SPECIES DISTRIBUTION MODEL OF THE NORTH PACIFIC LOGGERHEAD IN NORTH AMERICAN WATERS AND IMPLICATIONS FOR FISHERIES BYCATCH

By Aileen Lavelle

Dr. Jeffrey A. Seminoff, Advisor, NOAA SWFSC MTEAP
Dr. Andrew S. Maurer, Advisor, NOAA SWFSC MTEAP
Dr. Calandra N. Turner Tomaszewicz, Advisor, NOAA SWFSC MTEAP
Dr. Andrew Read, Advisor, Nicholas School of the Environment

April 26th, 2024

This master's Project was submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment at Duke University.

EXECUTIVE SUMMARY

The North Pacific loggerhead (*Caretta caretta*) is a vulnerable Regional Marine Unit (RMU) according to the IUCN Red List. The most pressing risk to North Pacific loggerhead populations is incidental capture, or bycatch, in fisheries throughout their range. An area of particular threat to this RMU is the Baja California Peninsula, where Peckham et al. (2007) estimated that more than a thousand loggerheads perish in artisanal fisheries in the Gulf of Ulloa annually. Thus, it is critical to more accurately understand and predict the density and timing of loggerhead occurrence in the California Current Large Marine Ecosystem (CCLME) to inform the most efficacious spatial extent and timing for protective measures, such as fisheries closures, to reduce sea turtle bycatch. Previous studies have found a tight parabolic relationship between loggerhead presence in the east Pacific and water temperature, suggesting that sea surface temperature (SST) could be used as an effective proxy to describe the habitat of loggerheads habitat.

To create a robust predictive species distribution model, we integrated four datasets (2003–2023): aerial surveys, shipboard surveys, satellite-tagged individuals, and citizen sightings with environmental co-variates of loggerhead presence. Using both generalized additive models and MaxEnt models, we found that in addition to SST, loggerhead presence in November–March during El Niño years within the southern CCLME is positively associated with chlorophyll-α, net primary productivity of carbon, sea surface elevation, magnitude of seafloor depth gradient, east-west gradient of seafloor depth, magnitude of wind velocity, west-east seawind and north-south seawind components. Loggerhead presence within the southern CCLME is negatively associated with the magnitude of seafloor depth gradient, particulate inorganic carbon, and north-south gradient of seafloor depth.

To our knowledge, this is the first species distribution model for loggerheads in the eastern Pacific. Our analysis revealed an important overlap between the predicted hotspots of loggerhead occurrence and two designated conservation areas: the Fishing Refuge Zone in the Gulf of Ulloa, Mexico, and the Pacific Loggerhead Conservation Area in Southern California. This concordance underscores the importance of these areas for the conservation of loggerhead sea turtles. However, our results also suggest that these measures could be expanded geographically and temporally more dynamically. Our study also demonstrates the power of citizen engagement in reporting species sightings, potentially increasing the predictive power of our models. We recommend incorporating species distribution modeling and additional environmental variables to inform dynamic fishery closures and protect the multiple uses of North American coastal waters.

The research questions for this project were:

1) Can we use environmental indicators to predict the presence of loggerhead sea turtles off the North American West Coast?

2) How can environmental indicators be used to adjust the spatial and temporal extent of fisheries closures to reduce sea turtle bycatch?

ACKNOWLEDGEMENTS

I would like to express my profound gratitude to everyone who helped me with this project.

- First, I thank my parents and family for their unwavering support in pursuing my dreams and passion for conservation. All of my achievements are testaments of your love.
- My mentors at the Marine Turtle Ecology & Assessment Program at NOAA SWFSC, particularly Dr. Jeffrey A. Seminoff, Dr. Andrew S. Maurer, and Dr. Calandra N. Turner Tomaszewicz.
- I am grateful to all who contributed to the loggerhead sightings database I was fortunate to use in my analysis, particularly Robin LeRoux, Lynn Massey, Erin LaCasella, and Garrett Lemons.
- Omkar Waingankar, thank you for your encouragement and for being by my side through the trials and triumphs of this program.
- Kathleen Dunn, Dr. Grant Murray, and Dr. Patrick Halpin, for their unparalleled advice in my academic career at Duke University.
- My advisor, Dr. Andrew Read, for his thoughtful and kind support throughout the CEM program.
- My fellow CEMs, thank you for providing valuable feedback on my MP presentation and, most importantly, for your friendship and community throughout the program.
- Dr. Kerry Ossi-Lupo, for her insightful feedback on my MP presentation and written drafts.

TABLE OF CONTENTS

INTRODUCTION

The North Pacific Loggerhead

The North Pacific loggerhead (*Caretta caretta*) is a vulnerable Regional Marine Unit, according to the IUCN Red List (Wallace et al., 2023; Figure 1). Regional management units (RMUs) are specific to sea turtles, allowing for conservation coordination at regional scales to address varied threats of different sea turtle life stages (Wallace et al., 2010).

The loggerhead sea turtle, like all other marine turtles found in U.S. waters, was first protected under the U.S. Endangered Species Act in 1978 (Bowen et al., 1995; NMFS & USFWS, 2020). In 2011, the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) determined that "the loggerhead sea turtle was made up of nine distinct population segments (DPS)" and that each DPS could be placed under protection through the U.S. Endangered Species Act (NMFS & USFWS, 2020). As the North Pacific loggerhead DPS constitutes a distinct genetic population, the North Pacific loggerhead DPS was then placed on the U.S. Endangered Species Act in 2011 (Bowen et al., 1995; Conant et al., 2009; Nichols et al., 2000; NMFS & USFWS, 2020). The North Pacific loggerhead is a highly migratory species and uses many different habitats, including some beyond Exclusive Economic Zones (EEZs) (Havice et al., 2018; Wallace et al., 2010; Wallace et al., 2011).

