DEVELOPMENT OF A SPECIES DISTRIBUTION MODEL FOR THE EAST PACIFIC GREEN SEA TURTLE USING ECOLOGICAL GEOPROCESSING TOOLS

A Thesis

by

ROXANNE GENEVIEVE DUNCAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Oceanography

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Approved by:

Chair of Committee,	Douglas Biggs
Committee Members,	Steven DiMarco
	Anthony Filippi
Head of Department,	Piers Chapman

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ABSTRACT

Development of a Species Distribution Model for the East Pacific Green Sea Turtle
Using Ecological Geoprocessing Tools. (August 2012)
Roxanne Genevieve Duncan, B.S., South Carolina State University
Chair of Advisory Committee: Dr. Douglas Biggs

East Pacific green sea turtles, *Chelonia mydas*, play ecologically important roles in marine habitats which range from grazing (and thus regularly “mowing”) algae and seagrass beds to cycling nutrients between the ocean and land. However, these important grazers have been hunted to ecological extinction in some places for their eggs, meat, and skin. The conservation initiative for the survival of sea turtles requires the protection of their primary habitats in conjunction with a decrease in their interaction with humans. One way these objectives can be met is through the creation of species distribution maps (SDMs). For this thesis, a SDM was created from a generalized additive model used to identify major feeding areas for East Pacific green turtles residing in the Galapagos Islands. The input for the model was green turtle sighting locations during a June 2010 marine life observation survey and remotely sensed values of four oceanographic parameters obtained from satellite sensors (Bathymetry, Sea Surface Temperature, Chlorophyll a, and Current Speed). Line transects of intertidal and subtidal shoreline regions of the islands of Isabela, San Cristobal, and Floreana were also completed, to describe similarities and differences in macroalgal abundance between the locations.

A generalized additive model (GAM) explained 56% of the data's null deviance and had a true positive rate of 0.83. The corresponding species distribution map indicated that East Pacific green sea turtles prefer to forage in warm, low chlorophyll a, slow moving waters at depths mostly less than 250m throughout the archipelago. ANOVA analyses showed that macroalgal abundance was statistically different (p-value < 0.01) between the islands of San Cristobal and Isabela. The line transects analysis also documented that red algae was the most prominent phyla at the sites and that the macroalgal abundance did not vary much between months June 2010 and April/May 2011. With these results, potential foraging areas for East Pacific green turtles can be identified and protected. Future studies will be focused on the collection of macroalgae from coastal areas outlined in the SDM and the interactions between green turtles and their competitors and/or predators. This information can be used to validate the areas delineated by the model and to further the understanding of the spatial-temporal effects on macroalgal abundance.

DEDICATION

I would like to dedicate this Master's thesis to my mother, Cheryl Duncan and my sister, Dr. Renee Duncan. There is no doubt in my mind that without their encouragement and support, I could not have made it through this course of research. I also dedicate my work to my deceased father, Kenneth Duncan.

ACKNOWLEDGEMENTS

I would never have been able to complete my thesis without the assistance of my Advisor and my committee members, advice from friends, and the unequivocal support from my family.

I would like to express my sincere gratitude to my Advisor, Dr. Biggs, who allowed me to focus my research on a topic for which I have a lot of passion. Without his support, I would never have been able to visit the Galapagos Islands to collect my data. I am very grateful to Dr. DiMarco and Dr. Filippi for their advice during the analysis of my data and creation of my model as well as for their in-depth comments on my thesis. I would like to thank Dr. Howard who aided me in the collection of my data layers.

I am thankful to Julia O’Hern, Michelle Johnston and my fellow volunteers from the Charles Darwin Research Station who helped me collected my turtle and macroalgal data during June 2010 and April and May 2011. I would like to thank the Instituto Oceanográphic de la Armada del Ecuador, the Charles Darwin Research Station, and the Parque Nacional Galápagos for their assistance with the rental of small boats in June 2010 and for the opportunity to observe the nesting of the East Pacific green turtle for two months. I am also indebted to the Department of Oceanography for their financial support during my research and my Master’s matriculation.

Most importantly, I would like to thank my mother, my sister and my friends, especially Candice Johnson, for their unwavering support during the good and not so good times. They have been a constant source of strength and encouragement throughout my research.

NOMENCLATURE

ANOVA	Analysis of Variance
ASCII	American Standard Code for Information Interchange
CARIS	Computer Aided Resource Information System
CART	Classification and Regression Trees
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
DEM	Digital Elevation Model
ENSO	El Niño/Southern Oscillation
ERDAS	Earth Resources Data Analysis System
ESRI	Environmental Systems Research Institute
ESW	Equatorial Surface Water
EUC	Equatorial Undercurrent
GAM	Generalized Additive Model
GIS	Geographic Information System
GIOVANNI	Goddard Earth Sciences Data and Information Services Center's Interactive Online Visualization and Analysis Infrastructure
GLM	Generalized Linear Model
HDF	Hierarchical Data Format
ITCZ	Intertropical Convergence Zone

MEI	Multivariate ENSO Index
MGET	Marine Geospatial Ecological Tools
MODIS	Moderate Resolution Imaging Spectroradiometer
NE	North-East
NECC	North Equatorial Counter Current
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
SDM	Species Distribution Model
SE	South-East
SEC	South Equatorial Current
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TIW	Tropical Instability Wave
TSW	Tropical Surface Water

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CHAPTER I

INTRODUCTION & LITERATURE REVIEW

Introduction

Green sea turtles, *Chelonia mydas,* are the largest-sized species of marine turtle in the *Cheloniidae* family (Pritchard and Mortimer, 1999). Greens can be distinguished from other marine turtles by their round skull, short snout, and multi-colored carapace, which have four pairs of non-overlapping keratinous scutes. The rhamphotheca or beak is serrated with spike-like denticles that aid in tearing and chewing macroalgae or seagrass (Wyneken, 2003). Green turtles are generally considered to be coastal herbivores (Hatase et al., 2006); however, in their hatchling stage, they live in oceanic waters and feed on planktonic animal matter until they return to coastal foraging grounds as juveniles and sub-adults that begin feeding on either macroalgae or seagrass, depending on specific geographic location (Reich et al., 2007). Recent studies have shown that adult green turtles will also consume animal matter, in small volumes (mean relative volume = 8.75%), to supplement their diet (Hatase et al., 2006; Carrion-Cortez et al., 2010). This species is most common in the tropical and subtropical waters of the Atlantic, Indian and Pacific Oceans. In each ocean, green turtles display intraspecific variations, for example by carapace length, clutch size and food preference. Green turtles residing in the Galapagos are smaller (81.9 cm) than green turtles inhabiting the coastal waters of Australia and Hawaii (102.4 cm and 92.2 cm respectively).

This thesis follows the style of Ecological Modelling.

Galapagos green turtles also produces the smallest egg clutch size and hatchling in the Pacific (Vanbuskirk and Crowder, 1994).

Regardless of their geographic home range, all green sea turtles display nest-fidelity (returning to the area of their birth to lay their eggs). In fact, many green turtles migrate thousands of miles to return to their birth place. For example, Atlantic green turtles feeding in Brazil's neritic waters travel approximately 2 000 km to Ascension Island to nest. Studies have shown that during their transatlantic journey, these green turtles use environmental cues such as ocean currents and, to a lesser extent, sea surface temperature to guide them on their journey (Plotkin, 2003). With their vast oceanic migrations and nearshore foraging lifestyle and with 38% of the human population living within 100km of the coast, turtles and humans live in close contact with each other. Despite their status as a protected species, human activities have resulted in an increased green sea turtle mortality rate; humans have had predator/prey and amensal relationships with sea turtles since 3000 B.C.E. (Frazier, 2003). These turtles have been preyed upon for their meat, fat, and eggs in nearly every geographic region where they reside thus decreasing their population numbers (Campbell, 2003).

Exposure to and bioaccumulation of metals and lipophilic compounds, that are anthropogenically introduced, and eutrophication threaten the survival of these creatures. Fortunately because of their herbivorous lifestyle (low trophic level status), heavy metal bioaccumulation in these turtles is lower than their *Cheloniidae* relatives that are carnivores. Conversely, the effects of eutrophication, on the other hand, can have disastrous consequences if the increase in nutrients increases blue-green algal species at the expense of their macroalgal food supply, and/or if eutrophication increases toxins and brevetoxins levels in the water. Toxins such as okadaic acid, produced by the dinoflagellates *Prorocentrum* spp. have been linked to fibropapilloma tumors found on green turtles. Overall, anthropogenic impacts have caused this species to be in critical need of conservation and protection (Milton and Lutz, 2003).

One noteworthy refuge for green turtles is the Galapagos Islands. Located in the equatorial Pacific Ocean, this group of islands is a major feeding and nesting site for the East Pacific green sea turtle. At this major nesting site, gravid females are tagged and measured every year by Ecuadorian researchers to access the health of the nesting population, which is composed of individuals from various locations within the eastern Pacific Ocean. Although these efforts are commended and must continue, a comprehensive understanding of the residential turtles' population statistics within the Galapagos Marine Reserve (GMR) is still lacking. This information can be used to determine if the population is improving or is on a decline. Countless numbers of East Pacific green turtles are killed every year as a result of natural causes, boat collisions, and bycatch by artisanal fishing as they swim to distant feeding grounds (Fig. 1). What is presently known about the feeding grounds of these turtles within the archipelago is still quite limited (Green, 1975). To improve our knowledge base and the conservation efforts within the archipelago, it is useful to have a detailed map of potential feeding areas within the GMR. Such a map is a predictive habitat model called a species distribution model.

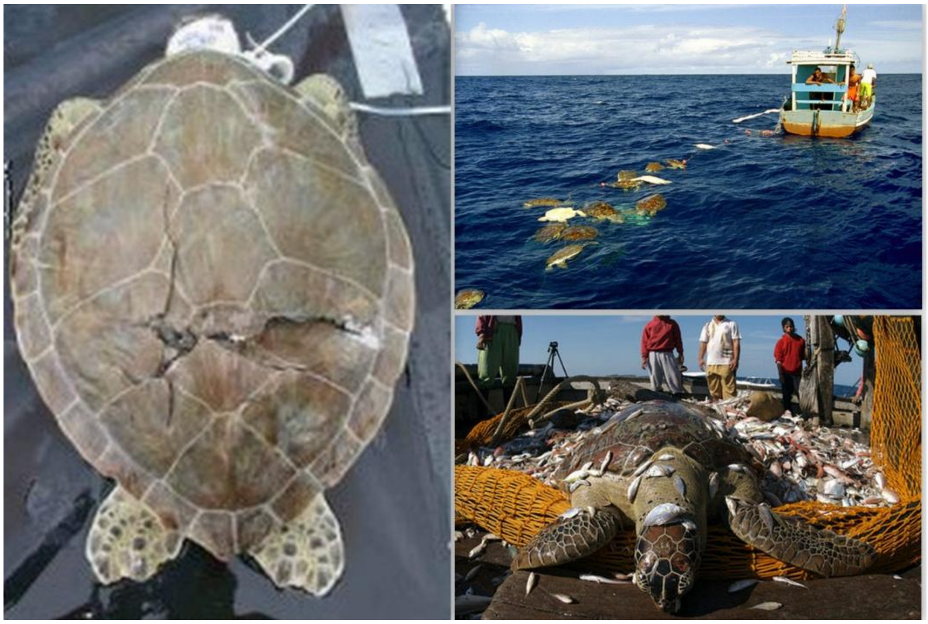

Fig. 1. Images of East Pacific green turtles caught in shrimp nets and long lines and the injury sustained from a boat collision. Adapted from (clockwise) Stokstad (2010) and Bermuda Turtle Project (2004)

Species distribution models (SDMs) have been used in the field of ecology for 30 years (Guisan et al., 2002; Guisan and Thuiller, 2005; Guisan and Zimmermann, 2000). Most seek to determine how geographical or physical parameters control and limit the distribution of target organisms. Predictive habitat models are characterized as static and probabilistic because they utilize field-derived or empirical data to predict the niche of the particular organism. The disadvantage of this characteristic is that the created model can only be used under the tested physical conditions. This drawback is compensated by the fact that these models are efficient in producing large-scale predictions without detailed preexisting knowledge of the organism (Guisan and Zimmermann, 2000). Fields of study where predictive models have been used extensively range from biogeography of plants and animals (both terrestrial and aquatic), to climate change impact, and to habitat and species management (Franklin, 1998; Guisan and Zimmermann, 2000; Rosa et al., 2012). Independent of the field of study, habitat models are created based on the type of response variable and its probability distribution which are then used to determine the type of statistical approach to be taken to predict and model the distribution.

Species Distribution Models

SDM response variables fall into three main groups, a) quantitative, b) semi-quantitative and c) qualitative (Guisan and Zimmermann, 2000). Quantitative variables can be metric, interval, continuous and/or discrete, and thus a numeric value is assigned (for example percent cover). Semi-quantitative variables are ordinal and can be rank-based using a quantitative measure (i.e., relative abundance). Qualitative variables are considered nominal and categorical because they are usually expressed in text (Guisan and Zimmermann, 2000; Price, 2010). Creation of a predictive habitat distribution model which utilizes presence and absence data can only occur with qualitative response variables whereby areas fitting the required description (presence or absence) are categorized or named accordingly. Qualitative variables can have either a multinomial or binomial distribution and the latter is the most appropriate choice for presence/absence data. Binomially distributed data can be statistically analyzed by various methods; for example, classification approach, environmental envelopes, Bayesian models and multiple regression techniques.

Statistical Techniques

The classification approach contains multiple techniques ranging from classification and regression trees (CART) to maximum likelihood classes (Guisan and Zimmermann, 2000; Myles et al., 2004). This group of methods applies a hierarchical system, devised of decision rules that divide the data into classes of the response variable. The advantage of this process is that it does not rely on singular linear relationships within the data to create the classes. However; this strength can become a disadvantage especially in situations where numerous divisions are required to group all the data. This results in a non-parsimonious classification tree which is also large, complex and difficult to interpret (Myles et al., 2004; StatSoftInc., 2011).

Bayesian networks use two sets of data, the likelihood and the prior distribution. Likelihood represents all the possible outcomes or hypotheses of the analysis. The second group represents any previous knowledge concerning the species in question. This information is usually composed of data originating from different sources, e.g. literature or direct/indirect observations, which have varying degrees of reliability (Lavine, 1991; Stassopoulou et al., 1998; O'Hagan and Forster, 2004). The Bayesian analysis links the two groups via conditional probabilities, which represent the relative frequency of each likelihood component to occur (Stassopoulou et al., 1998). The specialty of this technique lies in its ability to include and model the uncertainty present in the data and account for it in the results (Aspinall and Veitch, 1993; Stassopoulou et al., 1998). But, this method does have an innate limitation. The prior distribution data are highly dependent on the investigator, thus making such data open to subjectivity. This makes the results from the network sensitive to the reliability of the prior distribution data. So, if the prior distribution data are unreliable, e.g. these data inadequately represent the phenomenon being mapped, the results will span a wide range of possible probabilities, and so the model predictions may tend to be inconclusive (Lavine, 1991).

Environmental envelope is the collective name for a group of methods that creates sets of environments based on knowledge that the species resides at the chosen sites. This technique requires three sets of location data: a) surveyed presence, b) observed absence and c) possible presence or absence. The latter group shares similar environmental characteristics with the two former groups. An environmental envelope is created based on the environmental variables that are required for the survival of the target species such as climate, temperature or soil. For example, Walker and Cocks (1991) created environmental envelopes, based on climatic variables, to describe kangaroo distribution in Australia. Each envelope is modeled onto a geographic area to determine the species' potential range. This range contains the complete number of sites with environmental conditions conducive for the presence of the species as well as the locations that fit the description of the known locations (Walker and Cocks, 1991).

There are various methods cited in the literature that utilizes environmental envelopes to identify an organism's potential spatial range; for example BIOCLIM, HABITAT and DOMAIN. Each method is governed by different assumptions and classification processes and ranges in complexity (Walker and Cocks, 1991; Guisan and Zimmermann, 2000). BIOCLIM, also referred to as the Boxcar, is a good example of an environmental envelope modeling technique, which only uses climatic variables. It utilizes preexisting knowledge of location concerning the presence of the species and indicates and confirms the sites where the organism in question may be residing. Therefore, this technique operates under the assumption that the species spatial arrangement is accurate and that it is within the potential range (Walker and Cocks, 1991). Two shortcomings of this method are that the results are limited by the *a priori* knowledge of the species and if inaccurate, the 95% percentile area may contain null or species absence regions. Also in many situations, the amount of data needed to create the potential range are not available (Walker and Cocks, 1991).

