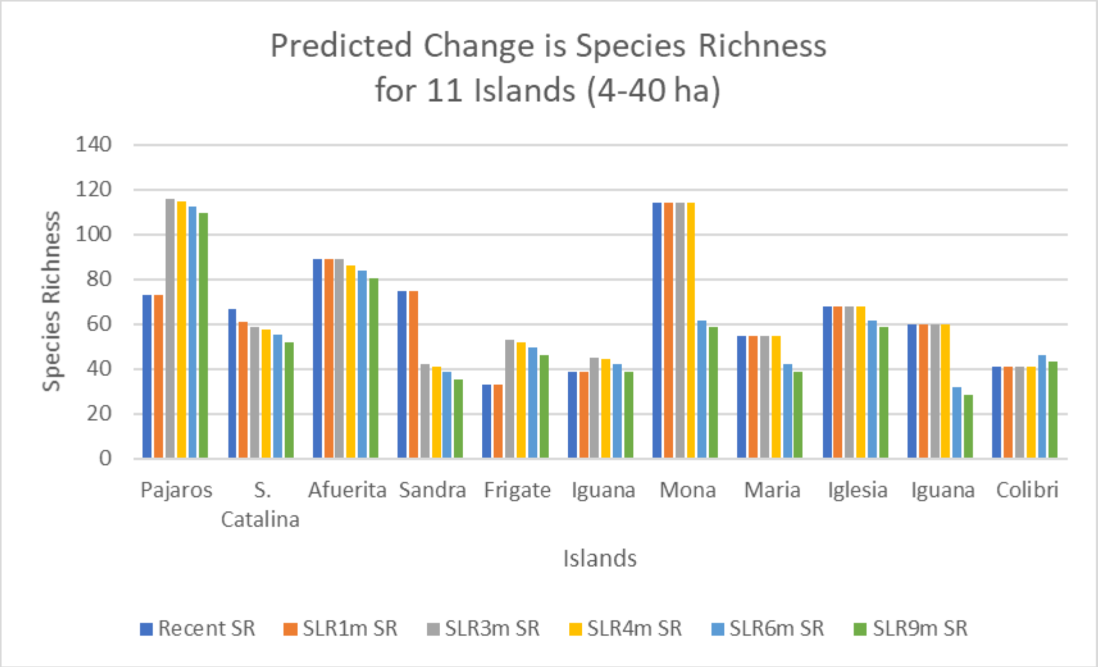


Figure 10. The known SR (dark blue) is plotted next to the predicted SR for each of the SLR scenarios for 11 medium-sized islands, listed from largest to smallest.