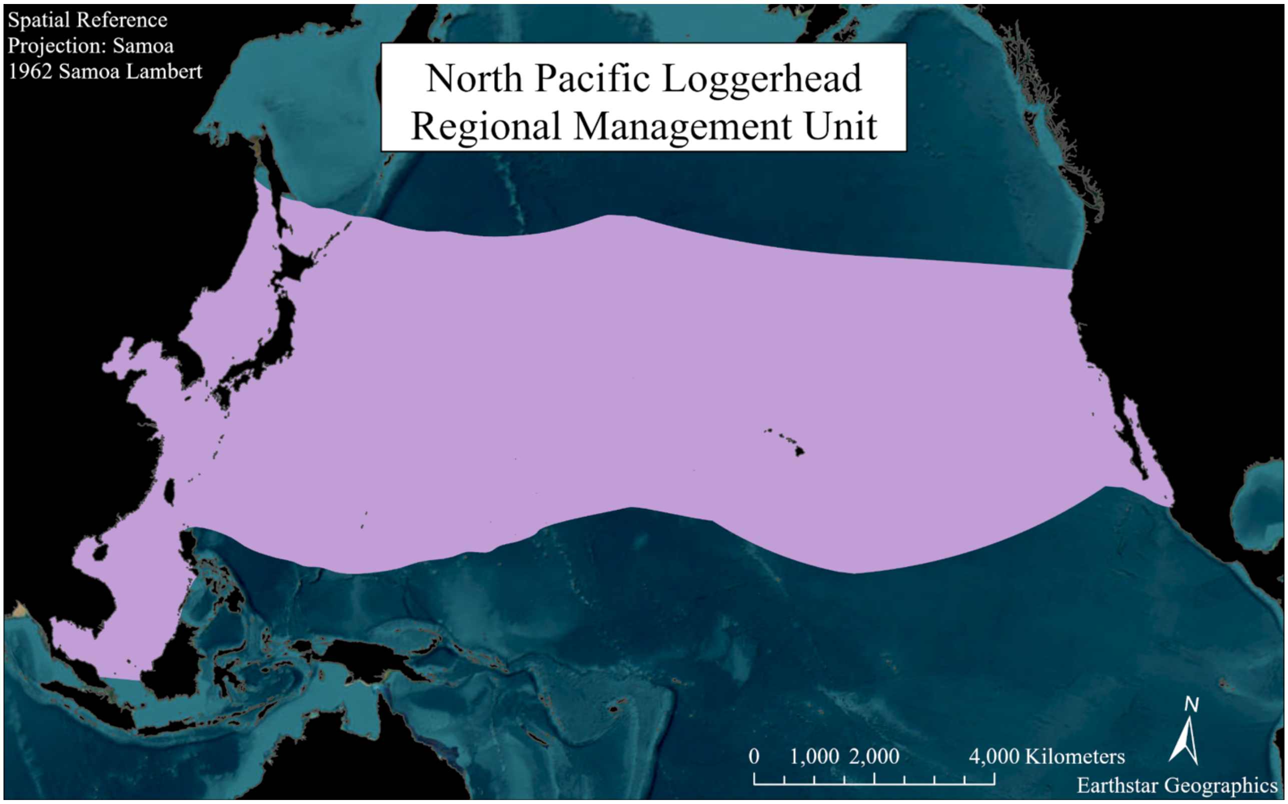


Figure 1. North Pacific loggerhead regional management unit. Adapted from Wallace et al., 2023.

In the North Pacific, loggerhead hatchlings depart from the West Pacific, almost entirely from Japanese nesting beaches (Okuyama et al., 2011; Turner Tomaszewicz et al., 2015). After "frenzy" swimming toward offshore currents, the Kuroshio Current and its extension passively transport small juvenile loggerheads in the Central North Pacific (CNP) (Okuyama et al., 2011). In addition to this passive movement, juvenile loggerheads are known to actively swim against currents to find productive foraging areas in the CNP (Briscoe et al., 2016; Christiansen et al., 2016; Polovina et al., 2006).

Juveniles then begin along developmental foraging migration in the CNP, with an unknown portion that cycles further eastward, moving into the eastern Pacific, with great abundances of loggerheads found in the Baja California Peninsula (BCP) (Briscoe et al., 2016; Hatase et al., 2002; Peckham et al., 2007; Seminoff et al., 2014). The eastern Pacific provides a productive foraging habitat for juvenile loggerheads (Bowen et al., 1995; Seminoff et al., 2004). The most productive neritic foraging area for the North Pacific loggerhead is off the BCP (Briscoe et al., 2016; Kobayashi et al., 2011; Peckham et al., 2007; Seminoff et al., 2014; Turner Tomaszewicz et al., 2015; Turner Tomaszewicz et al., 2017). Juvenile loggerheads found in the BCP are estimated to spend at least the first two decades of their lives there (Nichols, 2003; Turner Tomaszewicz et al., 2015; Wingfield et al., 2011). Upon sexual maturity, they return to Japanese nesting beaches for reproduction (e.g., Nichols et al. 2000) and stay in western Pacific neritic and/or oceanic waters for the remainder of their lives, never returning to the eastern Pacific (Hatase et al., 2002; Nichols et al., 2000; NMFS & USFWS, 2011; Watanabe et al., 2011).

Loggerhead sea turtles in the California Current Large Marine Ecosystem (CCLME) are either a result of loggerheads following the North Pacific Gyre in the CNP being able to move into the eastern Pacific, maybe through utilizing advantageous environmental conditions, termed a “thermal corridor” or loggerheads migrate northward from the BCP, Mexico (Briscoe et al., 2021; Peckham et al., 2011; Welch et al., 2019). However, even though loggerhead sea turtles are known to occur in Southern California—especially during El Niño years when environmental conditions are most favorable to their entry into the CCLME—the specific route and mechanism that allows their entry remains unknown (Eguchi et al., 2018). Allen et al. (2013) found that loggerhead turtles sampled in the Southern CCLME are not northward migrants originating from waters off the BCP but rather most likely came from the CNP, further supporting the “thermal corridor” hypothesis (Allen et al., 2013; Briscoe et al., 2021). Migratory routes taken by juvenile loggerheads may closely follow currents where loggerhead prey items are abundant (Allen et al., 2013; Cuevas et al., 2020; Pikesley et al., 2013; Polovina et al., 2000). This year-round presence and high abundance of loggerheads in the BCP is unique from other East Pacific foraging areas, as loggerheads have an ephemeral presence in Southern California (Eguchi et al., 2018; Seminoff et al., 2014).

Environmental Co-Variates

Past research has successfully used sea surface temperature (SST) to predict the occurrence of loggerhead sea turtles (Howell et al., 2008; Polovina et al., 2000; Polovina et al., 2001; Polovina et al., 2004). Unfortunately, emerging evidence suggests that climate change is causing large shifts in SST patterns that may render existing predictive models of loggerhead thermal habitat outdated (Siders et al., 2023). Thus, there is a growing need for comprehensive predictive tools informed by multiple environmental variables (Eguchi et al., 2018). The present study addresses this need by investigating the predictive power of various environmental indicators in predicting loggerhead sea turtle presence in the southern CCLME and informing the spatial extent and timing for fisheries closures to mitigate sea turtle bycatch.

Loggerheads are known to forage on a wide range of organisms, including gelatinous organisms that are passively transported along oceanic currents and, therefore, will be concentrated along convergent fronts that are visible in satellite imagery (Polovina et al., 2000; Polovina et al., 2001). However, most loggerhead foraging activity is focused on the ocean floor, consuming a variety of invertebrates, mollusks, and crustaceans (Bjorndal, 1997). Loggerheads are also known to feed on pelagic red crabs (*Pleuroncodes planipes*), which in the eastern Pacific are associated with warm periods and upwelling events (Eguchi et al., 2018; Nichols et al., 2000; Robinson et al., 200; Welch et al., 2018). Particulate inorganic carbon ($CaCO_3$) is ubiquitous in the ocean and, importantly, is the major component of Molluscan and Crustacean shells (Broecker & Peng, 1982; Gbenebor et al., 2016; Weiss et al., 2002). Therefore, new insights into foraging areas for loggerheads may be gained from remotely mapped suspended $CaCO_3$, as many of the major prey items of the North Pacific loggerhead are comprised of $CaCO_3$ (Balch et al., 2005).

Loggerheads prefer warm waters with high concentrations of chlorophyll-α at the surface (Polovina et al., 2000; Polovina et al., 2001; Polovina et al., 2004). This is because high chlorophyll-α concentration means primary producers are abundant, creating areas of high loggerhead prey abundance (Barceló et al., 2013). For example, the pelagic red crab (*Pleuroncodes planipes*), a major prey item of North Pacific loggerheads, is highly correlated with areas of high upwelling activity, creating areas of increased chlorophyll-α concentrations (Robinson et al., 2004).

Wingfield et al. (2011) found that Ulloa Bay is defined by an "upwelling shadow" due to its bathymetric and physical oceanographic features, causing this area to support very high levels of primary and secondary productivity (Wingfield et al., 2011). In addition, Zaytsev et al. (2003) found that upwelling in the BCP is greatest in areas with sharp slopes and narrow shelfs. The CCLME is home to many highly migratory species because of its unique and productive upwelling resulting from seasonal wind changes (Hazen et al., 2017; Wingfield et al., 2011; Zaytsev et al., 2003). North Pacific loggerheads spend the majority of their time close to the surface (Polovina et al., 2004).

Species Distribution Models

Species distribution models (SDMs) combine species sightings with environmental co-variates to describe existing patterns of species dispersion and can be used in a limited capacity to predict future species distributions (Elith & Leathwick, 2009). SDMs can elucidate critical spatial relationships for effective conservation prioritization (Guisan et al., 2013; Srivastava et al., 2019). Additionally, SDMs using remotely sensed variables can be low-cost, powerful solutions as such data are often freely and publicly available (Maxwell et al., 2015).