There are many different types of regression models; the simplest is the single regression which evaluates the relationship between a response and an explanatory variable. As the number of responses and dependent variables increase, different versions and extensions of the simple model are used. Two in particular are the Generalized Linear models (GLM) and Generalized Additive models (GAM). In the last twenty years, GLMs and GAMs have been used frequently to model species distribution and biodiversity in plants and animals, terrestrial and aquatic (Yee and Mitchell, 1991; Guisan et al., 2002). These modeling techniques are superior to the simple linear regression. One major difference is that the generalized models are able to analyze the effect of continuous and/or categorical predictors on either discrete (binomial, multinomial and even ordinal multinomial) or continuous response variables. They can accommodate both linear and non-linear relationships between the response and the predictors since they can be connected by a link function. Therefore, the link function eliminates the need to modify the data and the models are able to assess the realized niche of the species (Guisan et al., 2002; StatSoftInc., 2011). These advantages make both regression techniques ideal for modeling ecological data, which in many cases do not follow a linear distribution.

The present anthropogenic stress on East Pacific green turtles and the effects of El Niño-Southern Oscillation events on their main food source warrants the need for a conservation plan to minimize these anthropogenic impacts and to describe the macroalgal landscape of the islands. Therefore the purpose of this thesis was to create a GIS-based species distribution model, using the GAM technique, with remotely – sensed data of the Galapagos Islands and East Pacific green turtle sightings collected in June 2010 during a marine life observation cruise. The results will be used to predict areas within the archipelago where East Pacific green turtle presence is high. Also, macroalgal abundance data from line transects completed in areas where green turtles have been observed feeding will be analyzed in hopes of understanding the biological conditions and the importance of these sites.

CHAPTER II

ANALYSIS OF MACROALGAL ABUNDANCE IN THE GALAPAGOS ISLANDS

Galapagos Islands

The Galapagos Islands are approximately 1000 km west of the coast of South America and have been a territory of Ecuador since 1832. The archipelago is made up of 13 major islands, 6 minor islands and 42 islets with a combined area of 6 990 square kilometers (Woods, 1987). The islands Pinta, Marchena and Genovesa lie slightly north of the Equator while all other islands are located in the Southern Hemisphere. The archipelago was created by a volcanic hot spot under the Nazca Plate. Unlike the Hawaiian Islands chain, the molten lava which created the Galapagos Islands erupted through multiple fissures, so there is no clear consecutive order to the growth of the various Galapagos Islands. But with active volcanoes still present on the islands of Isabela and Fernandina and with today’s east-southeast movement of the Nazca plate, the youngest islands are those in the west of the archipelago and the oldest are to the east. Through radiometric and magnetic studies, it was concluded that the oldest island is Espanola, rising to the surface approximately 3.3 M years ago. The youngest islands, Fernandina and Isabela, have an estimated age of 0.7 M years (Simkin, 1984; Woods, 1987).

Ocean Circulation

The equatorial location of the Galapagos is the major contributor to the islands’ oceanographic characteristics. The four major currents that flow through the islands are the South Equatorial Current, the Equatorial Undercurrent, Peruvian currents and the Panama current (Fig. 2).

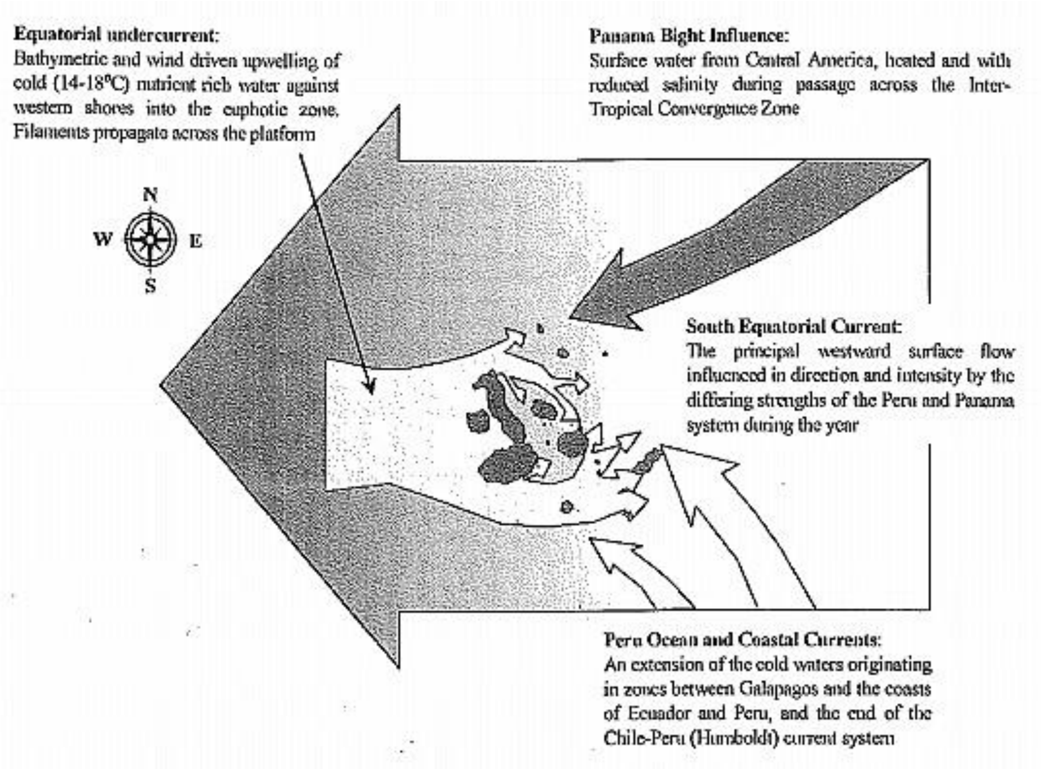

Fig. 2. Major oceanic currents around the Galapagos Islands. Adapted from Bustamante et al. (2008)

Firstly, the South Equatorial Current (SEC) has a western flow between 5°N-10°S and is at its peak from July to January and weakens from February to June. It is strengthened in the eastern Pacific by the Peru Current, the Equatorial Undercurrent, the Equatorial Counter Current and upwelled waters around the islands (Houvenaghel, 1984; Bustamante et al., 2008).

The Equatorial Undercurrent (EUC) is a narrow eastward flowing current, positioned at the equator. In the Western Hemisphere, the current is below the thermocline, but as it flows to the east, the thermocline shoals to the surface. The current is sustained by cold and salty subtropical subsurface waters flowing towards the equator. Owing to the convergence of the NE and SE trade winds at the equator, the undercurrent shoals and creates areas of upwelled water around the islands. The current is strongest to the west of the islands and decreases in strength due to mixing, friction and upwelling as it flows to the east. The Peruvian currents originate off the coast of Ecuador and Peru and from the Humboldt Current. They are salty (34-35) and cold (>20°C) and flow into the archipelago as Equatorial Surface waters (ESW). The Panama Current has a southward flow and is warm and low in salinity (<34). In the archipelago, these waters are labeled as Tropical Surface Water (TSW) (Houvenaghel, 1984; Bustamante et al., 2008).

Meteorological Characteristics

The Galapagos archipelago experiences two seasons, a warm and a cold season. The warm season begins in December and ends in May; it is characterized by light winds and is the season in which most of the rain falls on the archipelago. The cold season, which is referred to in the islands as Garúa, begins in June and ends in November; it is characterized by drizzles, fog and enhanced south to south-east trade winds (Sweet et al., 2007). During the warm season, the Intertropical Convergence Zone (ITCZ) is in its most southern extent. This seasonal oscillation increases the rainfall in the archipelago and brings Tropical Surface Waters (TSW) into the middle of the islands. The Southeast trade wind velocity is at a minimum (~ 2 m/s). The Equatorial Undercurrent (EUC) is strong (155 cm/s) and decreases in depth to the east of the archipelago. It also shoals on Isabela's west coast with a sea surface salinity (SSS) value of >34.9. The EUC's presence in the eastern portion of the archipelago is a result of the current shoaling near the South American mainland and entrainment into the SEC, which brings the upwelled waters westward (Sweet et al., 2007). In the warm season, macroalgae exposed at low tide are found mainly in small quantities (Shepherd and Hawkes, 2005) and generally have less spatial coverage than during Garúa (Fig. 3).

Fig. 3. Macroalgae on rocks exposed at low tide during April 2011.

During the Garúa, the ITCZ zone of rising air moves north of the equator; this change in position results in a velocity boost for the Southeast trade winds (~5 m/s) and a decrease in the sea surface temperature (SST) until November. The high-velocity EUC

(146 cm/s) flows near the thermocline, which is deeper (62 m) to the west of the archipelago (110°W). At 95°W, the current flows above the thermocline and stays at a depth of (~45 m) throughout most of the islands except along the western coast of Isabela. The EUC upwells off Isabela's west coast, resulting in an increase in the SSS (> 34.9). For the rest of the archipelago the surface water is characteristic of ESW (Sweet et al., 2007). During this season of increased nutrients in the surface waters, algal biomass shows visible signs of increase (Fig. 4).

Fig. 4. Macroalgal abundance at low tide during May 2011.

Climate Scale Variability

Two periodic phenomena that impact the Galapagos and adjacent Equatorial Pacific are the El Niño-Southern Oscillation (ENSO) and Tropical Instability Waves

(TIW). ENSO events are large-scale climatic and hydrographic interactions that occur in the tropical Pacific. These events negatively affect East Pacific green turtles by decreasing the abundance and availability of macroalgae. One of the worst ENSO events in recorded history for the Galapagos archipelago was the 1982-83 ENSO event, even though for the Eastern Tropical Pacific region the 1997-1998 ENSO event was stronger. In the Galapagos Islands, macroalgae in 1982-1983 experienced a high mortality rate especially among the Chlorophyta and Rhodophyta groups (Lobban and Harrison, 1994). Many subtidal algae were temperature-stressed due to the depression of the thermocline, which also reduced the near surface nutrient concentrations (Lobban and Harrison, 1994). In the Carrion- Cortez et al., (2010) paper, the authors speculated that the community of macroalgae in the Galapagos may have changed as a result of strong ENSO events thus altering the diet composition of East Pacific green turtles.

The Southern Oscillation is the atmospheric part of the system and it is governed by interannual anomalies in sea surface temperature in the equatorial pacific. It has a characteristic high pressure in the eastern Pacific and low pressure over the western Pacific (Philander, 1990; Stenseth et al., 2003). The Walker Circulation, named after Sir Gilbert Walker, is an ocean-based zonal air circulation system that is influenced by air pressure differences in the Eastern and Western Pacific. Under normal conditions, the Walker Circulation is maintained as dry air sinks in the eastern Pacific and flows west along the equator, steadily increasing in temperature. In the western Pacific, the now warm air rises, brings about heavy rainfall in the western Equatorial Pacific as the moves back east through the upper troposphere (Philander, 1990). The Walker Circulation is maintained once the sea surface temperature in the east is lower than in the west. The circulation system is usually ensured by the strong westerly winds that move warm waters to the west. Once the wind speeds decrease, the eastern Pacific begins to warm and the west Pacific begins to cool and conditions generally observed in the western Pacific begin to appear in the central and east Pacific (Philander, 1990).

Even though temperature anomalies during El Niño events can be as small as 0.5°C (Giese and Ray, 2011), if they persist for 3-6 months such El Nino events can have strong teleconnection effects on a global scale. For example, drought conditions in the Amazon basin and in southern Africa, and low sea levels in the western Pacific, heavy rainfall and increases sea surface temperatures in the eastern Pacific and abnormal weather patterns in southeastern Africa, the US and southwestern Canada (Philander, 1990; Giese and Ray, 2011). According to Sweet et al., (2007), ENSO events within the Galapagos archipelago, have limited effect on the SSS; however, because El Nino events raise the SST and lower the thermocline, strong El Nino events decrease near-surface nutrients (and hence near-surface chlorophyll a concentrations) and reduce the volume of both the SEC and the EUC (Sweet et al., 2007).

Under La Niña conditions, the Eastern Equatorial Pacific may experience the effects of Tropical Instability Waves (TIW). These waves are westward progressing and can be identified in sea surface temperature satellite images as oscillations in the Equatorial Front. There are two types of TIW, 17- and 33- day. The 17- day TIW is created from the cleaving of the SEC's northern lobe and from the EUC while the 33-day TIW receives water from the SEC and the NECC. Within the Equatorial Pacific, the effects of TIW are greatest to the west of the archipelago due to the barotropic instability created from the topographic blocking of the SEC by the islands (Sweet et al., 2009). Upwelling of the TIW can increase the iron concentration within the surface waters, generally leading to an increase in overall productivity in this high nutrient/low chlorophyll region (Sweet et al., 2009). As a result, increases in chlorophyll a concentrations have been documented in the Eastern Equatorial Pacific after upwelling (Sweet et al., 2009), after controlled iron fertilization (Martin et al., 1994) and/or in association with inputs of iron-rich atmospheric dust (Jickells et al., 2005).

Sea Turtles

Four species of sea turtles have been observed in the waters around the islands, hawksbill (*Eretmochelys imbricata*), leatherback (*Dermochelys coriacea*), olive ridleys (*Lepidochelys olivacea*) and the East Pacific green turtle (*Chelonia mydas*) (Fig. 5) (Fritts, 1981; Green, 1984). The East Pacific green turtle is the only sea turtle known to reside and nest in the Galapagos Islands, and the archipelago is one of the major nesting sites for this turtle in the eastern Pacific (Green, 1975; Seminoff et al., 2007; Carrion-Cortez et al., 2010). The East Pacific green turtle is the smallest green turtle in the world (average length just 84.5 cm) which may reflect a diet of almost exclusively macroalgae in this region. They produce small eggs, small clutches and small hatchlings (Green, 1975, 1993; Carrion-Cortez et al., 2010).

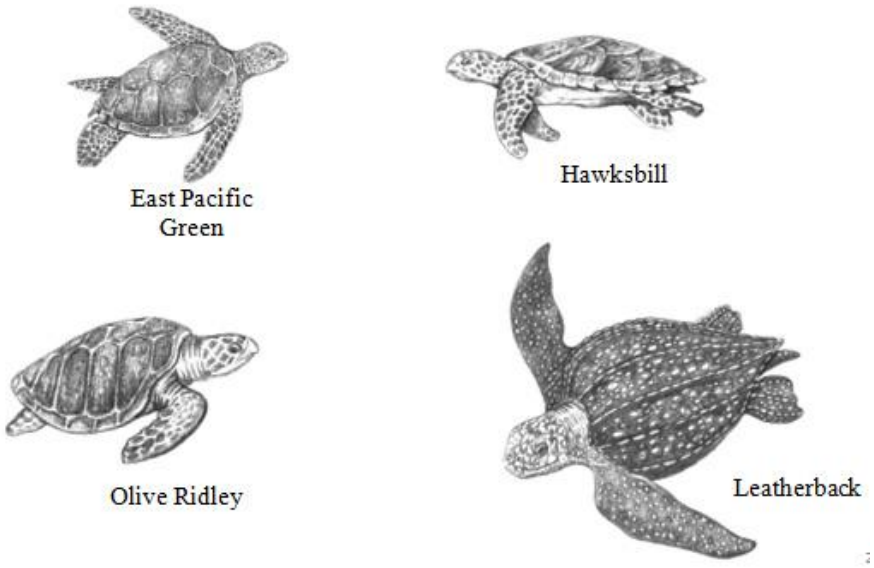

Fig. 5. The four marine turtles observed in the waters around the Galapagos Islands. Adapted from SeaWorld/Busch Gardens Animals website

The species is highly migratory, but does exhibit philopatry, returning to the general area of its birth to lay its eggs between the months of December and June in the Galapagos every 2 to 4 years (Carrion-Cortez et al., 2010). Four major nesting beaches in the Galapagos are Quinta Playa (Isabela), Bahía Barahona (Isabela), Las Salinas (Baltra), and Las Bachas (Santa Cruz); these beaches have been used to study the population ecology and posting-nesting behavior of the turtle for many years (Green, 1975). During the post-nesting period, the turtles return to their specific foraging grounds. According to Godley et al (2008), the turtles that nest in the Galapagos Islands are a combination of three types of post-nesting movements: a) Type A1 turtles that travel more than a thousand kilometers to return to their foraging grounds; for example the Gorgona National Park in Colombia, b) Type A3 individuals that remain in the neritic environments around their nesting sites, and c) Type B individuals feed in pelagic environments (Fig. 6) (Godley et al., 1998; Seminoff et al., 2007; Amorocho et al., 2012).

