A Critical Assessment of the Green Sea Turtle Central West Pacific Distinct Population Segment Utilizing Maxent Modeling on Nesting Site Locations

by

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To my late father, who loved wildlife

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Abbreviations

AUC	Area Under the ROC Curve
CITES	Convention on International Trade in Endangered Species
CNMI	Commonwealth of the Northern Mariana Islands
CWP	Central West Pacific
DPS	Distinct Population Segments
ESA	Endangered Species Act
FSM	Federated States of Micronesia
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MTCA	Marine Turtle Conservation Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
RMI	Republic of Marshall Islands
ROC	Receiver Operating Characteristic
RS	Remote Sensing
SDM	Species Distribution Model
USFWS	US Fish and Wildlife Service

Abstract

Global climate change is proceeding at an unprecedented rate, and one species that is particularly vulnerable are green sea turtles. Green sea turtles are excellent indicators of climate change impacts on coastal and marine habitats as they rely on both at different points in their life cycles. The green sea turtles (*Chelonia mydas*) were added to the Endangered Species Act in 1978. In 2015, a status review completed on the now eleven distinct population segments (DPS) identified three DPS as endangered and the other eight as threatened. Out of these eleven populations, this paper assesses the extinction risk of the endangered Central West Pacific (CWP) DPS with Maxent habitat suitability modeling of nesting sites under current climate conditions and an extensive assessment of factors influencing population dynamics. The Maxent model used 101 green sea turtle nesting sites located within the CWP DPS and seven of the 19 bioclimatic variables from WorldClim clipped to within a 12 kilometers shoreline buffer, because green sea turtles only nest along the shorelines. The Maxent results calculated the suitability threshold for the CWP DPS was 0.0652, which means that values below that threshold are nesting sites that are considered not suitable, and values above that threshold are nesting sites that are considered suitable. Out of all the shorelines in the CWP DPS, only 26 percent were considered suitable nesting habitat. The extinction risk analysis followed a criteria written for this thesis based on the knowledge of extinction risk status assessments of the IUCN Red List and Seminoff's 2015 Status Review. The results of the extinction risk analysis of the CWP DPS indicate they are at a medium risk of extinction. Although this population is not indicating a high risk of extinction currently, their population abundance is still low enough to be considered endangered which warrants more effective and efficient conservation measures to be implemented.

Chapter 1 Introduction

The green sea turtles (*Chelonia mydas*) are a charismatic, long-lived marine species that spends its life cycle both on land and in the ocean. They are an endangered keystone species that requires immediate conservation efforts and more effective management. A distinct population segment (DPS) is the smallest division of taxonomic species that the US ESA can protect (Seminoff et al. 2015). Green sea turtles have populations all over the world and have been divided into eleven DPSs because they are populations of varying physical, physiological, ecological, and behavioral differences (Seminoff et al. 2015). The green sea turtles' discreteness and significance relative to taxon had little influence of national boundaries and jurisdictions, and because of that, some of the DPS borders split countries between DPSs. The eleven DPS were established by the National Marine Fisheries Service (NMFS) and the US Fish and Wildlife Service (USFWS) in 2007 after completing a five-year review of the green sea turtle (Figure 1).

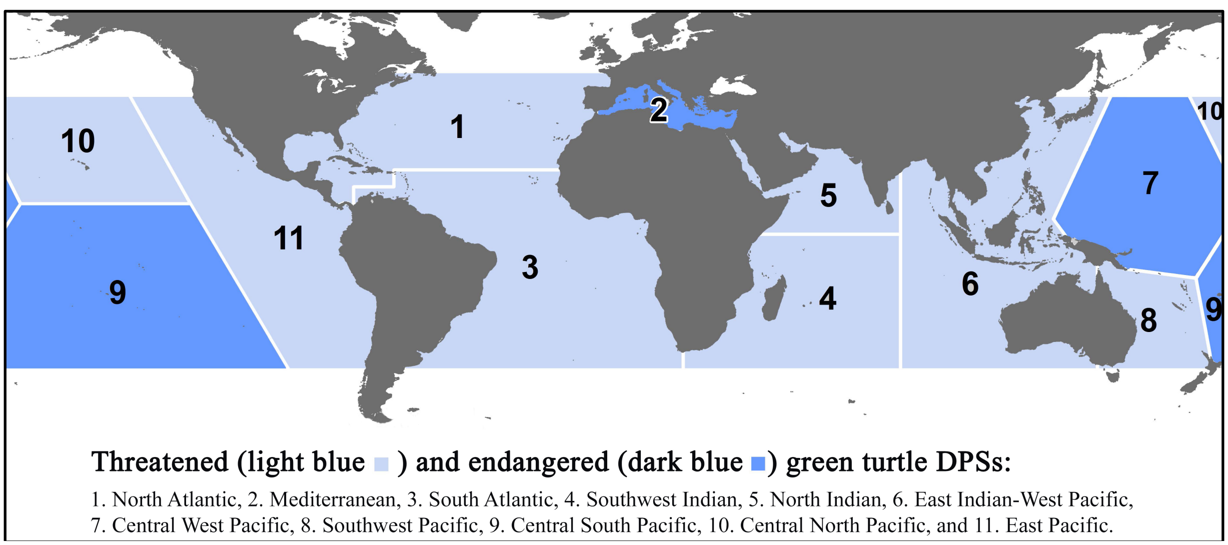

Figure 1. Map of the eleven green sea turtle DPSs (Source: NOAA)

These eleven DPSs are the North Atlantic, Mediterranean, South Atlantic, Southwest Indian, North Indian, East Indian-West Pacific, Central West Pacific (CWP), Southwest Pacific, Central South Pacific, Central North Pacific, and East Pacific. These eleven DPSs were analyzed and assessed, each being given an extinction risk status. The Central South Pacific, CWP, and the Mediterranean are all endangered, and the North Atlantic, South Atlantic, Southwest Indian, North Indian, East Indian-West Pacific, Southwest Pacific, Central North Pacific, and East Pacific are all threatened. These critical assessments were based on six elements: abundance; population growth rate or productivity; spatial structure; diversity and resilience; threats; and conservation efforts (Seminoff et al. 2015). Current climate change poses a major threat to global biodiversity. The extent of the threat, however, is dependent on a species' ability to quickly adapt to changes in their climatic niches. In the last 20 years, there have been over one hundred species extinctions due to climate change. This rate of extinctions is going to continue to increase more rapidly as global warming increases (Weins 2016). Sea turtles, like other species which are threatened by climate change, need to be conserved.

This chapter discusses the ecology of green sea turtles, the role of geographic information systems (GIS) and remote sensing (RS) in studying green sea turtles, and the importance of conservation. It also discusses the thesis study area, thesis goals, and the organization of this thesis. The thesis study area is the CWP DPS. The goal of this thesis is to assess the extinction risk of the CWP DPS under current climate conditions. This was accomplished using Maxent and creating a nesting site habitat suitability model. The thesis is organized in five chapters: this Introduction, Related Work, Methods, Results, and Discussion and Conclusion.

1.1. Ecology of Green Sea Turtles

Green sea turtles are one of seven species of sea turtles. They are the largest hard-shelled sea turtle with adults typically sized at one meter long and weight of approximately 200 kilograms (Seminoff et al. 2015). Their range is extensive. They are present throughout the tropical and subtropical waters, and some populations reside in temperate waters (Figure 2).

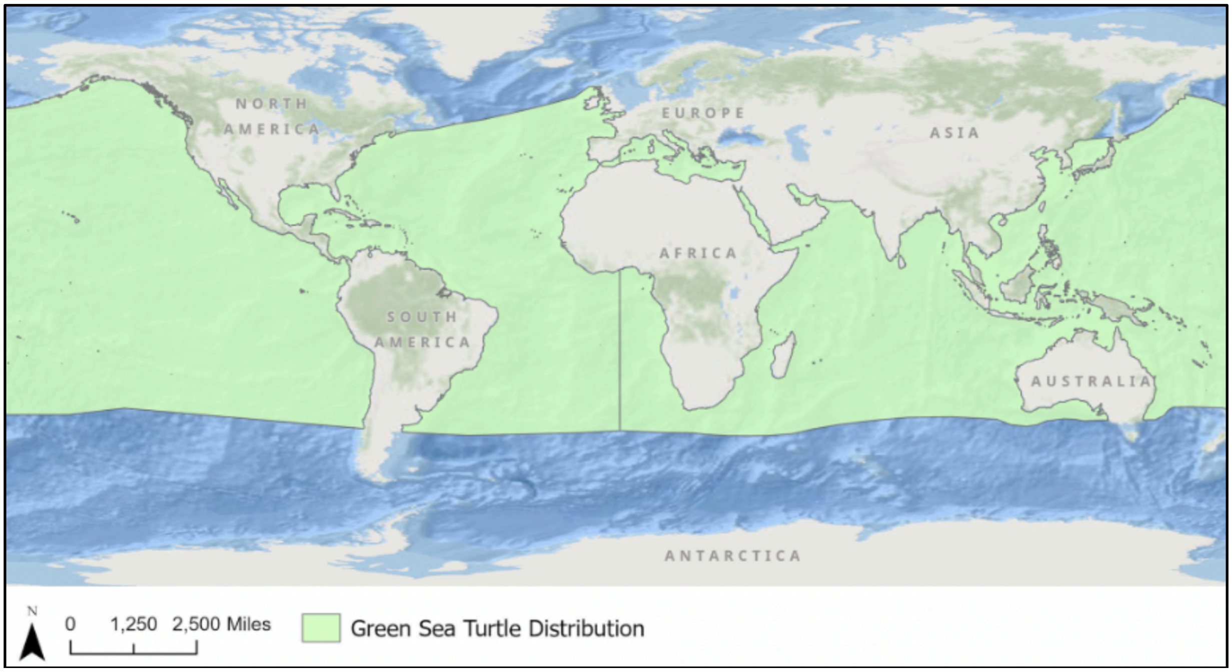

Figure 2. Map displaying the global distribution of green sea turtles (Data Source: SWOT)

Green sea turtles are migratory species, spending most of their adult life moving between nesting beaches and coastal foraging grounds in over 140 countries. These coastal foraging grounds include shallow waters of open coastline and protected bays and lagoons (Seminoff et al. 2015). Adult green sea turtles reach maturity between 15 to 35 years of age and may stay in their breeding cycle for over 30 years (Avens and Snover 2013). The females nest in coastal tropical and sub-tropical regions and lay their clutch of about 100 eggs on sandy shores. They typically lay about six clutches per breeding season and their breeding seasons occur on average every two to four years. However, some females can lay up to ten clutches per breeding season.

The hatchlings typically emerge after the clutch incubates for about 50 days, and then they find their way to the water where they spend several years feeding and growing in pelagic waters (Miller 1997).

The diet of the green sea turtle varies between distinct population segments, as prey abundance varies between geographic locations. Although green sea turtles are generally considered herbivores, the pelagic juveniles often eat plant and animal life. The diet of much of the adult green sea turtles consists of marine algae and seagrasses, but some populations might consume invertebrates like jellyfish, mollusks, and fish (Esteban et al. 2020). Their prey abundance has been negatively impacted by both humans and climate change. Plastic debris, either disposed of directly or indirectly, has been ingested by green sea turtles along numerous coasts, and this can potentially impact growth, development, and fecundity (Santos et al. 2011). Warming of the ocean threatens habitats and food sources, such as coral reefs, because the warmer temperatures cause a decrease in productivity, and less food available leads to decreased nesting activity and fewer sea turtles being hatched, which is a problem for endangered and threatened populations of green sea turtles.

1.2. The Role of GIS and RS

GIS and RS can help to illustrate the temporal and spatial changes of species distributions. They can be used for retrospective monitoring and prospective planning towards the conservation of species by bringing together different types of geospatial data collected from a variety of sensors. The ability to access ecological datasets collected from RS or derived with GIS at varying scales has drastically enhanced the effectiveness and efficiency of ecological research. Detecting and monitoring changes in environmental conditions has been made easier by synoptic perspective which includes space-based and aerial imagery to gather a broader view, temporal frequency, and repeatability of remotely sensed measurements (Miller and Rogan 2007). This data can be used to model species distribution and habitat suitability, along with mapping changes in species and environmental factors.

Sea turtles are a challenge to study as they are a migratory species that utilize an array of habitats throughout their life cycles. Geospatial technologies have been crucial in gathering data for sea turtles, mostly regarding range, habitat use, and nesting locations. Using a combination of satellite transmitter tags and satellite imagery, GIS can be used to create maps that illustrate migration paths, range extent, and nesting locations. These satellite tags are easy to put on sea turtles as they have a relatively large carapace. The tags are usually attached to adult females when they come ashore to lay their eggs (Hays and Hawkes 2018). The satellite transmitter data provides information, such as the turtles' location at different times and speed, which can be studied to assess movement patterns that are important for a migratory species. Web and mobile applications, such as Esri's Collector, QuickCapture, and Survey 123 have been implemented in the data collection process for surveying and assessing species abundance and distribution. Nesting locations can be monitored by collecting GPS locations of individual sea turtle nests each nesting season. This nesting data, if implemented into a database, can display changes in nesting activity over time and illuminate seasonal trends. This data would often include total number of nests deposited, species composition, number of marked nests by kilometers, and the livelihood of the nests deposited. This information gives insight into sea turtle population dynamics and habitat, both of which are important for conservation management.

Predictive models and maps are a great way to illustrate findings from collected data. A model predicting a particular nesting beach loss of nesting habitat under difference scenarios of sea level rise provides information that would be beneficial to assess threat level and types of conservation efforts needed. A microclimate model is also useful to see the influence of climate on a specific species and what requirements are needed for healthy growth, such as soil temperature at key sea turtle nesting grounds (Fuentes and Porter 2013). Finding the range of healthy soil temperatures and what threatens the hatchling sex ratio is useful for conservationists. Species distribution models (SDM), such as Maxent, provide a predicted distribution of species from a set of species presence data and environmental predictors (Fourcade et al. 2014). The predicted species distribution indicates habitat suitability, something that is essential for a population to thrive. GIS can also conduct spatial analyses comparing sea turtle density with activities such as shrimping, and overlay that with species abundance and intensity of fishery activity in a specific region which can provide information on the threat level of bycatch.

1.3. The Importance of Conservation

Plants and animals represent the livelihood of a healthy ecosystem, so when a species population decrease, it is an indication that the ecosystem is degrading. Species are constantly interacting with each other and their environment, so when one species becomes endangered, it can trigger a loss in other species as well (Eklof and Ebenman 2006). This is especially problematic for apex predators and keystone species who have an important role in the ecosystem and where a change in population can cause a variety of direct and indirect effects on humans (Ordiz et al. 2021). Humans are both impacted by endangered species and impact them. Although humans cannot change some past damages, such as light pollution from coastal development affecting baby sea turtles, they can provide and push for effective conservation efforts to keep those endangered species from going extinct, such as creating more prominent natural light sources near the ocean (Thums et al. 2016).

One of these conservation efforts was the creation of the US Endangered Species Act (ESA) which was passed in 1973. The ESA looks at species that have declining populations and through an extensive process determine whether they are threatened or endangered, and if so, they will become "listed". Green sea turtles were just one of many endangered species that were listed under the ESA in the late 1970s (Howell and Shaver 2021). The purpose of the ESA is to protect the listed species by increasing the species abundance and protecting their habitat. However, preventing species from extinction, even if the population remains relatively stable, is important too. Although the ESA has only recovered two percent of the listed species, this number is a poor measure of the act's success because most of the species have not been under protection for a sufficient time required for an expected recovery (Greenwald et al. 2019). To be a recovered species, the USFWS and NMFS has to determine that the species is no longer threatened or endangered through a five-factor analysis looking at abundance and distribution before they can officially delist them from the act (Neel et al. 2012). Each species listed has a recovery plan, and depending on the reproduction and maturity rates, the recovery plans may range anywhere from 20 to 60 years if the species have a relatively short generation time. For example, the average listed bird has been listed and under protection for only 36 years as of 2016, and the federal recovery plan estimates an average of 63 years for population recovery (Suckling et al. 2016). Therefore, the success rate of the ESA should not solely be based on delisting, but rather the percent of species that have populations that are stable or increasing.

Conservation efforts that were put in place between the 1950s and 1980s for specific species are just now making an impact on the population abundance (Kittinger et al. 2013). Some of these efforts include the Indian Wildlife Protection Act of 1972 which banned the export of sea turtles within Indian waters and the addition of sea turtles to the Convention on International

Trade in Endangered Species of Wild Fauna and Flora (CITES) in 1975 which outlaws commercial trade (Donnelly 2011). This means that populations that currently do not have any conservation policies in place or have been unsuccessful in their efforts are at risk of extinction as they do not have 30 or 40 years to recover (Seminoff et al. 2015). We need to put effective policies in place now to help them recover at a faster rate than the negative impacts they are facing from climate change. Education and spreading awareness are the first steps to conserving endangered species, and this paper aims to fulfill that first step.

1.4. Thesis Study Area

The study area is the Central West Pacific DPS boundary (Figure 3). Though green sea turtles are migratory species, they typically stay within their DPS boundaries, and it is rare to see individuals in other DPS. The CWP DPS has its northern boundary at 41°N latitude and is bounded by 41°N, 169°E in the northeast corner, going southeast to 9°N, 175°W, then southwest to 13°S, 171°E, northwest to 4.5°N, 129°E, then north to 41°N, 146°E. The countries and US Territories within the CWP DPS are Federated States of Micronesia (FSM), Republic of the Marshall Islands (RMI), Papua New Guinea, Solomon Islands, Guam, Commonwealth of Northern Mariana Islands (CNMI), Republic of Palau, and Japan's Ogasawara Islands.

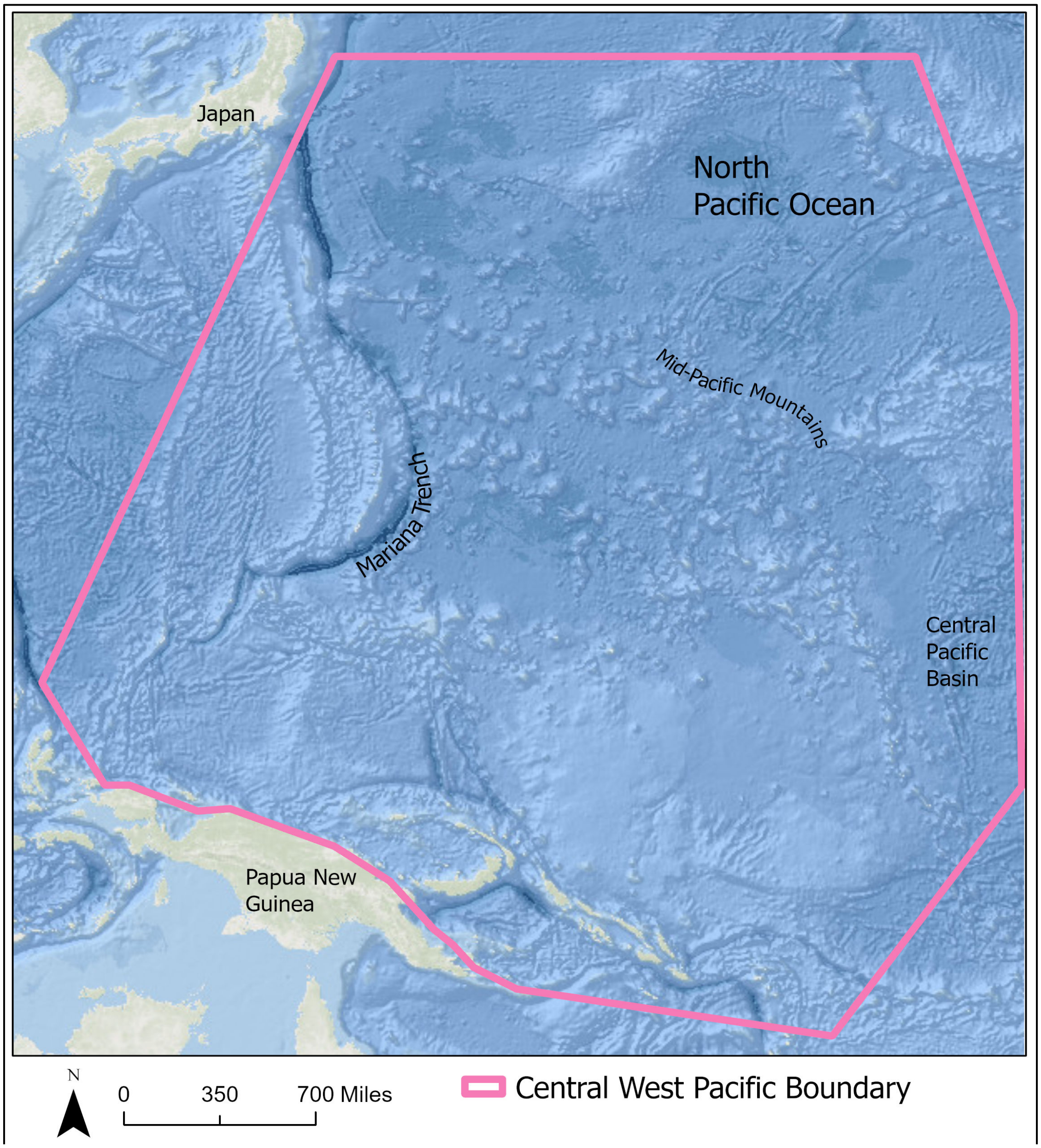

Figure 3. Map displaying one out of the eleven DPS of green sea turtles

FSM has a total of 607 small islands and atolls within four groups of island states: Pohnpei, Chuuk, Yap, and Kosrae (UNDP 2010). RMI has 1,156 individual islands and islets within a total of five islands and 29 coral atolls (World Atlas 2021). Papua New Guinea is the world's third largest island nation consisting of its mainland and 600 offshore islands (World Atlas 2021). It is also host to about six percent of the world's species in only one percent of the world's land area, making it a biodiversity hotspot (Barrows et al. 2009). The Solomon Islands are a wide-spread archipelago of over 900 mountainous, heavily forested volcanic islands and coral atolls, along with six major islands (World Atlas 2021). Guam is the largest and southernmost island in the Mariana Island chain, surrounded by steep coastal cliffs and covered in sandy beaches (Paulay 2003; World Atlas 2021). CNMI has 14 islands, the northern islands are mostly uninhabited due to danger of active volcanism, leaving the majority of the population to reside on Saipan, Tinian, and Rota (Paulay 2003; World Atlas 2021). Palau is a part of the Palauan archipelago and consists of over 300 islands geologically varying from larger volcanic islands to coral atolls to uplifted limestone which are commonly referred to as the "Rock Islands" (Fitzpatrick and Giovas 2021). The Ogasawara Islands are south of the main Japanese Archipelago and have more than 30 islands clustered within three island groups, surrounded by steep coastal cliffs and covered in subtropical forest and shrubland vegetation (UNESCO World Heritage 2011).