Understanding the relationship between species' environmental requirements and distribution is not a new field of study, but in recent years, the number of studies employing SDMs has increased due to concern over climate change causing changes in range and species distributions (Peterson & Soberón, 2012; Zurell et al., 2020). Climatic warming has already caused, and will continue to amplify, changes in species distributions as different species' ranges will be significantly altered (Chen et al., 2011).

Understanding changes in species distributions over time is essential to creating effective conservation management tools (Guisan & Thuiller, 2005; Putman et al., 2013). Management interventions can be most effective when species distributions are well understood (Winton et al., 2018). Dynamic fisheries management can respond to rapidly changing environmental conditions, such as changing the timing of fishing seasons or seasonal gear restrictions (Dunn et al., 2016; Hazen et al., 2017). Dynamic fisheries management informed by SDMs may have advantages over fixed time-area closures because they are intrinsically informed by environmental variables and, therefore, can be used to protect smaller areas for shorter periods while still achieving the same conservation goals (Dunn et al., 2016; Hazen et al., 2017; Maxwell et al., 2015).

Fishery Time-Area Closures

Incidental capture has been widely documented to be the primary cause of sea turtle population declines worldwide (Crowder & Heppell, 2011; Lewison et al., 2004; Peckham et al., 2015). For the North Pacific loggerheads, incidental capture in fishing gear is the greatest threat to their population's recovery throughout their wide and dispersed geographic distribution (Casale & Tucker, 2017; Finkbeiner et al., 2011; Gilman et al., 2007; NMFS & USFWS, 2020). In the east Pacific, loggerheads are found in the coastal waters and incidentally caught in the fisheries of the U.S. and Mexico (Peckham et al., 2007; Seminoff et al., 2014; Welch et al., 2019).

Established in 1976, the Magnuson-Stevens Fishery Conservation and Management Act forms the bedrock of marine fisheries oversight in U.S. federal waters (U.S. Department of Commerce et al., 2007; U.S. Department of Commerce et al., 2015). An important amendment in 2006, known as Section 610, conferred upon the Secretary of Commerce the unilateral authority to identify foreign nations implicated in the incidental capture, or bycatch, of protected living marine resources (PLMRs) under specific stipulations (Senko et al., 2017; U.S. Department of Commerce et al., 2007; U.S. Department of Commerce et al., 2015). This notable provision aimed to address mounting concerns about the adverse effects of bycatch within and outside U.S. waters on protected marine species, such as the North Pacific loggerhead, whose range is not restricted to a given country's EEZ (Senko et al., 2017).

An area of particular fishery management interest is the Gulf of Ulloa, along the Pacific coast of the BCP, Mexico, which serves as a North Pacific loggerhead foraging hotspot; it is also a site of significant bycatch-related mortality (Peckham et al., 2007; Peckham et al., 2011; Peckham et al., 2015). A shockingly high number (up to 1000) of juvenile to subadult loggerheads are estimated to perish yearly, most likely due to fishery interactions (Peckham et al., 2007). Seminoff et al. (2014) estimated that fishery interactions or natural threats take up to 11% of the BCP loggerhead population annually. Using this estimate, North Pacific loggerheads that spend 20 years in the BCP have a predicted survivorship rate of 10% (Turner Tomaszewicz et al., 2015).

In July 2012, a notable event unfolded along the Pacific coast of the BCP, Mexico, with a mass stranding of North Pacific loggerhead sea turtles coinciding with reports of significant bycatch in the region's artisanal gillnet fishery fleet (Senko et al., 2017; U.S. Department of Commerce et al., 2015). This might have been caused partly by Mexico's nationwide elasmobranch moratorium during the summer of 2012, causing subsistence fishers to shift fishery gear from surface targeting gear to bottom-set nets, which are more likely to incidentally capture loggerheads (Senko et al., 2017).

Subsequently, in 2013, NOAA NMFS, for the first time, invoked Section 610 of the Magnuson-Stevens Act to identify Mexico for the bycatch of a PLMR, specifically the North Pacific loggerhead (Senko et al., 2017; U.S. Department of Commerce et al., 2015). Under this provision, Mexico was granted a two-year period to develop a regulatory program aimed at reducing or eliminating loggerhead turtle bycatch in a manner comparable to that of the United States fisheries fleet (Senko et al., 2017; U.S. Department of Commerce et al., 2015). In 2015, NOAA NMFS negatively certified Mexico for its failure to effectively mitigate the high rates of loggerhead sea turtle bycatch mortalities in the Gulf of Ulloa, BCP, Mexico (U.S. Department of Commerce et al., 2015).

In response, Mexico created the "Fishing Refuge Zone" in the Gulf of Ulloa in April 2015 to reduce loggerhead sea turtle bycatch mortalities (Diario Oficial de la Federación, 2016; Figure 3). The Fishing Refuge Zone can be considered a static closure because it is enacted year-round and establishes a mortality cap of 90 turtles; then, within the Specific Fishing Restrictions Area, the Mexican Government has adopted specific gear restrictions to best reduce sea turtle mortalities such as no J hooks, seasonally larger gillnet mesh sizes aligning with time of high sea turtle density, and some in-vessel video monitoring (Diario Oficial de la Federación, 2016).

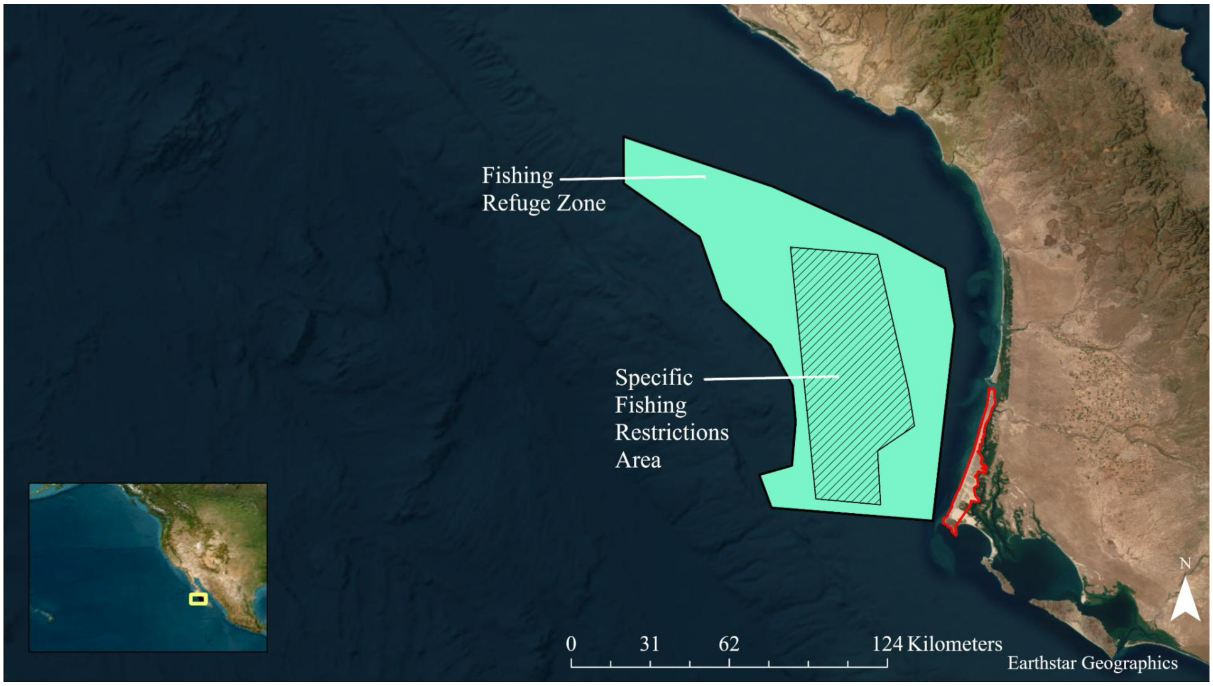


Figure 3. Map of Mexican loggerhead sea turtle conservation area. The red highlighted region is where the mass stranding event of North Pacific loggerheads occurred in July 2012.