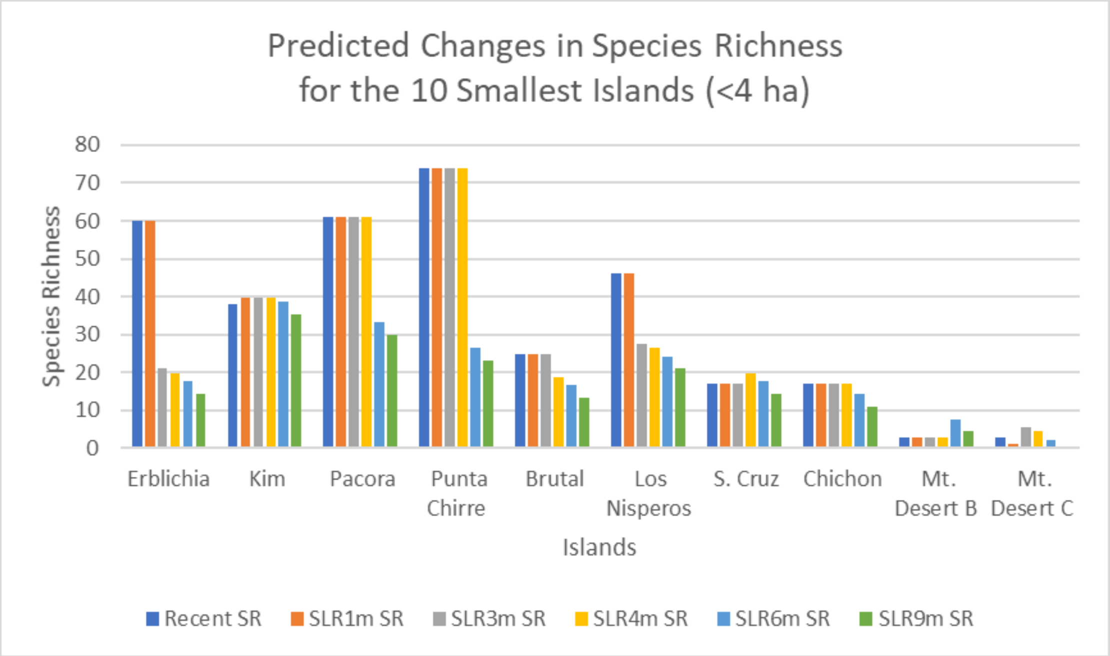


Figure 11. The known SR (dark blue) is plotted next to the predicted SR for each of the SLR scenarios for the 10 smallest islands, listed from largest to smallest.

Chapter 5 Discussion

Without ground-truthing the 2020 Vegetation Map (Figure 3), it is difficult to measure the accuracy of the vegetation distributions it predicts. Some of the discrepancies between the 2009 and 2020 maps make sense with the passage of time. The areas where fields have been replaced by pioneer forests and pioneer forests replaced by secondary forests follow the expected succession of vegetation types after land clearing. Other areas where cork oak has replaced mature forest are more difficult to explain and may be the result of errors in the classification process. If cork oak is overtaking mature forests, such a shift in vegetation cover would not be good for overall biodiversity since cork oak groves are less rich in species than mature forest cover, and mature forests stand to lose more area on average than cork oak groves.

Coiba Island accreted between 2002 and 2010, according to the classification and despite the 2010 image being a slightly higher tide level (< 0.5 m difference). While the remote sensing analysis in my study is weak due to the low temporal resolution of images at the same tide level, Ruiz-Beltran et al. (2019) extracted historic shorelines for their study site from SPOT-5 (Satellite Pour l’Observation de la Terre - 5) images and accepted the errors created by differences in tide level at each observation. However, Ruiz-Beltran et al. (2019) had much finer resolution than I had, due to their use of pan-sharpening assessment, which means that a pixel or two of error in their study is a much smaller error than it would be in this one. In this study, the largest differences in shoreline are on the eastern side of Coiba Island, around river mouths. It is possible that this result could be skewed by increased sediment run-off in 2010, which would change the color of the ocean close to shore.

If, however, the island has been accumulating sediment, then the mangroves, beaches and dry coastal forest around Boca Grande and the San Juan Mangroves may be buffered from SLR and lose less land than predicted. The source of this sediment is also of interest. If the sediment accretion on the eastern side of the island is coming from other parts of the island, then the lower risk of flooding on the east side comes at the expense of the higher risk elsewhere on the island. If, on the other hand, the sediment is traveling from the mainland, the situation is a net positive for Coiba Island. Unfortunately, this not a question that can be answered in the confines of this project; however, this question is not trivial since some coasts are changed much more dramatically by lateral accretion and erosion than by sea level changes (Ruiz-Beltran et al., 2019).

There are many small islands with steep coasts that may not lose much land area to rising sea levels until extreme sea level events occur. Of the study group, only one island (Mount Desert C) is predicted to be fully submerged, and only during a 9 m extreme sea level event. Based on a survey of global island biodiversity hot spots by Bellard et al. (2013) that found 6 m of SLR submerged up to 19% of islands, the CNP are at lower risk of disappearing into the ocean than average. This makes the CNP islands more valuable to biodiversity conservation efforts, because work on these islands will not be erased by the island's eventual disappearance (Courchamp et al., 2014). Diver and Ibáñez (unpublished manuscript) predicted that 3 islands in CNP would be inundated by 1 m SLR, but these small islands were not included in this study area because these islands are too small as defined by the ASTER Water Bodies Database. The Diver and Ibáñez study also predicted that Brutal Island would be entirely inundated by 10 m of SLR, but the ASTER GDEM measures its maximum elevation as 18 m. Discrepancies in the elevation and shoreline data available need to be resolved with better spatial and temporal resolution to improve predictions of future shorelines.