1.5. Thesis Goals

This thesis assesses the extinction risk of the endangered CWP DPS with an SDM and an extensive assessment of factors influencing population dynamics. Maxent will be used to create a habitat suitability model of nesting sites under current climate conditions. The assessment of green sea turtle population dynamics includes a literature review of published articles, books, and websites with information on both climate change and green sea turtles, which focuses on factors such as range, nesting, population structure, spatial structure, immediate threats, and conservation efforts. Supplemental information in the forms of graphs, maps, and tables are included. The primary objective is the assessment of the CWP distinct population segment of green sea turtles focusing on how their population and habitat have been impacted by climate change. This population was selected because of their endangered status and that there was sufficient information and data publicly available. From the results of the nesting site suitability model and extinction risk assessment, an opinion will be formed and suggestions for future conservation efforts of the CWP population.

1.6. Thesis Organization

This thesis report includes four additional chapters. The next chapter summarizes related work and starts by discussing the climate assessments from the Intergovernmental Panel on Climate Change (IPCC). The chapter provides robust information on environmental impacts on both land and ocean from climate change that specifically affect green sea turtles, along with a brief analysis of the CWP DPS and the importance of habitat suitability modeling. It also discusses important conservation laws that have been put in place in hopes of increasing the green sea turtle population. Chapter 3 describes the methods and different types of data used in the Maxent habitat suitability model. Chapter 4 describes the Maxent results, including the four Maxent model runs and model performance, and it discusses the nesting site suitability and extinction risk assessment of the CWP DPS. Chapter 5 discusses the significance of the results from the nesting site habitat suitability model and concluding remarks about the thesis and future work.

Chapter 2 Related Work

This chapter discusses climate change assessments on a global scale, environmental impacts of climate change on both land and ocean that affect green sea turtles, a short description of the CWP distinct population segment of green sea turtles, and a discussion on an assortment of conservation laws impacting sea turtles that have been in place since the 1950s. The discussion of climate change and environmental impacts are relevant to this project as the changes and impacts are reflected in the climate data. There is also a discussion of SDMs and habitat suitability models, specifically Maxent and related case studies that use Maxent modeling to assess suitable nesting habitats for green sea turtles.

2.1. IPCC Assessments

Conservationists rely on climate change assessments as significant sources of current and predictive future changes that impact threatened and endangered species, such as green sea turtles. The IPCC, established in 1988, is an organization that conducts climate change assessments on a regular basis, including information of climate change implications and potential future risks (IPPC 2013c). The IPCC has created multiple comprehensive and extensive assessment reports which detail the changes of climate change since the early 1990s and put forth future climate predictions. Their predictive long-term climate change outcomes are based on several Representative Concentration Pathways (RCPs) that make different assumptions based on trends in emission rates (Stocker et al. 2013). These scenarios range from a reduction in current emissions (RCP2.6), leading to a 1 degree Celsius increase in global average temperature by the end of the 21st century, to a ‘no drastic actions’ being taken scenario (RCP8.5) that results in an increase of 3 degrees Celsius global average temperature by the end of the 21st century. The current data suggests emissions are higher than RCP8.5, and without immediate changes by humans, emissions will cause severe negative impacts to the Earth and the species that inhabit it (Nazarenko et al. 2015). Global predictions for changes in land surface temperature, sea level rise, and precipitation events according to the most recent IPCC report are discussed in the following sections.

2.1.1. Global Surface Temperature

The four decades following 1980 were successively warmer at the Earth's surface than any previous decade on record since 1850 (IPCC 2014). This increasing change in temperature impacts the daily lives of species residing on land, such as nesting green sea turtles. An increase in surface temperature can alter the timing of nesting for the breeding females. Increased temperatures also impact green sea turtle prey and may reduce the productivity of species such as seagrass, macroalgae, and invertebrates (Seminoff et al. 2015). The global surface temperature has increased by an estimated 1.09 degrees Celsius since 1900 and is expected to exceed 2 degrees Celsius during the 21st century unless greenhouse gas emissions are deeply reduced. A prominent cause of increase in global surface temperature is from human-caused CO2 emissions, along with the increase in ocean acidification (Church et al. 2013). The years between 2016 and 2020 are the hottest five-year period recorded since at least 1850 (IPCC 2021). Regional temperatures are rising and causing a higher rate of ice loss. This decline in surface elevation from mass loss of the ice sheet increases the surface temperature and leads to additional ice loss. The melting of Antarctica's ice sheet alone has the potential to raise the global sea level by about 4.3 meters (IPCC 2021).

2.1.2. Global Sea Level Rise

The sea level rise caused by climate change has increased erosion on nesting beaches and led to significant habitat loss for green sea turtles (Seminoff et al. 2015). The average rate of the global mean sea level went from 1.3 millimeters per year between 1901 and 1971, to 1.9 millimeters per year between 1971 and 2006, and then further increased to 3.7 millimeters per year between 2006 and 2018 (IPCC 2021). The redistribution of water and ice mass has led to an increase in sea level rise at lower latitudes and a reduction in sea level rise at higher latitudes. This expansion of warming ocean water leads to shifting ocean currents that change the sea level in different locations, creating a difference in local and global sea level averages. (Church et al. 2013). The increase in sea level rise often leads to an increase in coastal flooding in low-lying areas and coastal erosion along most sandy coasts (IPCC 2019), and it is also a driving factor in the increase of storm surges (Church et al. 2013). These hydrological events are wreaking havoc on green sea turtles' coastal nesting beaches. Most of the oceans face an increase in mean regional sea level and green sea turtles reside in those regions. These changes, even if they are less than half a meter, can flood nesting beaches dramatically reducing coastal habitat and population abundance.

2.1.3. Global Precipitation Events

Green sea turtles are susceptible to the impacts of global precipitation events on both land and water. The intensity, frequency, and duration of heavy precipitation events have increased with global warming. At a global scale, for each one degree Celsius of global air temperature warming, precipitation events are projected to intensify by about 7 percent (IPCC 2021). The increase in intensity and frequency of these events, such as tropical cyclones, is associated with cascading impacts. Sea level rise, warming, and extreme climate events have degraded nearly 50 percent of coastal wetlands in the last 100 years (IPCC 2019), reducing the nesting habitats of green sea turtles significantly. The key impacts of climate change that are heavily affecting green sea turtles are the change in temperature, sea level rise, and weather patterns, which the IPCC has reported are increasing at an alarming rate.

2.2. Environmental Impacts on Green Sea Turtles: Land and Ocean

Climate change has been damaging and degrading the land and the ocean for years but is now spiraling at an unprecedented rate that could be hard to recover from (Pettorelli et al. 2021). Although green sea turtles spend most of their lives in the ocean, the females congregate at breeding grounds every few years. These breeding sites are typically located on coastal beaches and are experiencing negative impacts from climate change including sea level rising, increasing sand temperatures, and severe storms. Marine habitats, where sea turtles spend most of their life, are also experiencing negative impacts including sea surface temperature increases, ocean currents alterations which affect their migration and prey, and ocean acidification.

2.2.1. Land: Sea Level Rise

Green sea turtles are one of only a few species that lay their eggs on the shores of sandy beaches. These beaches are often the same beaches where the turtles hatched because green sea turtles have a homing behavior that guides the adult females back to their hatchling beach (Lohmann 2007) . Nesting on open beaches provides little to no protection from climatic changes. The rate of sea level rise has continued to accelerate throughout the 21st century, doubling each year at a pace too fast for species to physically adapt (Lindsey 2021). Coastal communities are already vulnerable to storm surges and coastal erosion; however, sea level rise poses an immediate and serious threat. In many locations across the coasts of the US, high-tide flooding has increased more than 900 percent in the last 50 years (Lindsey 2021). This flooding affects the coastal breeding sites of green sea turtles. A rise of 0.5 meters in sea level can flood up to 32 percent of total beach area available, which would be detrimental to all DPSs (Fish et al.

2005). This increase of sea level reduces the space necessary for nesting and pushes green sea turtles to nest in the intertidal zone which increases waterlogged clutches and decreases the number of viable baby turtles.

2.2.2. Land: Increased Sand Temperatures

Hatching success and sex determination of green sea turtles are dependent on temperature and are highly sensitive to any changes in temperature. Global warming poses a huge threat because warmer sand temperatures can skew sex ratios to be predominately female and decrease hatching success (Fuentes, Hamann, and Limpus 2010). The tolerable range of temperature for successful hatchings are between 26 and 32 degrees Celsius (Seminoff et al. 2015). Sea turtle eggs can withstand some higher temperatures, such as 34 and 35 degrees Celsius, but only for a short period of time (Howard, Bell, and Pike 2014). Hatching success rate decreases the longer the eggs incubate in these higher temperatures. Some beaches may experience lethal incubation sand temperatures, resulting in complete losses of hatchling cohorts. These lethal temperatures are dependent on the longevity of the high temperatures, but anything above 35 degrees Celsius may be lethal and most certainly 38 degrees Celsius and higher is lethal (Howard, Bell, and Pike 2014). Green sea turtle hatchlings time their emergence based on cool subsurface sand temperatures, almost exclusively at night. However, with increasing temperatures, the emergence may be inhibited (Seminoff et al. 2015).

Within the biological tolerance temperature range at which green sea turtles hatch, there is a smaller range known as the ‘pivotal temperature range’ where a constant incubation temperature produces equal numbers of both male and female green sea turtles. This pivotal temperature range is between 28 and 30.3 degrees Celsius (Blechschmidt, Wittmann, and Bluml 2020). Therefore, hatchlings experiencing incubation temperatures outside of this range will have a skewed sex ratio. The lower temperatures produce predominately males, and the higher temperatures produce predominately females (Seminoff et al. 2015). Fuentes, Hamann, and Limpus (2010) model the future sex ratio of green sea turtles and suggests that under an extreme emission scenario, A1T, by 2070 a near complete feminization will occur. This change in sex ratio will cause a massive decline in the overall abundance because of the lack of males to reproduce with the females. Without conservation efforts to protect against rising temperatures on nesting beaches, these populations will be greatly reduced. There is a chance that green sea turtles will adapt to the increased sand temperatures by choosing to have their clutches in cooler locations or by nesting during a cooler season (Hawkes, Broderick, Godfrey, and Godley 2009). However, by the time this evolutionary adaptation takes place, it might be too late for some of the DPS.

2.2.3. Land: Extreme Weather Events

Extreme weather events, such as hurricanes and tropical cyclones, are another impact of climate change that are affecting green sea turtles. These weather events have increased in both frequency and intensity since the mid-1970s, mostly due to an increase in sea surface temperature changes (Hoyos et al. 2006). The global occurrences of storm disasters have increased since 1950 and have been heavily impacting the coasts of the US (Figure 4). Tropical cyclones in the Pacific Ocean, often occur later in the year between July and November (NOAA 2021). Green sea turtles have a higher chance of being affected than other sea turtle species because their peak nesting season is later in the year, increasing their chances of being impacted by tropical cyclones (Mortimer 2002). The eye of a tropical cyclone when passing through islands interact multiple times with the coastline, increasing beach erosion rates and flooding which further endanger green sea turtle nesting habitats (Marler 2014). In the past few centuries, green sea turtles have been able to buffer these extreme weather events because of their large populations and geographically widespread nesting (Van Houtan and Bass 2007). However, the increasing rate of climate change is degrading nesting beaches and coastal areas at a faster rate, leaving behind little habitable land. This is especially problematic for the populations that rely and live on only a few small islands (Marler 2014). If these beaches are significantly reduced, the clutches will be reduced, and thus their populations will be reduced. As of 2021, green sea turtles do not have the luxury to evade or adapt to the climate change rate and conservation efforts need to be increased to combat the rise of extreme weather events from climate change.

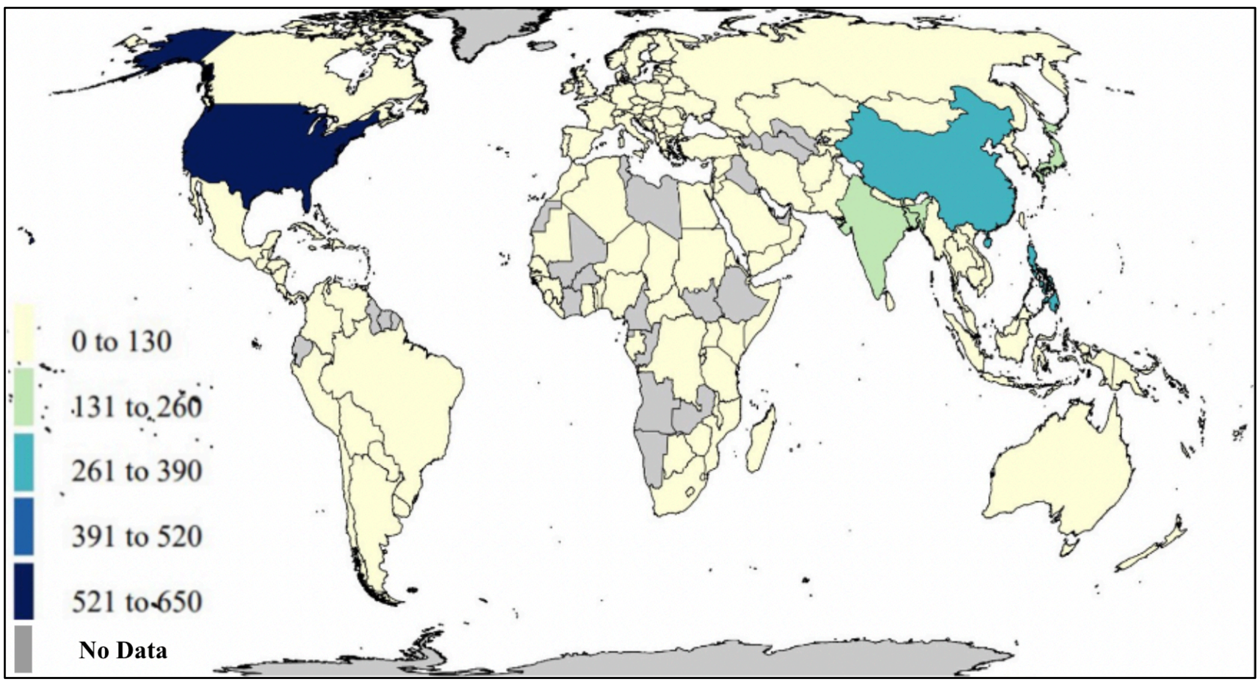

Figure 4. Map of global numbers of storm disasters between 1950 and 2020 (Source: EM-DAT)

2.2.4. Ocean: Increased Sea Surface Temperature

The ocean is where most juvenile and adult green sea turtles spend their lives, and it is not immune to the impacts of climate change. The average global sea surface temperature has increased by about 0.64 degrees Celsius over the last 50 years, and predictive modeling shows a steady increase that is likely to continue through the 21st century (Reid et al. 2009). These temperature changes alter marine ecosystems in numerous ways, such as plants and animals becoming stressed and declining in abundance, changing migration and breeding patterns, and threatening habitats such as corals and seagrass beds, all of which affect green sea turtles (Esteban et al. 2020). The increase of sea surface temperature, whether it is a small or large change, whether it is at a regional or global scale, will create negative impacts and may cause irreversible damage.

2.2.5. Ocean: Changed Ocean Circulation

Rising sea surface temperatures affect the speed and the direction of ocean circulation, and have had alarming changes in the tropics, where most green sea turtles reside (Ramirez et al. 2017). Changes in ocean circulation affect migratory patterns and prey abundance for all stages of the green sea turtle (Hays 2017). Newborn sea turtles follow oceanic currents to seek their nursery habitats, and if the currents are too strong for them, they must stay in their breeding areas until they have the strength to swim against them. Adult green sea turtles that are in the reproductive part of their life cycles, migrate between nesting beaches and feeding areas, but strong currents could cause navigational challenges for them (Luschi, Hays, and Papi 2003). In the last couple decades, the rising ocean temperatures have caused some currents to strengthen, causing an increase in recorded turtle mortality in juveniles and adults (Poloczanska, Limpus, and Hays 2009).

The prey abundance, specifically planktonic prey, is affected by both warming sea temperatures and oceanic circulation patterns. The warm sea surface temperatures increase the divide between the water column, causing the waters to become more nutrient poor which reduces the productivity of plankton. The changes in the ocean currents can shift the plankton regions, changing the turtles' traditional foraging grounds (Poloczanska, Limpus, and Hays 2009). When prey abundance decreases, green sea turtles may not be able to reach their energy reserves needed for reproduction and will have to increase their migration intervals to find enough food which will reduce their reproductive lifetime (Patrício et al. 2021).

2.2.6. Ocean: Acidification

Coral reefs, a critical habitat of green sea turtles, are being impacted by ocean acidification. Ocean acidification is caused by the reduction of pH in the ocean from the uptake of carbon dioxide from the atmosphere (Wood, Spicer, and Widdicombe 2008). Corals are made up of a calcium carbonate skeleton, and rely on their skeleton to keep them strong and healthy. The change in pH levels from ocean acidification decreases the elements needed for a healthy calcium carbonate skeleton, thus weakening their structures, making them more fragile and less useful for the ecological services they provide (Pandolfi, Connolly, Marshall, and Cohen 2011). This density reduction of coral structures leaves them more vulnerable to erosion through events such as excessive grazing and extreme storms. The increase of carbon dioxide can decrease coral calcification and growth by up to 40 percent affecting the structure and abundance of the coral reef. The reduction in their structural complexity will have a cascading effect, leading to a decline in habitat and biological diversity, along with some key prey of the green sea turtles (Hoegh-Guldberg et al. 2007). Some of these coral reefs are 200 million years old and are experiencing coral bleaching and other degradation at a rate that may make them extinct. Ocean acidification also decreases the availability of key nutrients, which impacts the abundance of prey such as plankton, as well as seagrass productivity (Patrício et al. 2021).

2.3. The CWP Green Sea Turtle DPS

The CWP DPS nesting and foraging areas are not highly concentrated in one area, but more spread out, providing some habitat-use diversity and population resilience. However, with more habitats in use, the risk of threats at each habitat increases (Seminoff et al. 2015). Its boundary is mostly open ocean from Micronesia to the Ogasawara Islands, Japan (Summers et al. 2018). The green sea turtle nesting grounds are fairly isolated, with a few popular locations in Gielop and Iar Island, Ulithi Atoll, Yap, and Chichijima. The adult green sea turtles typically forage around Guam, and juveniles in the Marianas Archipelago (Seminoff et al. 2015).

The region of the CWP DPS is well known for green sea turtle exploitation and trade, despite the fact that the harvest of sea turtles and eggs is illegal under the ESA (NMFS, NOAA, and USFWS 2016). Poaching of green sea turtle eggs and female nesters is currently the largest threat to the nesting population of green sea turtles in the CNMI and in Guam (NMFS, NOAA, and USFWS 2016; Summers et al. 2018). With the limited nesting data available, there is a decreasing trend in population and abundance in RMI and the CNMI (Seminoff et al. 2015). As noted above, the widespread nesting sites provide some habitat diversity and population resilience, but not a significant amount because of the threats faced by each individual nesting site. One climatic impact that has already caused problems for the current generation of green sea turtles is the increased temperature at nesting beaches in the CNMI. A 2018 survey concluded that this specific island population is female biased due to the warmer temperatures changing the sex ratio of the hatchlings (Summers et al. 2018). This is one of many populations that are already experiencing climate change impacts and where conservation efforts need to be in place to avoid loss of biodiversity and a lengthy recovery time. The severity of such climate change impacts on habitat suitability can be modelled for individual species for both current and future climate scenarios.

2.4. Species Distribution Models

SDMs are models that use a combination of observations of species occurrence or abundance with environmental data to gain ecological and evolutionary insights and to predict species distributions across landscapes (Elith and Leathwick 2009). The field of species distribution modeling has expanded immensely in the last few decades with advances in techniques, technical capabilities, and an enormous increase in abundance of data available (Kalinski 2019). SDMs can be developed using a few different algorithms including heuristic models such as BIOCLIM, statistical models such as generalized additive modeling, combinatorial optimization such as genetic algorithm for rule-set production, and machine learning such as Maxent (Sinclair et al. 2010). SDMs are powerful and prevalent tools (Kalinski 2019), revealing biogeographic patterns and helping find suitable sites for species. SDMs provide some information on the relationship between species and their environment, but the addition of a habitat suitability model will reveal sufficient information needed for a conservation of species.

2.4.1. Habitat Suitability Models

Habitat can be defined as the resources and conditions available in an area that support survival and reproduction by a given organism (Kirk et al. 2018). Habitat suitability can be defined as the capacity of a habitat to support a selected species based on the bioclimate and biophysical variables measured (Kellner, Brawn, and Karr 1992). The habitat is suitable when it can support survival and reproduction of the species, providing elements such as food, water, cover, and space (Yarrow 2009).

There are a few different methods to model habitat suitability, such as boosted regression tree, random forest, and maximum entropy (Rowden et al. 2017). Maximum entropy (Maxent) is a common one used with species distribution. Maxent is a sophisticated approach to modeling a species' geographic distribution and can generate probabilistic habitat suitability analyses at a spatial and temporal extent from presence only species data (Bissell 2013; Phillips, Dudik, and Schapire 2004). The use of presence only data as opposed to other models that require both species presence and absence data, has made Maxent increasingly popular as large presence only datasets have become more widely available (Phillips and Dudik 2007). Maxent can determine the density of a species within its habitat or predict suitable areas outside of its current habitat. Modeling habitat suitability is essential for determining current and potential suitable habitats for threatened and endangered species, such as sea turtles. A few case studies have been completed using Maxent to model nesting habitat suitability of individual species or all the species of sea turtles.