Moving to the northern range of the North Pacific loggerhead, Southern California is an ephemeral habitat for this species (Eguchi et al., 2018; Welch et al., 2019; Zaba & Rudnick, 2016). There was an increase in loggerhead sightings offshore of Southern California in 2015 that occurred at the same time as a warm water period as a result of a marine heat wave (Eguchi et al., 2018; Welch et al., 2019; Zaba & Rudnick, 2016). Additionally, southern California's loggerhead sea turtle bycatch records largely occur during El Niño conditions (Allen et al., 2013; Carretta, 2022; Eguchi et al., 2018; NMFS, 2000). In 2004, NOAA NMFS enacted a mandated fishery time-area closure, Federal Register 72 FR 31756, to reduce loggerhead bycatch mortalities within the drift gillnet fishery fleet off Southern California (NOAA NMFS, 2004; NOAA NMFS, 2007). This area can be considered a dynamic fisheries management area as the closure of the California drift gillnet fishery is triggered by changing environmental conditions, which may be different each year (NOAA NMFS, 2004; NOAA NMFS, 2007). Closures of the

“Pacific Loggerhead Conservation Area” are enacted in the summer (June–August) when the conservation area has warmer than average SST during an officially declared El Niño year (NOAA NMFS, 2004; NOAA NMFS, 2007; Welch et al., 2019; Figure 2). This is due to the tight parabolic relationship between North Pacific loggerhead presence in the eastern Pacific and warm SSTs (15–25 °C) (Howell et al., 2008; Polovina et al., 2000; Polovina et al., 2001; Polovina et al., 2004).

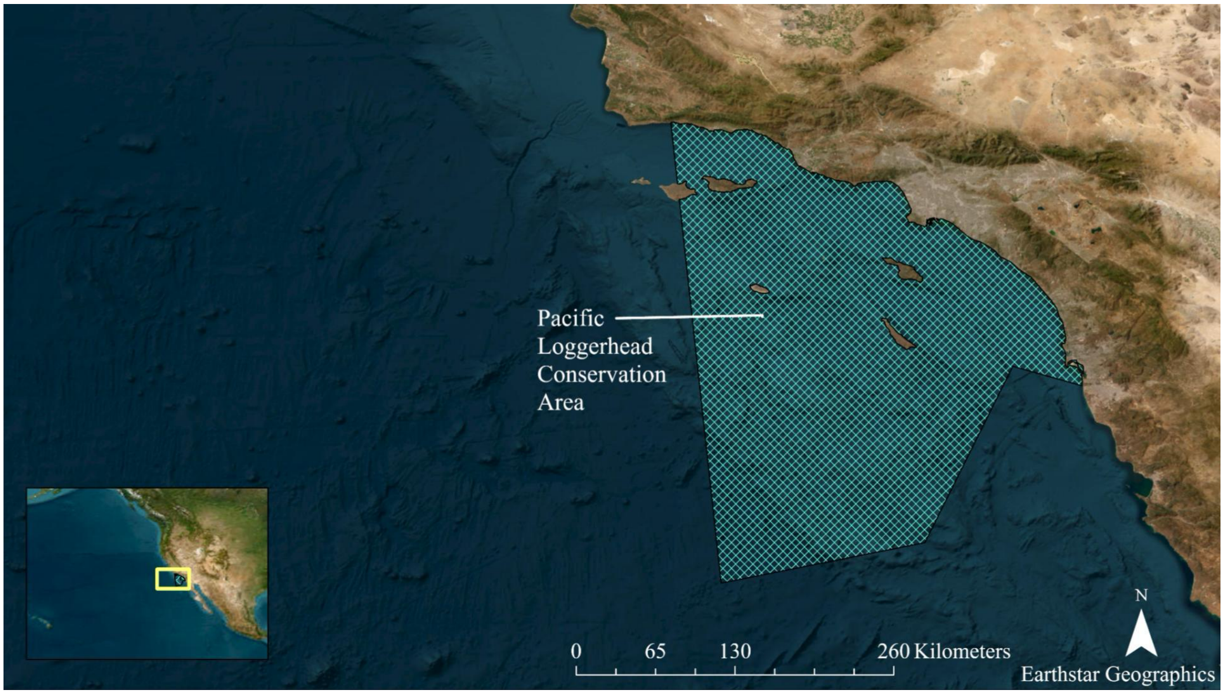


Figure 2. Map of United States loggerhead sea Turtle conservation area affecting the California Drift Gillnet Fishery.

Study Objective

The biggest mortality risk to the North Pacific loggerhead in North American waters is incidental capture in fishery gear, especially in artisanal fisheries in the EP and WP EEZs and in industrial fisheries in the high seas. Dynamic fishery time-area closures in the United States aimed at reducing loggerhead mortalities are largely based on sea surface temperature. Siders et al. (2023) found that climate change is causing rapid spatial and temporal changes in SST, which may cause these tools to be less effective at mitigating mortalities as the thermal habitat of loggerheads shifts into novel areas. It is possible that more accurate and precise models of loggerhead habitat could be informed by including additional environmental variables.

The research questions for this project are:

1) Can environmental indicators predict loggerhead sea turtle presence off the North American West Coast?

   This question was answered by running Generalized Additive Models and MaxEnt models in R Studio version 03.0+386 and ArcGIS Pro 3.1, inputting live sea turtle sightings from the MTEAP at NOAA SWFSC, and remotely sensed environmental variables from NOAA ERDAPP, which are free and publicly available.

2) How can environmental indicators inform the spatial extent and timing for fisheries closures to reduce sea turtle bycatch?

   This question was answered by comparing existing fishery time-area closures and predicted hotspots of seasonal loggerhead presence in the Southern CCLME.

METHODS

Loggerhead Sightings

A single sampling method may be insufficient to fully describe sea turtle distributions and habitat use, so it is often preferable to combine datasets with high temporal and spatial resolution (Zampollo et al., 2022). In the current study, four independent datasets were integrated to predict loggerhead presence in the southern CCLME: aerial line-transect surveys, California Current Marine Mammal Assessment Program's ship line-transect surveys, observations of the locations of satellite-tagged individuals, and sighting reports from the public. These four datasets were collected by the Marine Turtle Ecology & Assessment Program (MTEAP) at NOAA Southwest Fisheries Science Center (SWFSC). These data sources provided GPS locations and dates of loggerhead sea turtle sightings.

Initially, data from aerial surveys yielded the largest sample size (N = 884 sightings); these surveys followed the line-transect survey protocols outlined in Thomas et al. (2010). The aerial line-transect sightings in this study occurred only in Southern California, USA, and the Gulf of Ulloa, BCP, Mexico (Eguchi et al., 2018; Seminoff et al., 2014; Figures 4 and 5).

Data also came from members of the public who submitted sighting reports to the West Coast Stranding Hotline at (562) 506-4315. Since 2022, sighting reports from the public were obtained through a voluntary survey hosted under ArcGIS survey 123. Stickers made by Dr. Michelle Maria Early Capistrán were strategically placed throughout San Diego to interest participants who could simply scan a QR code and report sea turtle sightings. In data filtering, all entries with the following terms were removed: "hawksbill," "Carlsbad," and "green." Loggerheads are found in the offshore waters of California, so a buffer of 10 miles off the coast of California was created to exclude likely non-loggerhead sightings. Additionally, a buffer with a 2-mile radius was placed around the Channel Islands, as these would be primarily Green Sea turtle sightings (pers. comm., Jeffrey Seminoff). When observation descriptions described sightings of multiple animals, the coordinates were repeated for each animal count so that later models had an accurate number of individuals. For example, the term dozens in this study was interpreted as twelve individuals to quantify the minimum number of individuals sighted.