As expected, coastal vegetation types such as beaches, dry coastal forest and mangroves face the largest loss of area due to sea level rise. Of the coastal land effected, beaches make up the largest part of the inundated land. A portion of the area classified as beach is exposed sand and not beach vegetation, so every square meter lost from beaches does not translate to direct loss of plants. As seen in the 2009 Vegetation Map, the beach vegetation on Coiba Island grows as a border between exposed sand and the forest interior, above hightide. In this position, the beach vegetation has reduced exposure to waves, which at hightide, can rise 2 m above the average sea level. As such, the 77,162 m^2 of beach inundated by 1 m of SLR probably does not support much vegetation, but the new hightide line (SLR3 m) will determine where the beach vegetation can grow.

While mangroves are usually capable of handling tidal pressures, storms have been recorded to wash away sections of mangrove forest in other locales and the reforestation process would likely change the species composition and distribution. Mangrove species distribution is largely determined by salinity gradients with high tolerance species like *R. mangle* and *R. racemosa* living closer to the ocean and low tolerance species like *A. germinans* and *L. racemosa* living more inland (Ibáñez, 2011). As such, with increasing saltwater flooding and increasing exposure to wave energy, *R. mangle* and *R. racemosa* will suffer first. There has been a lot of research into mangroves’ responses to sea level rise, because of their ecological importance and low elevation range. Mangroves may avoid inundation by either migrating inland or by benefiting from soil elevation gains. Cahoon and Hensel (2006) find that subsurface processes like root growth and decomposition control changes in soil elevation, rather than surface accretionary processes; however, these processes should be assessed locally.

Most of the buildings on the islands are located along the coasts and a high proportion of them will be flooded by extreme sea level events. By contrast, the fields created by cattle grazing and agriculture are far enough inland to avoid rising waters for the most part. Since building and resource use on the islands are regulated in CNP, it should be possible to limit the impact of rebuilding projects on each island's biodiversity.

The lack of relationship between isolation metrics and species richness across the islands, suggests that either the islands are not sufficiently isolated for isolation to be a limiting factor, or the metrics used in this study do not capture the isolation-related variables influential on plant species richness in this region. The proportion of surrounding land has been shown to explain 86.1% of the variation in species richness on 453 islands all over the world (Weigelt and Kreft, 2012). In lake environments, the buffer method of measuring isolation captures the effect of isolation on lake island species richness at spatial scales much finer than those considered here (Diver, 2008). Proportion of land with similar species composition may improve this isolation metric.

The strong predictive relationships between island size and species richness as well as habitat heterogeneity (e.g. elevation range) and species richness, supports the use of these metrics to predict species losses on each island. Other island biogeography and coastal ecology studies link elevation gradients to species richness

(Dapporto, 2009; Jimenez et al. 2009; Moeslund et al., 2011), and thus support the results presented in this thesis. Elevation gradients can affect the number of plant species on as island due to elevational and aspect variations in microhabitat (e.g. differences in temperature, moisture, wind exposure, soil quality, slope steepness).

The regression method I used in this study is one of many that have been tried by researchers in the quest to understand how plant species populations will respond to the effects of climate change. Climate change will redistribute other abiotic factors of species distribution. Bioclimate envelope models predict changes in distribution of suitable niche space for plant species based on climate data, and in the case of the SPECIES method, soil data (Pearson and Dawson, 2003; Pearson et al., 2002). While these models describe changes for specific plant species rather than landscape species richness patterns, using bioclimate envelopes to identify new areas that could be colonized by plant species at risk of losing their current range may be useful to CNP managers (Mbogga et al., 2010). Both my methodology and the bioclimate envelope models are correlative approaches to forecasting, but correlative methods are inherently limited by the fact that they describe relationships between variables under current conditions and cannot account for how these relationships may change (Pearson and Dawson, 2003). Correlations with environmental factors that have direct connections to the mechanisms that control plant distribution should be more reliable than correlation with factors whose correlation with species richness is the result of additional factors. Many studies that model SLR impacts of species richness assume the mechanism by which SLR changes species richness is destruction of individuals species established distribution range, causing extinctions (Bellard et al., 2013; Courchamp et al., 2014). If such assumptions hold true, then the species richness-elevation range relationship of islands should reliably describe islands risk of losing species to SLR, because islands with higher elevations should always have a high proportion of species with ranges above the threat of inundation. No model will ever predict the future perfectly, but the method I used here makes use of pre-existing datasets and can easily be modified to include more environmental variables to improve its predictive power, so long as collinearity with elevation range is avoided. By using existing data to provide an initial prediction of the future, this study can provide a starting point for action.