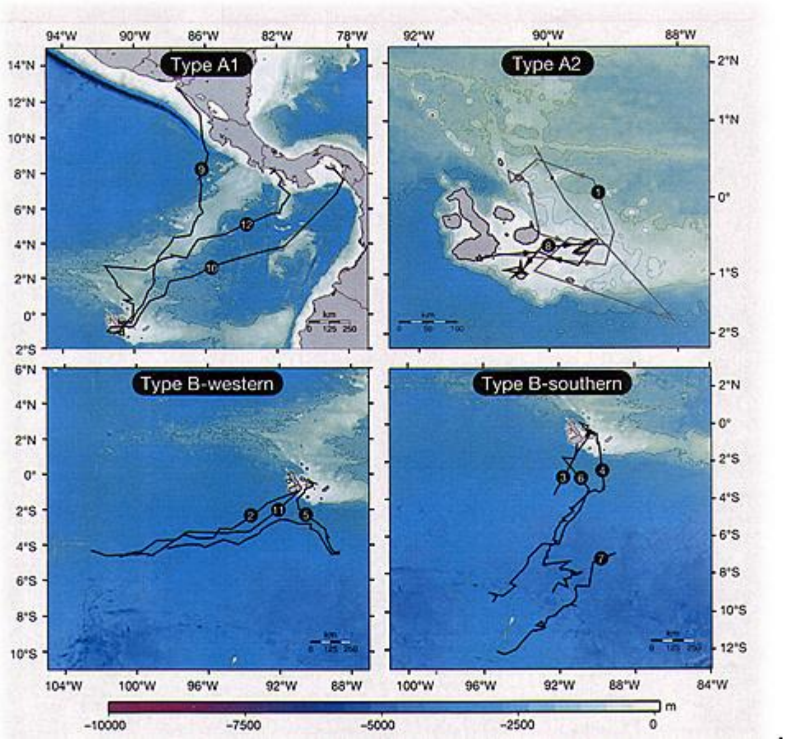

Fig. 6. Map displaying the post-nesting movements of twelve green turtles. (Seminoff et al., 2007)

Feeding Habitats

Galapagos Islands' green sea turtles are almost exclusively herbivorous animals that forage mainly on benthic macroalgae (Green, 1975; Carrion-Cortez et al., 2010). In a recent paper, Carrión-Cortez et al., (2010) reported that these turtles feed mainly on *Ulva* spp*.*, *Polysiphonia* sp., *Hypnea* sp., and *Dictyota* sp. The green algae, *Ulva spp.* was the preferred food for Galapagos green sea turtles, even though it is less nutritious and is difficult to digest. One reason could be that it can persist during the warm seasons when other algal species such as the red alga *Polysiphonia* sp., which is more nutritious, are on a decline. There are major feeding spots where resident and migratory green turtles forage. Resident green turtles are usually sub-adults and juveniles and they feed mainly in bays and coves between Isabela and Fernandina (Bahía Elizabeth, Caleta Derek and Punta Espinoza). Migratory and residential adults have been found to frequent foraging spots in the central and eastern parts of the archipelago such as Punta Nunez and Caleta de la Tortuga Negra (Santa Cruz) (Green, 1975; Carrion-Cortez et al., 2010).

The Galapagos is also the foraging grounds of a yellowish- hued sea turtle; which is aptly named the yellow green turtle. It not only differs in color, but it also has a high fat content for long migrations (Carr, 1964; Fritts, 1981; Green, 1993). Amorocho et al., (2012) showed through haplotype analysis that this population of green turtle nests in the Western Pacific, in the French Polynesia and Micronesia Islands.

Macroalgae

Macroalgae species vary in color, shape and complexity and are grouped into three main phyla of Chlorophyta, Phaeophyta, and Rhodophyta. Each group has both multicellular and unicellular representatives and life stages. In the Galapagos, there are 46 species of brown algae, 237 species of red algae, and 42 species of green algae (Chiriboga et al., 2011). Macroalgae or seaweeds differ from vascular plants in that the functions of the leaves, stems, and roots are analogous to the macroalgae’s blade, stipe, and holdfast respectively (Lobban and Harrison, 1994).

Similar to terrestrial plants, macroalgae are sessile photosynthesizing organisms which require stable substrata for attachment at depths within the photic zone.

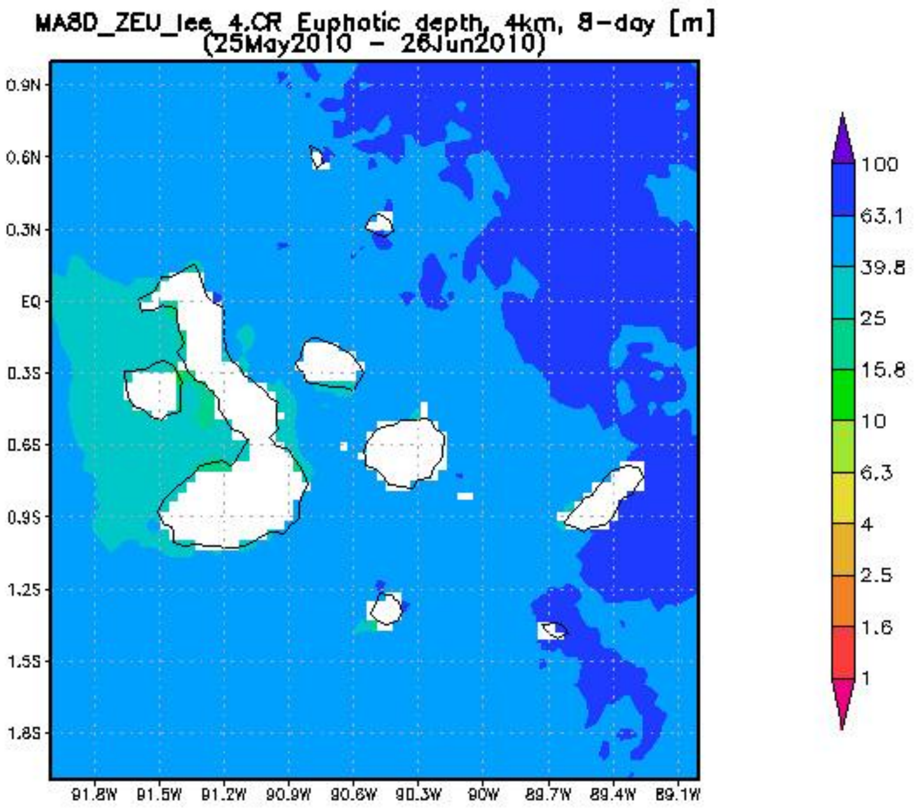

Fig. 7. A map of the Euphotic depth (m) in the Galapagos Islands for the month of June 2010 from the MODIS Aqua.satellite using GIOVANNI

The photic zone is the depth within the water column where the sun's irradiance is 1% and net primary production is zero. Within the Galapagos Islands, the photic zone is shallower along the western coast of Isabela and Fernandina, ranging from 25-39 m. The majority of the bathymetry in this area is at depths greater than 1000 m; therefore, a large portion of this area is unsuitable for macroalgal growth. Conversely, the photic depth in the eastern and central regions of the archipelago is deeper than the western region and it also covers a larger area. In the eastern and central region, the average water depth is 500 m. This combination of features of deeper photic depth and shallower waters create a better environment for the macroalgae to anchor and flourish (Fig. 7).

Stable Isotope Analysis

Macroalgae can also be identified by their stable isotope values. By definition, stable isotopes are two or more varieties of a non-decaying element that have the same atomic number but different mass number (their neutron number is different). Because of the mass difference, stable isotopes of an element will react differently in physical and chemical reactions. In both processes, the degree of fractionation is dependent on the isotope's weight. For example, in a kinetic process such as photosynthesis, the lighter isotope will accumulate faster in the product (simple sugars) than the heavier isotope.

The isotopic composition of a sample is calculated as:

$$\delta^{n}X = \frac{\left(\frac{heavy}{light}\right)_{sample} - \left(\frac{heavy}{light}\right)_{standard}}{\left(\frac{heavy}{light}\right)_{standard}} \text{ x } 10^{3}$$

The standard used in the equation depends on the element being measured and basically acts as a reference point. If $\delta^{n}X$ is positive, then the sample is enriched with the heavier isotope, on the other hand, if $\delta^{n}X$ is negative, then the sample is enriched with the lighter isotope. $\Delta 13C$ and $\delta^{15}N$ are commonly used to determine the source of the sample (carbon) and in the cases of primary and secondary consumers, the trophic level of the sample (nitrogen).

Table 1
Average stable isotope composition of macroalgae and sea urchins from Playa Negro, Isla Floreana (June 2010).

Samples	**δ^{15}N**	**δ^{13}C**
Dictyota (Brown)	6.40	-19.79
Ulva (Green)	6.17	-16.08
Polysiphonia (Red)	6.15	-19.01
Lytechinus semituberculatus Green urchin	8.16	-13.90
Eucidaris thouarsii Slate pencil urchin	8.52	-12.35

The table above lists average δ^{13}C and δ^{15}N values for three algal species and two species of sea urchins from beaches on Isla Floreana. The samples were analyzed in duplicate. Although replication was limited to just two subsamples of each material, the values show that the three algae are isotopically distinct from each other. Concerning the sea urchins, their δ^{13}C signatures are more positive than the macroalgae therefore they are enriched with the heavier isotope due to their higher metabolic rate. The urchins' δ^{15}N values are approximately 2‰ higher than the algae, establishing the link that they are primary consumers of the algae. These stable isotope values from this one location are probably not representative for the entire eastern Tropical Pacific region because each algal habitat will have different ambient conditions. Therefore, the macroalgal and herbivore values measured at the Galapagos, which is a tropical, high nutrient area, will be different from macroalgal and herbivore values from other regions. For example, some of the green turtles feeding in the Japan's Ogasawara Islands are neritic herbivores possessing δ^{13}C and δ^{15}N values of -17.92 and 8.8 respectively (Hatase et al., 2006).

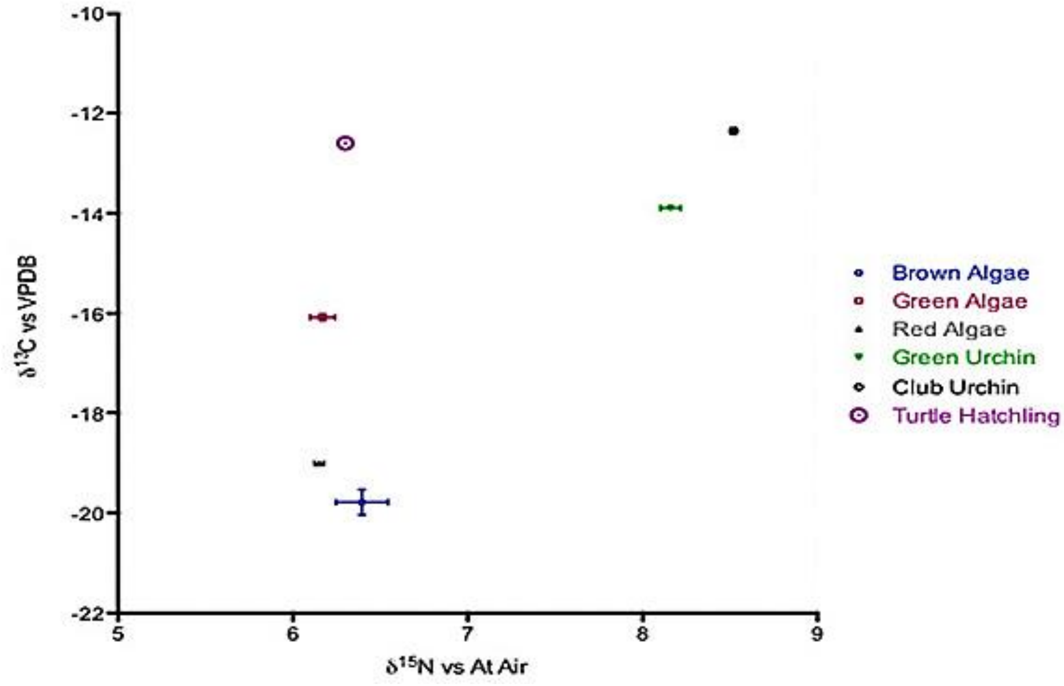

Fig. 8. Stable isotope values of macroalgae, sea urchins and a green turtle hatchling tissue.

Nevertheless, the samples' isotope values have been graphed above along with the mean δ^{15}N and δ^{13}C values from eight newly-hatched green turtles which are 6.3 and -12.6, respectively (Fig. 8) (Arthur et al., 2008). The ranges of the values are 5.7 to 6.8 and -15.0 to -10.3 respectively. Although the hatchlings did not emerge from a beach in the Galapagos (they actually hatched in Australia), their isotope values reflect the feeding habits of the mother, since the hatchling's only source of nutrition during its developmental stage is the egg yolk. The turtle hatchling data shows that the mother was a macroalgae feeder because its $\delta^{13}C$ value is similar to the sea urchins' values.

Data Analysis

In the case of the macroalgal data, one-way ANOVAs were used to analysis the data. ANOVA is an analysis of variance test to determine if different groups of data have a common mean. This test is essentially a simple linear model which evaluates one defining characteristic in the data. The model equation is:

$$Y_{ij} = \alpha_{.j} + \varepsilon_{ij}$$

Y_{ij} = the observation matrix where each column is a different group

$\alpha_{.j}$ = matrix of the group means

ε_{ij} = matrix of random noise in the data

The model returns a calculated probability value or p-value which calculates the probability of rejecting or accepting the null hypothesis. If the p-value >0.05 then the probability of accepting the null hypothesis is high. If the p-value <0.05, then the null hypothesis should be rejected because one of the group means is significantly different from the other means. The ANOVA presumes that the data is normally distributed, has equal variance and is mutually independent. In this analysis, a box plot was chosen to display the ANOVA data. A box plot presents the quartiles, and median values of the data groups. It can also show any outliers (usually represented as a cross or circle) present in the data. The shape and size of each box can be used to describe the skewness or variability of the data groups (MATLAB, 2010).

Aim and Hypotheses

The aim of this chapter is to analyze the macroalgal abundance from three islands (four locations) using the one-way ANOVA statistical technique.

The hypotheses of this study are:

- The macroalgal abundance varies among the different islands due to the upwelling of nutrient-rich waters from the Equatorial Undercurrent.
- The abundance of macroalgae is influenced by the type of substrate on the sea floor.
- The algal abundance based on phyla is not significantly different at the three islands.
- Time of year or season determines the algal abundance at the three locations.
- Changes in algal abundance cannot occur over short periods of time during the warm season.

Methods and Materials

Study Area

The acquisition of macroalgae data occurred during the non-nesting month of June 2010, on the islands of Floreana and San Cristobal, and in the nesting months of April and May 2011 on Isla Isabela. Varying line transects lengths and quadrant sizes were used to quantify the macroalgal cover (Table 2).

Table 2
A table showing the different sites, dates, line transects lengths and quadrant sizes used to collect the macroalgal data.

Site	Coordinate	Date	Line transect length	Quadrant size
San Cristobal				
Punta Carola	00° 53’28.39’’S, 89° 37’43.70’’W	06/14/2010	72 ft	0.09 ft^2
Lobería	0° 55’ 35.796”S, 89°36’ 2.264”W	06/14/2010	51 ft	0.17 ft^2
Floreana				
Puerto Velasco Ibarra	1° 17’ 00’’S, 90° 29’ 00’’ W	06/18/2010	30 ft	0.09 ft^2
Isabela				
Crab site	01° 00’ 2772’’S 91° 05’ 8.88’’W	05/06/2011 05/18/2011	99 ft 99 ft	1 ft^2 1 ft^2
Turtle site	01°00’ 30.66’’S, 91°05’ 16.62’’W	05/05/2011 05/19/2011	99 ft 99 ft	1 ft^2 1 ft^2
Lava platform	01° 00’ 28.8’’S, 91° 05’ 15.9’’W	04/20/2011 05/20/2011	33 ft 60 ft 99 ft	1 ft^2 1 ft^2 1 ft^2

At San Cristobal, one line transect were performed at Punta Carola and at Lobería. On the island of Floreana, two line transects were completed at Puerto Velasco Ibarra. These locations were chosen because a number of turtles had been observed swimming and feeding in the neritic waters. During April and May, 13 line transects were performed on the island of Isabela at the lava platform, the “crab site” (named for the abundance of Sally Lightfoot shore crabs observed on the rocks) and the “turtle area” (a rocky shoreline area where sea turtles were seen actively feeding). Quinta Playa was chosen because it is one of the major beaches for green turtle nesting in the Galapagos and non-nesting green turtles could be observed feeding in the neritic waters off the nesting beach. All line transects were performed during the low tide period.