2.4.2. Maxent Modeling of Sea Turtle Nesting Habitats

The first case study (Pike 2013) uses Maxent to predict potential spatial distributions of nesting of all seven species of sea turtles along coastlines world-wide. The species presence data was georeferenced nesting beach locations for all seven marine turtle species which was acquired by a compilation of existing datasets. The climate data was a selection of nine out of the 19 bioclimatic variables from WorldClim. The nine used in this study were independent predictor variables of mean diurnal range in temperature, isothermality, maximum temperature of the warmest month, annual range in temperature, precipitation seasonality, precipitation of the wettest quarter, precipitation of the driest quarter, precipitation of the warmest quarter, and precipitation of the coldest quarter (Pike 2013). These variables were selected because of their biological importance to successful sea turtle reproduction because variation in temperature and moisture strongly influences the viability of eggs, and air temperatures correlate with nest temperatures (Pike 2013). The climate variables downloaded from WorldClim were of current climatic conditions which were averaged over the period 1950-2000 and consisted of grid cells at a 4 kilometers x 4 kilometers spatial resolution at the equator (2.5 arcmin). Pike clipped the climate data to be within eight kilometers of the ocean to reduce the influence of terrestrial environments on model performance, as sea turtles only nest along the coastline. The results from Maxent indicated a predicted distribution of sea turtle nesting habitat under current climate conditions for each of the seven species. The habitat suitability was divided into four quantiles: marginal, moderate, good, and excellent. This study looked at the niche overlaps between the different species of sea turtles, identified species nesting hotspots, and discussed the link between current geographic patterns of nesting and climate and the impact of regional or global changes in environmental conditions on the distribution of the species (Pike 2013).

A second case study, also performed by David Pike (2014), used Maxent to model sea turtle nesting distribution of just the loggerhead species under current and predicted future climate scenarios. His focus was the comparison between temperate and tropical hatching success of the loggerheads. The species presence data for this case study was only nesting sites for loggerheads, but the climate variables from WorldClim remained the same as his previous study. The future climate data was a combination of four climate change models (Canadian Centre for Climate Modelling and Analysis, Commonwealth Scientific and Industrial Research Organisation, Hadley Centre for Climate Prediction and Research, and National Institute for Environmental Studies) under three emission families (A1, A22A, and B2A) which encompassed the central 80 percent of predicted climate change for 2020, 2050, and 2080 (Pike 2014). The results from the study indicate that the loggerhead populations in the tropics produce nearly 30 percent fewer hatchlings per nest than those in temperate populations, suggesting a strong correlation between empirical hatching success and habitat quality. However, only 26.6 percent of loggerhead nesting beaches are in the tropical latitudes (Pike 2014). The results of the habitat quality, generated using Maxent relationships between temperature and precipitation, explained most of the variation in hatching success among the different populations of loggerhead sea turtles globally (Pike 2014). Understanding the role and effect of temperature and precipitation on sea turtles under the current climate conditions and predicted future climate condition is an effective way to prepare for the ecological effects of the changing climate.

A third case study used Maxent to model loggerhead, green, and leatherback turtle nesting site range to current and future climate threats (Fuentes et al. 2020). The study area was the nesting grounds along the USA coastline. The study used the same nine bioclimatic variables as the Pike studies, along with the Relative Exposure Index variable and looked at habitat suitability of current (2010-2014) and future (2050) climatic conditions. The future climate data that was downloaded from WorldClim included the nine bioclimatic variables for five different global climate models within the RCP 4.5 scenario for the 2050 period (average for 2041-2060) from CMIP5 multi-model ensemble simulation. The RCP 4.5 scenario was chosen, instead of the 2.6, 6.0, and 8.5, because it captures a conservative scenario for the likely amount of climate change for the 2050s (Fuentes et al. 2020). The Maxent results of nesting habitat suitability were displayed at very high-high-medium-low-not suitable and indicated that the loggerhead, green, and leatherback turtles are expected to lose 78-81 percent of climatically suitable nesting, specifically due to sea-level rise (Fuentes et al. 2020). Although marine turtles may try to adapt by changing the distribution of their nesting grounds and nest depth, adjust their pivotal temperature, or nest in cooler months, it is important to conserve what climatically suitable nesting they currently have. There may not be a lot that can be done about the climatic threats, but in considering non-climatic threats, such as coastal development, conservation efforts should seek to create laws that protect the suitable nesting habitat from development or other construction.

2.5. Conservation Laws

Green sea turtles are a migratory species and are distributed globally. This ecological trait makes it difficult to put conservation frameworks in place because they must involve collaboration between many nations to be successful. Active monitoring and protection from government and other agencies is essential to provide the necessary safety on nesting beaches and in foraging grounds to encourage success throughout all the green sea turtle life cycles. Without continuous enforcement of conservation laws, green sea turtles are likely headed towards extinction.

The US granted green sea turtles protection under the ESA in 1978 (Seminoff et al. 2015). They were listed because of overexploitation for commercial and other purposes, the lack of adequate regulatory mechanisms and effective enforcement, evidence of declining numbers, and habitat loss and degradation (NMFS and USFWS 1998). The ESA prohibits the harassment or killing of protected species and requires a recovery plan for each listed species. However, that did not yield the recovery needed, especially for the populations of green sea turtles in the Atlantic. In 1991, a recovery plan was put into place for the US population of Atlantic green turtles, and within seven years, two more recovery plans were established for the US Pacific populations of the green turtles and the US Pacific populations of the East Pacific green turtles (Seminoff et al. 2015).

In the early 2000s, the NMFS became responsible for sea turtles in the ocean, and the USFWS was given jurisdiction over them on land. Congress passed the Marine Turtle Conservation Act (MTCA) in 2004 which gave the USFWS an international leadership role in over 30 countries. An international leadership role is important because, as migratory species, green sea turtles often migrate hundreds of miles through different national jurisdictions to go from their foraging grounds to their breeding grounds annually. The Convention on the Conservation of Migratory Species of Wild Animals (CMS) was established in 1979, and its goal is to provide safe passage and conservation of terrestrial, marine, and avian migratory species throughout their ranges. Although, there are not any stringent participation requirements for party states, the CMS has facilitated the creation of over 100 "action plans" that have helped stabilize populations of migratory species, such as the Wadden Sea seals (Hensz and Soberon 2018).

Green sea turtles have been heavily exploited for their meat and eggs and continue to be hunted in multiple countries within the Pacific Ocean, and specifically within the CWP DPS. The MTCA has set laws and objectives to help alleviate the pressures the turtles face from exploitation, and to also support long term studies to assess potential effects of climate change on the green sea turtles (US Fish and Wildlife Service 2011). The Convention on International Trade in Endangered Species (CITES) has put all the sea turtle populations under protection from international trade by all countries that have signed the treaty (Seminoff et al. 2015). As of 2021, there are 183 countries that are participating members of CITES, leaving twelve countries that are unsigned (Foster and Vincent 2021). Though this is a start, almost half of those unsigned countries are in Oceania, where the endangered CWP DPS green sea turtles reside. They are just one of many threatened and endangered species that are vulnerable living within those unsigned countries.

Chapter 3 Methods

This project assesses the risk of extinction of the CWP DPS by first constructing an SDM of the nesting site locations and then using the results of the model to conduct an extensive critical assessment of the population status. The construction and implementation of the SDM is described in this chapter and the results are assessed in the following chapter. The following sections of this chapter describe: the research design for constructing the SDM using Maxent; selection of environmental variables used in the SDM; data employed; data processing; and steps employed to run a series of models in Maxent and select the most appropriate output.

3.1. Research Design

The method implemented in this thesis is to assess the extinction risk of the CWP DPS with a SDM, using current climate data and green sea turtle nesting sites (Figure 5). Multiple datasets were used in the SDM and are described in further detail in the next section. These datasets were prepared and processed in ArcGIS Pro to match the data input specifications needed for Maxent and are described in further detail in section 3.3. The study area for this project and for Maxent is the CWP DPS and is described in further detail in section 3.4. Before running the Maxent model, the selection of environmental variables must be determined, and the process is described in section 3.5. Finally, the running of Maxent models and the creation of habitat suitability maps are described in section 3.6.

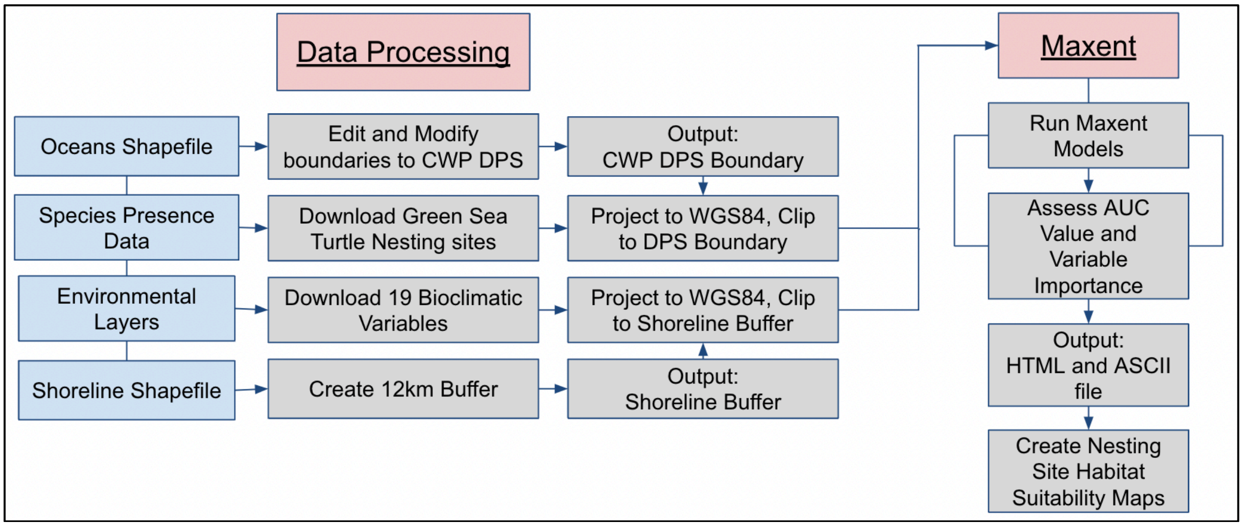

Figure 5. Overview flowchart for creating the CWP DPS SDM using Maxent

3.2. Data Description

All data used in this project were obtained from free and open sources online. These data sets are summarized in Table 1 and described in more detail in the following subsections.

Table 1. Data used in the CWP DPS SDM

Name	Purpose	Edits Required	File Type	Source
Green Sea Turtle Nesting Beaches	Nesting Beaches	• Selected only the *Chelonia mydas* data • Clipped data to be within certain DPS'	Point Shapefile	The State of the World's Sea Turtles (SWOT)
Pacific Ocean	DPS boundary	• Downloaded the North and South Pacific Ocean • Combined to Pacific Ocean and then modified the CWP for the DPS boundary	Polygon Shapefile	Marine Regions
19 Bioclimatic Variables	Environmental data for Maxent	• Downloaded and manipulated data for both current climate conditions • Clipped data to be within 4 km of shorelines on both sides within certain DPS'	GeoTIFF	WorldClim – Global Climate Data
Coastline/Shoreline	Buffer for Maxent	• Downloaded at high resolution the boundary between land and ocean • Created a 6 km buffer on both sides of the shoreline	Polygon Shapefile	NOAA

3.2.1. CWP DPS Boundary

A CWP DPS boundary layer was needed to clip all the data to be within its extent, however, after scouring the internet, there was no boundary layer to be found. A boundary layer was then created in ArcGIS by editing an ocean shapefile. The "Global Oceans and Seas v01" dataset was downloaded from the Marine Regions website which was composed by the Flanders Marine Data Centre. The dataset represents the boundaries between the 10 main oceans and seas: Artic Ocean, North and South Atlantic Ocean, North and South Pacific Ocean, Southern Ocean, Indian Ocean, Baltic Sea, Mediterranean Region, South China and Eastern Archipelagic Seas.

3.2.2. Environmental Layers

Maxent requires raster layers that describe the environmental conditions of the species within the study area. The environmental layers can be drawn from any source. A few popular choices, especially for bioclimatic variables, are CHELSA, DayMet, PRISM, and WorldClim (Helliwell and Chapman 2013; Sadoti et al. 2020). WorldClim is often preferred because of its rich set of climate variables and high resolution datasets, but has limitations with certain topographical situations, such as mountainous regions (Kalinski 2019). However, sea turtles nest on coastal beaches, so this topographical issue is not relevant for this project. WorldClim provides historical climate data, historical monthly weather data, and future climate data. The historical climate data, which includes averaged data from 1970-2000, is the only current data available and was used in this project. The environmental data is available at four spatial resolutions: 30 seconds, 2.5 minutes, 5 minutes, and 10 minutes. WorldClim's 19 bioclimatic variables were used in this project, as they have been used in previous sea turtle Maxent studies (Pike 2013; Pike 2014). Their bioclimatic variables were derived from monthly temperature and rainfall values and were generated to create more biologically meaningful variables. These variables represent annual trends, seasonality, and extreme or limiting environmental factors. For this project the 19 bioclimatic variables were downloaded from WorldClim at the 30 second spatial resolution (~ 1 kilometers squared), variables known as Bio1 through Bio19 as a single GeoTIFF file (Table 2).

Table 2. WorldClim Bioclimatic Variables (WorldClim - Global Climate Data)

Bioclimatic Variable Code	Bioclimatic Variable
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (x100)
BIO4	Temperature Seasonality (standard deviation x 100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

3.2.3. Shoreline Buffer

The shoreline data layer used to create the buffer was from the Global Self-consistent, Hierarchical, High-resolution Geography Database from NOAA. The polygon data layer was organized into four levels: boundary between land and ocean, boundary between lake and land, boundary between island-in-lake and lake, and boundary between pond-in-island and island, and displayed in five resolutions: crude, low, intermediate, high, and full. The specific shoreline data layer that was used in this project was downloaded at high resolution and was organized as the boundary between land and ocean.

3.3. Data Processing

The data required a significant amount of preparation and processing before meeting the requirements to be successfully employed in Maxent. A DPS boundary and shoreline buffer needed to be created as they were used in the process of preparing the species presence data and environmental data layers to be Maxent ready.

3.3.1. Choice of Coordinate System

Ideally, a projected coordinate system (PCS) and geographic coordinate system (GCS) would have been established for all the data layers. However, because of the scale of the study area, a PCS was not useful. The CWP DPS, as it says in its name, is in the central part of the west Pacific Ocean, covering both the North and the South Pacific Ocean. Because of the location and the size of the boundary, the CWP DPS was too large for a PCS to display the results without significant distortion throughout its area. Therefore, only a GCS was established for all of the data layers and WGS84 was selected because the green sea turtle data was originally in this coordinate system.

3.3.2. Creation of the DPS Boundary

The CWP DPS boundary shapefile had to be created from scratch. The "Global Oceans and Seas v01" dataset was downloaded from the Marine Region website and then uploaded into ArcGIS Pro. The dataset contained all the oceans and seas globally in WGS84 as polygons. Only the Central West Pacific was needed for this thesis, so the *Select by Attribute* tool was used to select only the North and South Pacific Ocean from the attribute table and then was exported to create a new feature class polygon. From this new feature class of the combined Pacific Ocean shapefile, the boundary was modified and reshaped to the coordinates of the CWP DPS according to Seminoff's 2015 Status Review.

3.3.3. Creation of the Shoreline Buffer

The geographic extent used in Maxent was the CWP DPS boundary, but as Pike (2013) notes, sea turtles only nest along the coastline. Therefore, following the prior literature, a buffer was used to reduce the impact from mainland climate, (e.g. Guo 2014; Pike 2013; Pike 2014). The buffer was created using the *Buffer* tool and the shoreline polygon layer. Although the prior studies used an eight-kilometer buffer (four kilometers on either side of the shoreline), a twelve-kilometer buffer was chosen for this project to account for the relatively low resolution of the shoreline layer. At this width, the buffer encompassed all but one CWP nesting location. Figure 6 displays a portion of the CWP DPS featuring the shoreline data layer, the CWP DPS nesting locations, and the twelve-kilometer buffer.

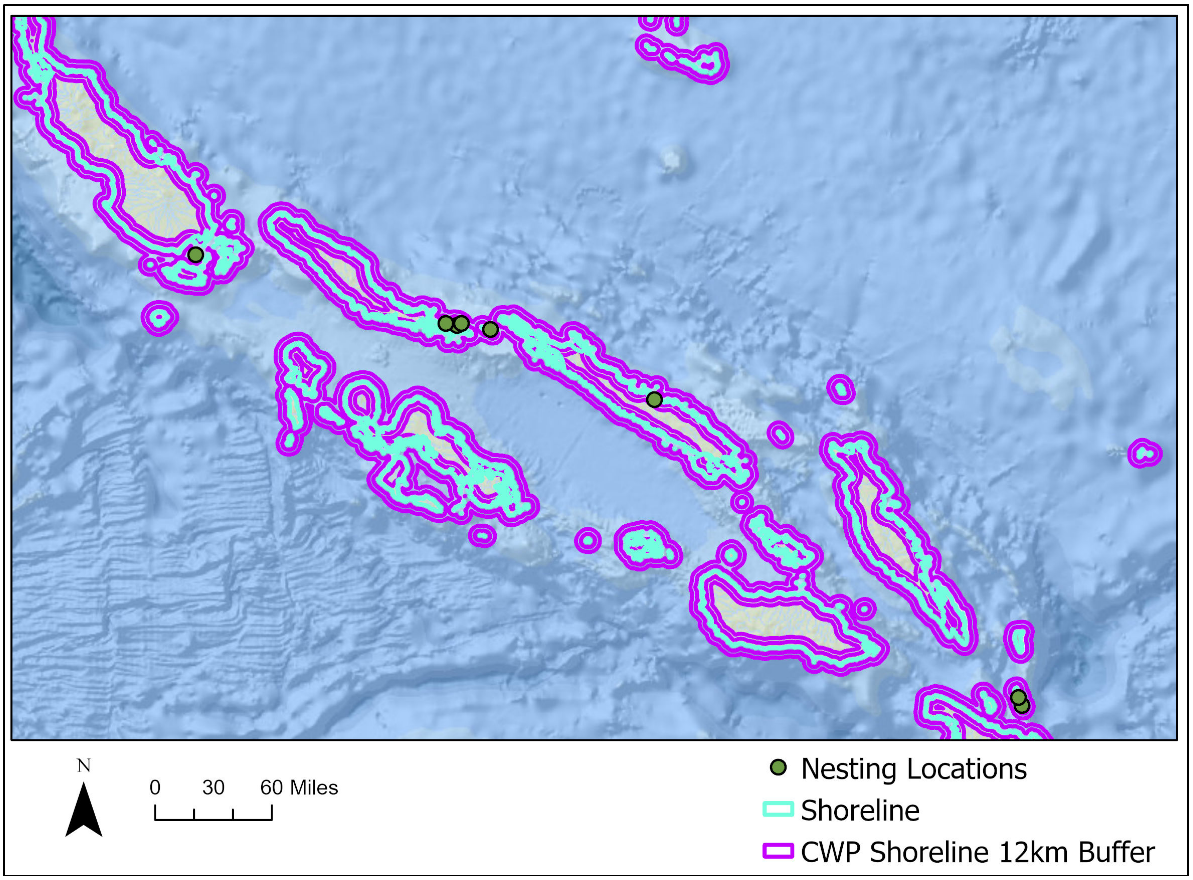

Figure 6. Map displaying a selection of the CWP shoreline, buffer, and nesting locations

3.3.4. Preparation of Species Presence Data

The species presence data consisted of georeferenced nesting site locations of the green sea turtle downloaded from the State of the World's Sea Turtles (SWOT) website. SWOT has an interactive map and database of sea turtle biogeography hosted and maintained by Duke University's OBIS-SEAMAP, the International Union for Conservation of Nature (IUCN) Marine Turtle Specialist Group, and an international team of hundreds of local organizations, scientists, and conservationists (Guo 2014). This database has thousands of data records that have been contributed worldwide and sourced from published literature, including sea turtle nesting data, satellite telemetry data, species distributions, genetic data, and more. The global nesting beaches data for all species of sea turtles was downloaded from SWOT as point shapefiles and were uploaded into ArcGIS Pro and displayed with WGS84 as their geographic coordinate system. Only the green sea turtle data was needed for this thesis, so the *Select by Attribute* tool was used to select only the green sea turtle data from the attribute table from both shapefiles and then was exported to create new feature class polygons.

The original datasets included 2,618 records from 340 contributors of nesting site locations globally for the green sea turtles between 1970 and 2021. However, only 1,568 nesting site locations were available for public download. These nesting site locations were then uploaded into ArcGIS Pro and thoroughly examined. Duplicate records and incomplete data points were removed. The attributes of these nesting site locations included the site name, country, years monitored, and geographic coordinates (in WGS 1984) for each nesting site location. Individual nest count data for each nesting site was shown online but was unavailable to be downloaded by the public without special permissions. The nest count data was not necessary for Maxent but would have been beneficial for assessing the popularity of each individual nesting site. For this project, only the nesting site locations located within the CWP DPS were required, so these nesting site locations were clipped in ArcGIS Pro to be within the CWP DPS boundary. There were 101 out of the original 1,568 nesting site locations that were within the CWP DPS boundary. This was a sufficient number of presence data as Maxent performs well with limited presence data, especially with sample sizes greater than 50 (Kalinksi 2019).

For the CWP DPS, the 101 nesting locations within the boundary were exported from ArcGIS Pro into an Excel document where excess attributes were removed, leaving only the name of the species, and the latitude and longitude coordinates of each nesting location. This edited document was then saved as a comma-separated values (CSV) file as Maxent requires the biological data to be in CSV format with the data organized under the column headers of species, longitude, and latitude.

3.3.5. Preparation of Environmental Layers

Environmental raster layers must have the same cell size, geographic extent, and geographic coordinate system to function properly in Maxent. The chosen cell size of the WorldClim data was easy to determine as it had to be the smallest cell size, which happened to be the annual mean temperature (Bio1). Bio1 had a cell size of 0.83 kilometers squared in the center of the CWP DPS. The geographic extent was to be within the previously described twelve-kilometer shoreline buffer with the CWP DPS.

Preparation of the WorldClim data was executed in ArcGIS Pro using the *Extract by Raster* tool within the *Spatial Analyst* toolbox. Each layer was individually processed to have the same cell size as Bio1, the smallest cell size, the same extent as the 12 kilometer shoreline buffer, and the same geographic coordinate system, WGS84. These raster layers were then converted to ASCII format with the *Raster to ASCII* tool within *Conversions* tools, and the resulting .ASC files were used in Maxent.