Although the species richness-elevation range model is statistically significant with an acceptably high regression coefficient for ecological studies, the model yielded unexpected gains in species richness values for certain islands. The species-area relationship and the species-patch richness relationship both provide further evidence that species richness should only decline as SLR increases and land disappears. It seems likely that there are other factors suppressing current measured species richness relative to the potential richness predicted by elevation range on some islands. On the other hand, several islands have much higher species richness than predicted by the current elevation range. Understanding the factors that improve species richness beyond the effect of elevation range may yield insights for preventing species loss.

To make more specific predictions about which species may disappear from which islands, it is necessary to compare vegetation type losses with the species density of those vegetation types to predicted species richness loses for islands that behave consistently with the species richness-elevation range relationship. The islands deemed to behave most consistently with the species richness-elevation range relationship have a difference between measured and modeled SR for current conditions within ± 2 species or 5% of each other. Islands that fall in this category are Mount Desert B and C, Santa Cruz, Erblichia and Coiba in the park and Chichon, Canales de Tierra and Punta Chirre outside the park.

Mount Desert B and C host three known plant species that are all associated with dry coastal forests: *Pitcairnia halophila*, *Pityrogramma dealbata*, and *Rhynchospora cephalotes*. Both islands are taller than the SLR1m. Mount Desert C will be flooded by an elevated hightide (SLR3m), but only beaches should be affected, so it is unlikely that this scenario will lead to species loss. Once an extreme sea level hits, however, one or all three of these species may be lost, depending on the degree of severity. Without data about the distribution and population size of these three species, it is hard to distinguish between the risk posed to species within a vegetation type.

Chichon and Santa Cruz are slightly bigger, and both have a species richness of 17. Similar to the Mount Desert islands, Chichon and Santa Cruz are predicted to lose size and elevation during extreme sea level events. The 10 species associated exclusively with dry coastal forest on Santa Cruz is at higher risk of local extinction because dry coastal forest is flooded first (SLR4m) and in greater proportions than beaches. Depending on the severity of the extreme sea level event, 1 to 6 species could be lost. On Chichon, beaches are flooded first (SLR6m) and to a great degree, but the 5 species associated with beach vegetation are also associated with dry coastal forest which may shift risk away from these species and towards the 10 species only associated with dry coastal forest. A large extreme sea level event is predicted to cause the local extinction of 2 to 5 species.

Like Chichon, Punta Chirre is unaffected by SLR scenarios until a 6m or 9m extreme SLR event occurs. In these scenarios, Equation 1 predicts that 2 to 6 species will be lost. Punta Chirre is inhabited by mature forest, dry coastal forest, mangroves and beaches, but only beaches and mangroves may be flooded. If 2 species are lost in the SLR6m scenario, they must be lost from the eastern section of beach. Of the island's 74 plant species, 12 are associated with beach vegetation. *Amphitecna latifolia*, *Brassavola nodosa* and *Ximenia americana* are all found only with beach vegetation. In SLR9m, beach and mangrove areas lost 15% and 14% of their land respectively. This will put more pressure on the beach vegetation that may already be stressed. There are only two mangrove species known to grow on this island and both are epiphytes: *Werauhia sanguinolenta* and *Tillandsia bulbosa*. Since there were no known true mangroves on this island in 2012, it is possible that this area is misclassified. The two epiphyte species are associated with other vegetation types on the island and seem unlikely to be a risk due to SLR.

Erblichia has a species richness of 60 that will decline by 2 to 8 species depending on the severity of SLR. In the SLR3m and SLR4m are expected to wipe out beaches, meaning that in these scenarios and those more intense, 2 to 3 of the 12 beach vegetation species are expected to disappear. Again, which species become locally extinct will depend on factors like species distribution and population size that this study does not know; however, *Brassavola nodosa, Talipariti tiliaceum* var. *pernambucense,* and *Terminalia catappa* are only associated with beach vegetation areas. By SLR9m, 43% of the island's beaches will be flooded as well as 40% of the island's dry coastal forest, putting an additional 28 dry coastal forest species at risk as well.