San Cristobal

The line transects were completed on the 14th of June at 7:58 am and 11:08 am respectively. At Punta Carola, a 72 ft transect with a heading of 282° was completed using a 0.09 ft^2 quadrant while at La Lobería, a 51 ft line , heading 251°, was done utilizing a 0.17 ft^2 quadrant. Photographs of the macroalgae cover were taken every 3 ft along both lines using a digital Olympus Stylus Tough camera (5 mm focal length). The number of turtles encountered and their activity (swimming, resting or feeding) were also recorded.

Floreana

On the 18th of June, two 30 ft transects, with headings 256° and 310° were performed using a 0.09 ft^2 quadrant. Photos of macroalgae cover were also taken every 3 ft using the Olympus camera. The temperature and salinity of the waters close to the harbor were also measured and recorded with hand-held YSI 30 meter.

Isabela

Over the period of seven days during the months of April and May, 13 line transects were achieved. All line transects were in Sector A of Quinta Playa and the exact position was recorded using a Garmin Etrex Vista H hand-held GPS (± 9 ft accuracy). Macroalgae cover was documented at every 3 ft using a 1 ft^2 quadrant and recorded with either the Olympus camera or video. On the 20th of April, two line transects were performed at the lava platform. The first line was 33 ft with a heading of 239° and the second was 60 ft with the same heading. On the 20th of May, the same location was redone; however, the line was 99 ft in length and it began 9.8 ft from the edge and was run inland with a 331° heading.

Two 99 ft transects were also completed on the 5th of May at the ‘turtle’ area. For each transect, the heading was recorded and video was used to record the macroalgae cover. From 9:42 to 10:42 AM, both lines were completed. The first line was performed diagonally across the area with a heading of 200° and the second was stationed 24 ft from the shore and parallel to the beach with a 198° heading. On the 19th of May, the same area was surveyed again and three videos were shot; two diagonal across the area with headings of 180° and 70° and the second was 24 ft from the shore with a heading of 239°. On the 6th of May, between 10:23 and 11:23AM, another two 99 ft line transects were accomplished at the “crab site” with headings of 298° and 20°. On the 18th of May, from 9:05 to 10:05AM, the same site was resurveyed utilizing the same heading.

Analysis of Line Transect Data

Images were extracted from the videos at every 3 ft using the Final Cut Pro software in the Videography Lab in the TAMU Geography Department. Macroalgal abundance was quantified in each picture using the ImageJ program and then separated into the three major phyla of Chlorophyta, Rhodophyta and Phaetophyta. Scatter plots were created to visualize the data. Using MATLAB, ANOVA and multiple comparison analyses were performed on the data to test seven null hypotheses based on the data collected on the islands of San Cristobal, Floreana and Isabela.

Results

Line transects data collected from the three islands varied in number per island, length of line, and the size of quadrat used so caution should be used by anyone trying to generalize preferred habitat from the data presented here. Algal abundance surveyed on the three islands ranged from 0.96 ft^2 to 88.96 ft^2 along a 99 ft^2 transect, with the majority of algae in the Rhodophyta group and the minority in the Phaetophyta group. Red algae were found on all three islands while brown algae were only observed on the island of San Cristobal and Floreana. All line transects were performed in coastal areas with varying amounts of sand and rocks.

The first ANOVA tested the null hypothesis that there is no significant difference in algal abundance on the three islands. The ANOVA calculated a p-value <0.01, so this hypothesis was rejected. The multiple comparisons test showed that the abundance means of islands San Cristobal and Isabela were significantly different from each other and Floreana was intermediate in character to these two islands. The box plot shows that Isabela has the largest range of values while Floreana had the smallest range (Fig. 9a). The second ANOVA tested the null hypothesis that there is no significance difference between the algal abundance at the three sites where the line transects were made on the south shore of Isabela. A p-value of < 0.01, so this hypothesis was also rejected and the multiple comparisons test showed that the means of algal abundance at the crab and turtle sites were very similar while the lava platform mean was significantly different from the two former sites. The box plot shows that the lava platform data had the largest range and is right-skewed while the crab and turtle sites data are left-skewed (Fig. 9b).

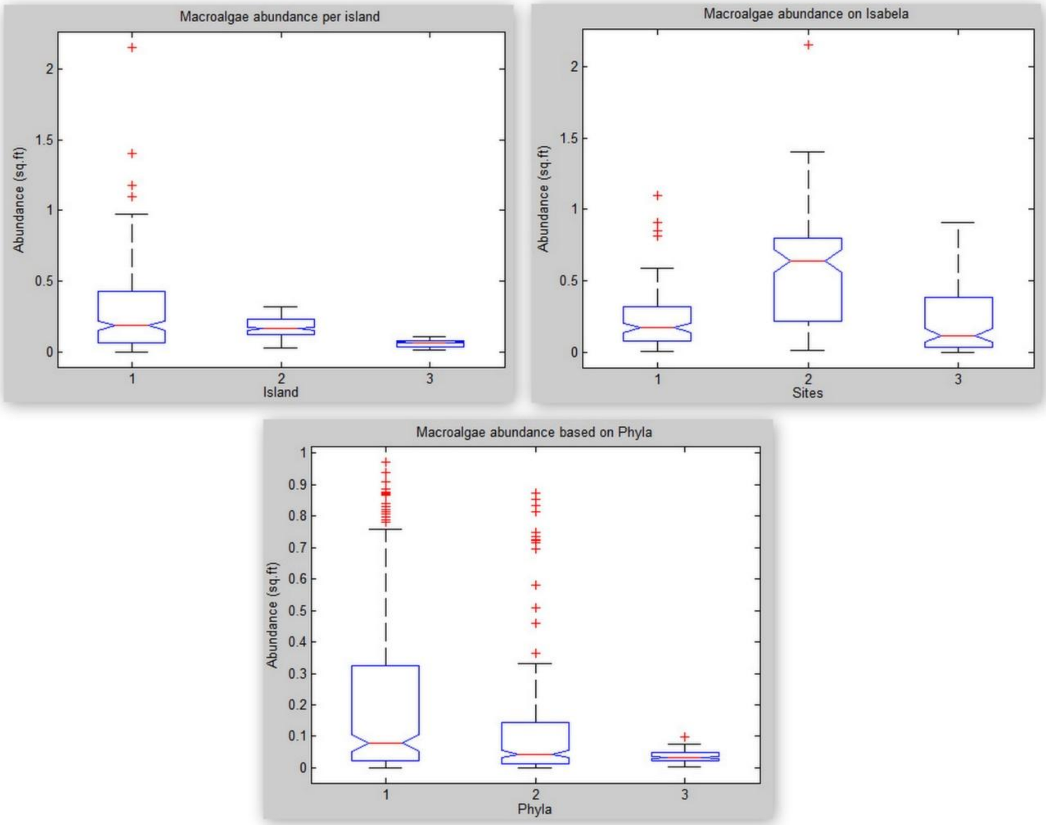

Fig. 9. Box plots of the first three ANOVA analyses.
a) Algal abundance (ft^2) on the three islands. Isabela= 1, Floreana = 2 and San Cristobal = 3.
b) Algal abundance (ft^2) on the island of Isabela. 1= crab site, 2= lava platform, 3= turtle site.
c) Algal abundance (ft^2) based on Phyla. 1= Rhodophyta, 2= Chlorophyta and 3= Phaetophyta.

There was a significant difference in algal abundance (p-value < 0.01) between the three algae phyla represented in the Galapagos. The multiple comparisons test showed that the line transects in which red algae was abundant were distinct from those in which green and brown algae were abundant. The box plot of the Phyla data showed that brown algae had the smallest data range while the red algae data had the largest range and was left-skewed. The green algae data was also left-skewed (Fig. 9c). A similar ANOVA test was done on the data from the two sites on San Cristobal; however, these two sites were not significantly different (p-value = 0.31).

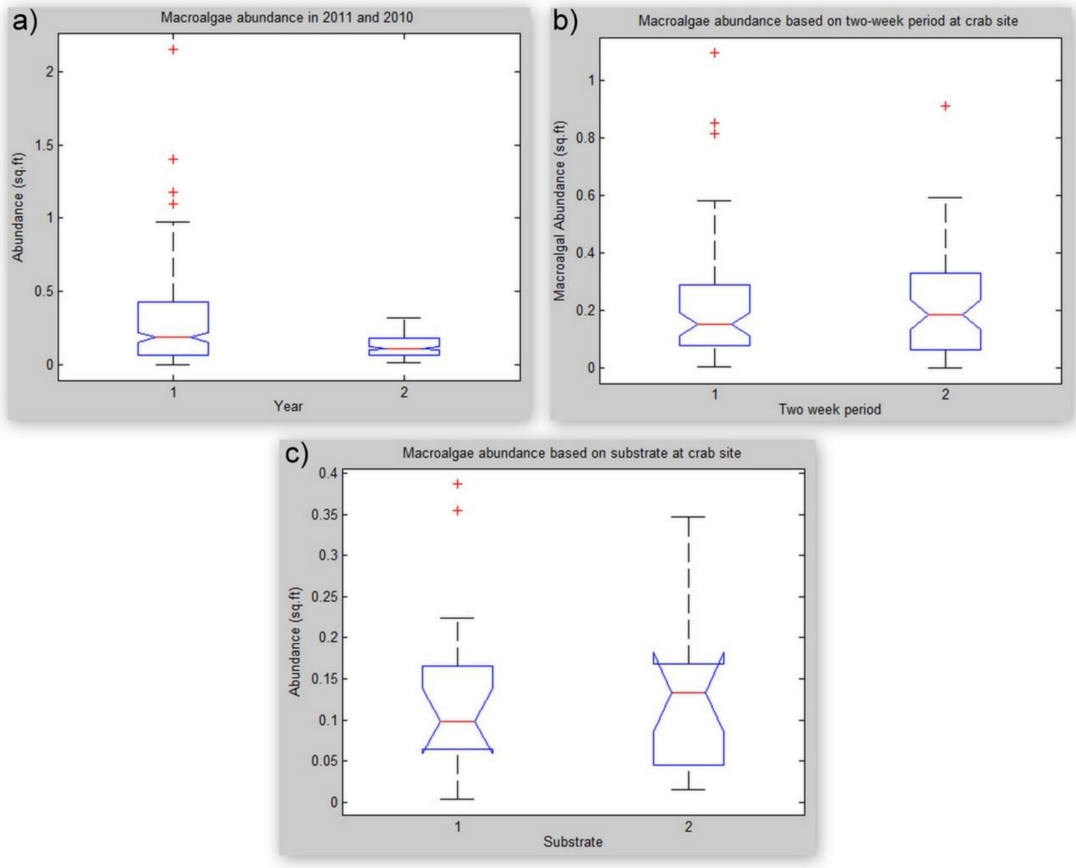

Fig. 10. Box plots of the last three ANOVAs analyses.
a) Algae abundance (ft^2) based on time and/or season.1= 2011 and 2 = 2010.
b) Algal abundance (ft^2) over a two-week time period where 1= 6th May and 2= 18th May.
c) Algal abundance (ft^2) based on the substrate type found at the crab site 1= rocky substrate and 2= sandy substrate.

The ANOVA of the null hypothesis of no significant difference in algal abundance based on time (samples from 2010 and 2011) or season (upwelling or non-upwelling) produced a p-value < 0.01. The box plot showed that the data ranges of the two years were different with 2011 having the larger range. This could be due to a larger number of line transects (13) being completed in 2011 than 2010 (Fig. 10a). Another one-way ANOVA was completed on the crab site data to test the null hypothesis that there was no change in algal abundance over a two-week time period. The result was a p-value of 0.95. The multiple comparisons test again showed that the algal abundance at the two sampling times were similar because of their similar means and large variances. The box plot corresponds with the results from the multiple comparison; the two data groups has similar ranges and percentiles (Fig. 10b).

Some of the transect lines on Isabela were executed across differing substrates, for example the substrate at the crab site had areas of sand as well as areas of rocks. The transect lines were conducted at two independent times (6th & 18th of May, 2011). A one-way ANOVA was performed to test the null hypothesis that there was no significant difference among algal abundance when correlated with substrate type. The ANOVA produced a p-value of 0.98 and the multiple comparisons test showed that the algal abundance on the different substrates were very similar. The box plot showed that the data from the crab site based on substrate type had similar medians at the 5% significance level (Fig. 10c).

Discussion

Algal abundances in intertidal and subtidal zones on Isabela and San Cristobal were found to be different to each other. Not only do the two islands differ in age but Isabela is the second island in the archipelago where the Equatorial undercurrent upwells. Oceanic currents are major transport mediums for the dispersal of organisms globally. The upwelling of high nutrient waters and shallow areas makes Isabela a good location for new algal species to settle. According to Houvenghal (1984) and (Bustamante et al., 2008), the undercurrent bifurcates into two branches as it flows through the archipelago, creating persistent upwelling zones on the western coast of most of the islands including San Cristobal., However, the Humboldt and Peru Currents also flow through the islands during the Garúa season, bringing species from South America into the eastern (San Cristobal) and south central (Floreana) regions of the Galapagos (Bustamante et al., 2008). This has a greater impact on the species found on San Cristobal then on Isabela (Bustamante et al., 2008).

Floreana was found to be very similar to both islands and this could be as a result of its position in the south central zone of the archipelago. This zone is a major mixing zone for species from South America, Ecuador and Central Pacific. Garske (2002) stated that the algal abundance in the south central region were very similar in species richness to the western islands. For example, the endemic *Bifurcaria galapagensis*, which are not found on the central and eastern islands can still be found on Isabela and Floreana (Garske, 2002). The similarity between San Cristobal and Floreana could stem from the Peruvian currents flow through the Galapagos (Bustamante et al., 2008).

One essential characteristic required for the growth of macroalgae in coastal waters is the type of substrate. Although the algae do not derive any nutrients from the substrate, it acts as an anchor for the whole organism against strong currents and frequent wave action. In the sporophyte stage, algae prefer to settle in microhabitats where the conditions are conducive to its growth and survival. The substrate also provides escape from grazers as well (Zakaria et al., 2008). For these reasons, macroalgae will preferentially settle and flourish in rocky areas. Sandy areas, conversely, lack the stability needed by algae, although some species, like *Ulva intestinalis* are able to thrive in sandy areas because they can vegetatively reproduce through the growth of rhizomes. On Isla Isabela, the effect of substrate type on algal abundance can be clearly observed from the line transects data. The crab site was made up of a mixture of sand and rocks (Fig. 11a).

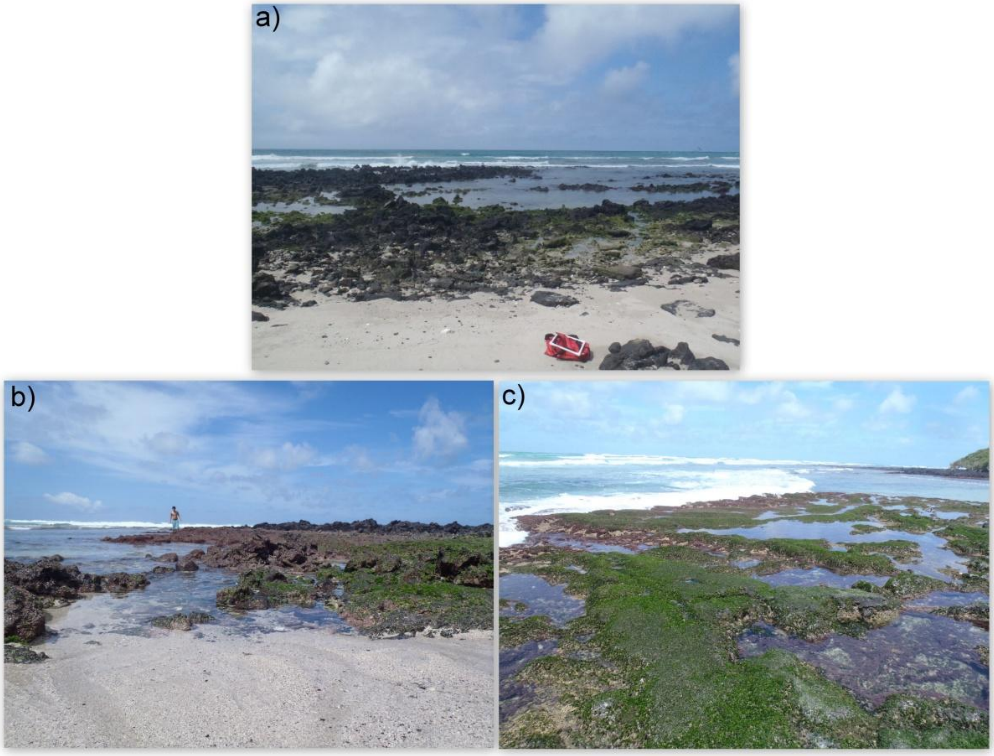

Fig. 11. Photographs of the line transect sites at Quinta Playa taken at minus tide at: a) lava platform, b) turtle site, c) crab site.