Data compiled by Eguchi et al. (2018) included opportunistic loggerhead sightings from the NOAA SWFSC California Current Marine Mammal Assessment Program's ship surveys, in which scientists were searching for marine mammals but also documented loggerhead sightings. The California Current Marine Mammal Assessment Program's ship surveys started in 1991, covering much of the waters in Southern California, USA (Eguchi et al., 2018).

Finally, four satellite-tagged individuals have been tracked in the southern California Bight (SCB) since 2015 by NOAA SWFSC MTEAP (NMFS permit #14510), three (Ruth, Char-Char, and Coco) after release from rehabilitation centers at the Aquarium of the Pacific and SeaWorld, San Diego, and one (Matteo) that was hand captured in offshore waters of the SCB (pers. comm., Jeffrey Seminoff). In this study, GPS locations tagged individuals from different days were quantified as unique sightings, as we were aiming to understand the probability of loggerhead presence in a given area or habitat. Coco had 44 locations, Matteo had 99 locations, Ruth had 90 locations, and Char-Char had 93 locations (pers. comm., Jeffrey Seminoff).

Table 1. NOAA SWFSC MTEAP collected twenty years of North Pacific loggerhead sightings from four independent data streams and the number of individual sightings (N=1719).

Dataset	Years	Number of individuals (*Caretta caretta*) sighted
Aerial Surveys	2005–2007, 2011, 2015, 2018	884
Ship-based Surveys	1991–2015	139
Satellite-Tagged Individuals	2015–2016, 2021	326
Public Sightings	2003, 2005–2006, 2008–2010, 2013–2016, 2019–2020, 2023	370

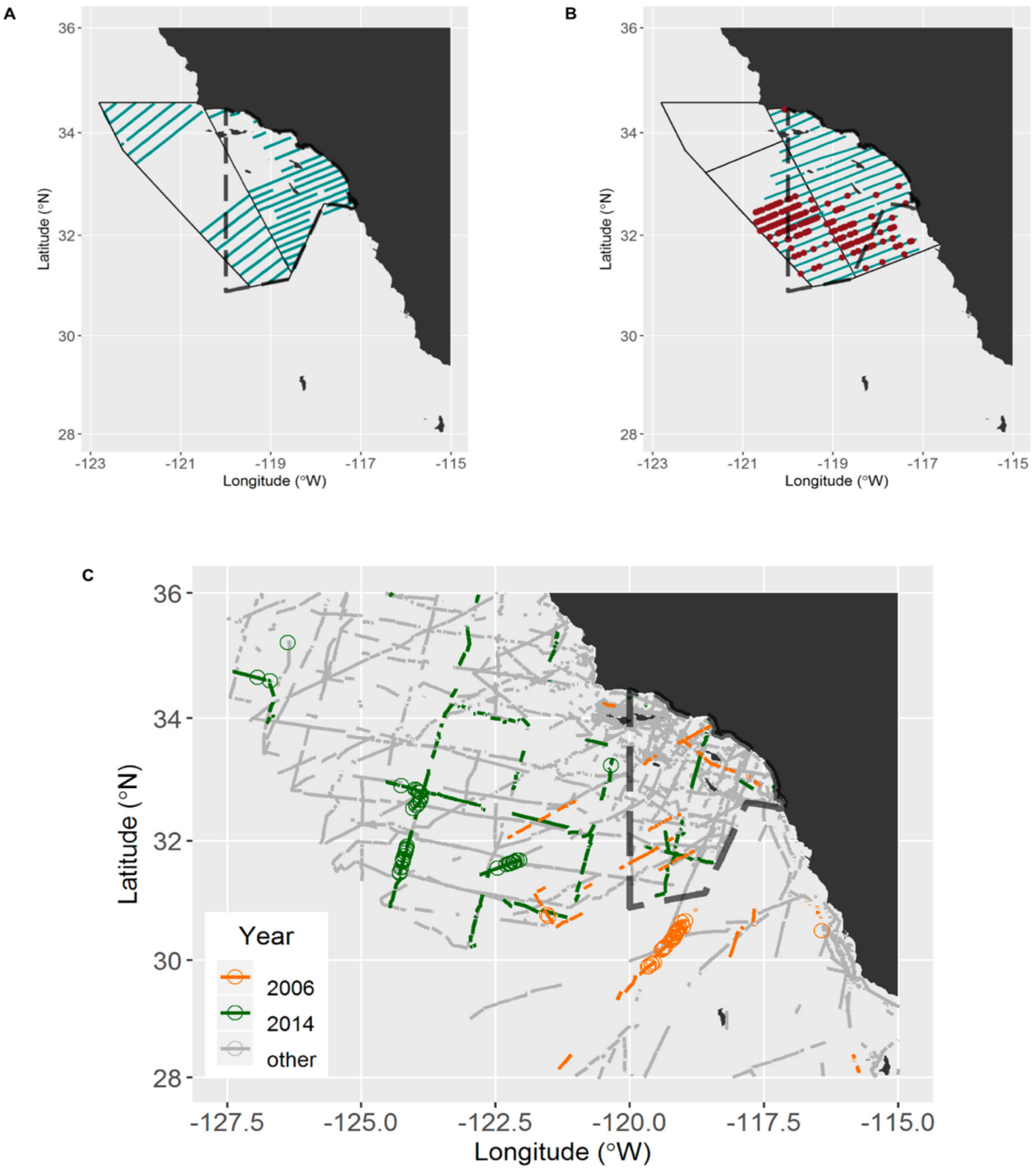


Figure 4. Eguchi et al. (2018) produced maps "showing the survey lines of the aerial survey conducted in 2011 (A) and 2015 (B) and sighted loggerhead sea turtles(C). Data from marine mammal ship-board surveys are colored by survey year. The study area for the aerial survey is outlined with solid black lines, and the completed aerial survey track lines are shown in blue. Each colored point Along the track lines shows an individual loggerhead sighting. Additionally, the dashed line shows the Pacific Loggerhead Conservation Area triggered during official El Niño years."