3.4. Selection of Environmental Variables

To decide which of the 19 bioclimatic variables from WorldClim to include in the model, research from previous case studies determined that the mean diurnal range (Bio2), isothermality (Bio3), maximum temperature of warmest month (Bio5), temperature annual range (Bio7), precipitation seasonality (Bio15), precipitation of wettest quarter (Bio16), precipitation of driest quarter (Bio17), precipitation of warmest quarter (Bio18), and precipitation of coldest quarter (Bio19) were ideal for sea turtles, out of the 19 bioclimatic variables from WorldClim. These nine environmental variables were chosen as they provided the maximum climate information, while avoiding strongly correlated variables (Pike 2013; Pike 2014; Fuentes 2020). They also have biological importance to successful sea turtle reproduction because temperature and moisture are strong influences on eggs and nests (Table 3).

Table 3. Climate change impacts of the nine bioclimatic variables

Bioclimatic Variables	Influencing Climatic Factor	Impact on Sea Turtles	Climate Change Impact
Bio 2, 3, 5, 7	Temperature	• Determines sex (high temperature female dominant) • Thermal tolerance range (high temperature lethal to eggs)	• Increased temperature
Bio 15, 16, 17, 18, 19	Precipitation	• Eggs exposed to erosion and sand deposition • Inundation of eggs • Reduced nest temperature increases incubation time	• Increased storm frequency and intensity • Increased moisture

3.5. Maxent Model

The nine previously mentioned bioclimatic variables were initially used in the Maxent model, and multiple runs were needed to remove variables that had 0 permutation importance for the green sea turtles in the CWP DPS.

3.5.1. Maxent Model Settings

The Maxent settings used for these model runs were mostly default parameters and constraints (Table 4). To better understand Table 4, the number of species presence data refers to the presence only data of the green sea turtles in the CWP DPS, the regularization multiplier of 1 is a smoothing parameter, where the larger number increases the amount of smoothing. The fewer maximum number of background points that are assigned will give a larger probability of presence to each cell (Kalinski 2019). The replicate option can be used to conduct multiple model runs for the same species, however that was not necessary for this project. The maximum number of iterations allows the model to have more or less time for convergence to properly predict the relationships (Kalinski 2019; Phillips 2017). The raw output was selected as it produced an easy to interpret result.

Table 4. Maxent model parameters and constraints for the CWP DPS.

Model Parameters and Constraints	Value
Number of species presence data	101
Regularization multiplier	1
Maximum number of background points	10,000
Number of replicates	1
Maximum number of iterations	500
Output format	Raw

The Maxent model settings that were used for these trials included response curves, make pictures of the prediction, create a Jackknife graph, select auto features, and a raw output in ASC file format. The response curves were selected because it generated response curves that allowed assessment of how each environmental variable affected the model. The make pictures of prediction were selected to provide an immediate visual representation of where the Maxent model thought the green sea turtle nesting sites would be most to least suitable. The Jackknife test graph generated alternate estimates that indicated and identified variables that are most important within the model (Phillips 2017). Feature classes in Maxent are the mathematical transformations used on a variety of covariates to create the model's distribution surface and are assigned based on the species location count. Maxent assigned a combination of all 5 feature classes: linear, quadratic, product, threshold, and hinge as the species location count exceeded 80 (Kalinski 2019). A regularization multiplier of 1, which was default, was suggested and used (Fuentes et al. 2020; Phillips and Dudik 2008). The output format for Maxent models have three different formats: raw, cumulative, and logistic. The raw format is simply the Maxent exponential model itself (Phillips 2017), which was recommended when possible, and is useful for comparing different models for the same species (Merow et al. 2013). The indicators for which combination of bioclimatic variables to use for the final Maxent model was the AUC value which assessed the predictive accuracy of species distribution and the Jackknife test, which evaluated variable importance (Guo 2014). The AUC curve measures the model's ability to differentiate between background points and species presence locations (Kalinski 2019).

3.5.2. Maxent Model Runs

The first Maxent run included only the nine bioclimatic variables used in the Pike studies: Bio2, Bio3, Bio5, Bio7, Bio15, Bio16, Bio17, Bio18, and Bio19. The highest valued variables were Bio17, Bio2, Bio3, Bio5, and Bio7 which had a 29.5, 23.8, 17.6, 11.8, 7.9 percent contribution and 11.5, 0.3, 21.3, 19.5, 37.3 permutation importance respectively. Bio18 had a percent contribution of 1.9 but a permutation importance of 0. The training AUC was 0.966, a high value but the model included a variable which had no importance to the results.

The second Maxent run included all of the bioclimatic variables that Pike used in their case study except for Bio18 which in the previous Maxent run had 0 permutation importance. Bio2 had 23.8 percent contribution but had 0 permutation importance. The highest valued variables were Bio17, Bio3, Bio5, and Bio 7 which had a 29.7, 17.9, 12.1, 8.4 percent contribution and 9.6, 23.9, 13.6, 39.5 permutation importance respectively. The training AUC was 0.966, a rather high AUC value but the model included Bio2 which had no importance to the results.

The third Maxent run included all of the bioclimatic variables that Pike used except for Bio18 and Bio2 which had 0 permutation importance. The highest valued variables were Bio17, Bio7, Bio3, and Bio5 which had a 29.3, 27.1, 25.7, 10.8 percent contribution and 10.8, 28, 30, 16.7 permutation importance respectively. The training AUC was 0.965, a slightly lower AUC value but the model did not include any variables that received 0 permutation importance.

The fourth Maxent run included all of the bioclimatic variables that Pike used except for Bio18 and Bio2 which had 0 permutation importance, and Bio19 which had a 2.4 permutation importance, the lowest value from the previous run. The highest valued variables were Bio17, Bio7, Bio3, and Bio5 which had a 30.5, 28.4, 25.4, 10.9 percent contribution and 12.8, 44.3, 17.4, 16.9 permutation importance respectively. The training AUC was 0.960, a lower value than the two previous model runs. The third Maxent run, which had the highest AUC value without inclusion of any variables that had no importance to the results, was the set of variables used to create the nesting site suitability map under the current climate conditions.

3.5.3. Maxent Output Files

After a Maxent model has been run successfully, a set of charts and graphs are created based on the settings chosen for the model. The first graph is the analysis of omission/commission, which displays the omission rate and predicted area at different cumulative thresholds (Smolek 2015). The second graph is the sensitivity vs 1-specificity, which is the receiver operating characteristics (ROC) curve of the area under the curve (AUC). The specificity is defined using predicted area instead of true commission (Phillips et al. 2004). The ROC curve indicates the proportions of correctly and incorrectly classified predictions over a specific range of threshold values which are relative to the random sampling performed. These values can be used to evaluate the quality of the model and the appropriate threshold probability value to use in differentiating between suitable and unsuitable habitat (Phillips et al. 2004; Poti 2022). Some common thresholds and their corresponding omission rates are produced in a table, including the "Balance training omission, predicted area and threshold" value that is used as the minimum habitat suitability value. A representation of the Maxent model output for the species is displayed as a picture where warmer colors show areas with better predicted conditions and white dots show the presence locations used for training. Two sets of response curve graphs are created for each environmental variable, one that shows how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value, and another that shows how the corresponding variable reflects the dependence of predicted suitability both on the selected variable and on dependences induced by correlations between the selected variable and other variables (Phillips et al. 2004). An analysis of variable contribution table is produced giving estimations of relative contributions of each of the environmental variables to the Maxent model. The final Maxent output is of a Jackknife of regularized training gain test of variable importance, which shows the training gain of each environmental variable if the model was run in isolation, and compares it to the training gain with all the variables (Smolek 2015).

The previously discussed results of the Maxent run are summarized within an HTML file and includes a graphic representation of the habitat suitability results as an ASCII file. The ASCII file can be directly uploaded to ArcGIS Pro and processed as a float, which is symbolized as a range of values between 0 and 1. To display a binary suitable and unsuitable habitat, the *Reclassify* tool was used and two breaks were entered manually. The habitat suitability for this thesis was defined through the use of the Balance threshold which was calculated in Maxent. The Balance threshold balances training omission, predicted area, and threshold value. It is considered a relaxed threshold, providing a more inclusive output of low, marginal, moderate, and high suitability locations (Pike 2013). The inclusion of a range of suitability is valuable because low and marginal suitable locations may become more important due to climate change impacts. The threshold for suitability was at 90 percent sensitivity and the value for the threshold was found in the Maxent results CSV file under "Balance training omission, predicted area and threshold value." The lowest value to this threshold was classified as zero and the highest value was classified as one. The area of suitable and unsuitable habitat was calculated by looking at the raster count of the above and below the suitability threshold. Within the suitable habitat threshold, the range was divided into three equal breaks to represent low, medium, and high suitability.

Chapter 4 Results

The results of the nesting site suitability and extinction risk analysis of the CWP DPS are discussed below. Multiple Maxent model runs were necessary before finding the best combination of the WorldClim bioclimatic variables which were then used to create two nesting site habitat suitability models under current climate conditions (1970-2000). The Maxent model performance and the environmental variables were evaluated. An assessment of extinction risk was performed, and after analyzing the results of the suitability model and literature review, the CWP DPS was determined to be at a medium risk of extinction.

4.1. Maxent Model Runs and Model Performance

Four Maxent model runs were performed, each model run removing the variable with the lowest permutation importance. The third out of the four Maxent model runs had the ideal combination of bioclimatic variables and a relatively high AUC value, indicating a high performing model.

4.1.1. Maxent Model Runs

Finding the perfect combination of bioclimatic variables that represented what was most environmentally influencing for green sea turtles required multiple Maxent model runs. Although 19 of WorldClim's bioclimatic variables were downloaded, only nine were being considered for this project. It is important for the variables to not be intercorrelated, otherwise the results from the Maxent run cannot be interpreted properly. The nine bioclimatic variables were the only ones out of the 19 variables to be not correlating and showed biological significance to sea turtle nesting, according to Pike's article (Pike 2013). Thus the first Maxent run included all nine of these variables, even though the species of sea turtle and location varied between Pike's article and this project.

The first Maxent run included Bio2, Bio3, Bio5, Bio7, and Bio15-19. The training AUC value was 0.966, a relatively high value considering a score of 1 would be considered a perfect model. The environmental variables were each given a percent contribution and permutation importance seen in Table 5.

Table 5. Bioclimatic variable analysis from Maxent Model Run 1

Variable	Percent Contribution	Permutation Importance
Bio2	23.8	0.3
Bio3	17.6	21.3
Bio5	11.8	19.5
Bio7	7.9	37.3
Bio15	0.5	4
Bio16	5.4	5.3
Bio17	29.5	11.5
Bio18	1.9	0
Bio19	1.5	0.8

The variable with the highest permutation importance was temperature annual range (Bio7) with 37.3 and the lowest was precipitation of warmest quarter (Bio18) with 0. Bio18 had very little data to contribute and was also shown to have 0 permutation importance to nesting of the CWP green sea turtles. Precipitation of driest quarter (Bio17) had the most data to contribute but had medium permutation importance. Another result from the Maxent run which produced information on the environmental variables was the Jackknife test (Figure 7). The Jackknife test determined that the mean diurnal range (Bio2) when used in isolation, had the highest gain and thus had the most useful information by itself. Maximum temperature of warmest month (Bio5) and precipitation of wettest quarter (Bio16) had the lowest gain, providing the least useful information by themselves. The maximum temperature of warmest month (Bio5) decreased the gain the most when it was omitted, which means it had the most information that was not present in the other environmental variables. Even though the AUC value was high, because of a variable with 0 permutation importance, another Maxent run was performed after removing Bio18.

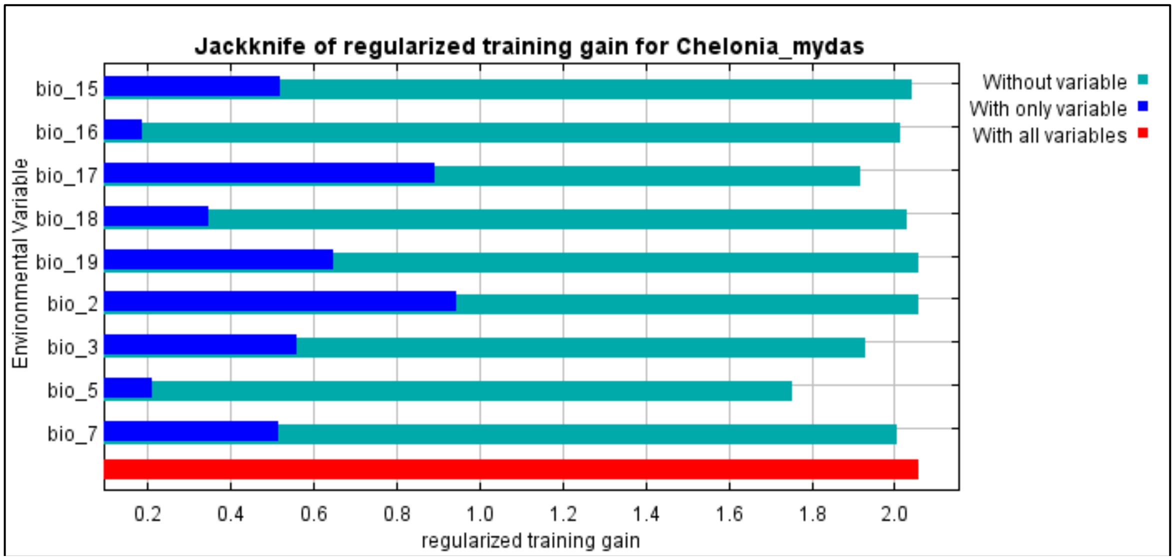

Figure 7. Jackknife test results for the current climate conditions from Maxent Model Run 1

The second Maxent run included Bio2, Bio3, Bio5, Bio7, Bio15-17, and Bio19. The training AUC value was 0.966, the same value as the previous model run. The environmental variables were each given a percent contribution and permutation importance seen in Table 6.

Table 6. Bioclimatic variable analysis from Maxent Model Run 2

Variable	Percent Contribution	Permutation Importance
Bio2	23.8	0
Bio3	17.9	23.9
Bio5	12.1	13.6
Bio7	8.4	39.5
Bio15	0.6	4.8
Bio16	4.8	6.1
Bio17	29.7	9.6
Bio19	2.7	2.5

The variable with the highest permutation importance was temperature annual range (Bio7) with 39.5 and the lowest was mean diurnal range (Bio2) with 0. Bio2 had a lot of data to contribute but was shown to have 0 permutation importance. Precipitation of driest quarter (Bio17) had the most data to contribute but had medium permutation importance. The results of the environmental variables from the Jackknife test are seen in Figure 8. The Jackknife test determined that Bio2 when used in isolation, had the highest gain, and Bio5 and Bio16 had the lowest gain. Bio5 decreased the gain the most when it was omitted. These results were very similar to the previous Maxent run. Even though the AUC value was high, because of a variable with 0 permutation importance, another Maxent run was performed after removing Bio2.

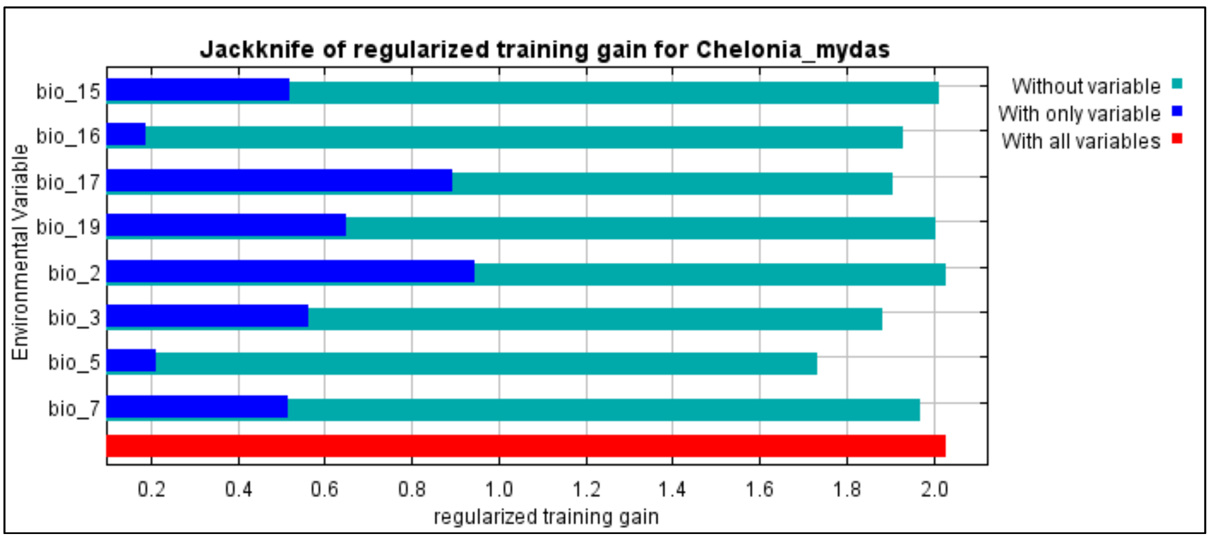

Figure 8. Jackknife test results for the current climate conditions from Maxent Model Run 2

The third Maxent run included Bio3, Bio5, Bio7, Bio15-17, and Bio19. This Maxent run was chosen to be used for the nesting site suitability maps, and the results are discussed in greater detail in Section *4.1.2 Model Performance*. The training AUC value was 0.965, a lower value than the two previous runs but only by 0.001. Even though there were no variables that had

0 permutation importance, because of a decrease in AUC value, another Maxent run was performed removing Bio19 which had the lowest permutation importance with a value of 2.4.

The fourth Maxent run included Bio3, Bio5, Bio7, and Bio 15-17, the fewest of variables of all the Maxent runs. The training AUC value was 0.960, the lowest value out of all the runs. The environmental variables were each given a percent contribution and permutation importance seen in Table 7.

Table 7. Bioclimatic variable analysis from Maxent Model Run 4

Variable	Percent Contribution	Permutation Importance
Bio3	25.4	17.4
Bio5	10.9	16.9
Bio7	28.4	44.3
Bio15	0.3	3.6
Bio16	4.5	5.1
Bio17	30.5	12.8

The variable with the highest permutation importance was Bio7 with 44.3 and the lowest was precipitation seasonality (Bio15). Bio15 and Bio16 both had the lowest percent contribution and lowest permutation importance. The results of the environmental variables from the Jackknife test are seen in Figure 9. The Jackknife test determined that Bio17 when used in isolation, had the highest gain, and Bio5 and Bio16 had the lowest gain. Similar results to the previous Maxent runs, except that Bio7 decreased the gain the most when it was omitted. The AUC score was the lowest, even with no variables having 0 or less than 3 permutation importance. Therefore, Maxent model run 3 would be used for the nesting habitat suitability under current climate conditions.

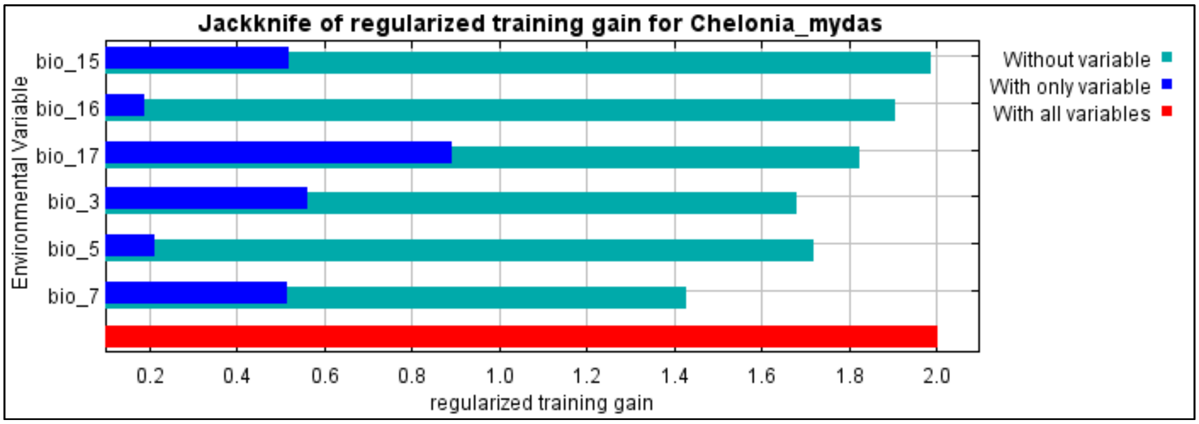

Figure 9. Jackknife test results for the current climate conditions from Maxent Model Run 4

4.1.2. Model Performance

Maxent is often referred to as a black box, given that the data is inputted into the model and the model generates an output. The quality of the Maxent output is the same quality as the data inputted, therefore selecting the right data will produce a quality model. AUC is a widely used SDM metric and quantifies whether the Maxent model correctly orders random presence data versus random background data (Kalinski 2019). Model performance can be measured by assessing the AUC value in the Maxent results. An AUC value of 0.5 is considered the result of random sampling, between 0.5 – 0.7 indicates poor model performance, between 0.7 – 0.9 indicates moderate performance, and values above 0.9 indicate a high performing model (Dowling 2015; Kalinski 2019). The nesting site suitability map was created using the bioclimatic variable selection from Maxent model run 3. The AUC from that run was 0.965, a value representing high model performance (Figure 10).