The turtle (Fig. 11b) site was similar to the lava platform but the former had pockets of sea urchin spines that suggest that urchin grazers found favorable conditions there. The lava platform was solely lava rock and accessible to marine organisms only at high tide (Fig. 11c). In Table 3, the turtle site had the largest macroalgal abundance followed by the lava platform. The turtle site is able to provide more support for macroalgae to anchor and grow than the crab site. Conversely, the algal abundance from the different substrates at the crab site was not significantly different. Some of the areas classified as sandy did contain some rocks which may have provided stable substrate and adequate habitat for the algae to grow thus increasing the macroalgal abundance in the middle of the small bay (sandy areas).

Table 3

Algal abundance at the three locations on Quinta Playa (Total m^3 coverage along a 99 ft transect).

Location	Algal abundance (m^2)
Lava platform	2.7
Crab site	2.6
Turtle site	3.0

At Quinta Playa on the south shore of Isla Isabela, the major Rhodophyta genus was *Polysiphonia*. The Rhodophyta phyla is a large component of the macroalgae found in the Galapagos comprising of over 230 species, 30% of which are endemic to the islands. *Polysiphonia* dominated at all the sites because it is well suited to survive on bare precipitous-sloping rock faces as well as in rocks pools (Fig. 12). Brown algae were only observed at the sites on Floreana and San Cristobal. Green algae, mainly *Ulva,* were found on all three islands and this group prefers to settle in areas close to the shore to prevent thallus loss due to wave-shearing. As shown in Fig. 12, Ulva *sp.* is growing on the outer edges of the rock pools on the lava platform where the wave energy is lower than in the pools. As a corollary, though, green algal growth can quickly replace tissue lost to wave action and/or grazing (Lobban and Harrison, 1994).

Fig. 12. *Polysiphonia* sp. inhabiting heavy wave action areas and in rock pools surrounding by *Ulva* sp. at minus tide.

The ANOVA calculated that the abundance of macroalgae in June 2010 was significantly different to April/May 2011. This finding was supported by the Multivariate ENSO Index (MEI) and the Niño 1+2 indices for the three months. The Niño 1+2 index is based on the monthly averaged SSTs, spanning the years1950-present, from within a defined area (5°N -5°S, 90°W- 80°W) (Stenseth et al., 2003). The MEI is computed on a bimonthly window using the data of 6 variables in the tropical Pacific. The variables (sea-level pressure, SST, total cloudiness, surface air temperature, zonal and meridional surface wind) are combined and are used as input into a Principal Component Analysis. The first component is then used as the MEI for the two month period (Wolter and Timlin, 1993).

According to the National Weather Service's Climate Prediction Center, the Niño 1+2 index for June 2010 was 22.6°C with a temperature anomaly of -0.27, making this month a La Niña month. For April and May 2011, the Niño 1+2 index was 25.76°C and 24.89°C with temperature anomalies of 0.16 and 0.62 respectively. The increase in temperature makes these months El Niño months (NationalWeatherService, 2011). The MEI for the June/July period was ranked the 7th strongest La Niña month for all June/July periods from 1950 to 2011. For April/May 2011, its MEI was ranked 20th for all April/May periods from 1950 to 2012; therefore, it was a moderate El Niño period (Wolter, 2012). Comparing the Niño 1+2 indices and the MEIs, I speculate this may account for the difference observed in the algal abundance during the specified months.

Since the whole month of May was characterized as an El Niño month, a time period of two weeks between transect surveys in April-May 2011 may not be long enough to show a marked change in algal mass and the ANOVA test is consistent with this interpretation.

Conclusion

Algal abundance in the Galapagos is influenced by location, time/season and substrata type. Floreana lies in the mixing zone of the currents flowing through the Galapagos Islands. As a result, it shares common species with Isabela, which is greatly influenced by the Equatorial Undercurrent and San Cristobal, which is the first island to interact with the Peruvian currents entering the archipelago. Rocky stable shorelines are ideal substrata for macroalgal growth, because such shorelines provide anchorage for adult algae and also a safe haven for developing sporophytes. The macroalgal abundance observed in June 2010 was different from April/ May 2011 because of the change in season. The two week time period in May was no long enough to observe any changes in algal abundance at the crab site.

CHAPTER III

SPECIES DISTRIBUTION MODEL OF THE EAST PACIFIC GREEN TURTLE IN THE GALAPAGOS

Introduction

Generalized Linear models (GLMs) and Generalized Additive models (GAMs) are modeling techniques that are able to quantify the statistical relationship between the response and the explanatory variables. Scientists use this information to determine species presence in areas that may not have been surveyed. Thus, models of probability presence can be created from GLMs and GAMs once the essential predictors are identified (Guisan et al., 2002). Generalized Linear Models can yield predictions from a wide selection of data types (e.g. Poisson, negative binomial or Gaussian). Since ecological or natural data can possess various distributions, this is a vital advantage for GLMs over other techniques, yet GLMs lack the flexibility to model non-parametric data, for example bimodal distributed data (Yee and Mitchell, 1991). In these cases, GAMs are superior to its linear counterpart. GAMs can yield predictions from the same types of distributions as GLMs; however, the major difference is the replacement of the linear functions with smoothed functions. A smoothed function is created from the original function and a smoother, which is selected based on the data's distribution. The smoother is applied to each variable separately and then combined to calculate the response, thus giving the technique its additive characteristic. GAMs are considered data-driven and are the preferred modeling tool when the data's distribution is unknown. Because GAMs can accommodate different data distributions, unlike other non-parametric fitting methods, they can reduce or eliminate the time required to transform the data as well as allow hypothesis evaluation of each variable (Yee and Mitchell, 1991; Guisan et al., 2002).

Calibration Techniques

Since no modeling technique is perfect, some degree of calibration must be performed on the model. Calibration involves the modification of the model to improve its alignment to the data set thus improving the model's accuracy and predictive power. This requires either a reduction in explanatory variables or the calculation of the model's D^2 (similar to the R^2) value. A reduction in the explanatory variable can increase accuracy and predictive power; however, there is a risk of increasing the model's prediction error. Harrell et al. (1996) conjured the equation $m/10$ (where m represents the number of observations in the smallest category in a binary response) as a measuring stick for the number of predictions to be used in a model to ensure high accuracy and low variance in models. The D^2 value is calculated from the null and residual deviances and is a measure of the model's fit; therefore the larger the adjusted D^2, the better the model's fit to the data (Guisan and Zimmermann, 2000).

Model Evaluation

Once the ecological profile for the species has been calibrated, the next step would be to evaluate the predictions made with the chosen statistical technique. The predictions can be evaluated based on their error rate and/or accuracy in predicting the species' pattern of occurrence. The analysis can be done two ways. The first is called the split-data approach which utilizes two independent datasets (one for training the model and the other for evaluating it) and the second method uses one dataset and applies different validation tests, such as Jack knife, bootstrap or cross-validation, to examine the results. The use of the split-data approach is very popular because it is straightforward; however, with smaller training and evaluating sets, this may cause error rates to be exaggerated and the model's accuracy to decrease. Thus, the first technique can only be used once the original dataset is large. If this is not the case, then the second method should be used but with caution. Because the evaluating dataset is the testing set, false error rates, as a result of over-fitting the model, can occur. The effects of over-fitting can be evaluated through the validated procedures associated with the one dataset approach (Fielding and Bell, 1997; Guisan and Zimmermann, 2000).

Regardless of the approach used to evaluate the model, prediction errors can be either algorithmic (a result of the sampling process or the statistical technique used to classify the data) or biotic (effects from inter- or intraspecific interferences such as Competition, Predation and social order). A good example of an algorithmic error is the case where presence and absence points share similar conditions. Under these conditions, it is difficult for the statistical technique or classifier to distinguish differences between the two sets of points. This results in an increase of false positives and therefore, the decrease in the technique's performance (Fielding and Bell, 1997). For presence/absence models, the evaluation process creates a confusion matrix which is a table listing the true positive, true negative, false positive and false negative counts in terms of the threshold criteria. The true positive count represents the number of presence points the model accurately classified as presence. The true negative count is the number of absence points the model accurately grouped as absence. The false positive count is the number of absence points that were inaccurately classified as presence and the false negative value represent the positive points that were inaccurately grouped as absence by the model (Table 4). These counts can be used to calculate different descriptions of accuracy for the model; for example; the sensitivity, specificity, positive predictive power and negative predictive power values (Fielding and Bell, 1997).

Table 4
An example of a typical confusion matrix.

	Actual Positive	**Actual Negative**
Predicted Positive	True positive	False positive
Predicted Negative	False negative	True negative

The equation for sensitivity (S_e) is:

$$S_e = \frac{true\ positives}{(true\ positives + false\ negatives)}$$

This estimate quantifies the proportion of presence points that were accurately classified. Specificity (S_p) is calculated as:

$$S_p = \frac{true\ negatives}{(true\ negatives + false\ positives)}$$

This is the ratio of presence points that were not accurately classified; it is essentially the opposite of sensitivity. The positive predictive power basically measures the competence of the classifier to correctly classify presence points as presence points. The positive predictive power (P) is computed as:

$$\mathrm{P} = \frac{true\ positives}{(true\ positives + false\ positives)}$$

And the negative predictive power (N) statistic measures the classifier’s proficiency at categorizing absence points. The following equation is used to calculate this statistic.

$$\mathrm{N} = \frac{true\ negatives}{(false\ negatives + true\ negatives)}$$

Some other known measures that can be computed from the confusion matrix are the odds ratio, the false positive rate and the false negative rate; a detailed explanation of these and other measures can be found in the 1997 review paper written by Fielding and Bell.

These statistics are dependent on the counts within the confusion matrix. The evaluation process applies the threshold criteria to a continuous variable, with values between 0 and 1, that was produced by the statistical method. The value of the threshold can be modified depending on the aim of the model. For example, if the number of false negative cases for sea turtle presence in an area is relatively high and the aim of the model is to outline areas for sea turtle conservation, the threshold criterion can be adjusted to decrease these counts; however, the data’s distribution must be taken into consideration. The data’s distribution can negatively affect the criterion’s ability to alter the number of counts. This is usually observed with bimodal data. The solution in such situations is the creation of a receiver operating characteristic curve or ROC curve (Zweig and Campbell, 1993; Fielding and Bell, 1997).

Receiver Operating Characteristic (ROC) Curve

The ROC curve is threshold independent and is created by plotting all the sensitivity/specificity pairs. The y-axis represents the true positive fraction or sensitivity and the x-axis represents the true negative fraction (1 - specificity) in terms of threshold probability. The curve can be either smooth and parametric or stepped and non-parametric. In the case of a GAM, the curve is stepped and nonparametric. The threshold criterion is calculated by moving a line from the upper left corner, where the true positive and false positive rates are 1 and 0 respectively. The point of intersection of the line and the stepped curve identifies the true positive/false positive pair. In the Binomial GAM output, the value represented by the true positive/false positive pair is called the cutoff value. This value symbolizes the model’s best performance. In lieu of the shape of the arc, the area under the curve (AUC) can be computed as a comprehensive measure of accuracy that is independent of the threshold. The AUC is calculated as an integral of the dependent values bounded by the function and the two axes. The value of the AUC usually falls between 0.5 and 1.0, where 0.5 means that there is major overlap between the presence and absence points and 1.0 means that the two groups are discrete (Zweig and Campbell, 1993; Fielding and Bell, 1997)

Mapping Techniques

After the evaluation process, the next logical step is to map the predictions in a suitable geographical space. The space, in many instances, represents the species' environment; therefore, the model's spatial output can be used to infer the species potential habitat of occurrence, abundance or entity. The easiest way to visualize these potential habitat maps is by utilizing Geographic Information Systems (GIS) programs from vendors such as ESRI, ERDAS, and CARIS. Each visual aid has its advantages and disadvantages; for example, ArcInfo tools lack the ability to perform graphical evaluations to maps (Guisan and Zimmermann, 2000). To execute all these methodology steps, each one may require a range of programs and tools to operate, and many times, they may not all work together. For example, the results from some statistical methods are simply not compatible with geospatial programs like ArcGIS. Also the geographical layers of predictor variables, especially those that are remotely sensed, are packaged in different ways (ASCII, HDF or netCDF configuration), which require conversion before they can be inputted into a visual medium such as a GIS. The lack of interoperability between programs increases the complexity of the task (Guisan and Zimmermann, 2000; Roberts et al., 2010).

Marine Geospatial Ecological Toolbox

One solution to this problem is the use of the Marine Geospatial Ecological Toolbox (MGET) software. The ArcGIS-compatible program was created at the Duke University's Marine Geospatial Ecology Laboratory. Its objective is to help the environmental scientific community generate ecological models and maps without the need to be technologically proficient in analytical and mathematical based programs. MGET contains more than 250 tools that vary in functionality and their reliance on analytical and mathematical programs. For example, to produce a predictive habitat model, MGET accesses the statistical program R to create not only the graphs associated with the model but also the data needed to generate the map (Roberts et al., 2010).

Since MGET is fully integrated into ArcGIS, the model's predictions can be used to evaluate each pixel in the oceanographic layers to create a predictive habitat distribution map. Recently, the MGET toolbox has been used to determine the oceanic habitat of seabirds (Louzao et al., 2009), skipjack tuna (Mugo et al., 2010), Atlantic green turtles (McClellan and Read, 2009) and North Pacific humpback whale communities (Rosa et al., 2012). This toolbox is not known to be previously used to predict the habitat distribution of the East Pacific green turtle in the Galapagos Islands.

Aim and Hypotheses

The objective is to create a predictive habitat distribution model, using the oceanic parameters sea surface temperature, chlorophyll a, ocean currents and bathymetry, to determine the spatial location for the East Pacific green sea turtle within the Galapagos archipelago.

The hypotheses of this study are:

- East Pacific green sea turtles will stay in the coastal waters around the islands, which allow them the shortest distance to their feeding area.
- As poikilotherms, East Pacific green turtles prefer warmer waters to cooler waters.

- There is a negative relationship between East Pacific green sea turtle spatial distributions and remotely-sensed, near-surface chlorophyll concentrations since higher chlorophyll concentrations are indicators of cooler waters.
- There is a correlation between ocean current speed and the East Pacific green sea turtle observation points since observations of turtles in regions of stronger currents can simply indicate interisland transit rather than foraging.

Methods

Four predictor parameters were used in the model; sea surface temperature (SST), chlorophyll a concentration, oceanic currents and bathymetry (Fig. 13). Images of all the parameters were collected from the month of June 2010. Each variable was represented as an ArcGIS layer. The Bathymetry layer was created from an ETOPO1 Digital Elevation Model (DEM) image which had a spatial resolution of 0.03 km. It was downloaded from NOAA's National Geophysical Data Center. The image was converted to contour lines 10, 20, 50, 100, 250, 500, 1000, 2000, 3000 and 4000 meters using the Contour tool within the Spatial Analyst Toolbox.

Sea surface temperature and chlorophyll a data were acquired using the MODIS Aqua satellite, defined and downloaded from the Goddard Earth Sciences Data and Information Services Center's Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) application. Both datasets had a spatial resolution of 4 km. The June 2010 sea surface temperature and chlorophyll a data were interpolated using the universal kriging process in ArcMap to ensure each pixel received a sea surface temperature and chlorophyll value. Universal kriging is a type of geostatistical analysis whereby values for unmeasured locations are calculated through a weighting system. To calculate current speed and direction, zonal and meridional velocity component rasters were downloaded from NOAA's Ocean Surface Current Analyses – real time website.