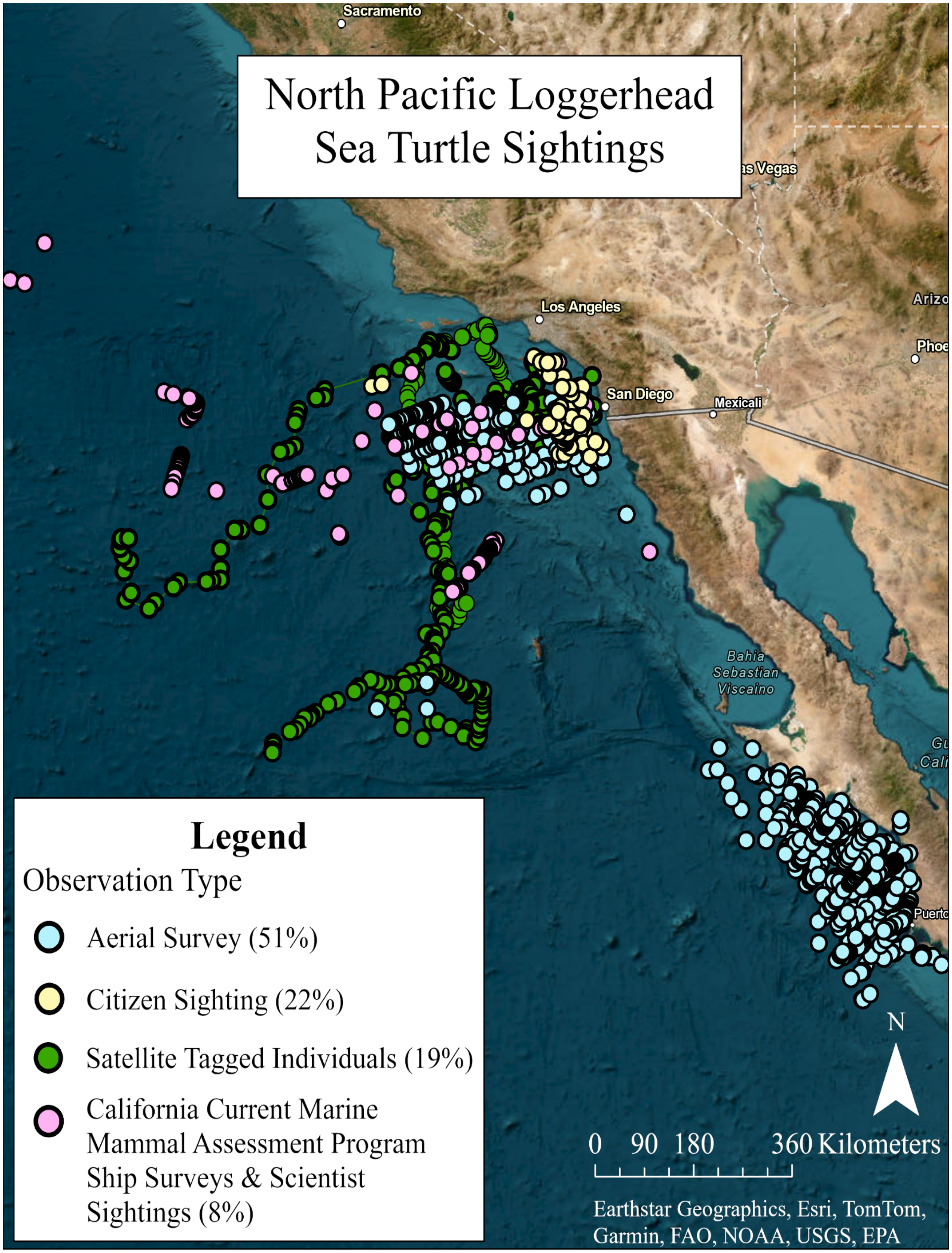


Figure 5. Map of live loggerhead sightings used for predictive species distribution models. Points are colored based on the data source and the contribution of each data source.

Environmental Co-variates

Following the protocol outlined in Liang et al. (2022), environmental co-variates were obtained from NOAA's ERDDAP, Version 2.23, for the two study sites: the southern CCLME (Xmin: -115.517414; Ymin: 23.11274; Xmax: -110.290654; Ymax: 27.7526) and southern California (-132.11243, -108.75468, 21.83586, 47.90313) (Table 2).

Table 2. This study used data on environmental variables from remotely sensed variables collected from the NOAA NMFS SWFSC's ERDAPP online server. All variables had the same coordinate reference system (GCS WGS 84). * Denotes variables used in the MaxEnt model for the southern CCLME but not in the GAM for the Southern California area.

Environmental Variable	Source	Period	Spatial Resolution	Temporal Resolution	Units
Chlorophyll-α*	Aqua MODIS, NPP, West US, Experimental	2002–present	0.0125 degrees	Monthly Composite	mg m^{-3}
Net Primary Productivity of Carbon	Aqua MODIS	2003–2016	0.0125 degrees	Monthly Composite	mg C m^{-2} day^{-1}
Extended Reconstructed Sea Surface Temperature (SST)	ICOADS 3.0	1993–2002, 2023	2° × 2° horizontal grid	Monthly Composite	°C
Sea Surface Temperature (SST)	Aqua MODIS	2003–2022	0.0125 degrees	Monthly Composite	°C
Sea Surface Height (SSH)	HYCOM	1992-present	0.25 degrees	Monthly Composite	Centimeters
Magnitude of Sea Floor Depth Gradient	Estimated Seafloor Depth Gradients: srtm30plus	2019-present	0.01666 degrees	N/A	Meters
East-West Gradient of Sea Floor Depth*	Estimated Seafloor Depth Gradients: srtm30plus	2019-present	0.01666 degrees	N/A	Meters

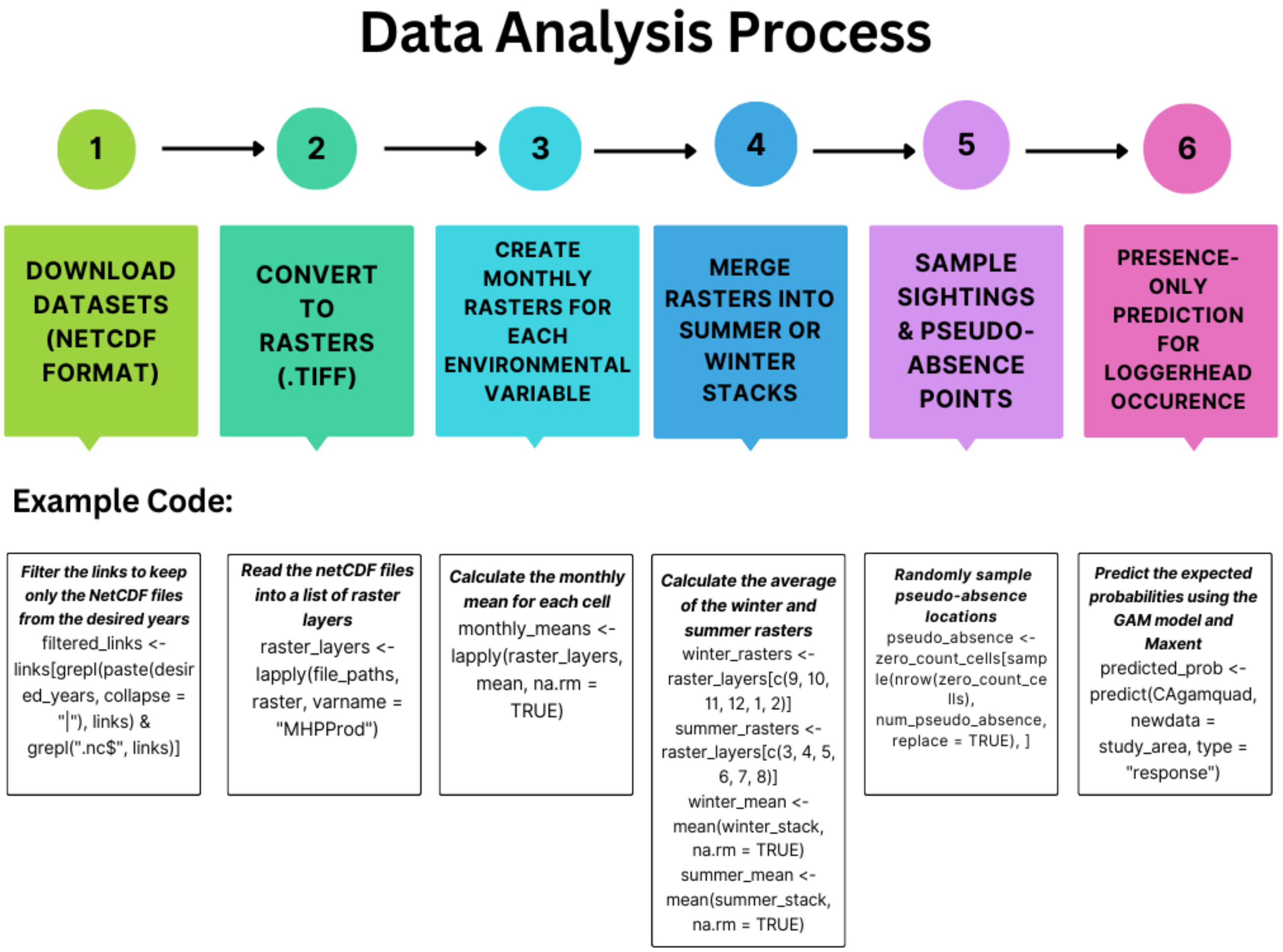
North-South Gradient of Sea Floor Depth*	Estimated Seafloor Depth Gradients: srtm30plus	2019-present	0.01666 degrees	N/A	Meters
Magnitude of the Wind Velocity*	Sea Surface Wind, NOAA NCEI Version 2.0	1987-present	0.25 degrees	Monthly Composite	m/s
Zonal (East-West) Wind Component*	Sea Surface Wind, NOAA NCEI Version 2.0	1987-present	0.25 degrees	Monthly Composite	m/s
Meridional (North-South) Wind Component*	Sea Surface Wind, NOAA NCEI Version 2.0	1987-present	0.25 degrees	Monthly Composite	m/s
Particulate Inorganic Carbon ($CaCO_3$)*	Aqua MODIS	2003-present	4.64 km	Monthly Composite	mol m^{-3}

Data Conversion

We downloaded the raw datasets from the NOAA ERDAPP online server, and then in R Studio, version 202023.03.0+386, we converted all NETCDF files into rasters using the “raster” package (Figure 6). Then, in R, we ran correlations between environmental variables to ensure there was no redundancy. Some data were obtained at a daily time step, so we had to merge all the daily data into a raster that was monthly averages of the environmental variable of interest. Once we had created rasters of monthly averages, we created seasonal stacks of rasters, winter and summer, to predict loggerhead occurrence over a given period (Figure 6). In this study, winter months are defined as November-March, and summer months are defined as April–October.