Canales de Tierra is considerably larger than the other islands reviewed and hosts 328. This large island has apparently steep shoreline, not losing land until SLR6m. While the island hosts all land cover categories, beaches, fields and mature forest are hit first and worst. All three categories loss roughly the same amount of land both in absolute terms and relative to the vegetation type totals. The only beach vegetation species known to grow on Canales de Tierra is the tree *Spondias mombin*. This could mean that *S. mombin* is dominant and has a large population size. It could also mean that the beach vegetation makes up a small portion of the total beach area. Understanding this tree's response to past storms may reveal how capable it is of handling future extreme sea level events. Meanwhile, there are 8 species associated with Canales de Tierra's fields and 6 associated with its mature forests.

The west side of Coiba Island should feel the effects of sea level rise first, since most of the land inundated buy the 1 meter of SLR is on the west coast, but storms will hit inlets around the island hard. There are three known endemic species in the study area, all of which are found on Coiba: *Desmontes incomparabilis, Fleishmania coibensis*, and *Psychotria fosteri*. For these three species, the risk of local extinction could mean total extinction. *D. incomparabilis* and *P. fosteri* are found only in the mature and gallery forests on Coiba. Less than 1% of Coiba's mature forests are expected to flood in each SLR scenario. In Guia Botanica del Parque Nacional Coiba (Botanical Guide to Coiba National Park) by Ibáñez, species distribution maps show that *D. incomparabilis* is found far enough inland to avoid flooding. Two of the three *P. fosteri* sites are near flooding zones, starting with scenario SLR3m. These northern *P. fosteri* populations may be at high risk. *F. coibensis* may also be at risk, because it grows in rocky coastal areas and all three known populations on Coiba are in areas flooded by all six scenarios. *F. coibensis* also grows on Santa Cruz, Maria, Chichon, and Colibri, but I do not know the distribution of these populations.

Regional and global studies of sea-level rise and its effects on islands often focus on endemic species losses (Bellard et al., 2013; Courchamp et al., 2014). This focus on endemics fails to account for other species losses, which may be significant to island and mainland biodiversity, if islands serve as a haven for species that have lost habitat on the mainland, as is the case for several species in CNP. On the other hand, islands have higher rates of vascular plant and terrestrial vertebrate endemism than mainland areas, contributing a great deal to global biodiversity (Kier et al., 2009). In New Caledonia, Bellard et al. (2013) predicted the distribution losses of endemic species and found that species that lost most land were the species classified at higher risk of extinction by the IUCN. Conservation of endemic islands species may require direct intervention in the distribution of the species.

Ultimately, changes in the species richness of vascular plants on the study islands will have impacts of the diversity of other taxonomic groups living on the islands. Islands rich in endemic vascular plant species tend to be rich in terrestrial vertebrate species ($R^2 = 0.83$, Kier et al., 2009). Several island biogeography studies have found that habitat heterogeneity as defined by plant communities have significant correlations with the distribution of the animal species studied (Baldi and Sadler, 2008; Dapporto and Dennis., 2009). If vascular plant species are lost with rising sea levels, there will be consequences for species in other taxonomic groups as well.