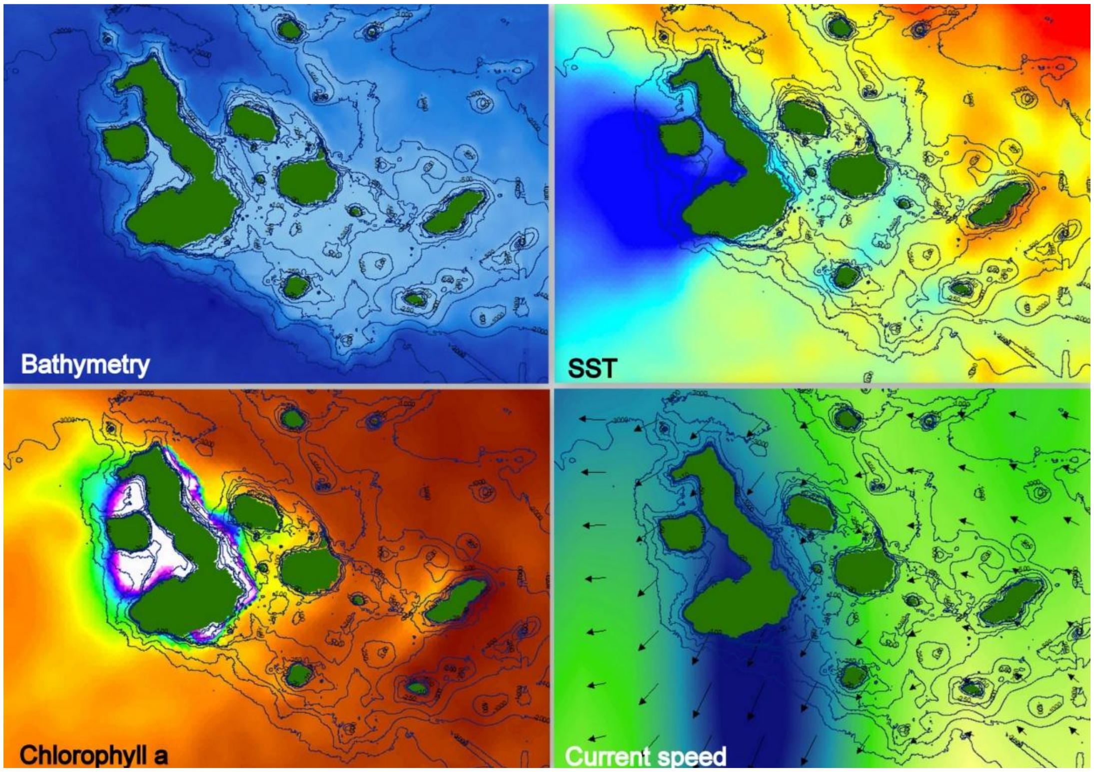

Fig. 13. Images of the physical oceanographic predictor variables used in the binomial GAM to determine potential sea turtle areas.

With a spatial resolution of 33 km, the rasters were used to calculate the speed of the currents around the archipelago with the Raster Calculator tool:

$$\text{Speed} = \sqrt{u^2 + v^2}$$

Using the Create Lines tool in the Marine Geospatial Ecology Toolbox, the currents' direction was calculated and added to the model as arrows. A base map of the Galapagos Islands was supplied by Dr. Jana Jeglinski of the University Bielefeld in Germany. The base map shapefile was created from a high resolution Blue Marble image with a spatial resolution of 0.50 km.

Table 5
A list of the MGET tools used to create the presence and absence attribute table.

Tool	Function
Buffer	Creates a 10km buffer around each presence point
Erase	Erases the track lines that intersect the buffer
Create random points	Points are randomly chosen on the track line
Create XY values	Records the latitude and longitude coordinates for the random points
Merge	Combines separate attribute tables into one

Table 5 itemizes the MGET tools that were utilized to create the final attribute table of turtle presence and absence points. The coordinate points of the cruise track line and the turtle observation data from the June 2010 Galapagos survey were separated into days and added separately into the ArcMap (Fig. 14). The track line and turtle points from the 5th, 6th, 8th, 9th, 11th, 13th, 16th and 17th June were used in the model. Each track line file contained date, time, and latitude and longitude data. Once input into ArcMap, the track line points were used to create a time line. To create the absence points, the turtle presence points were then added to the map and a 10 km buffer was created around each point. This distance was chosen based on the methodology used to observe the turtles in the water (small boat survey with binoculars) and with the idea that each location not classified as a presence point can be a potential absence point along the survey track line. The Erase tool in ArcMap was used to erase sections of the track line that fell within the buffer zone. The Create Random Points tool was used to create random absence points along the length of the remaining track line.

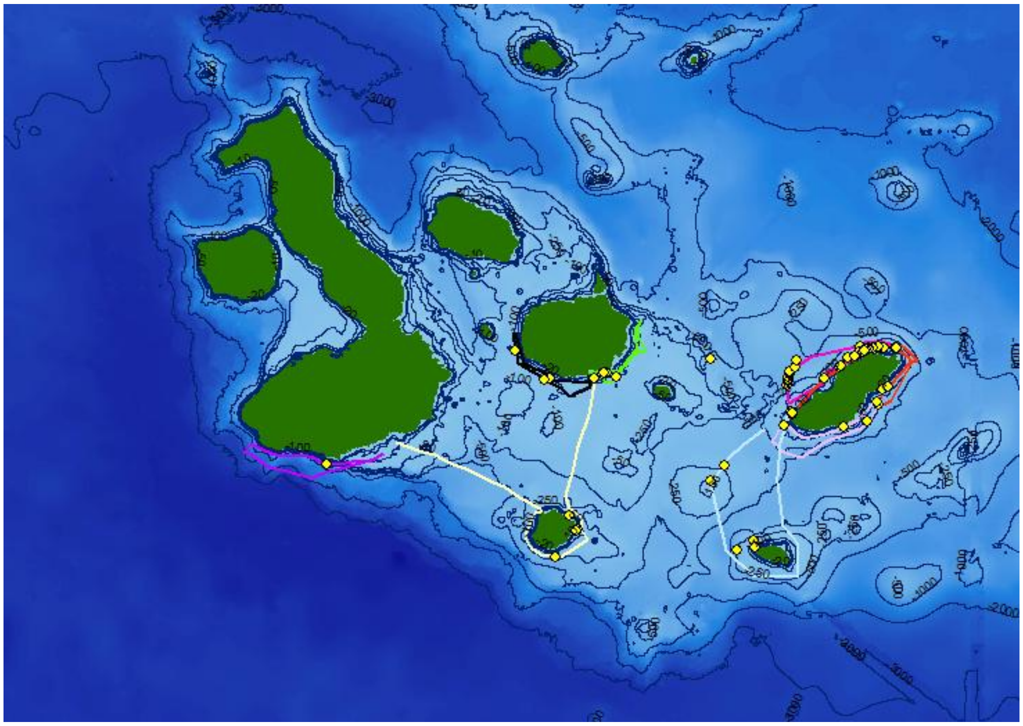

Fig. 14. Map showing the survey track lines and turtle presence points collected in June 2010.

The remaining track line lengths varied depending on the number of buffer zones on the line and the shape of the line; thus the number of random points assigned to each line varied between 15 and 40. The location of each point was calculated using the Create XY Coordinate tool. A presence field was added to both the turtle and absence point attribute tables; a value of 1 for presence and 0 for absence. The two tables were then joined to create one attribute table with a total of 272 absence and presence points. The predictor parameters were sampled at each turtle absence and presence point and the values were added as fields or columns to the attribute table. To determine the extent of disparity between the absence and presence data, density histograms were created for and analyzed each predictor parameter.

Once the explanatory variables were added to ArcGIS, a binomial Generalized Additive Model (GAM) was created. To accomplish this, the marine life observation data were divided into two groups; one set, (the training set) consisted of two-thirds of the data, and the rest of the data were grouped in an evaluation set. The Fit GAM tool was used to model the data using the following formula:

Presence ~ s (abs (Bathymetry)) + s (SST) + s (log10 (Chlorophyll)) + s (Current_speed)

The equation is written in R syntax where the tilde represents the equal sign and the lower cap “s” represents the smoothed values of the predictor variables. Thus the equation states that turtle presence will be predicted as an additive multiple regression using the smoothed absolute values of bathymetry, smoothed sea surface temperature values, the smoothed log transformed values of chlorophyll a and smoothed current speed. The absolute values of bathymetry were used because they can be easily assimilated into the model. For chlorophyll a, the log-transformed data was used in the model because they had a stronger relationship with the other three variables and a normal distribution. The Fit GAM tool created partial residual plots for each term used in the formula, a summary of the statistics of the GAM and a fitted model file to be used in the succeeding steps. A Receiving Operating Characteristic (ROC) curve was then created to determine an appropriate cutoff value for the GAM. This was done using the Plot ROC of Binary Classification Model function. Once the ROC curve was completed, the fitted model file from the GAM function, the cutoff value and the predicator parameter rasters were used in concert with the Predict GAM from rasters tool to predict the probability of presence for green sea turtles in the Galapagos Islands. Two additional maps were also created; a standard error of prediction map and a binary presence/absence map.

Results

Each kernel density histogram shows the absence and presence values for each parameter as standardized percentages of occurrence (Fig. 15). For Bathymetry, the histogram showed that the highest presence percentage was found between 200m to the coast with a secondary higher density at a depth of approximately 450 meters. This secondary correlation probably reflects some sample bias in our data as surveys for sea turtle distribution were run along the 500 m isobath and along the 1000 m isobath during two half-days of small boat work in mid June 2010 off the island of Santa Cruz. The absence points showed a similar distribution as the presence points excluding the peak at the 450 meter depth. For chlorophyll a, presence data peaked at 0.3 mg m^{-3} with a smaller peak at 0.2 mg m^{-3}. The absence points follow a similar pattern with the highest percentage at a concentration slightly greater than 0.3 mg m^{-3} and a secondary peak around 0.22 mg m^{-3}.

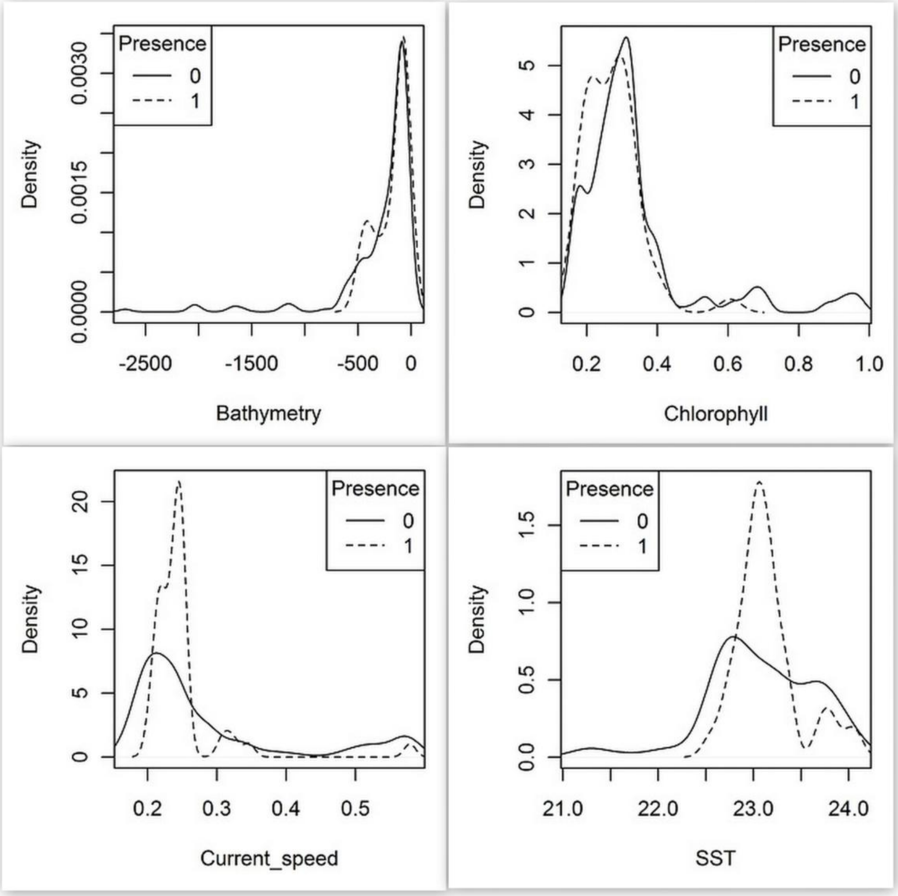

Fig. 15. Kernel density histograms of the standardized percent occurrence of green sea turtle presence produced by MGET and based on the four predictor parameters.

For Current Speed, sea turtle presence peaked at a speed of 0.25 m/s with a smaller peak at to 0.22 m/s and 0.32 m/s. Its absence points showed a high speed of 0.21m/s, but at percentages less than 10 turtles per m/s. For Sea Surface Temperature, the presence percentages were greater at 23°C while absence points showed a smaller peak at 22.7°C with a small cluster of points at approximately 23.9°C. The presence values are slightly higher than the averaged sea surface temperature (22.2°C) measured during the June 2010 survey.

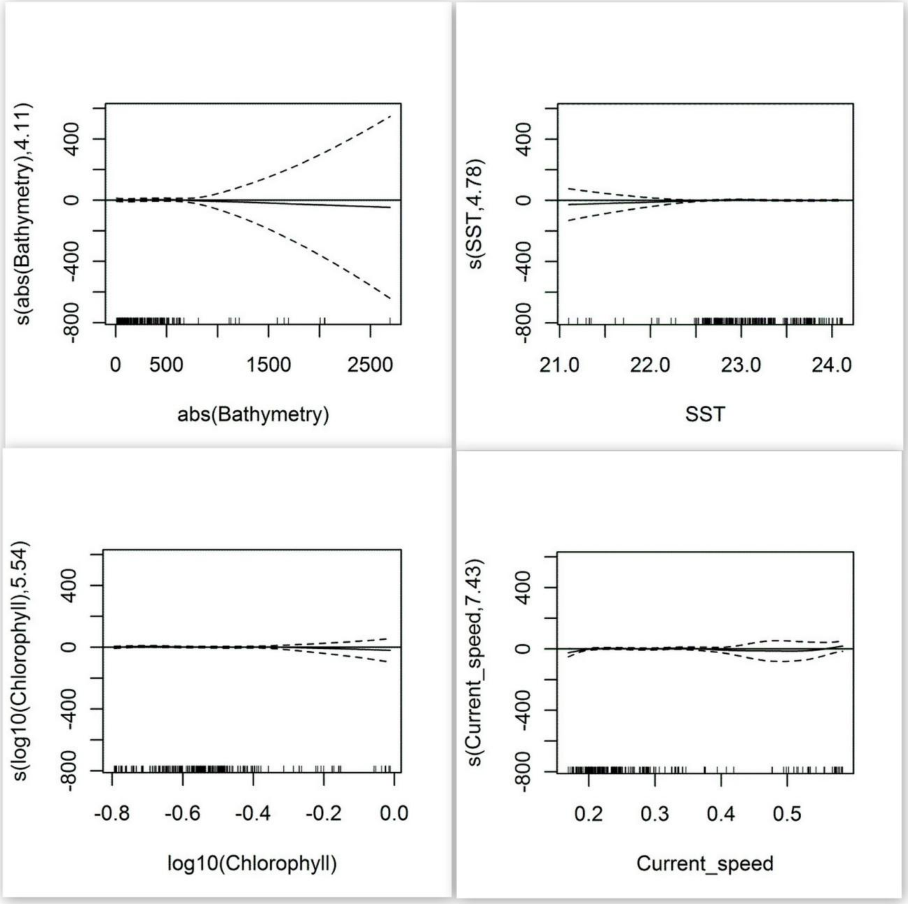

Fig. 16. Partial residual plots for each oceanographic parameter used in the sea turtle habitat model.

Using a cutoff value of 0.2789, the GAM explained 55.7% of the null deviance and received an unbiased risk estimator score of -0.42. The model also received an overall an AUC value of 0.936. Of the four parameters, only Sea Surface Temperature and Current Speed had a p-value less than 0.05 thus only these two variables were considered statistically significant in the determination of turtle presence. Chlorophyll and Bathymetry received a p-value of 0.197 and 0.991 respectively. Bathymetry showed a weak correlation to turtle presence in very shallow waters which gradually decreased as the water depth increased. Sea Surface Temperature had a negative correlation at low temperatures, which slightly increased at higher temperatures. Chlorophyll showed very little correlation at low concentrations (0.4 mg m^{-3}) and negative correlations at higher concentrations with turtle presence. Current Speed showed an overall weak correlation but at the higher speeds, the correlation slightly decreased (Fig. 16).