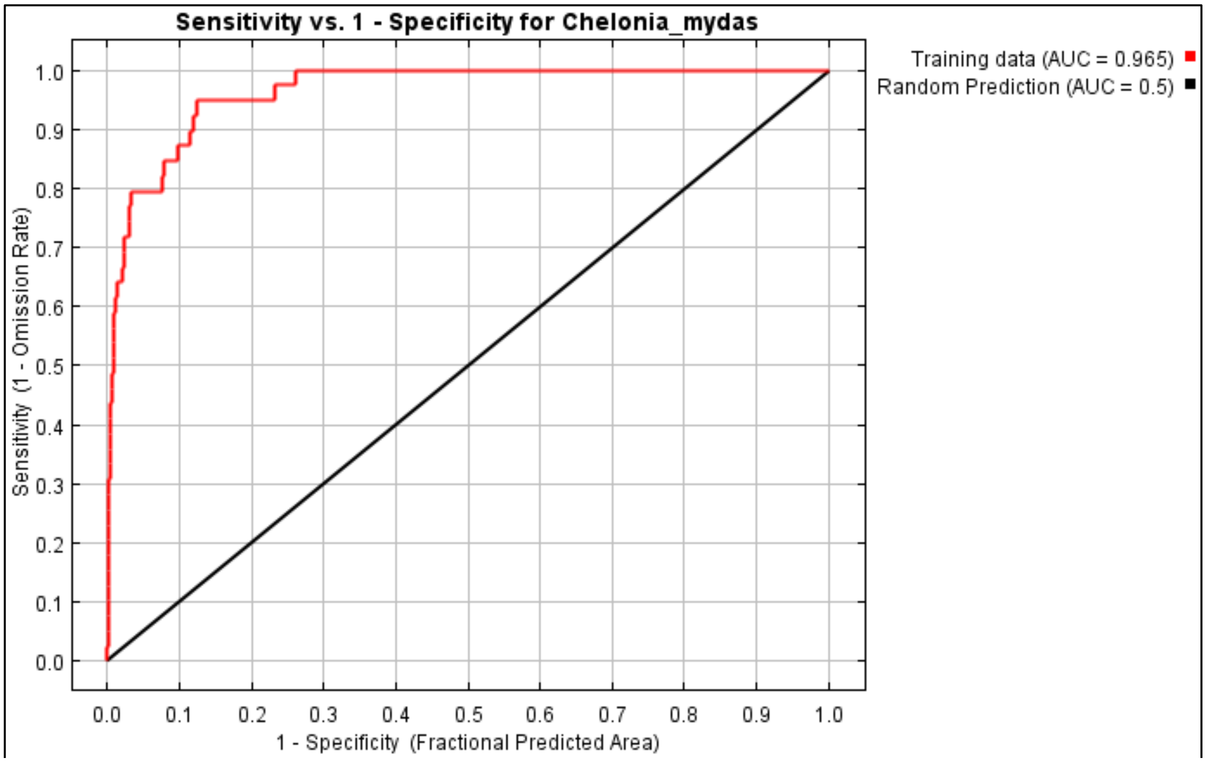

Figure 10. AUC for Maxent model run 3

Maxent produces several outputs that address each environmental variable's importance in the results. The variables are ranked by variable contribution and are represented through a Jackknife test where each model is run eliminating one variable at a time and then by running each variable independently (Dowling 2015; Phillips 2017). This illustrates the varying importance of variables in relation to each other and the final result. Seven out of the 19 bioclimatic variables were used in the final Maxent model run. Under the current climate conditions, the seven bioclimatic variables are listed in a table with their percent contribution and permutation importance (Table 8).

Table 8. Current (1970-2000) bioclimatic variable analysis from Maxent Model Run 3

Variable	Percent Contribution	Permutation Importance
Bio3	25.7	30
Bio5	10.8	16.7
Bio7	27.1	28
Bio15	0.6	5.5
Bio16	3.7	6.6
Bio17	29.3	10.8
Bio19	2.8	2.4

The precipitation of the driest quarter (Bio17) had the highest percent contribution at 29.3 percent, followed by temperature annual range (Bio7) at 27.1 percent, and then isothermality (Bio3) at 25.7 percent. Precipitation seasonality (Bio15) had the lowest percent contribution. Bio3 had the highest permutation importance at 30 percent, followed by temperature annual range at 28 percent, and then maximum temperature of warmest month (Bio5) at 16.7 percent. Precipitation of coldest quarter (Bio19) had the lowest permutation importance.

An alternative method to estimate variable importance in the Maxent model is by running a Jackknife test. The Jackknife test has each variable be excluded in turn, and a model is created with the remaining variables. Then one model is created using each variable in isolation and another model is created using all the variables (Phillips 2017). The result of the Jackknife test for the current climate condition (Figure 11) showed that precipitation of driest quarter (Bio17) had the highest gain when used in isolation, which means it had the most useful information by itself. Maximum temperature of the warmest month (Bio5) and precipitation of wettest quarter (Bio16) achieved almost no gain, so the variable by itself is not useful for estimating the nesting distribution for the green sea turtles. Temperature annual range (Bio7) decreased the regularized training gain the most when it was omitted, which means it had the most information that was not present in other variables. Bio7 is the maximum temperature of the warmest month (Bio5) subtracted by the minimum temperature of the coldest month (Bio6). Precipitation seasonality

(Bio15) and precipitation of precipitation of coldest quarter (Bio19) increased the regularized training gain the most when it was omitted, which means its information was partially correlated with other variables and did not provide significant individual data.

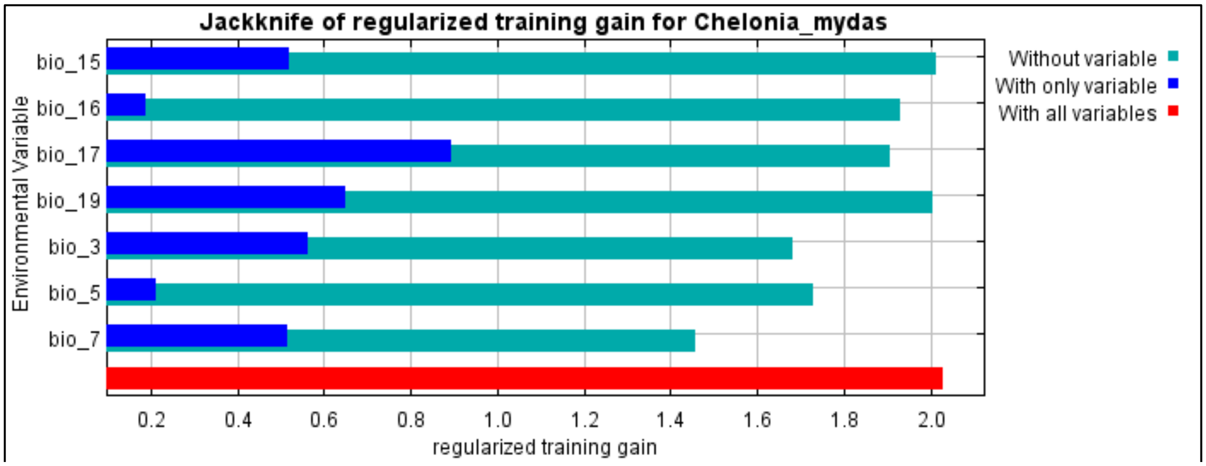

Figure 11. Jackknife test results for the current climate conditions from Maxent Model Run 3

4.2. Nesting Site Habitat Suitability

The CWP DPS is a large boundary of open ocean with some clusters of islands. Although the islands are not large in area, the green sea turtles only nest along the shorelines, leaving most of the island untouched. A nesting habitat suitability model was created for current climate conditions (1970-2000) and two maps were created in ArcGIS Pro displaying unsuitable and suitable nesting habitat. A 90 percent sensitivity was set within the Maxent model for determining habitat suitability and a logistic threshold value is noted.

4.2.1. Nesting Sites: Suitable and Unsuitable Habitat

Using the Maxent model run 3, under current climate variables, Maxent produced 21,972 kilometers squared as suitable nesting habitat for the CWP population, and 61,923 kilometers squared as unsuitable nesting habitat. Maxent assigned the habitat suitability threshold to 0.0652, which meant the Maxent output values that were above that threshold were considered suitable, and those below were considered not suitable. Only 26 percent of the CWP DPS land was suitable for green sea turtle nesting, leaving a majority of the land unsuitable. A few popular nesting areas are displayed in maps illustrating the suitable and unsuitable nesting habitat.

The Solomon Islands are in the southernmost part of the CWP DPS, east of Papua New Guinea. They are the biggest islands in the CWP DPS but they only have eight nesting sites. However, a few of those nesting sites have a nester abundance of over 200 and are located on shorelines that Maxent deemed suitable nesting habitat (Figure 12). One cluster of nesting sites are near the southern edge of Choiseul Island on Wagina Island and Sikopo Island. Another cluster of nesting sites are on Malaupaina Island, just north of San Cristobal Island and is entirely suitable nesting habitat. Both Choiseul Island and Santa Isabel Island have mostly suitable nesting habitat. However, the majority of the Solomon Islands' shorelines are not suitable for nesting habitat, especially Guadalcanal Island and San Cristobal Island.

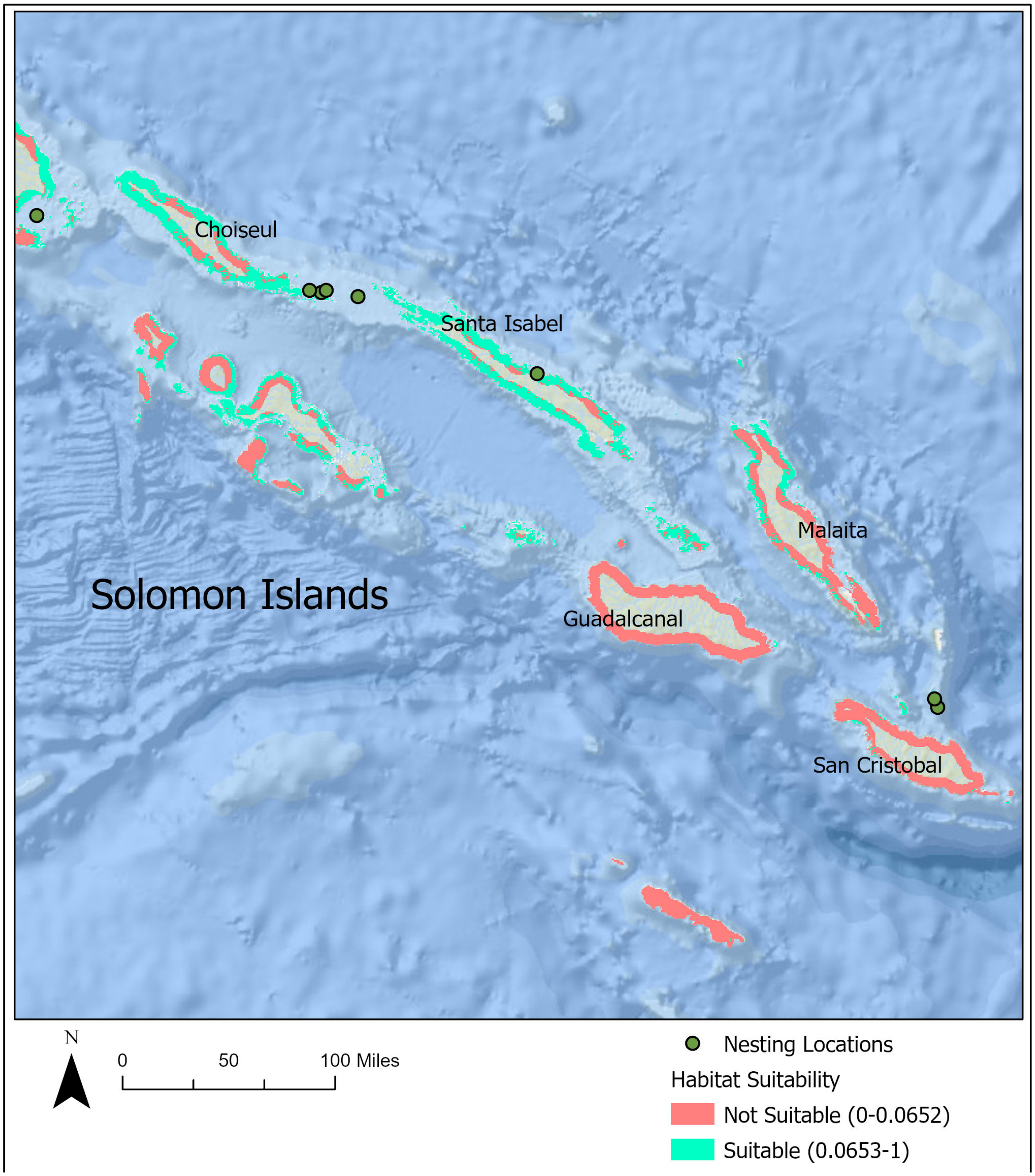

Figure 12. Nesting site suitability of the Solomon Islands

Guam and the CNMI are on the western side of the middle of the CWP DPS. Guam, the southernmost of the Mariana Islands and the CNMI are almost entirely suitable nesting habitat (Figure 13). Guam has 16 nesting sites spread out around the island, but only 22 nesters. CNMI also has 16 nesting sites, but spread out over multiple islands and 39 nesters total (Seminoff et al.

2015; Summers et al. 2018). Rota Island, the southernmost island of CNMI, has the majority of nesting sites for CNMI on its shores which are suitable nesting habitat. However, in the center of Rota Island there is one cell of not suitable habitat, though green sea turtles would most likely not nest that far inland.

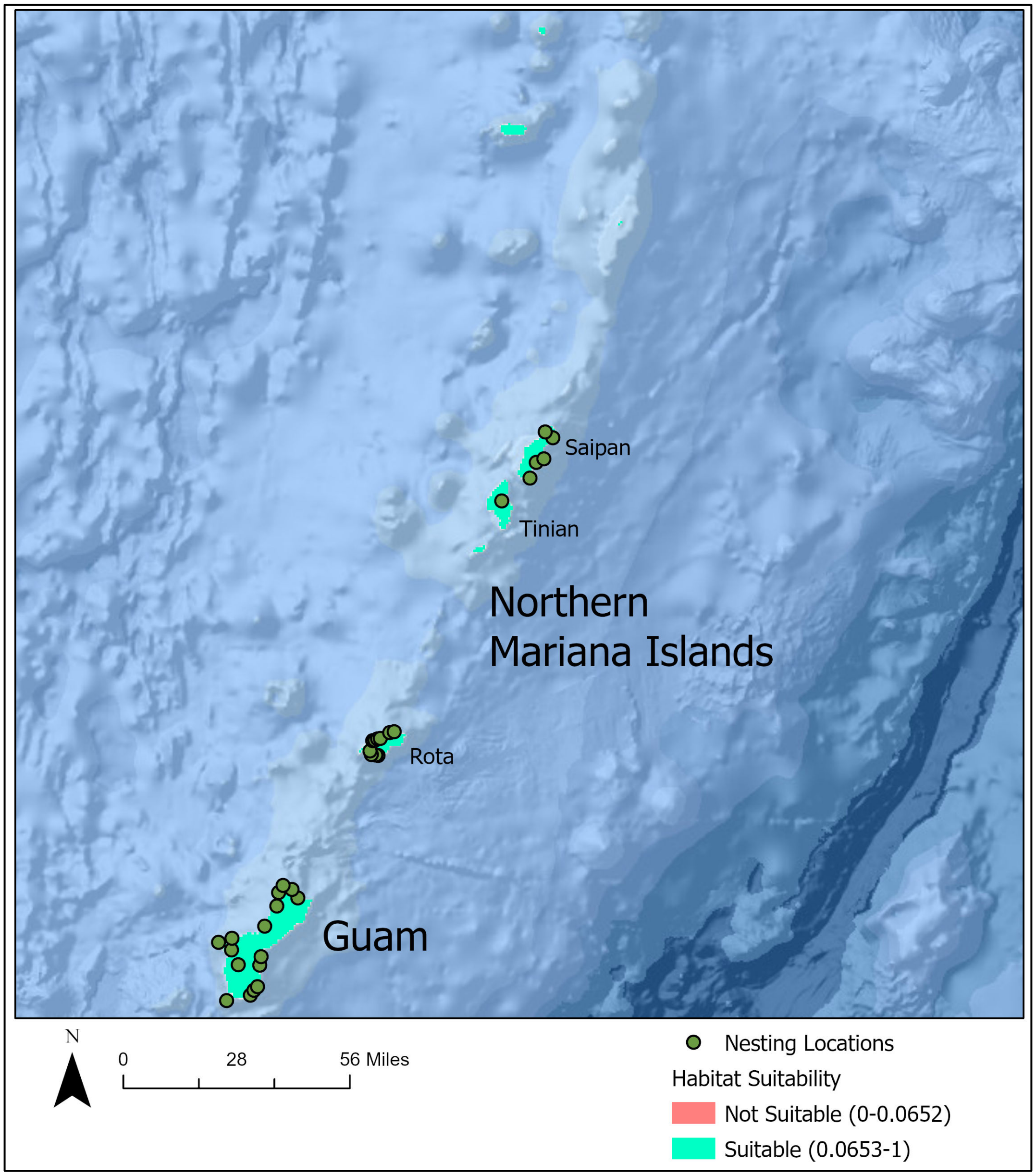

Figure 13. Nesting site suitability of Guam and the CNMI

Palau is south of Guam and tucked away to the west edge of the CWP DPS. It only has 12 nesting sites throughout the country's islands, even though it is almost all suitable nesting habitat (Figure 14). There are only two nesting sites on the main island, Babeldaob, which is completely suitable nesting habitat. Although there are not a lot of nesting sites, there are two significant nesting beaches: Merir Island with 441 nesters and Helen Island with 141 nesters (Seminoff et al. 2015).

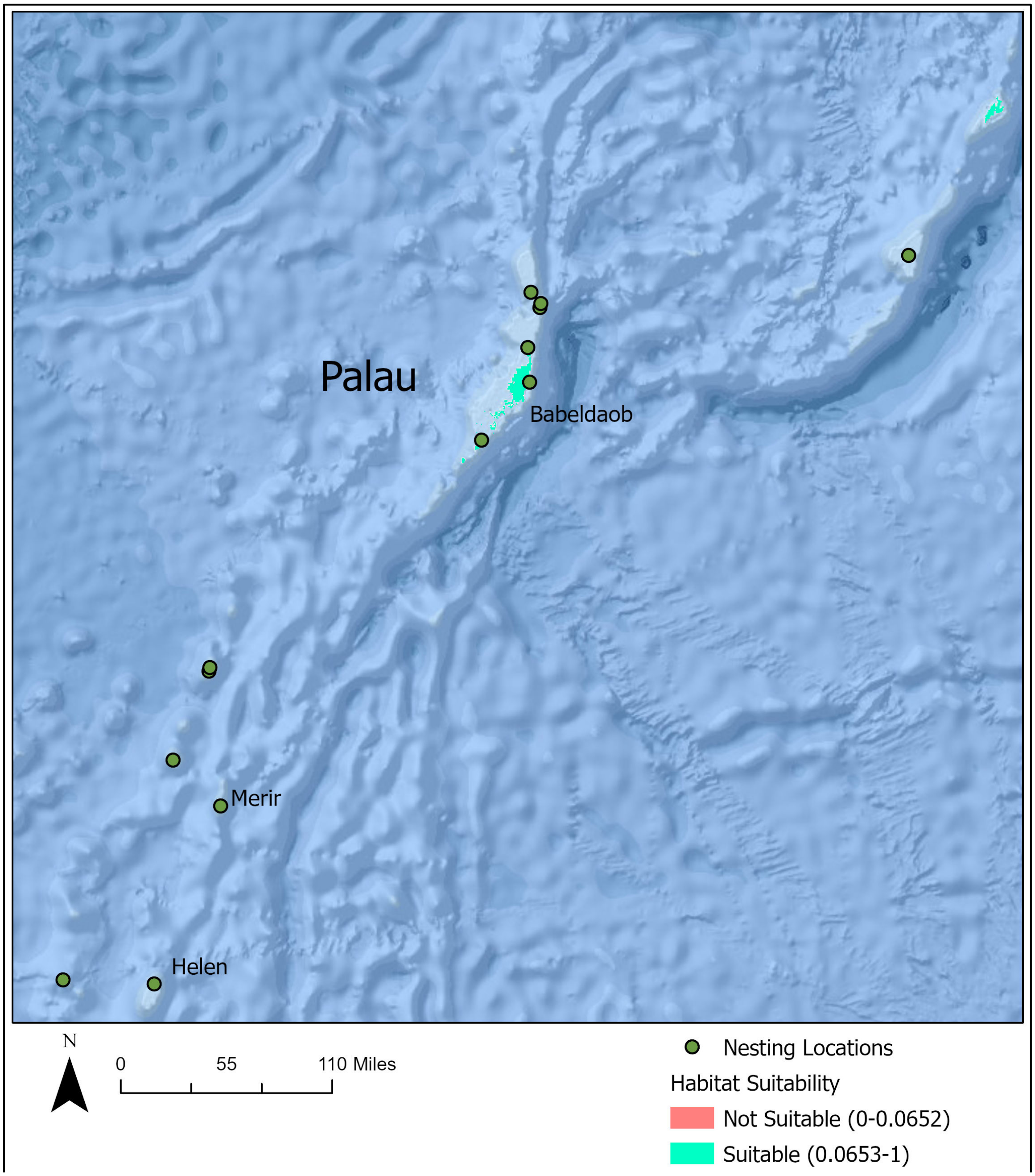

Figure 14. Nesting site suitability of Palau

Papua New Guinea is mostly outside of the CWP DPS, however, New Ireland and New Britain are just within the southern boundary. New Ireland of Papua New Guinea is mostly not suitable nesting, but still has eight nesting sites (Figure 15). The cluster of nesting sites are on various atolls in between New Hanover and New Ireland with suitable habitat or no data. The

Saint Matthias Islands are mostly suitable habitat with two nesting sites, one on each island. The Tabar Group of islands do not have any nesting sites but are completely suitable nesting habitat. Papua New Guinea has little nesting data available, but there is an estimation of 10-100 nesters amongst all the islands in the country (Maison et al. 2010).