Chapter 6. Conclusion

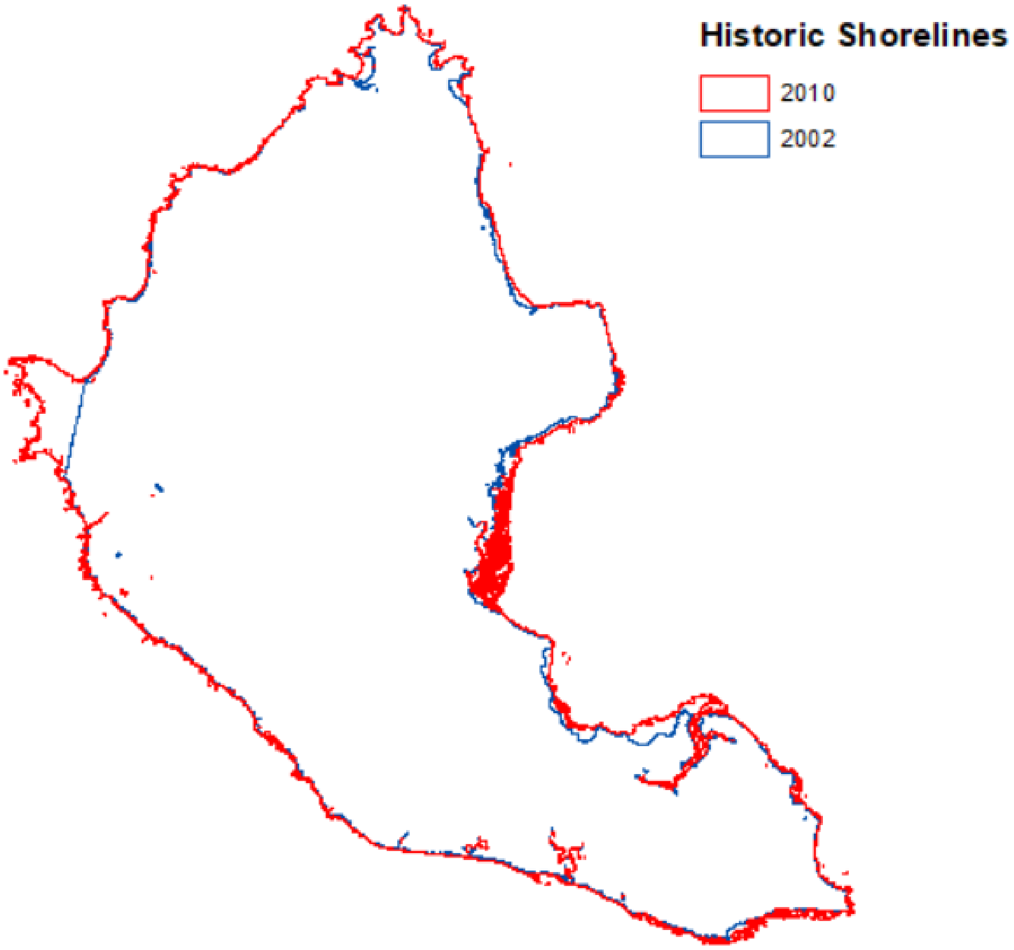
The SLR predictions I have presented in this thesis represent a range of outcomes with different temporal frequencies based on the IPCC's RCP8.5 climate change scenario projected for the end of the century. The three extreme sea level events may not describe the average future conditions of the islands but do mark areas that will be temporarily disturbed by an influx of water, salinity and wave energy. The effects of those SLR scenarios on the morphology of the islands assumes a simple "bathtub" model, where all contiguous lowlands are flooded. Future shorelines will be shaped by lateral movement of sediment with currents and other factors not accounted for in my thesis work. Further investigation of historic shorelines may add reveal patterns and add nuance to predictions of the future.

As the sea level rises, certain plant species are at risk of going regionally extinct. This risk is not evenly distributed, rather it is concentrated on the vegetation communities on low-lying sections of the coast. These high-risk vegetation types are beaches, coastal dry forests, mangroves and on smaller islands, mature forest. Identifying specific species most at risk is outside the scope of this study for all, except for cases were inundation is expected to species-poor vegetation communities and for the cases of the three endemic species on Coiba Island. On Coiba, species distribution data evidence that two endemic species are at high risk of inundation with a SLR of 3 m or more. The threat of extinction across the region's islands, however, will not be limited to endemic species. Further investigation of the risks to specific species requires more species distribution data and further research that accounts for changes in area, elevation range and isolation on the patch level and that incorporates species biological responses to SLR.