For southern California, we created a study area raster consisting of 0.25 decimal degree grid cells to count the number of loggerhead sea turtle sightings per cell. Then, we made random pseudo-absence points by subsetting cells with zero loggerhead counts and randomly sampling monthly raster times, matching the quantity and time of presence data in Southern California (Figure 6). We chose this method because past research has found SDMs fitted an equal number of pseudo-absences to the known presence points to produce the most accurate models (Barbet-Massin et al. 2012).

We then were able to sample the environmental variables (“sample tool”) for each sea turtle sighting in ArcGIS Pro 3.1; we also tested the environmental variables at the GPS locations of all the pseudo-absence points at the same monthly averaged rasters as the actual presence sightings. Next, we extracted the environmental variables at each cell's GPS location (longitude and latitude) within the study area raster from the merged summer and winter rasters, respectively (Figure 6).



Filter the links to keep only the NetCDF files from the desired years

```
filtered_links <- links[grepl(paste(desired_years, collapse = "|"), links) & grepl(".nc$", links)]
```

Read the netCDF files into a list of raster layers

```
raster_layers <- lapply(file_paths, raster, varname = "MHPProd")
```

Calculate the monthly mean for each cell

```
monthly_means <- lapply(raster_layers, mean, na.rm = TRUE)
```

Calculate the average of the winter and summer rasters

```
winter_rasters <- raster_layers[c(9, 10, 11, 12, 1, 2)]
summer_rasters <- raster_layers[c(3, 4, 5, 6, 7, 8)]
winter_mean <- mean(winter_stack, na.rm = TRUE)
summer_mean <- mean(summer_stack, na.rm = TRUE)
```

Randomly sample pseudo-absence locations

```
pseudo_absence <- zero_count_cells[sample(nrow(zero_count_cells), num_pseudo_absence, replace = TRUE), ]
```

Predict the expected probabilities using the GAM model and Maxent

```
predicted_prob <- predict(CAgamquad, newdata = study_area, type = "response")
```

Figure 6. Workflow for scraping data, merging files, and creating loggerhead prediction surface.

Spatial Autocorrelation (Global Moran’s I)

The Moran's Index (I) measures spatial autocorrelation of inputted data points (Kumari et al., 2019). Cliff & Ord (1973) outline that “the Global Moran's I tool evaluates the spatial pattern of a dataset and determines whether it is dispersed, clustered, or random, based on the locations and values of the features.” The resulting Global Moran's I range from -1 to +1, +1, indicating that the inputted feature is more spatially clustered. The global Moran's I statistic is given as follows:

$$I = \frac{n}{s_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_j z_j}{\sum_{i=1}^{n} z_i^2}$$

Where Cliff & Ord (1973) define the variables as the following:
“n is the number of points, and
Zi is the deviation of an attribute for each point
i from its mean ((xi−x)), and
wi,j is the spatial weight of each point i and j.”

In ArcGIS Pro 3.1, we employed the geoprocessing tool "Global Moran’s I" to quantify the spatial autocorrelation among environmental co-variates at loggerhead presence locations. Aerial transects introduce uneven spatial coverage or observer bias, so understanding the potential biases in this dataset of loggerhead sightings arising from the sampling design, we mitigated these effects by implementing row standardization. Furthermore, we chose Euclidean distance for analyzing aerial line transect survey data because its simplicity allows for easy distance calculation between sighting points.

Generalized Additive Model and Prediction

In this study, we first performed a generalized additive model (GAM) for Southern California only, with seven environmental co-variates (primary productivity, SST, SST anomaly, estimated seafloor depth gradients ETOPO, estimated seafloor depth gradients srtm30plus, sea surface height, SST smoothed frontal gradients; Table 2). The pseudo-absence and presence points were combined into a single data frame to run a GAM. We implemented the results of our GAM to predict the expected response for new predictor (Southern California study area) values. Created by Hastie & Tibshirani (1986), the GAM can be used to “create a prediction matrix, which maps the vector of response values (dependent variable values) to the vector of fitted values (predicted values).” Hastie & Tibshirani (1986) define these functions as the following: “the vector of predictions is then ˆµp=Xpˆβ, and µp∼N(Xpˆβ, Xp(XTWX+ j λjSj)−1XpTφ)”. Therefore, in R, we used the “predict.gam(x, new data, type, se)” function to predict seasonal loggerhead occurrence in a given cell (0.25 x 0.25 decimal degrees) over the study period.

MaxEnt Model

We used the MaxEnt spatial statistics geoprocessing tool built in ArcGIS Pro 3.1 for presence-only modeling of seasonal loggerhead sea turtle occurrence within the southern CCLME. Exploratory maps were also made to predict the monthly probability of loggerhead sea turtle occurrence in the southern CCLME, where there was sufficient data (Appendix A-G). MaxEnt is an SDM based on maximum entropy; the model applies machine learning to assign a probability of a species presence (0 to 1) in a given grid cell of the study area using the inputted environmental variables with known presence points and "randomly selected background locations" (Phillips et al. 2006; Phillips & Dudík 2008). Our model input consisted of 1719 georeferenced live loggerhead turtle sightings (compiled by MTEAP at NOAA SWFSC) and twelve environmental variables (chlorophyll-α, net primary productivity of carbon, extended reconstructed sea surface temperature, sea surface temperature, sea surface height, the magnitude of seafloor depth gradient, the east-west gradient of seafloor depth, the north-south gradient of seafloor depth, magnitude of the wind velocity, zonal wind component, meridional wind component, particulate inorganic carbon; Table 2).

The omission curve can help to determine the right threshold for their SDM, as it shows how the omission rate changes for different thresholds (Girerd, 2022). SDM omission occurs when a presence is incorrectly assigned as an absence (Girerd, 2022).

To evaluate our MaxEnt models, we compared the ROC (receiver operating characteristic curve) using the AUC (area under the receiver operating characteristic curve), which ranges from 0 to 1. AUC values < 0.5 indicate model performance is worse than random, and AUC values >0.9 indicate high model performance (Jiang et al., 2018). However, it is important to be cautious when interpreting AUC values, as they can be misleading for various reasons (Gonzalez et al., 2011). AUCs evaluate a model's performance across the ROC curve, with extremes at low and high thresholds. Our study focuses on thresholds where the predicted probability of occurrence exceeds 0.50, indicating model performance is better than random chance (Gonzalez et al., 2011). The ROC indicates model performance regardless of the threshold researchers selected (Jiang et al. 2018).

In this study, we employed two spatial statistics geoprocessing tools for presence-only modeling of species distributions, acknowledging their distinct advantages and limitations. While MaxEnt shares similarities with GAMs, notable differences influence their prediction surfaces. Notably, MaxEnt models a probability distribution across all grid cells within a study area, assigning non-negative probabilities to all grid cells, including those with no data, which is helpful because GAMs treat grid cells with no true presence as absences, which may not be true to real conditions (Phillips et al., 2006). Another important distinction between GAMs and MaxEnt, particularly relevant to our study due to sparse loggerhead sightings at sea, is that MaxEnt employs a generative approach (machine learning) while GAMs utilize discriminative methods (Phillips et al., 2006). Therefore, a generative approach may yield better SDMs even with "limited data" (Phillips et al., 2006).