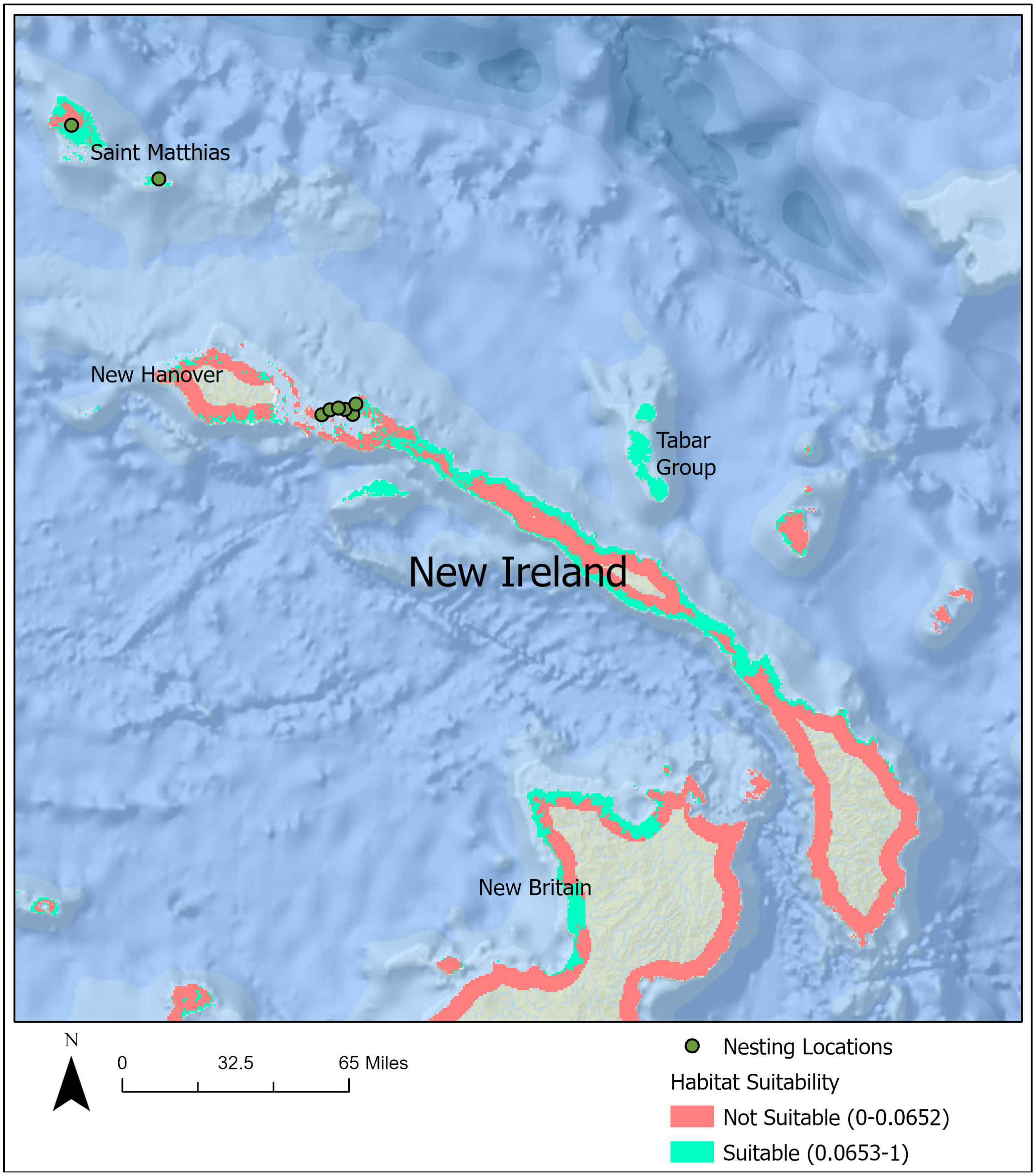

Figure 15. Nesting site suitability of New Ireland, Papua New Guinea

4.2.2. Nesting Sites: Scaled Suitable Habitat

Within the 26 percent suitable nesting land, the suitable values range from 0.0652 to 1, and were equally divided and visualized as low, medium, and high suitability. The same nesting sites are now displayed indicating the quality of the suitable habitat. Of the suitable nesting sites, 19,379 kilometers squared had low suitability, 1,482 kilometers squared had high suitability, and 1,111 kilometers squared had medium suitability.

The majority of the Solomon Islands are not suitable and low suitability, with a few areas of medium and high suitability (Figure 16). The nesting sites are found on low suitable habitat with little medium and no high suitability. The cluster of nesting sites on Wagina Island are located on low suitability habitat, but the east side of that island has medium and high suitability. A few edges of the larger islands, such as Choiseul, Santa Isabel, and Malaita have medium and high suitable nesting habitat.

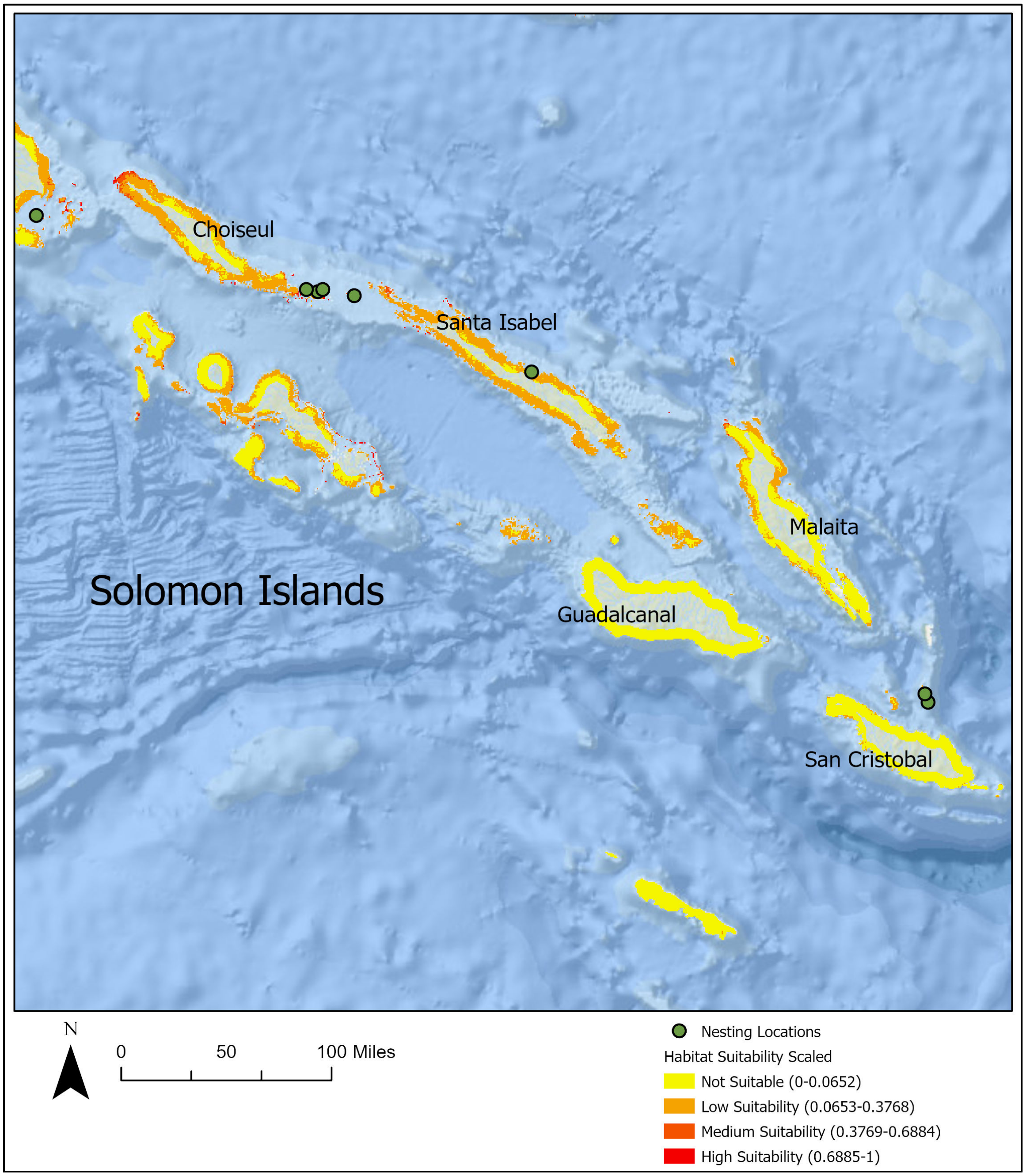

Figure 16. Nesting site scaled suitability range of the Solomon Islands

Guam and the CNMI are almost entirely highly suitable, with a few areas that are low suitability (Figure 17). Guam is covered in high suitability except for a small area inland, an area with no known nesting sites and most likely is too far inland for green sea turtles to nest. The CNMI are mostly medium and high suitability, Tinian Island is entirely high suitability, but Rota

Island and Saipan Island have a mix of medium and highly suitable nesting habitat. Anatahan, a small island north of Saipan with an active volcano, is mostly low suitability with a few areas of high suitability.

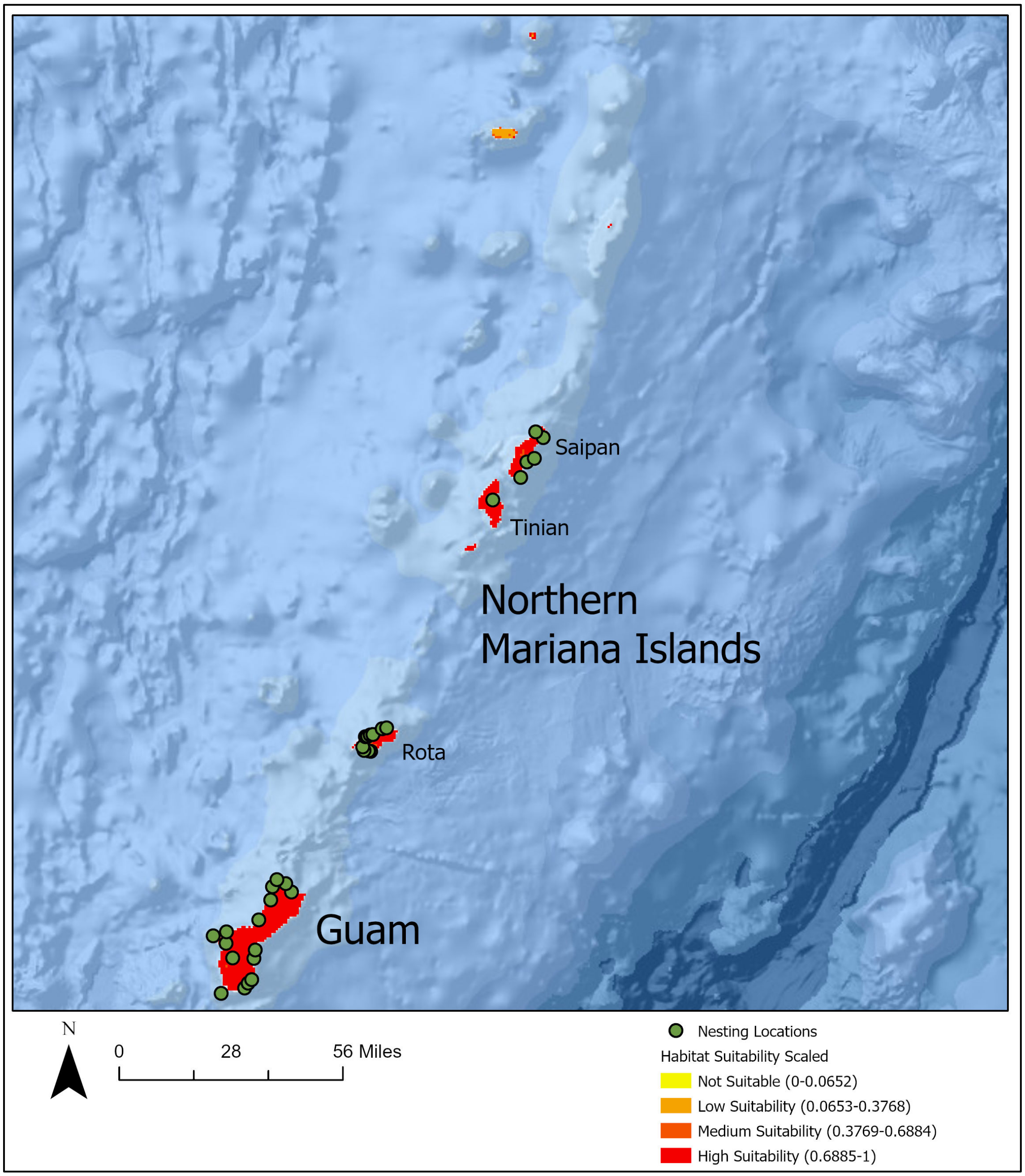

Figure 17. Nesting site scaled suitability range of Guam and the CNMI

Palau is mostly low suitability and medium suitability, with no unsuitable habitat (Figure 18). The few nesting sites on Babeldaob Island and nearby are located on mostly medium suitability, as opposed to the low suitability habitat. Out of the three nesting sites north of Merir Island and south of Babeldaob Island, two nesting sites are on medium suitability and one is on low suitability.

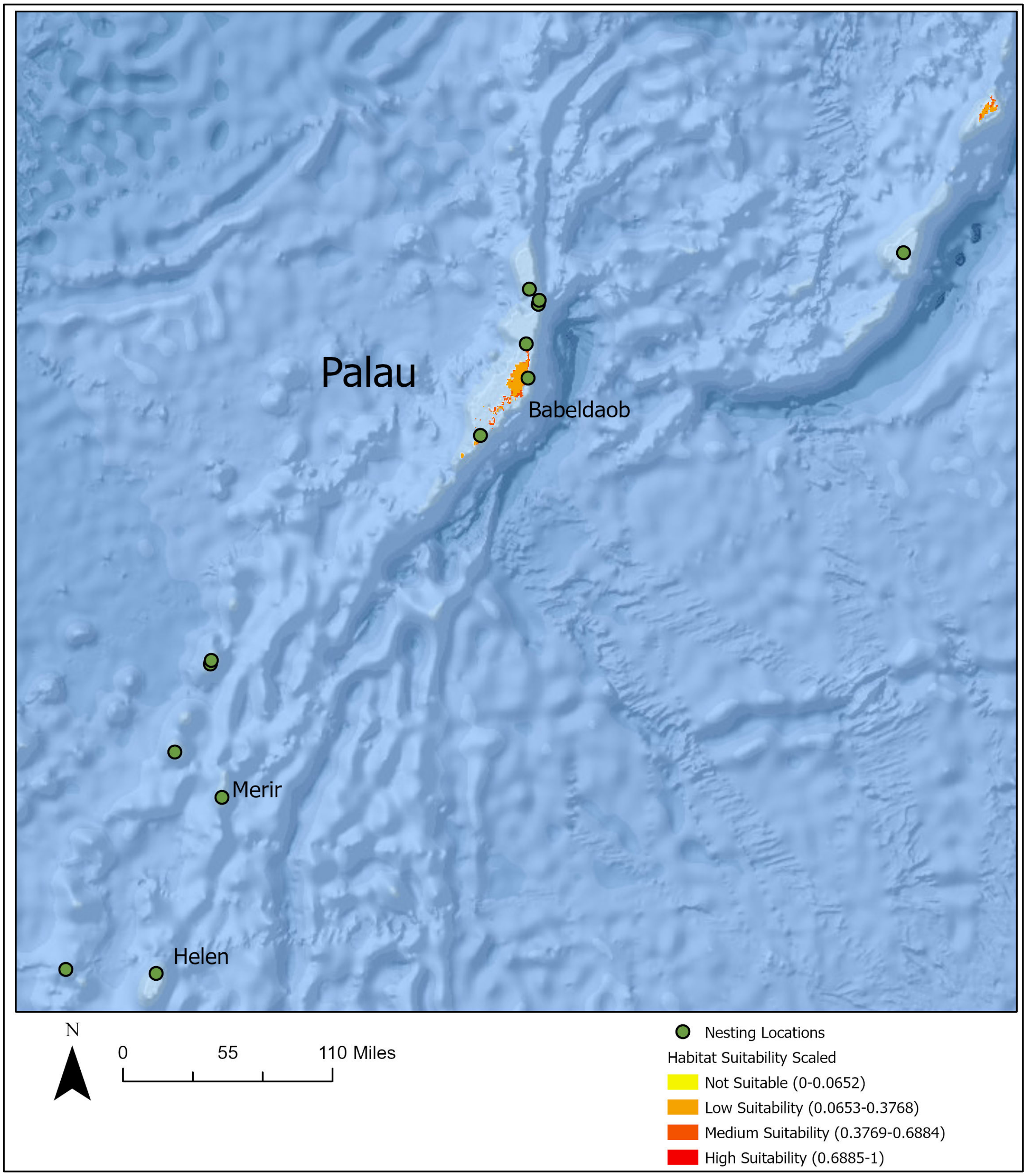

Figure 18. Nesting site scaled suitability range of Palau

New Ireland in Papua New Guinea is mostly not suitable with some low suitability nesting habitat which is where the nesting sites are located (Figure 19). The nesting sites clustered east of New Hanover and on the Saint Matthias Islands are all located on low suitability nesting habitat. Although the Tabar Group of Islands may not have any green sea turtle nesting sites, the northern island is mostly medium and high suitability and the southern island is mostly low suitability. The majority of the mainland and New Britain is not suitable nesting habitat, with a few areas of low suitability.

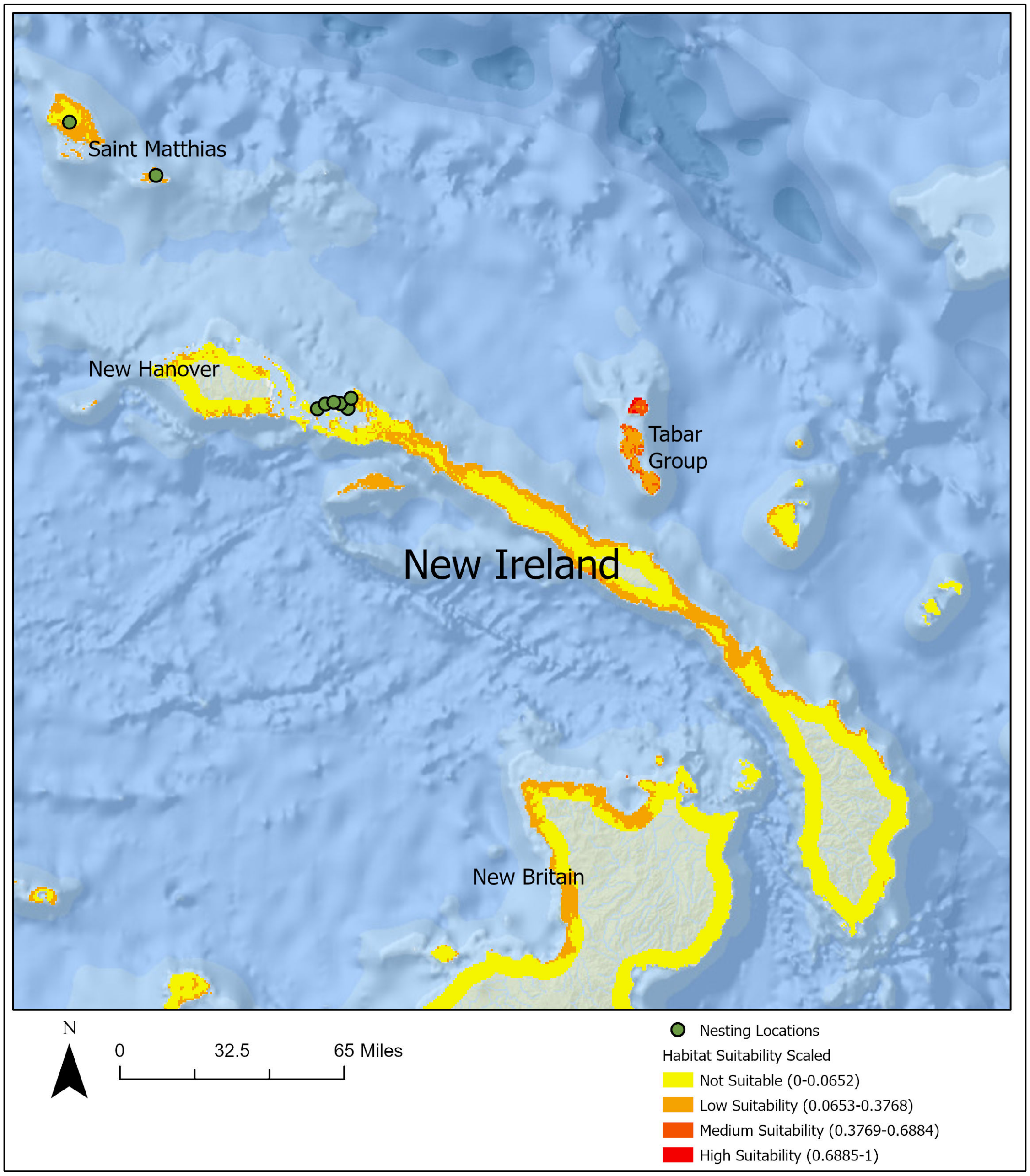

Figure 19. Nesting site scaled suitability range of New Ireland, Papua New Guinea

4.3. Extinction Risk Assessment

The risk of extinction is essential to avoid for all species listed under the ESA, especially those that are critically endangered and endangered like the green sea turtles. This risk does not necessarily mean there are no individual species left, but rather that the species or DPS has such an incredibly low abundance, coupled with declining trends and limited distribution and diversity, that there is a high chance of little to no potential for recovery (Seminoff et al. 2015). The extinction risk will assess these factors: number of nester abundance and nesting data, population trends, spatial structure, immediate threats, conservation laws, and nesting site suitability results from the SDM.

4.3.1. Extinction Risk Criteria

The extinction risk criteria was created only for the purpose of this thesis and its evaluation of green sea turtles. The factors used in the criteria and their indication of extinction risk status low/medium/high were established from the knowledge gathered on how the IUCN Red List and Seminoff's 2015 Status Review assess species. The IUCN Red List, the most widely used global imperiled species list, classifies its species as imperiled (Critically Endangered, Endangered, or Vulnerable), not imperiled (Near Threatened or Least Concern), extinct (Extinct, Extinct in the Wild), or data deficient. Species will be added to the Red List if they meet any of these quantitative thresholds: decline in population size, small geographic range, small population size plus decline, very small population size, or quantitative analysis (Harris et al. 2011). Seminoff's 2015 Status Review is more aligned with the ESA and their assessment criteria, looking at: abundance, population growth rate or productivity, spatial structure, diversity/resilience, threats, and then also conservation efforts (Seminoff et al. 2015).

The extinction risk status for this project is a low, medium, or high status and only pertains to an already endangered species, like the CWP DPS green sea turtles (Table 9).

Table 9. Extinction risk criteria and status for green sea turtles.

Extinction Risk Status	Extinction Risk Criteria
Low	• High number of nester abundance and nesting data • Population abundance is increasing • Spatial structure promotes sufficient diversity and resilience • Very few to no immediate threats • Many international and local conservation laws on both land and water • Nesting suitability is mostly suitable and considered medium to high suitability
Medium	• Medium number of nester abundance and nesting data • Population abundance is overall stable • Spatial structure is not limiting but does not promote adequate diversity and resilience • Limited threats that can be reduced with improved efforts • Numerous international and local conservation laws on both land and water • Nesting suitability is about 25-50 percent suitable and considered low to medium suitability
High	• Low number of nester abundance and nesting data • Population abundance is decreasing • Spatial structure limits diversity and resilience • Many threats that cannot be reduced with improved efforts • Little to no international and local conservation laws on both land and water • Nesting suitability is less than 25 percent suitable and what is suitable is mostly low suitability

The extinction risk assessment took into consideration attributes that impact the status of the CWP green sea turtle population, such as range and nesting distribution, population trends and spatial structure, immediate threats, and existing conservation laws and efforts.