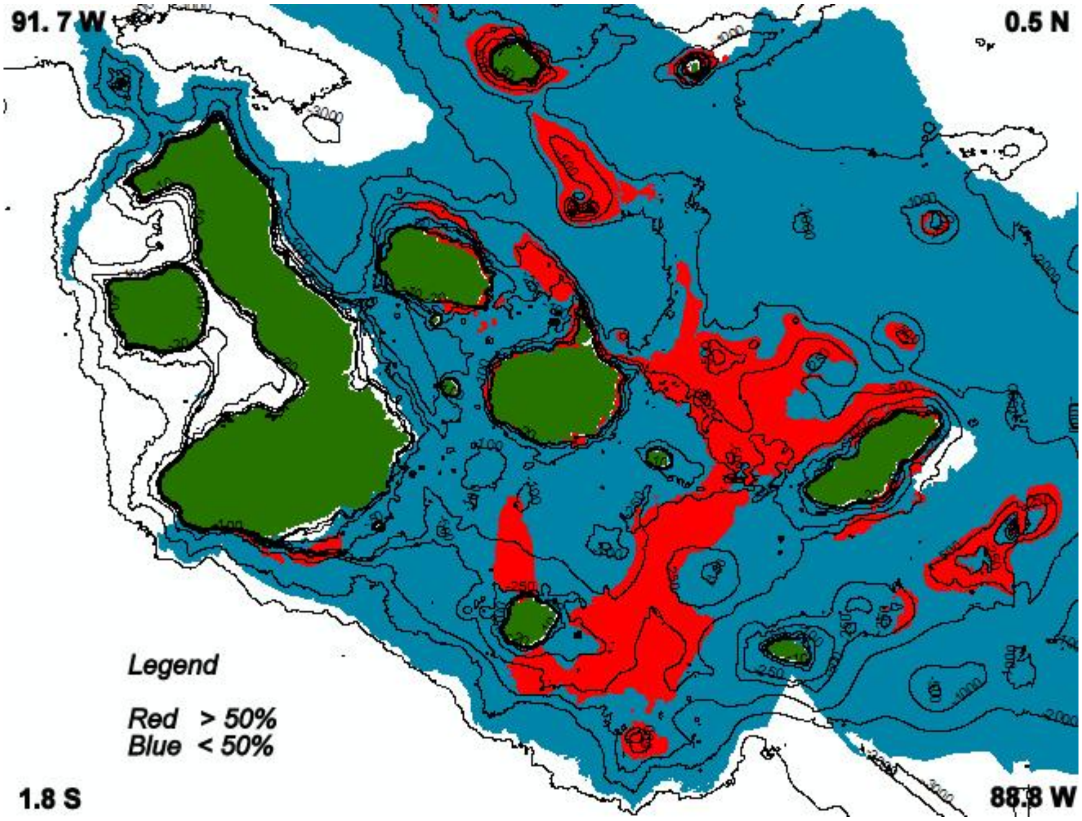

Fig. 17. The presence probability map for east pacific green sea turtles residing in the Galapagos.

The high probability prediction areas are shallow (500m and less), have low concentrations of chlorophyll (0.36-0.45mg/m^3); warm (22-23°C) with current speeds between 0.2-0.4m/s moving in an overall westerly direction (Figure 17).

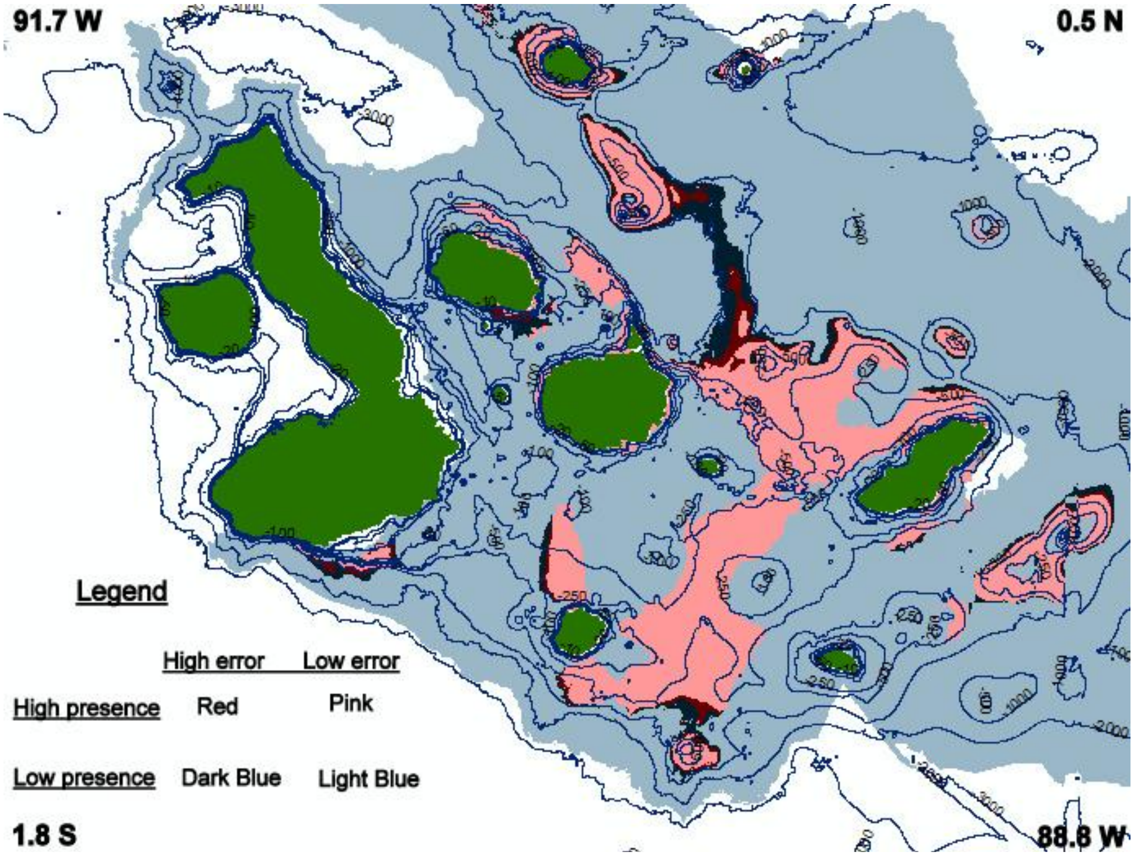

Fig. 18. Overlay of the predicted presence and the standard error maps.

Figure 18 shows the presence map with the standard error map overlay. The map shows four areas, high error/high presence (dark red), high error/low presence (dark blue), low error/high presence (pink) and low error/low presence (light blue). Overall, the pink regions are located in areas where the water depth is less than 500m; for example the northern and eastern coast of Santiago, the majority of the coastal waters of Santa Cruz and Baltra, northern coast of San Cristobal, southern coastal waters of Isabela. There are also some areas of low error/high presence located at a few isolated sea mounts.

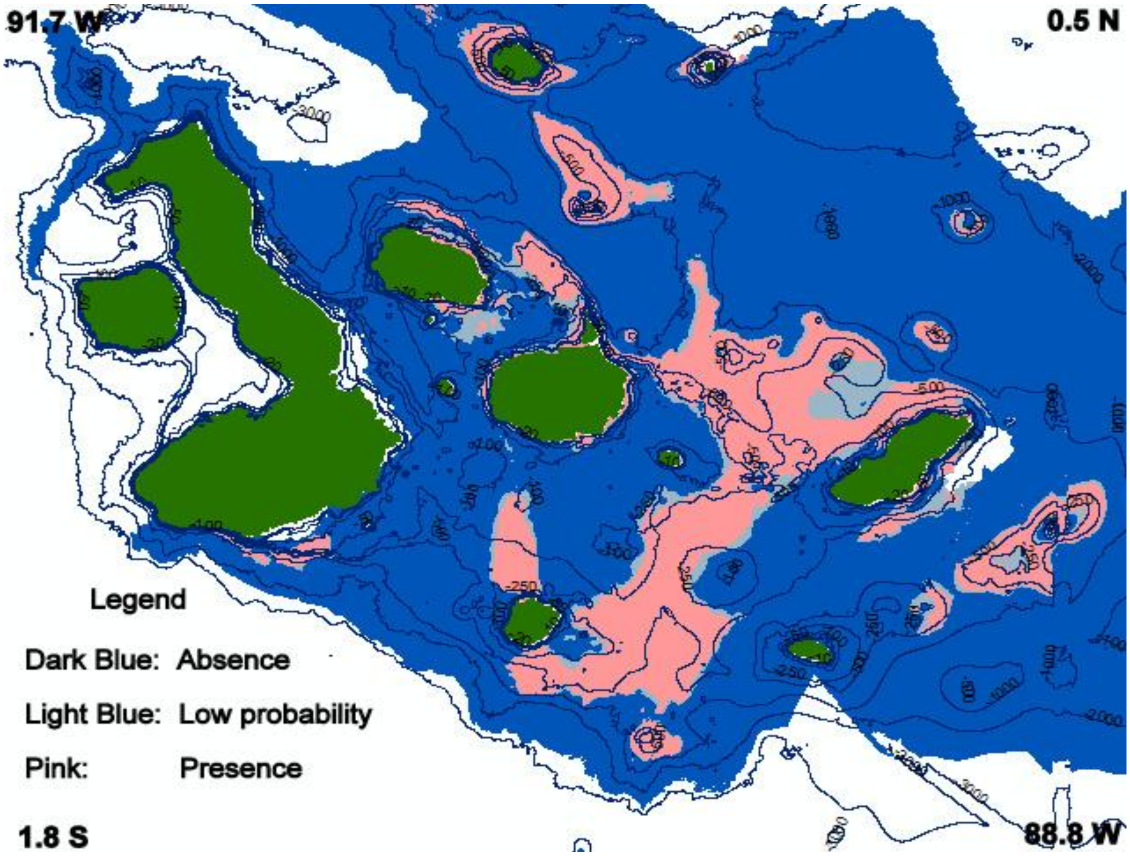

Fig. 19. Overlay of the predicted presence and the binary response maps.

The binary classification map displays the areas where the values classified as presence exceeded the ROC cutoff value (Fig. 19). The map shows three areas. The dark blue regions represent areas that did not exceed the cutoff value and therefore were accurately classified as absence points. The light blue regions, on the other hand, represent areas that were classified as presence points by the cutoff value but received a low probability for presence in the predictive model. The pink regions represent areas that were correctly classified for sea turtle presence. The true positive rate or sensitivity value when using the cutoff value was 0.829 and the false positive rate was 0.062. The true negative rate or specificity value was 0.937.

Discussion

Of the 69 turtle sightings, 27 (39%) were observed on the 13th of June around the island of San Cristobal., The survey was performed on the eastern coast of the island in waters no deeper than 250 meters. Green (1975), described Playa Sardina (89.363 W, 0.703S) as a major feeding area for green turtles and during the up-leg of the survey, several turtles were observed in the vicinity of the beach. Multiple turtles were also observed during the surveys on the 11th and 12th of June in the beach's vicinity (Fig. 20). Conditions at Playa Sardina were warm (23°C) with low chlorophyll concentrations (0.22 mg m^{-3}) and current speeds (0.24 m/s) for the month of June. The survey along the southern coast of Isabela (5th of June) had the lowest number of sightings. This survey occurred in water depths of 500-2000 meters, with high chlorophyll concentrations (0.55 mg m^{-3}- 0.99 mg m^{-3}), low SST (21°C – 22.8°C) and strong current speeds moving in a south-southwest direction.

Along with Playa Sardina, the model also predicted a high probability/low standard error for two other known foraging sites for sea turtles (Fig. 19). In the model, there is no clear relationship between bathymetry and sea turtle presence. East Pacific green turtle prefers coastal waters, bays and lagoons to deeper water; however, both turtle presence and absence occurred in shallow waters with a few observations (7) of turtles in deeper waters (Green, 1975; Plotkin, 1997). Hatase (2006) tagged and tracked four turtles, two of which were observed feeding in more than 200 m waters. Green (1975) also mentioned that during non-nesting months, sea turtles move from island to island more than during nesting months. The movements of the seven turtles could be accounted for by inter-island movements, assuming these turtles were transiting and not foraging in deeper waters.

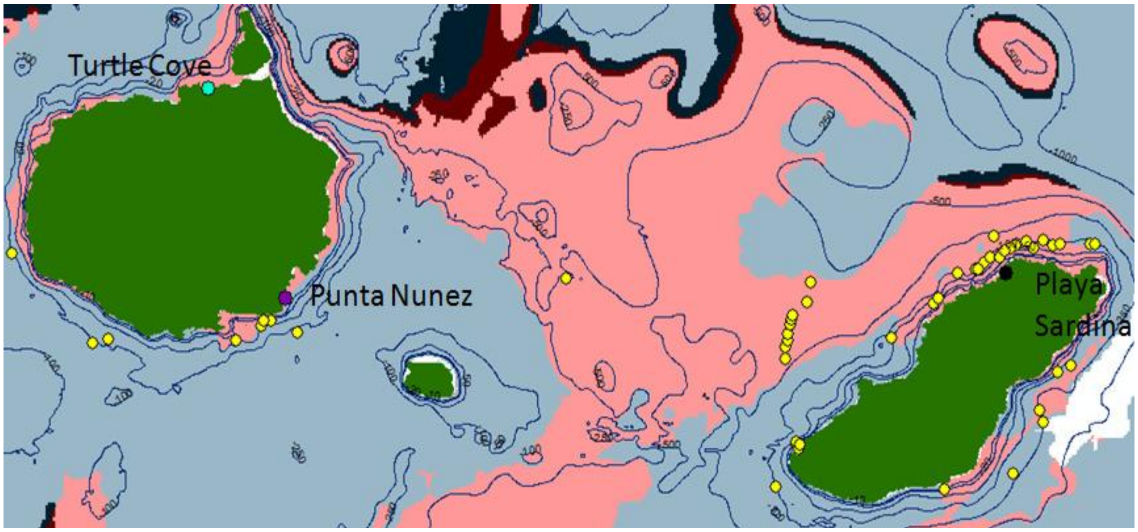

Fig. 20. A close-up of the islands of Santa Cruz and San Cristobal, showing two known sea turtle foraging locations: Caleta de la Tortuga (cyan) and Punta Nuñez (purple). No small boat surveys reached the northern part of Santa Cruz in June 2010, but turtles were observed off Punta Nuñez and in a few other locations along the south shore of Santa Cruz. Playa Sardina at San Cristobal is also labeled (black dot), showing the numerous sightings of sea turtles around the site in June 2010.

Turtles seem to prefer waters with a low chlorophyll a concentration. Seminoff et al. (2008) concluded from their study that sea turtles in neritic waters experience a wide range of chlorophyll concentrations (0.47 mg m^{-3} ±0.22 mg m^{-3}). Although these values include chlorophyll a concentrations from neritic areas from the Galapagos and the South American mainland, the turtle presence chlorophyll a values from the model are within range (0.26 mg m^{-3} ± 0.07 mg m^{-3}) of their observations. It is unclear why green turtles would prefer low chlorophyll areas. There are areas within the archipelago (western coast of Isabela) where chlorophyll a concentrations are higher; however, these areas could not be modeled due to the lack of small-boat observations there.

In the model, turtle presence strongly correlated with sea surface temperature. For the month of June, temperatures range between 20°C to 25°C. Seminoff et al. (2008) also hypothesized that Galapagos residential sea turtles may be able to survive in these temperatures due to a higher tolerance for lower temperatures since they do not travel long distances into warmer regions. Living in the Galapagos, sea turtles may be able to withstand lower temperatures and prevent the effects of cold stunning; however, the effects of cold stunning on East Pacific green turtles residing in the Galapagos has never been studied. Cold stunning, akin to hypothermia, is a condition whereby sea turtles and other marine reptiles become lethargic, stop eating and may die if their body temperatures continue to drop. Overall, the speed during June is not very large (0.1m/s to 0.6m/s) but turtle presence was significant at low current speeds. Galapagos turtles may be able to access stronger currents, which occur in the western islands, but due to the lack of observations in this area, the model cannot give any useful information pertaining to the presence of turtles in faster flowing waters.

Conclusion

The Marine Geospatial Ecology Toolbox (MGET) is proficient at implementing remotely sensed oceanographic and in-situ data into the creation of a habitat prediction distribution map of the East Pacific green sea turtle residing in the Galapagos Islands. The resulting model had an overall accuracy of 92% and it explained approximately 56% of the null deviance in the data. The model predicted areas with low chlorophyll a concentrations, sea surface temperatures of 23°C, low current speeds in shallow waters as possible areas for sea turtle presence. With more turtle observations, the model should be able to give a prediction in low observation areas such as on the western coast of Isabela.