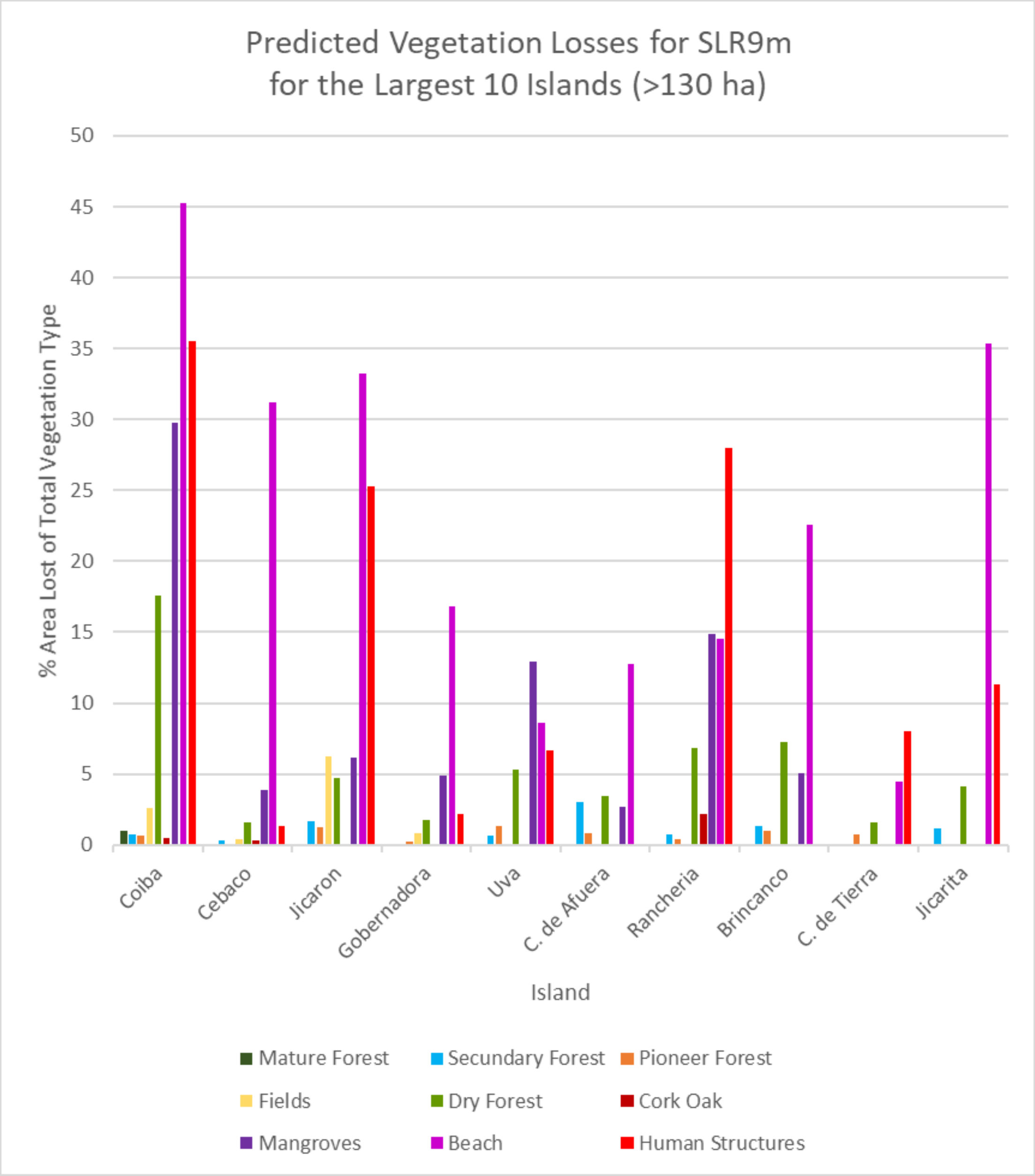
The average species lost per island predicted by changes in elevation range points to the urgency that responding to climate change demands. As CNP's managers plan for the future, responses to climate change and sea level rise will have to consider the impact on terrestrial and marine ecosystems. While they may lose species, the Coiba National Park islands and their easterly neighbors will not disappear. With the possible exception of Mount Desert C, conservation efforts on these islands will not be entirely drowned by rising sea levels, even if climate change is not mitigated. Action is needed to save threatened species and preserve the current species richness, but these actions have the potential to turn into long-term successes.

Climate change is an anthropogenically-induced force changing ecosystems around the world from pollution sources around the world, with many of those pollution sources located in the US. It is only right that these observations from afar interrogate the earth system processes that connect me as a researcher and Coiba National Park. The conclusions of this study implicate me, and all of us who benefit from the current economic and political systems that have made climate change possible.