4.3.2. Nester Abundance and Nesting Data

Nesting turtle data, as opposed to information on foraging turtles, provides the best data for assessing the resilience of a population (NMFS, NOAA, and USFWS 2016). Therefore, nesting data will have a larger impact in the assessment of extinction risk. The nesting population is spread across roughly 2,500 miles wide from Palau to the RMI and 2,500 miles long from Ogasawara, Japan to the Solomon Islands (Seminoff et al. 2015). There were at least 101 nesting locations according to SWOT. And according to Seminoff's 2015 Status Review, as of 2012, there were 13 of the 101 nesting locations that had an estimated nesting abundance of over 200 females laying eggs (Figure 20).

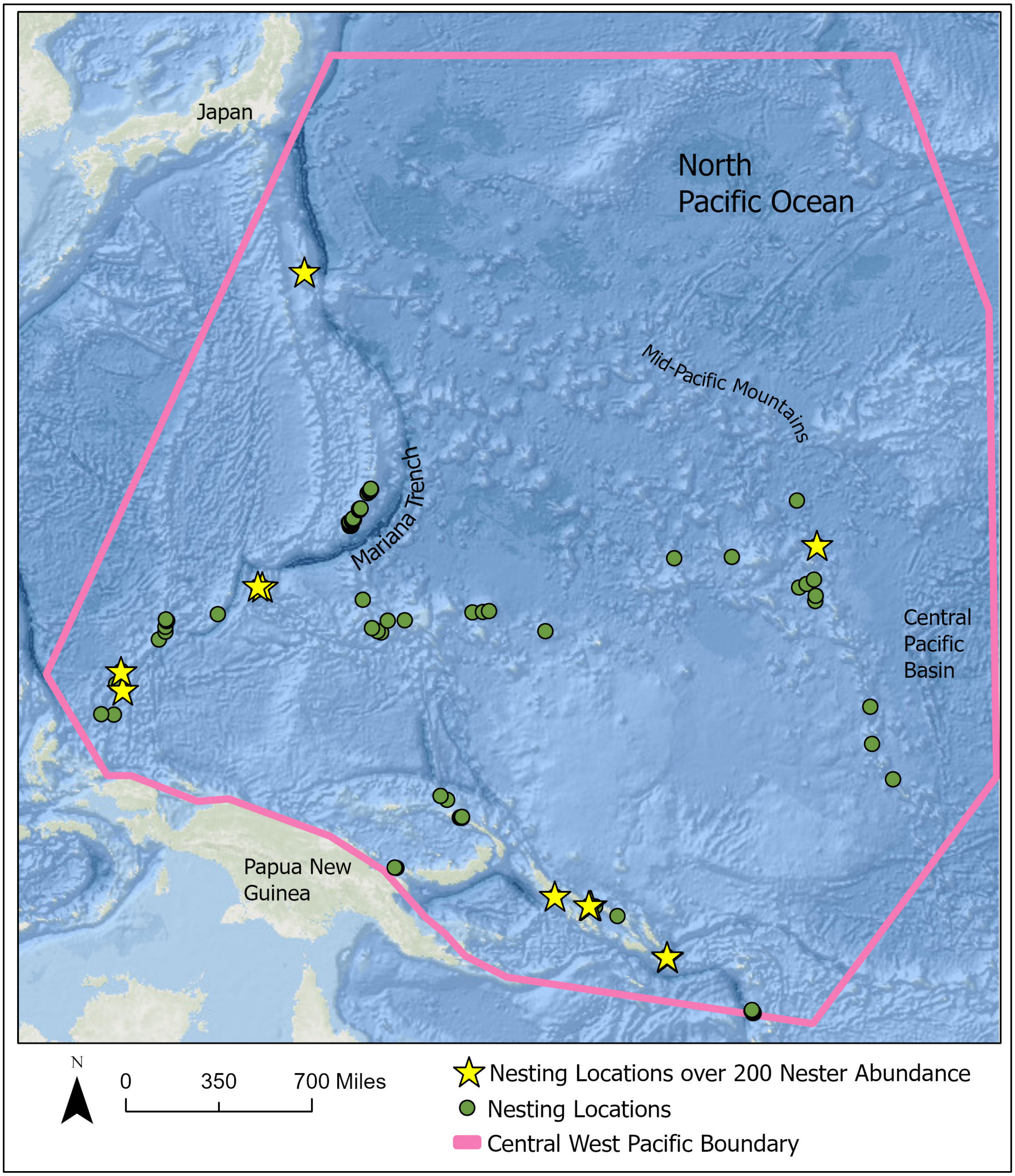

Figure 20. CWP DPS featuring 101 nesting locations

The nesting locations that had a count of over 200 in estimated female nesting turtles based on the Status Review are listed in Table 10. Compared to other DPS, the CWP exhibits low nesting abundance over widespread nesting sites on islands and atolls (NMFS, NOAA, and

USFWS 2016). The nesting sites at Ulithi Atoll Gielop Island, Iar Island, and Chichi-jima represent 41 percent of the estimated nester abundance for the CWP DPS. Chichi-jima, a nesting site within the Ogasawara Islands, has seen a steady increase in sea turtle population since the early 1980s with an estimated annual growth of 6.8 percent per year (Maison et al. 2010). As of 2015, there are an estimated 6,518 nesting females in the whole DPS, a number that can be found on just one of many nesting sites in other DPS (Seminoff et al. 2015).

Table 10. Selected nesting locations for the CWP DPS (Source: Seminoff et al. 2015)

Country	Nesting Site	Estimated Nester Abundance
FSM	Ulithi Atoll Gielop and Iar Island	1,412
Japan	Chichi-jima	1,301
Palau	Merir Island, Sonsorol State	441
Marshall Islands	Bikar Atoll	300
Solomon Islands	Ausilala	225
Solomon Islands	Balaka	225
Solomon Islands	Maifu	225
Solomon Islands	Malaulaul	225
Solomon Islands	Malaupaina	225
Solomon Islands	Wagina	225

4.3.3. Population trends

Population trends consider the mortality and birth rate of the populations and compare it to the abundance of individuals. It is important that a healthy and successful population is sufficiently abundant to provide resilience to environmental variations observed in the past and expected in the future (Seminoff et al. 2015). From the limited data available, there are some nesting populations decreasing, such as the ones on the RMI, and other nesting populations that are increasing, such as on Chichi-jima (Seminoff et al. 2015).

4.3.4. Spatial Structure

The spatial structure is important as it considers the number of habitat patches, the locations of the habitat patches, and the quality and durability of those patches. The spatial structure shows nesting sites that were separated by more than 1,000 kilometers had significantly different genetic data, which increases their diversity and resilience. However, most nesting sites were closer than 1,000 kilometers to each other. Flipper and satellite tagging information indicate that nesting females often migrate to areas within and outside of the boundaries of the CWP DPS. Their demographics show variation which suggests substantial spatial structuring (Seminoff et al. 2015).

4.3.5. Immediate Threats

The immediate threats that the CWP DPS face are habitat degradation, overutilization, disease, predation on the beach, incidental bycatch, and pollution and oil spills. Throughout the DPS, the habitat is experiencing erosion from storm events, and at high and low-density nesting beaches there is beach and marine pollution, dredging, and destructive fishing practices. The marine environment around Guam was heavily degraded by the impacts of combat during World War II (Maison et al. 2010). This population is struggling with Fibro papillomatosis disease at high-density nesting beaches, particularly in the FSM region. The consumption of nesting turtles and their eggs is a significant source of turtle mortality in the RMI. Throughout the DPS green sea turtles, mostly juveniles and adults, are becoming incidental bycatch in fishing nets, incurring damage from vessel strikes, and there is pollution at some of the low-density nesting beaches (Seminoff et al. 2015).

4.3.6. Existing Conservation Laws and Efforts

The green sea turtles within the CWP DPS have some legislative protection from a few international treaties, along with national and territorial laws. Most of the countries within this DPS have national legislation that protects sea turtles and their nesting habitats, though there is a lack of adequate enforcement of such laws. The harvest of sea turtles and their eggs are illegal under the ESA, the Inter-American Convention for the Protection and Conservation of Sea Turtles, and local laws in the CNMI and Guam (NMFS, NOAA, and USFWS 2016). In addition to the protection of green sea turtles under the federal ESA, they are also protected through the Endangered Species Act of Guam which has additional penalties at the local government level for violations of the federal ESA (Maison et al. 2010). There are only a few countries that have site-specific conservation for sea turtle habitat protection. Palau is one of them, with two national mandated protected areas where there are restrictions for entry and fishing within the areas (Seminoff et al. 2015). FSM, a country that has the largest nesting site in the CWP DPS, is not a participating party to CITES, a law that prohibits commercial trade of green sea turtles. The RMI is also not a member of CITES (Maison et al. 2010). However, the RMI has a minimum size limit for green sea turtles, 34 inches carapace length, and a date range when no turtles can be taken or killed of any size from June 1 through August 31st and December 1st through January 31st, according to the Pohnpei State law (Buden and Edward 2001; Maison et al. 2010).

4.3.7. Extinction Risk Status

Taking into consideration the DPS range, the analysis factors, and the existing conservation efforts, an estimation on extinction risk can be determined. The CWP DPS is at a medium extinction risk. The population abundance is relatively stable, with some nesting sites increasing in abundance and some decreasing. The spatial structure of the foraging grounds and nesting sites does not promote adequate diversity and resilience, but is not limiting. The analysis factors illuminate many threats to the survival the green sea turtles of this DPS, and the few conservation efforts in place have been doing an adequate job at protecting the population from a rapid decline, but better enforcement is necessary.

Chapter 5 Discussion and Conclusion

An analysis of the results from the Maxent nesting habitat suitability model and a critical assessment of the CWP DPS determined that the population currently is at a medium risk of extinction. The Maxent model results show that there is limited nesting site suitability of green sea turtles within the CWP DPS. The model strength and weaknesses, along with the results of the nesting habitat suitability are discussed. Climate change will continue to cause issues for this population, affecting both the habitat suitability and population dynamics. Future conservation efforts and research are discussed for the CWP DPS, but they can also be implemented more generally to other DPSs.

5.1. Maxent Model Strengths and Weaknesses

Maxent was an appropriate SDM selection for this thesis as it is known to model species distributions from presence only data at a high quality (Fuller et al. 2008), it outperforms other SDMs, and there were numerous case studies that used it with sea turtle data (Fuentes et al. 2020; Pike 2013; Pike 2014). All four of the Maxent model runs had high AUC values, indicating quality data and biologically important environmental variables.

5.1.1. Species Data

There were not a lot of public sources that had green sea turtle nesting site data on a large scale. The few datasets that were available, were often for a different DPS, such as the Mediterranean or were limited only to a specific nesting island, such as Ascension Island. From the few case studies that used Maxent for green sea turtles, the majority of their species presence only data was also from SWOT, making it a credible and reliable source to use.

Not all of the nesting site locations overlapped with the bioclimatic variable data, five of the 101 nesting sites within the CWP DPS did not receive any variable data. This gap of environmental data is most likely because of the nesting sites being located on uninhabited islands and atolls within the Pacific Ocean. The 101 nesting sites have been surveyed and monitored at least once between 1970-2021, but many of them have not been consistently monitored and so there may be some nesting sites that are no longer populated and there may be some nesting sites that are underrepresented. However, if this was an issue, it would be insignificant because green sea turtles are a unique species that return to the same nesting beach as where they were born. Even though the data may not be updated, it is safe to assume that unless the beach has been completely degraded, the nesting sites are still populated.

5.1.2. Environmental Variables

The choice to use WorldClim's 19 Bioclimatic Variables was appropriate and worked well for this project, as it provided quality results and was used in previous sea turtle case studies (Fuentes et al. 2020; Pike 2013; Pike 2014). However, a difficulty with the WorldClim's 19 Bioclimatic Variables was that they were downloaded as a single GeoTIFF file but had to be individually uploaded into ArcGIS Pro. These variables took a significant amount of time to load with pyramid structures and significant storage space to process, requiring enough space to store both the raw data and the processed data. WorldClim's 19 Bioclimatic Variables most "current" climate data, the dataset used in this project, included data from 1970-2000. This climate data is over 20 years old, and the climate changes and environmental impacts discussed in Chapter 2 include more recent data. Although the most recent climate changes and environmental impacts were not included in the Maxent model, one can assume that the environmental impacts increased and intensified just as the climate change rate as increased. These changes vary throughout the CWP DPS as it encompasses thousands of miles of ocean and hundreds of islands and atolls.

Due to the large study area extent, the CWP DPS, the environmental variables varied slightly in cell size. Even though all of the bioclimatic variables were set to the same cell size of Bio1, which was 0.83 kilometers squared, that was measured in the middle of the DPS. At the equator (0 degrees latitude), the cell size would be 0.86 kilometers squared, and presumably, at the top or bottom of the DPS, it would have varied a few more tenths of a kilometer (Pradhan and Setyawan 2021). Variations in cell size can be impactful in Maxent because the program uses the relative probability of the presence of an individual species in each cell, and with varying cell size, the probability varies (Merow et al. 2013). For example, a larger cell size would increase the probability of a green sea turtle nesting site's presence, and vice versa for a smaller cell size. However, for this project, the cell size used in the Maxent input was edited to be the same 0.83 kilometers squared everywhere within the DPS boundary.

Although the selected bioclimatic variables used in this project were in other sea turtle Maxent studies, there were other environmental variables that might have provided a more accurate representation of habitat suitability. The geomorphology of these coastal beaches, such as aspect, elevation, beach slope and width are other environmental variables that are important in nesting site suitability. However, this information is not often collected, especially from rural or uninhabited islands and atolls, like the nesting sites in the CWP DPS.

5.2. Nesting Site Habitat Suitability Model

Terrestrial nesting habitat of green sea turtles are characterized by distinct climatic conditions, which are connected to physical conditions necessary for successful egg hatching and hatchling dispersal (Pike 2014). These climatic conditions, which were discussed in detail in

Chapter 2, are captured in WorldClim's 19 Bioclimatic Variables current climate data, which was used in the Maxent model. Suitable nesting conditions, which can be identified through a Maxent habitat suitability model, combined with understanding the environmental conditions needed for a successful hatching and dispersal, can increase population abundance and reduce the risk of extinction.

5.2.1. Nesting Site Habitat Suitability

The nesting site habitat suitability of the CWP DPS was displayed in a binary suitable/unsuitable map and also a scaled suitability range (unsuitable-low-medium-high). When looking at the binary suitable/unsuitable results, no obvious trend or major geographic shifts in suitable nesting habitat in relation to the equator were evident. Where there was habitat suitability data in the CWP DPS, 26 percent was suitable and 74 percent was not from the SDM results. Due to the nature of the CWP DPS, an area full of islands and atolls, a lot of nesting sites were located on beaches that had little to no environmental data available from WorldClim. Also, the shoreline buffer used in Maxent to clip the environmental data layers was not as geographically accurate as one would prefer, and because of this some of the clipped environmental data did not overlap with the nesting sites. When looking at the scaled suitability results, there was a slight trend of islands with smaller surface areas having more medium and high suitability and areas north of the equator having more medium and high suitability. Sea turtle nesting is largely pan-tropical, but green sea turtles are known to also nest in more temperate areas (Pike 2013).

Out of the 101 nesting sites within the CWP DPS, not a single one was located on unsuitable nesting habitat. However, this Maxent model was performed using current climate conditions (1970-2000), so with the changing climate, the quality and amount of suitable nesting habitat would most likely have decreased. Individual sea turtles have a homing behavior which allows adults to return to the beaches where they were hatched. Unfortunately, because of this, it will be difficult for adult females to continue to successfully nest if their beaches have undergone unsuitable climate conditions, increasing their extinction risk.

5.2.2. Extinction Risk

Extinction of an endangered species, especially a keystone species like the green sea turtles, can cause cascading effects on the whole ecosystem. Green sea turtles forage on seagrass, which increases the productivity and nutrient content of the seagrass beds, impacting predator and prey relations. A decline in green sea turtles would result in a loss of productivity in the food web, impacting other marine species and humans. To reduce the pressures on a declining population, critically assessing the threats is the first step.

The critical assessment looked at all the influencing factors of the CWP DPS and its suitable habitat, and assessed the extinction risk status to be medium. Even as one of the smaller DPS boundaries, the green sea turtles in the CWP DPS do not inhabit the north and northeast section of the boundary. Within this inhabited area, there were only 13 nesting beaches out of the 101 that had over 200 estimated nesting females. That is a low number of total nesting sites in a mostly unoccupied DPS and a low abundance of nesting females. The majority of the nesting sites have 100 or fewer annual nesters, with many estimated to have 10 or less (Maison et al. 2010; Seminoff et al. 2015). And although the nester count is low, because they are spread out among many different islands, their genetic makeup will be more unique and thus will be important for recovery of the species abundance (Maison et al. 2010). The population abundance amongst these different islands remain relatively stable overall with some populations increasing and some decreasing. Some of the population decline can be attributed to human related activities, not just climate change. There is a slight trend between local legislation and nesting abundance, where larger nesting sites occur in countries that have strong legal protection of green sea turtles and countries with less protective regulations seem to have smaller nesting populations (Maison et al. 2010). FSM is an exception where there is a lack of legal protection but there is high nesting density. As migratory species, the inconsistency in laws and regulations are problematic because the green sea turtles may be protected where they are foraging but when they migrate to their nesting grounds, they may be on an unprotected beach and are vulnerable there.

5.3. Significance of the Model

This nesting site habitat suitability model of green sea turtles in the CWP DPS is significant because to my knowledge, no other models like this have been performed. More often than not, habitat suitability models use species observations as the species presence data. However, this model used nesting site locations as the species presence data. Maxent has been used to model nesting site habitat suitability for all sea turtle species or a few sea turtle species (Fuentes et al. 2020; Guo 2014; Pike 2013; Pike 2014), but there has not been a model focusing on only green sea turtles. The scale of this thesis was unique as most of the case studies and articles about green sea turtles or any other sea turtle species, focused on the species' global extent (Fuentes et al 2020; Guo 2014; Pike 2013; Pike 2014) or a different DPS or regional extent than the CWP (Guo 2014; Pierri et al. 2019), or at a much smaller scale such as individual nesting islands and beaches (Galvez et al. 2021; Shafiezadeh et al. 2018; Wright et al. 2022).

5.4. Future Work

The CWP is one of the more endangered DPS and more research and conservation efforts should go into this specific region of green sea turtles. Future research efforts should include creating habitat suitability models to quantify green sea turtles' realized niche, species-environment relationships, characterize geographical patterns or test the effect of climate change on species distribution (Lauria et al. 2015). Research into improving nesting site suitability models specifically for the CWP DPS should include slope and vegetation characteristics as they greatly influence sea turtle nesting (Sunarto et al. 2019). Acquiring this environmental variable information would require surveying either from the ground by people or from drones or other aerial imagery technology. This is just one option of future work which might increase the accuracy of suitability models.

Another option, specifically for green sea turtles, is the inclusion of estimated nester abundance data for each nesting site which would provide Maxent with more information when calculating its habitat suitability mode. Maxent's default is to use basic, non-attributal point data for the presence-only data and calculate the likelihood of the species presence across the landscape (Merow et al. 2013). The addition of having the count of estimated nester abundance for each nesting site point data would add meaning to the relative occurrence rate prediction and increase accuracy and broaden the habitat suitability results. This improvement of the suitability models would help local, federal, and international agencies better protect and conserve the suitable nesting sites, especially the ones with high estimated nester abundance.

An international agency, the IUCN, declared that green sea turtles need conservation actions in the form of increasing law and policy, along with compliance and enforcement of said laws and policies. This is not surprising given the information gathered concerning the CWP DPS, as many of these nesting sites are in unprotected areas and have little enforcement where there are laws and policies against illegal harvesting of turtles and their eggs. The countries that have minimum size regulations for sea turtle harvesting are not suitable for long-term sustainable management because large juveniles and adults have the highest reproductive value, and without them it is difficult to increase population abundance (Maison et al. 2010). FSM, Papua New Guinea, the RMI, the Republic of Palau, and the Solomon Islands are all countries that have substantial green sea turtle nesting sites and need to increase their protection from more than just minimum size harvesting to full protection.

A lot of the threats that the CWP DPS green sea turtles are facing effect other populations as well. The information gathered and the conservation efforts discussed for the CWP DPS can also be implemented on a broader scale. Although this thesis focused heavily on nesting and its effect on population dynamics, foraging habitats and mixed stock genetic analyses are also important and necessary to provide a more complete assessment of a DPS extinction risk status.

References

Avens, Larisa and Melissa L. Snover. 2013. "Age and age estimation in sea turtles." In: Wyneken, Jeanette, Lohmann, Kenneth J., Musick, John A. (Eds.), The Biology of Sea Turtles, Volume III. CRC Press, pp. 97-133.

Bissell, Matthew. 2013. "Using Volunteered Geographic Information to Model Blue Whale Foraging Habitat, Southern California Bight." Thesis for Master of Science GIST at the University of Southern California.

Blechschmidt, Jana, Meike J. Wittmann, and Chantal Blüml. 2020. "Climate Change and Green Sea Turtle Sex Ratio—Preventing Possible Extinction." *Genes* 11, no. 5: 588.

Buden, Donald W. and Asher Edward. 2001. "Abundance and Utilization of Sea Turtles on Pohnpei, Federated States of Micronesia: Islanders' Perspective." *Micronesica* 32(1): 47-54.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan. 2013. Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Donnelly, Marydele. 2011. "Sea Turtles and CITES." *SWOT Report* vol. 6.

Dowling, Caitlan. 2015. "Maxent Modeling to Predict Habitat of Mountain Pine Beetles in Response to Climate Change." Thesis for Master of Science GIST at the University of Southern California.

Eklof, Anna, and Bo Ebenman. 2006. "Species Loss and Secondary Extinctions in Simple and Complex Model Communities." *Journal of Animal Ecology* 75, no. 1: 239–46.