CHAPTER IV

CONCLUSION

Ecological Context

The green sea turtle, *(Chelonia mydas)*, is listed on the Appendix I of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) and has been considered endangered since 1982 (Seminoff, 2004). Due to its almost exclusive diet of macroalgae, anthropogenic impacts are a real threat to the survival of these sea turtles. Marine turtles face different threats at sea such as diseases, collision with boats, and entrapment in fishing nets. On average, 40,000 turtles are killed as bycatch by long lines per year and 150,000 turtles are killed as bycatch by shrimp trawl nets (Parra et al., 2011). The need for conservation strategies for the East Pacific green sea turtle within the Galapagos Islands is urgent. Conserving the population of green sea turtles that forage and lay eggs within the islands would require not just a detailed map of the known and possible foraging locations for green turtles, but a better understanding of the physical and biological requirements that makes the Galapagos an ideal foraging area.

Summary

In this thesis, these objectives were addressed. Using a generalized additive model (GAM), with remotely sensed data (chlorophyll a, ocean currents and sea surface temperature), bathymetry, and turtle presence data as input, a habitat suitable model and map with a high accuracy and sensitivity was created. The map showed that green turtles can be found in both deep (>200m) and shallow areas. It also demonstrated that they prefer low chlorophyll a concentrations, slow moving waters, and warm temperatures. An understanding of the biological requirements of the East Pacific green turtle was addressed through ANOVA analyses of the macroalgal abundance at three locations. The analyses showed that there are inter-island differences in macroalgal abundance in the archipelago and that the red algae grows extensively in the islands even though its abundance is affected by the El Niño/Southern Oscillation more than other groups such as green algae (Carrion-Cortez et al., 2010).

This thesis shows that using predictive habitat distribution models can be used to preserve and protect the East Pacific green turtle. However, the effect of competitors and predators on turtles needs to be evaluated, and the interaction with other parameters not measured in this thesis research and their subsequent effect on the model must be investigated.

Suggestions for Future Studies

Although the objective of this study was to create a predictive habitat distribution model and to perform primary analyzes on the macroalgal abundance. However, the following recommendations are made concerning the both the model and the macroalgal analyses.

Collection of More Observations

More green sea turtle observations are needed, especially at Bolivar Channel, the northern coast of Santa Cruz, and the northern islands of the archipelago (Genovesa, Pinta and Marchena). Known feeding locations for green turtles along the Bolivar Channel are Bahía Elizabeth, Caleta Derek (Isabela), and Punta Espinoza (Fernandina);

distribution data from these areas will extend the map into these unmodeled regions. At these known foraging areas, line transects should also be completed so the importance of these areas can be quantified based on algal abundance, substrate type and species richness.

Verification of the Map

Additional surveys should be performed at the areas outlined as high probability/low standard error; for example in the waters south east of San Cristobal and the islands of Marchena, Genovesa and Santiago. These surveys will validate the results of the model as well as record the behavior (feeding, resting, and swimming) of green turtles observed in the area.

Model Modifications

In the Generalized Additive Model (GAM) used in this project, certain effects were omitted that should be included in future work. For example, the omission of the effects of competitors (marine iguanas and crabs) and predators (sharks and humans) on the green sea turtle distribution model could cause some of the high prediction areas to be considered as unsuitable habitat. Also the cross-product effects of parameter interactions were not acknowledged in the present GAM model; for example interactions between Sea Surface Temperature and Current speed may influence the presence of East Pacific green turtles in an area. These interactions should be considered in future work. Although parameter interactions are harder to decipher and elucidate, and they can increase the number of parameters, interactions should be investigated because they have the ability to improve model fit, especially, in areas where the standard error value was high (Guisan and Thuiller, 2005). Also, concerning the size of the buffer zone used to create the absence points, a cross-covariance analysis should be performed on the presence and absence data to determine the distance that the points are considered statistically different.

REFERENCES

Amorocho, D.F., Abreu-Grobois, F.A., Dutton, P.H., Reina, R.D., 2012. Multiple distant origins for green sea turtles aggregating off Gorgona Island in the Colombian Eastern Pacific. Plos One 7, 1-12.

Arthur, K.E., Boyle, M.C., Limpus, C.J., 2008. Ontogenetic changes in diet and habitat use in green sea turtle (*Chelonia mydas*) life history. Marine Ecology-Progress Series 362, 303-311.

Aspinall, R., Veitch, N., 1993. Habitat mapping from satellite imagery and wildlife survey data using a Bayesian modeling procedure in a GIS. Photogrammetric Engineering and Remote Sensing 59, 537-543.

Bermuda Turtle Project, 2004. Threats to sea turtles. <http://www.conserveturtles.org/bermuda/threats.htm>. 06/04/2012.

Bustamante, R.H., Okey, T.A., Banks, S., 2008. Biodiversity and Food-web structure of a Galapagos shallow rocky-reef ecosystem. In: McClanahan, T.R., Branch, G.M. (Eds.), Food webs and the dynamics of marine reefs. Oxford University Press, New York, pp. 135-161.

Campbell, L.M., 2003. Contemporary culture, use, and conservation of sea turtles, In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The biology of sea turtles, vol. 2. CRC Press, Boca Raton, Florida, pp. 307-338.

Carr, A., 1964. Transoceanic migrations of the green turtle. BioScience 14, 49-52.

Carrion-Cortez, J.A., Zarate, P., Seminoff, J.A., 2010. Feeding ecology of the green sea turtle (*Chelonia mydas*) in the Galapagos Islands. Journal of the Marine Biological Association of the United Kingdom 90, 1005-1013.

Chiriboga, A., Ruiz, D., Ziemmeck, F., Banks, S., Jaramillo Diaz, P., 2011. CDF Checklist of Galapagos Algaea - FCD Lista de especies de algas de Galapagos., In: Bungartz, F., Herrera, H., Jaramillo, P., Tirado, N., Jimenez-Uzcategui, G., Ruiz, D., Guezou, A., Ziemmeck, F. (Eds.), Charles Darwin Foundation Galapagos Species Checklist. <http://www.darwinfoundation.org/datazone/checklists/algae/>. 05/17/2012.

Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation 24, 38-49.

Franklin, J., 1998. Predicting the distribution of shrub species in southern California from climate and terrain-derived variables. Journal of Vegetation Science 9, 733-748.

Frazier, J., 2003. Prehistoric and ancient historic interactions between humans and marine turtles, In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The biology of sea turtles, vol. 2. CRC Press, Boca Raton, Florida, pp. 1-38.

Fritts, T.H., 1981. Marine turtles of the Galapagos Islands and adjacent areas of the Eastern Pacific on the basis of observations made by Slevin,J.R. 1905-1906. Journal of Herpetology 15, 293-301.

Garske, L.E., 2002. Macroalgas marinas. In: Danulat, E., D., Edgar, G.J. (Eds.), Reserva Marina de Galapagos Linea Base de la Biodiversidad. Santa Cruz, Galapagos Islands, Ecuador, pp. 419-439. <http://throughthewaves.com/uploads/3/0/7/7/3077288/rmg-linea-base-2002-garske-algas.pdf>. 05/17/2012.

Giese, B.S., Ray, S., 2011. El Nino variability in simple ocean data assimilation (SODA), 1871-2008. Journal of Geophysical Research-Oceans 116, 1-17.

Godley, B.J., Thompson, D.R., Waldron, S., Furness, R.W., 1998. The trophic status of marine turtles as determined by stable isotope analysis. Marine Ecology-Progress Series 166, 277-284.

Green, D., 1975. Population ecology of the east pacific green turtle (C*helonia mydas agassizii)* in the Galapagos Islands, In: Oehser, P.H., Lea, J.S., Link Powars, N. (Eds.), National Geographic Society Research Reports, vol. 16. National Geographic Society, Washington, D.C., pp. 463-476.

Green, D., 1984. Long distance movements of Galapagos green turtles. Journal of Herpetology 18, 121-130.

Green, D., 1993. Growth-rates of wild immature green turtles in the Galapagos Islands, Ecuador. Journal of Herpetology 27, 338-341.

Guisan, A., Edwards, T.C., Hastie, T., 2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. Ecological Modelling 157, 89-100.

Guisan, A., Thuiller, W., 2005. Predicting species distribution: offering more than simple habitat models. Ecology Letters 8, 993-1009.

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135, 147-186.

Hatase, H., Sato, K., Yamaguchi, M., Takahashi, K., Tsukamoto, K., 2006. Individual variation in feeding habitat use by adult female green sea turtles (*Chelonia mydas*): are they obligately neritic herbivores? Oecologia 149, 52-64.

Houvenaghel, G.T., 1984. Oceanographic setting of the Galapagos Islands, In: Perry, R. (Ed.), Key environments: Galapagos. Pergamon Press Ltd., Oxford, England, pp. 43-54.

Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., et al., 2005. Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308, 67-71.

Lavine, M., 1991. What is Bayesian statistics and why everything else is wrong. The Journal of undergraduate Mathematics and its applications 20, 1-7.

Lobban, C.S., Harrison, P.J., 1994. Seaweed Ecology and Physiology. Cambridge University Press, New York, N.Y.

Louzao, M., Becares, J., Rodriguez, B., Hyrenbach, K.D., Ruiz, A., Arcos, J.M., 2009. Combining vessel-based surveys and tracking data to identify key marine areas for seabirds. Marine Ecology-Progress Series 391, 183-197.

Martin, J.H., Coale, K.H., Johnson, K.S., Fitzwater, S.E., Gordon, R.M., et al., 1994. Testing the iron hypothesis in ecosystems of the Equatorial Pacific Ocean. Nature 371, 123-129.

MATLAB, 2010. Version 7.10.0 (R2010a). The MathWorks Inc., Natick, Massachusetts.

McClellan, C.M., Read, A.J., 2009. Confronting the gauntlet: understanding incidental capture of green turtles through fine-scale movement studies. Endangered Species Research 10, 165-179.

Milton, S.L., Lutz, P.L., 2003. Physiological and genetic responses to environmental stress, In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The biology of sea turtles, vol. 2. CRC Press, Boca Raton, Florida, pp. 163-198.

Mugo, R., Saitoh, S.I., Nihira, A., Kuroyama, T., 2010. Habitat characteristics of skipjack tuna (*Katsuwonus pelamis*) in the western North Pacific: a remote sensing perspective. Fisheries Oceanography 19, 382-396.

Myles, A.J., Feudale, R.N., Liu, Y., Woody, N.A., Brown, S.D., 2004. An introduction to decision tree modeling. Journal of Chemometrics 18, 275-285.

National Weather Service, 2011. Monthly Atmospheric and SST Indices. NOAA/National Weather Service, Camp Springs, Maryland. <http://www.cpc.ncep.noaa.gov/data/indices/ersst3b.nino.mth.81-10.ascii>. 06/18/2012.

O'Hagan, A., Forster, J., 2004. Kendall's advanced theory of Statistics, 4th Edition ed. Arnold Publishers, London.

Parra, M., Llerena, A., Marquez, L., Espinoza, E., 2011. Monitoring nesting activity of the green sea turtle *Chelonia mydas* in Galapagos, In: Duncan, R. (Ed.), Santa Cruz, Galapagos Islands, Ecuador.

Philander, S.G.H., 1990. El Niño, La Niña, and the Southern Oscillation. Academic Press Inc., San Diego, California.

Plotkin, P., 2003. Adult migrations and habitat use, In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The biology of sea turtles, vol. 2. CRC Press, Boca Raton, Florida, pp. 225-242.

Price, M., 2010. Mastering ArcGIS, 4th Edition ed. McGraw-Hill, New York.

Pritchard, P.C.H., Mortimer, J.A., 1999. Taxonomy, external morphology, and species identification. Research and Management Techniques for the Conservation of Sea Turtles, vol. 4. <http://college.holycross.edu/faculty/kprestwi/chelonia/pubs/3_book_chapters/06_Pritchard%26Mortimer_English.pdf>. 05/25/2012.

Reich, K.J., Bjorndal, K.A., Bolten, A.B., 2007. The 'lost years' of green turtles: using stable isotopes to study cryptic lifestages. Biology Letters 3, 712-714.

Roberts, J.J., Best, B.D., Dunn, D.C., Treml, E.A., Halpin, P.N., 2010. Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C plus. Environmental Modelling & Software 25, 1197-1207.

Rosa, L.D., Ford, J.K.B., Trites, A.W., 2012. Distribution and relative abundance of humpback whales in relation to environmental variables in coastal British Columbia and adjacent waters. Continental Shelf Research 36, 89-104.

SeaWorld Parks & Entertainment. Sea turtles. SeaWorld/Busch Gardens Animals. <http://www.seaworld.org/animal-info/info-books/sea-turtle/scientific-classification.htm>. 06/04/2012.

Seminoff, J.A., 2004. *Chelonia mydas*. UICN–SSC Red List Authority, USA. <http://www.iucnredlist.org/>. 05/23/2012.

Seminoff, J.A., Zarate, P., Coyne, M., Foley, D.G., Parker, D., et al., 2007. Post-nesting migrations of Galapagos green turtles *Chelonia mydas* in relation to oceanographic conditions: integrating satellite telemetry with remotely sensed ocean data. Endangered Species Research 4, 57-72.

Shepherd, S.A., Hawkes, M.W., 2005. Algal food preferences and seasonal foraging strategy of the marine iguana, *Amblyrhynchus cristatus*, on Santa Cruz, Galapagos. Bulletin of Marine Science 77, 51-72.

Simkin, T., 1984. Geology of Galapagos Islands, In: Perry, R. (Ed.), Key environments: Galapagos. Pergamon Press Ltd., Oxford, England, pp. 15-41.

Stassopoulou, A., Petrou, M., Kittler, J., 1998. Application of a Bayesian network in a GIS based decision making system. International Journal of Geographical Information Science 12, 23-45.

StatSoftInc., 2011. Electronic statistical textbook, Tulsa, OK. <http://www.statsoft.com/textbook/>. 04/24/2012.

Stenseth, N.C., Ottersen, G., Hurrell, J.W., Mysterud, A., Lima, M., et al., 2003. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Niño Southern Oscillation and beyond. Proceedings of the Royal Society of London Series B-Biological Sciences 270, 2087-2096.

Stokstad,E., 2010. Sea turtles suffer collateral damage from fishing. ScienceNOW, Washington D.C. <http://news.sciencemag.org/sciencenow/2010/04/sea-turtles-suffer-collateral-da.html>. 06/04/2012.

Sweet, W.V., Morrison, J.M., Kamykowski, D., Schaeffer, B.A., Banks, S., McCulloch, A., 2007. Water mass seasonal variability in the Galapagos archipelago. Deep-Sea Research Part I-Oceanographic Research Papers 54, 2023-2035.

Sweet, W.V., Morrison, J.M., Liu, Y., Kamykowski, D., Schaeffer, B.A., et al., 2009. Tropical instability wave interactions within the Galapagos archipelago. Deep-Sea Research Part I-Oceanographic Research Papers 56, 1217-1229.

Vanbuskirk, J., Crowder, L.B., 1994. Life-history variation in marine turtles. Copeia, 66-81.

Walker, P.A., Cocks, K.D., 1991. HABITAT - A procedure for modeling a disjoint environmental envelope for a plant or animal species. Global Ecology and Biogeography Letters 1, 108-118.

Wolter, K., 2012. MEI Ranks. NOAA Earth System Research Laboratory, Physical Sciences Division. <http://www.esrl.noaa.gov/psd/enso/mei/rank.html>. 06/04/2012.

Wolter, K., Timlin, M., 1993. Monitoring ENSO in COADS with a seasonally adjusted principal component index., Proceedings of the 17th Annual Climate Diagnostics Workshop. NOAA/NMC/CAC/NSSL,Oklahoma Clim. Survey,CIMMS,Univ. of Oklahoma, Norman, OK, pp. 52-57.

Woods, M.C., 1987. The Galapagos Islands-province of Ecuador. The Department of Conservation, Division of Mines and Geology, California, USA, pp. 185-189.

Wyneken, J., 2003. The external morphology, musculoskeletal system and neuro-anatomy of sea turtles, In: Lutz, P.L., Musick, J.A., Wyneken, J. (Eds.), The biology of sea turtles, vol. 2. CRC Press, Boca Raton, Florida, pp. 39-78.

Yee, T.W., Mitchell, N.D., 1991. Generalized additive models in plant ecology. Journal of Vegetation Science 2, 587-602.

Zakaria, M.H., Chia, W.S., Bujang, J.S., Arshad, A., Ogawa, H., 2008. Macroalgae diversity and life forms of inter-tidal rocky shores. Marine Research in Indonesia 32, 163-168.

Zweig, M.H., Campbell, G., 1993. Receiver-operating characteristic (ROC) plots - a fundamental evaluation tool in clinical medicine. Clinical Chemistry 39, 561-577.

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