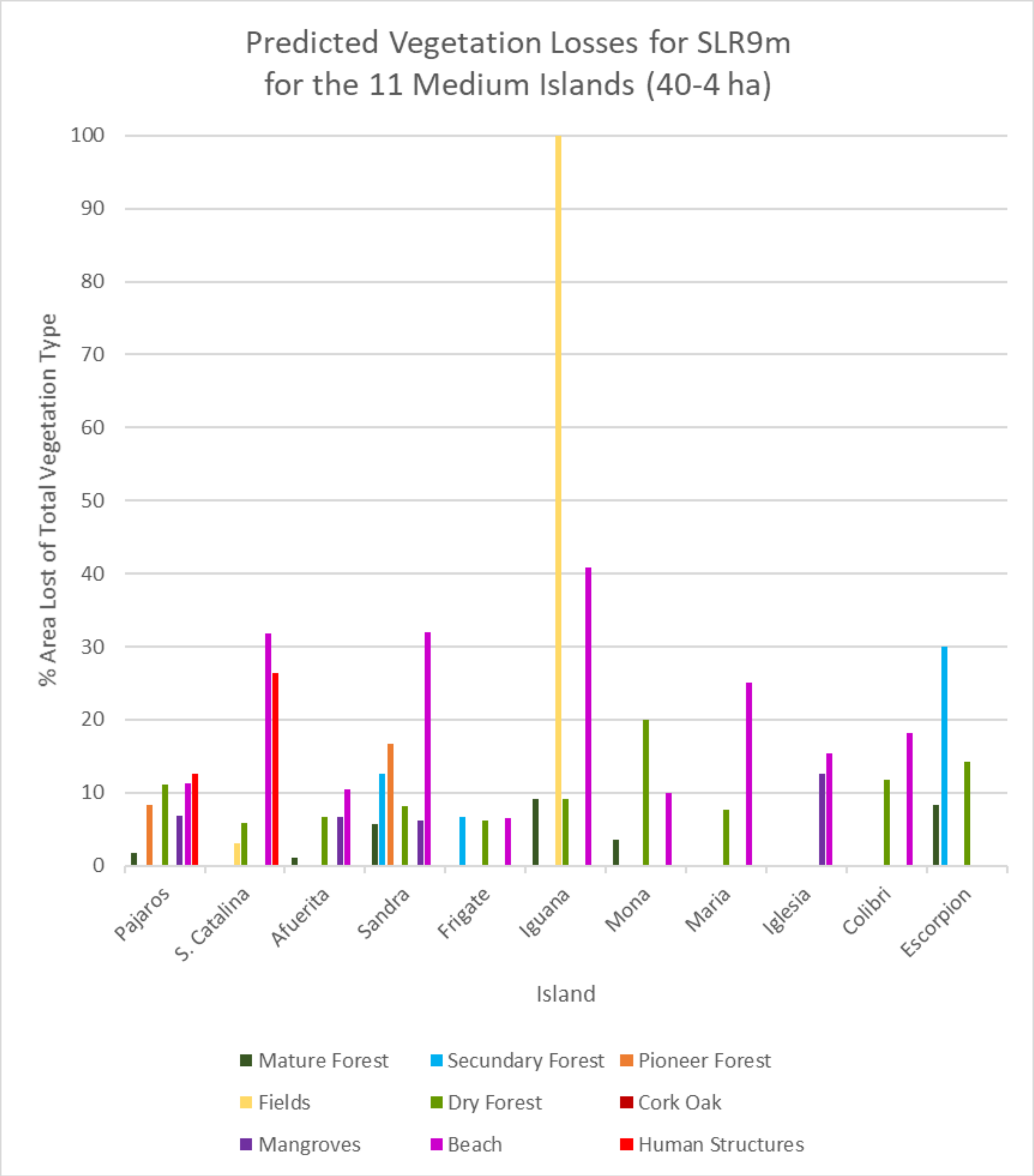
Appendices



Appendix 1. Shorelines of Coiba Island from 2002 (blue) and 2010 (red) produced by ENVI Maximum Likelihood Classifier with sea level at 2.04m and 2.06m above Mean Lowest Low Water respectively. The 2002 shoreline is unknown for the western-most peninsula, because this part of the island was not captured by the ASTER image.



Appendix 2. Area losses for each vegetation type on the largest 10 islands, as a proportion of the total area occupied by each vegetation type on each island.



Appendix 3. Area losses for each vegetation type on ll medium-sized islands, as a proportion of the total area occupied by each vegetation type on each island.

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