Emergency Events Database. EM-DAT Public Mapping Tool. https://public.emdat.be/mapping Accessed March 23, 2022.

Esteban, Nicole, Jeanne A. Mortimer, Holly J. Stokes, Jacques-Olivier Laloë, Richard K. Unsworth, and Graeme C. Hays. 2020. "A Global Review of Green Turtle Diet: Sea Surface Temperature as a Potential Driver of Omnivory Levels." *Marine Biology* 167, no. 12.

Fish, Marianne, Isabelle M. Côté, Jennifer A. Gill, Andy P. Jones, Saskia Renshoff, & Andrew R. Watkinson. 2005. "Predicting the Impact of Sea-Level Rise on Caribbean Sea Turtle Nesting Habitat." *Conservation Biology* 19: 482–491.

Fitzpatrick, Scott M., and Christina M. Giovas. 2021. "Tropical Islands of the Anthropocene: Deep Histories of Anthropogenic Terrestrial–Marine Entanglement in the Pacific and Caribbean." *Proceedings of the National Academy of Sciences* 118, no. 40.

Foster, S.J. and A.C.J. Vincent. 2021. "Holding Governments Accountable for Their Commitments: CITES Review of Significant Trade for a Very High-Volume Taxon." *Global Ecology and Conservation* 27.

Fourcade, Yoan, Jan O. Engler, Dennis Rödder, and Jean Secondi. 2014. "Mapping Species Distributions with Maxent Using a Geographically Biased Sample of Presence Data: A Performance Assessment of Methods for Correcting Sampling Bias." *PLoS ONE* 9, no. 5.

Fuentes, Mariana M.P.B., Mark Hamann, and Colin J. Limpus. 2010. "Past, Current and Future Thermal Profiles of Green Turtle Nesting Grounds: Implications from Climate Change." *Journal of Experimental Marine Biology and Ecology* 383, no. 1: 56–64.

Fuentes, Mariana M.P.B., and Warren P. Porter. 2013. "Using a Microclimate Model to Evaluate Impacts of Climate Change on Sea Turtles." *Ecological Modelling* 251: 150–57.

Fuentes, Mariana, et al. 2020. "Potential adaptability of marine turtles to climate change may be hindered by coastal development in the USA." *Regional Environmental Change* 20:104

Fuller, T., Morton, D., and Sarkar, S. 2008. "Incorporating uncertainty about species potential distributions under climate change into the selection of conservation areas with a case study from the Arctic Coastal Plain of Alaska." *Biological Conservation* 141: 1547-1559.

Galvez D., Castellan G., Radulović M., PicciulinM., Falkner R., VučurBlazinić T., Rako-Gospić N., Frleta-Valić M., Antoninić V., Constaratas A., Madricardo F., Ghezzo M. 2021. "Creation of habitat suitability models (HSMs) that provide the expected distribution of target organisms." SOUNDSCAPE project, WP4, 28 pp.

Guo, Jing. 2014. "Modelling loggerhead sea turtle nesting habitat." Thesis for Geo-Information Science and Earth Observation at the University of Twente. https://library.itc.utwente.nl/papers_2014/msc/nrm/guo.pdf

Harris, J. Berton, J. Leighton Reid, Brett R. Scheffers, Thomas C. Wanger, Navjot S. Sodhi, Damien A. Fordham, and Barry W. Brook. 2011. "Conserving Imperiled Species: A Comparison of the IUCN Red List and US Endangered Species Act." *Conservation Letters* 5, no. 1: 64–72.

Hawkes, Lucy A., Annette C. Broderick, Matthew H. Godfrey, and Brendan J. Godley. 2009. "Climate Change and Marine Turtles." *Endangered Species Research* 7: 137–54.

Hays, Graeme C. 2017. "Ocean Currents and Marine Life." *Current Biology* 27, no. 11.

Hays, Graeme C., and Lucy A. Hawkes. 2018. "Satellite tracking sea turtles: Opportunities and challenges to address key questions." *Frontiers in Marine Science 5*.

Helliwell, Richard and Josh Chapman. 2013. "Use of species distribution models in conservation biology." US Department of Agriculture Forest Service, Region 6 and US Department of Interior Oregon/Washington Bureau of Land Management.

Hensz, Christopher Michael, and Jorge Soberón. 2018. "Participation in the Convention on Migratory Species: A Biogeographic Assessment." *Ambio* 47, no. 7: 739–46.

Hoegh-Guldberg, Ove, Peter J. Mumby, A. J. Hooten, Robert S. Steneck, Paul Greenfield, Edgardo D. Gomez, Catherine D. Harvell, Peter F. Sale, Alasdair J. Edwards, Ken Caldeira, Nancy Knowlton, C. Mark Eakni, Roberto Iglesias-Prieto, Nyawira Muthiga, Roger H. Bradbury, Alfonse Dubi, and Marea E. Hatziolos. 2007. "Coral Reefs Under Rapid Climate Change and Ocean Acidification." *Science*: 1737-1742.

Howard, Robert, Ian Bell, and David Pike. 2014. "Thermal tolerances of sea turtle embryos: Current understanding and future directions." *Endangered Species Research* 26: 75-86.

Howell, Lyndsey N., and Donna J. Shaver. 2021. "Foraging Habits of Green Sea Turtles (*Chelonia Mydas*) in the Northwestern Gulf of Mexico." *Frontiers in Marine Science* 8.

Hoyos, Carlos D., P.A. Agudelo, Peter J. Webster, and Judith A. Curry. 2006 "Deconvolution of the factors contributing to the increase in global hurricane intensity." *Science* 312, no. 5770: 94-97.

Intergovernmental Panel on Climate Change. 2013c. "IPCC Factsheet: What is the IPCC? Intergovernmental Panel on Climate Change website." Available at https://www.ipcc.ch/site/assets/uploads/2018/02/FS_what_ipcc.pdf. Accessed on June 10, 2022.

Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* by R.K. Pachauri and L.A. Meyers.

Intergovernmental Panel on Climate Change. 2019. Summary for Policymakers. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate,* by H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer.

Intergovernmental Panel on Climate Change. 2021. Summary for Policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, by Valerie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L. Connors, Clotilde Péan, Sophie Berger, Nada Caud, Yang Chen, Leah Goldfarb, Melissa I. Gomis, Mengtian Huang, Katherine Leitzell, Elisabeth Lonnoy, J.B. Robin Matthews, Thomas K. Maycock, Tim Waterfield, Ozge Yelekçi, Rong Yu, and Baiquan Zhou.

Kalinski, Cass. 2019. “Building better species distribution models with machine learning: Assessing the role of covariate scale and tuning in Maxent models.” Thesis for Master of Science GIST at the University of Southern California.

Kellner, Christopher J., Jeffrey D. Brawn, and James R. Karr. 1992. “What Is Habitat Suitability and How Should It Be Measured?” *Wildlife 2001: Populations*, 476–88.

Kirk, David Anthony, Allysia C. Park, Adam C. Smith, Briar J. Howes, Brigid K. Prouse, Naschelly G. Kyssa, Elizabeth N. Fairhurst, and Kent A. Prior. 2018. “Our Use, Misuse, and Abandonment of a Concept: Whither Habitat?” *Ecology and Evolution* 8, no. 8: 4197–4208.

Kittinger, John N., Kyle S. Houtan, Loren E. McClenachan, and Amanda L. Lawrence. 2013. “Using Historical Data to Assess the Biogeography of Population Recovery.” *Ecography* 36, no. 8: 868–72.

Landry, Melissa S. and Christopher T. Taggart. 2009. “Turtle Watching’ Conservation Guidelines: Green Turtle (Chelonia Mydas) Tourism in Nearshore Coastal Environments.” *Biodiversity and Conservation* 19, no. 1: 305–12.

Lauria, V., M. Gristina, M. J. Attrill, F. Fiorentino, and G. Garofalo. 2015. “Predictive Habitat Suitability Models to Aid Conservation of Elasmobranch Diversity in the Central Mediterranean Sea.” *Scientific Reports* 5, no. 1.

Lindsey, Rebecca. 2021. “Climate Change: Global Sea Level.” Climate Change: Global Sea Level | NOAA Climate.gov.

Lohmann, Kenneth J. 2007. “Sea Turtles: Navigating with Magnetism.” *Current Biology* 17, no. 3.

Lovich, Jeffrey E., Joshua R. Ennen, Mickey Agha, and J Whitfield Gibbons. 2018. “Where Have All the Turtles Gone, and Why Does It Matter?” *BioScience* 68, no. 10: 771–81.

Luschi, Paolo, Graeme C. Hays, and Floriano Papi. 2003. “A Review of Long-Distance Movements by Marine Turtles, and the Possible Role of Ocean Currents.” *Oikos* 103, no. 2: 293–302.

Maison, Kimberly A., Irene Kinan Kelly, and Karen P. Frutchey. 2010. “Green turtle nesting sites and sea turtle legislation throughout Oceania.” NOAA Tech. Memo. NMFS-F/SPO; 110.

Marler, Thomas E. 2014. “Pacific Island Tropical Cyclones Are More Frequent and Globally Relevant, Yet Less Studied.” *Frontiers in Environmental Science* 2.

Mazaris, Antonios D., Gail Schofield, Chrysoula Gkazinou, Vasiliki Almpanidou, and Graeme C. Hays. 2017. “Global Sea Turtle Conservation Successes.” *Science Advances* 3, no. 9.

Merow, Cory, Matthew J. Smith, and John A. Silander. 2013. "A Practical Guide to Maxent for Modeling Species' Distributions: What It Does, and Why Inputs and Settings Matter." *Ecography* 36, no. 10: 1058–69.

Miller, Jeffrey. 1997. "Reproduction in sea turtles." In: Lutz, Peter L., Musick, John A. (Eds.), The Biology of Sea Turtles Volume I. CRC Press LLC, Boca Raton, pp. 51–82.

Miller, Jennifer and John Rogan. 2007. "Using GIS and remote sensing for ecological modeling and monitoring." In: Integration of GIS and Remote Sensing edited by Victor Mesev, Ch 10.

Mimura, Nobuo. 2013. "Sea-Level Rise Caused by Climate Change and Its Implications for Society." *Proceedings of the Japan Academy, Series B* 89, no. 7: 281–301.

Mortimer, Jeanne. 2002. "Sea Turtle Biology and Conservation in the Arnavon Marine Conservation Area (AMCA) of the Solomon Islands."

National Oceanic and Atmospheric Administration. 2021. "Tropical Cyclone Climatology." NATIONAL HURRICANE CENTER and CENTRAL PACIFIC HURRICANE CENTER. Accessed August 14, 2022. https://www.nhc.noaa.gov/climo/.

National Marine Fisheries Service and US Fish and Wildlife Service. 1998. "Recovery Plan for US Pacific Populations of the Green Turtle (*Chelonia mydas*)." National Marine Fisheries Service, Silver Spring, MD.

National Marine Fisheries Service, National Oceanic and Atmospheric Administration, and US Fish and Wildlife Service. 2016. "Endangered and Threatened Wildlife and Plants; Final Rule to List Eleven Distinct Population Segments of the Green Sea Turtle (Chelonia mydas) as Endangered or Threatened and Revision of Current Listings Under the Endangered Species Act." *Federal Register* 81, no. 66: 20058-20090.

Nazarenko, L., Schmidt, G.A., Miller, R.L., Tausnev, N., Kelley, M., Ruedy, R., Russell, G.L., Aleinov, I., Bauer, M., Bauer, S., Bleck, R., Canuto, V., Cheng, Y., Clune, T.L., Del Genio, A.D., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Lo, K.K., Menon, S., Oinas, V., Perlwitz, J., Puma, M.J., Rind, D., Romanou, A., Sato, M., Shindell, D.T., Sun, S., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S., Zhang, J. 2015. "Future climate change under RCP emission scenarios with GISS ModelE2." J. Adv. Model. Earth Syst. 7, 244–267.

Neel, Maile C., Allison K. Leidner, Aaron Haines, Dale D. Goble, and J. Michael Scott. 2012. "By the Numbers: How Is Recovery Defined by the US Endangered Species Act?" *BioScience* 62, no. 7: 646–57.

Ordiz, A., Aronsson, M., Persson, J., Støen, O.-G., Swenson, J. E., & Kindberg, J. 2021. "Effects of human disturbance on terrestrial apex predators." *Diversity*, *13*(2), 68.

Pandolfi, John M., Sean R. Connolly, Dustin J. Marshall, and Anne L. Cohen. 2011. "Projecting Coral Reef Futures Under Global Warming and Ocean Acidification." *Science* 333, no. 6041: 418–22.

Patrício, A.R., L.A. Hawkes, J.R. Monsinjon, B.J. Godley, and MMPB Fuentes. 2021. "Climate Change and Marine Turtles: Recent Advances and Future Directions." *Endangered Species Research* 44: 363–95.

Paulau, Gustav. 2003. "The marine biodiversity of Guam and the Marianas." *Micronesica* 3536:3-25.

Pettorelli, Nathalie, Nicholas A. Graham, Nathalie Seddon, Mercedes Maria da Cunha Bustamante, Matthew J. Lowton, William J. Sutherland, Heather J. Koldewey, Honor C. Prentice, and Jos Barlow. 2021. "Time to Integrate Global Climate Change and Biodiversity Science-Policy Agendas." *Journal of Applied Ecology* 58, no. 11: 2384–93.

Phillips, S. J., M. Dudik, and R. E. Schapire. 2004. "A Maximum Entropy Approach to Species Distribution Modeling." Proceedings of the 21st International Conference on Machine Learning 655–655–662.

Phillips, Steven J. and Miroslav Dudik. 2007. "Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation." *Ecography* 31: 161-175.

Phillips, Steven J. 2017. A Brief Tutorial on Maxent. Available from url: http://biodiversityinformatics.amnh.org/open_source/maxent/.

Pierri, Cataldo, Manuel Marra, Paolo Colangelo, Roberto Carlucci, Gianluca Cirelli, Annachiara Pisto, Giuseppe Corriero, Giovanni Scillitani. 2019. "Habitat suitability for loggerhead turtle nesting sites along the Southern Adriatic and Northern Ionian (Central Mediterranean Sea)." IMEKO TC-19 International Workshop on Metrology for the Sea.

Pike, David A. 2013. "Climate Influences the Global Distribution of Sea Turtle Nesting." *Global Ecology and Biogeography* 22, no. 5: 555–66.

Pike, David A. 2014. "Forecasting the viability of sea turtle eggs in a warming world." *Global Change Biology* 20, 7-15.

Poloczanska, Elvira S., Colin J. Limpus, and Graeme C. Hays. 2009. "Chapter 2 Vulnerability of Marine Turtles to Climate Change." *Advances in Marine Biology* 151–211.

Pradhan, Prakash and Ahmad Dwi Setyawan. 2021. "Filtering multi-collinear predictor variables from multi-resolution rasters of WorldClim 2.1 for Ecological Niche Modeling in Indonesian context." *Asian Journal of Forestry* 5, no. 2:111-122.

Ramírez, Francisco, Isabel Afán, Lloyd S. Davis, and André Chiaradia. 2017. "Climate Impacts on Global Hot Spots of Marine Biodiversity." *Science Advances* 3, no. 2.

Reid, Phillip C., Astrid C. Fischer, Emily Lewis-Brown, Michael. P. Meredith, Mike Sparrow, Andreas J. Andersson, Avan Antia, et al. 2009. "Chapter 1 Impacts of the Oceans on Climate Change." *Advances in Marine Biology*, 1–150.

Rowden, A, O.F. Anderson, S.E. Georgian, D. A. Bowden, M.R. Clark, A. Pallentin, and A. Miller. 2017. "High-Resolution, Habitat-Suitability Maps for the Conservation and Management of Vulnerable Marine Ecosystems on the Louisville Seamount Chain, South Pacific Ocean." *Frontiers in Marine Science* 4

Runge, Claire A., Ayesha Tulloch, Edd Hammill, Hugh P. Possingham, and Richard A. Fuller. 2015. "Geographic range size and extinction risk assessment in nomadic species." *Conservation Biology* 29: 865-876.

Sadoti, Giancarlo, Stephanie A. McAfee, E. Fleur Nicklen, Pamela J. Sousanes, and Carl A. Roland. 2020. "Evaluating Multiple Historical Climate Products in Ecological Models under Current and Projected Temperatures." *Ecological Applications* 31, no. 2.

Santos, R.G., Martins, A.S., Farias, J.D.N., Horta, P.A., Pinheiro, H.T., Torezani, E., Baptistotte, C., Seminoff, J.A., Balazs, G.H., Work, T.M. 2011. "Coastal habitat degradation and green sea turtle diets in Southeastern Brazil." *Marine Pollution Bulletin* 62: 1297–302.

Seminoff, Jeffrey A., Camryn D. Allen, George H. Balazs, Peter H. Dutton, Tomoharu Eguchi, Heather Haas, and Stacy A. Hargrove et al. 2015. "Status Review of the Green Turtle (Chelonia Mydas) Under the Endangered Species Act." La Jolla, CL: US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service [Southwest Fisheries Science Center].

Shafiezadeh, Mohammad, Hossein Moradi, Sima Fakheran, Saeid Pourmanafi, and Josef Senn. 2019. "Integrated Coastal-Terrestrial Conservation Planning for Landscape-Scale Reserve Design in Southeastern Iran." *Ecological Indicators* 103: 756–65.

Sinclair, Steve J., Matthew D. White, and Graeme R. Newell. 2010. "How Useful Are Species Distribution Models for Managing Biodiversity under Future Climates?" *Ecology and Society* 15, no. 1.

Smolek, Audra. 2015. "Spatial distribution of the greater sage-grouse in the powder river basin in northeastern Wyoming." Thesis for Master of Science GIST at the University of Southern California.

Stocker, T.F., Dahe, Q., Plattner, G.-K., Alexander, L. V., Allen, S.K., Bindoff, N.L., Bréon, F.-M., Church, J.A., Cubash, U., Emori, S., Forster, P., Friedlingstein, P., Talley, L.D., Vaughan, D.G., Xie, S.-P. 2013. IPCC Technical Summary AR5. In: [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V.B. and P.M.M. (Ed.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on

Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 33–11z

Suckling, Kieran, Loyal A. Mehrhoff, Ryan Beam, and Brett Hartl. 2016. "A Systematic Review of Bird Recovery Under the Endangered Species Act." *Center for Biological Diversity*

Summers, Tammy M., Summer L. Martin, Jessy R. Hapdei, Joseph K. Ruak, and T. Todd Jones. 2018. "Endangered Green Turtles (Chelonia Mydas) of the Northern Mariana Islands: Nesting Ecology, Poaching, and Climate Concerns." *Frontiers in Marine Science* 4.

Sunarto, M.N. Malawani, M.H. Sasongko, I. Elvira, I.P. Nastiti, P. Arlita, and E.S. Arinda. 2019. "A Geomorphological Evaluation of Sea Turtles Nesting in the Southern Sea of West Java." *IOP Conference Series: Earth and Environmental Science* 256: 012028.

Thums, Michele, Scott D. Whiting, Julia Reisser, Kellie L. Pendoley, Charitha B. Pattiaratchi, Maira Proietti, Yasha Hetzel, Rebecca Fisher, and Mark G. Meekan. 2016. "Artificial Light on Water Attracts Turtle Hatchlings during Their near Shore Transit." *Royal Society Open Science* 3, no. 5: 160142.

UNDP. 2010. "Millennium Development Goals and Status Report 2010 of Federated States of Micronesia: United Nations Development Programme." Accessed August 16, 2022. https://www.undp.org/pacific/publications/millennium-development-goals-and-status-report-2010-federated-states-micronesia.

UNESCO World Heritage. 2011. "Ogasawara Islands." Accessed August 16, 2022. https://whc.unesco.org/en/list/1362/.

US Fish and Wildlife Service. 2011. "Marine Turtle Conservation Act: Activities Report for the Wildlife Without Borders - Species Programs Six Year Report FY 2005-FY 2010." Printed December 2011. Accessed on February 23, 2022. https://www.fws.gov/international/pdf/summary-report-marine-turtle-2005-2010.pdf.

Van Houtan, Kyle S. and Oron L. Bass. 2007. "Stormy Oceans Are Associated with Declines in Sea Turtle Hatching." *Current Biology* 17, no. 15.

Wiens, John J. 2016. "Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species." PLOS Biology 14, no. 12.

Wilson, Clevo and Clem Tisdell. 2003. "Conservation and Economic Benefits of Wildlife-Based Marine Tourism: Sea Turtles and Whales as Case Studies." *Human Dimensions of Wildlife* 8, no. 1: 49–58.

Wright, Marsha K., Lance R. Pompe, Deepak R. Mishra, Dustin S. Baumbach, Lidia Salinas, and Stephen G. Dunbar. 2022. "Hawksbill Presence and Habitat Suitability of a Marine Reserve in Honduras." *Ocean & Coastal Management* 225: 106204.

Wood, Hannah L, John I Spicer, and Stephen Widdicombe. 2008. "Ocean Acidification May Increase Calcification Rates, but at a Cost." *Proceedings of the Royal Society B: Biological Sciences* 275, no. 1644: 1767–73.

WorldAtlas. "Guam Maps & Facts." WorldAtlas. WorldAtlas, February 25, 2021. Accessed on August 10, 2022. https://www.worldatlas.com/maps/guam.

WorldAtlas. "Marshall Islands Maps & Facts." WorldAtlas. WorldAtlas, February 25, 2021. Accessed on August 10, 2022. https://www.worldatlas.com/maps/marshall-islands.

WorldAtlas. "Northern Mariana Islands Maps & Facts." WorldAtlas. WorldAtlas, February 25, 2021. Accessed on August 10, 2022. https://www.worldatlas.com/maps/northern-mariana-islands.

WorldAtlas. "Papua New Guinea Maps & Facts." WorldAtlas. WorldAtlas, February 25, 2021. Accessed on August 10, 2022. https://www.worldatlas.com/maps/papua-new-guinea.

WorldAtlas. "Solomon Islands Maps & Facts." WorldAtlas. WorldAtlas, February 25, 2021. Accessed on August 10, 2022. https://www.worldatlas.com/maps/solomon-islands.

Yarrow, Greg. 2009. "Habitat Requirements of Wildlife: Food, Water, Cover and Space." *Forestry and Natural Resources.* Accessed on July 12, 2022. https://dc.statelibrary.sc.gov/bitstream/handle/10827/41214/CU_ES_FNR_Fact_Sheet_14_2009-05.pdf?sequence=1.