RESULTS

Southern California Spatial Autocorrelation (Global Moran's I)

The Global Moran's Index values obtained for all environmental variables at loggerhead presence locations are greater than zero, suggesting positive autocorrelation or a highly clustered pattern (Table 3). Furthermore, the obtained *p*-values are less than 0.001 ($p \leq 0.001$) for all environmental co-variates, meaning environmental values associated with loggerhead presence are not due to random chance (Table 3).

Table 3. Global Moran's I, *p*-values, and z-scores for environmental variables. The *p*-values are statistically significant, and the z-scores are positive for all environmental variables. This indicates that the spatial distribution of values for all environmental variables in this study is clustered.

Environmental Variables	Moran's Index	Expected Index	Variance	z Score	*p* Value
Sea Surface Temperature (SST)	0.490318	-0.002123	0.000243	31.582521	$p < 0.001$
Depth Gradient	0.427571	-0.002119	0.000241	27.706316	$p < 0.001$
Primary Productivity	0.271885	-0.002123	0.000232	17.976380	$p < 0.001$
Surface Elevation Mean (SSH)	0.259293	-0.002123	0.000242	16.809571	$p < 0.001$
Frontal Edge	0.074322	-0.002123	0.000239	4.943577	$p < 0.001$
Bathymetry	0.733957	-0.002119	0.000243	47.257729	$p < 0.001$

Southern California Generalized Additive Model

For the GAM applied to Southern California, we investigated the relationship between seven environmental co-variates (primary productivity, SST, SST anomaly, estimated seafloor depth gradients ETOPO, estimated seafloor depth gradients srtm30plus, sea surface height, SST smoothed frontal gradients) and the presence of North Pacific loggerheads. Our findings revealed a positive association between loggerhead occurrence in Southern California and bathymetry and frontal edges, while a negative association was observed with surface elevation mean and primary productivity (Table 4). Effects of SST were assumed quadratic with a minimum of around 15°C (Table 4). The predictive R^2 of the Southern California SDM is 36%, with 1492 sightings (746 true sightings and 746 pseudo-absence points). This suggests that loggerheads exhibit ephemeral presence in Southern California, with the highest likelihood found in near-shore, highly productive, and relatively flat seas (Table 4). The predicted loggerhead occurrence during El Niño years is highest in the coastal areas from Southern California to the upper portion of the Baja California Peninsula (Figure 8). Low predicted loggerhead occurrence during El Niño years occurs further offshore (Figure 8).

Table 4. Southern California generalized additive model. Population-level coefficient estimates, standard error, standard score, and *p*-value from a generalized additive model relating loggerhead presence with environmental co-variates.

Environmental Variables	**Estimate**	**Std. Error**	**z Value**	***p* Value**
Sea Surface Temperature (SST)	-1.213e-01	1.706e-02	-7.111	1.15e-12***
Primary Productivity	-3.963e-03	5.401e-04	-7.339	2.15e-13 ***
Surface Elevation Mean (SSH)	-8.369e-03	1.182e-03	-7.081	1.44e-12 ***
Frontal Edge	1.316	3.545	0.371	0.71
Bathymetry	1.138e-03	7.463e-05	15.248	< 2e-16 ***

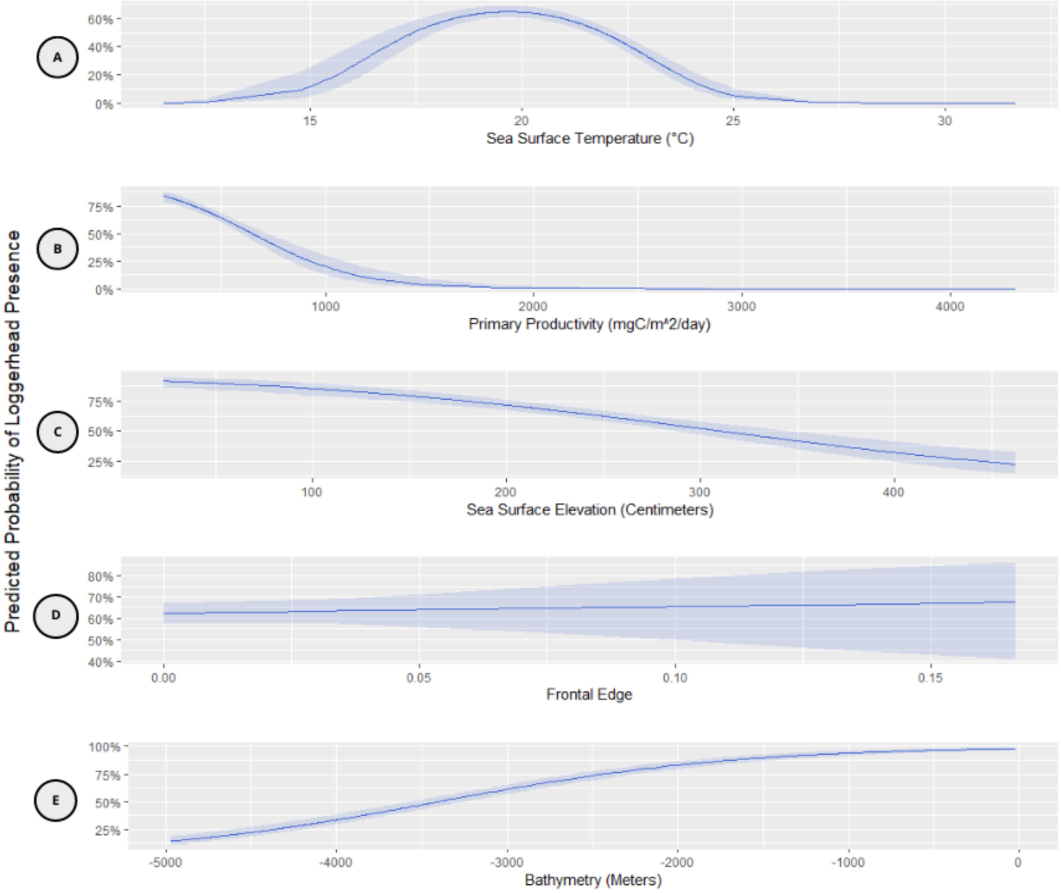


Figure 7. Relationship of variable and loggerhead presence in Southern California during El Niño years with 95% confidence interval. (A) Loggerhead presence was statistically higher in locations with sea surface temperatures of 17.5 to 22.5 ($z = -7.111$, $df = 1433$, $p < 0.001$) (B) Loggerhead presence was statistically higher in areas of low primary productivity ($z = -7.339$, $df = 1433$, $p < 0.001$). (C) Loggerhead presence was statistically higher in waters with shorter wave heights ($z = -7.081$, $df = 1433$, $p < 0.001$). (D) Loggerhead presence was slightly higher closer to the edge of frontal eddies ($z = 0.371$, $df = 1433$, $p < 0.1$). (E) Loggerhead presence was statistically higher closer to the shore ($z = 15.248$, $df = 1433$, $p < 0.001$).

In our study, the remotely sensed sea surface temperatures we sampled for our loggerhead sea turtle sightings ranged from 15.14 to 20.26°C; the sightings data skewed toward higher temperatures. Additionally, this study's range of sea surface temperatures found at sea turtle sighting locations is smaller than Eguchi et al. (2018). This is likely because sea surface temperatures were sampled from remotely sensed environmental rasters of monthly averages rather than more instantaneous measurements that were taken through the *in-situ* shipboard surveys conducted by the California Cooperative Oceanic Fisheries Investigation used by Eguchi et al. (2018).

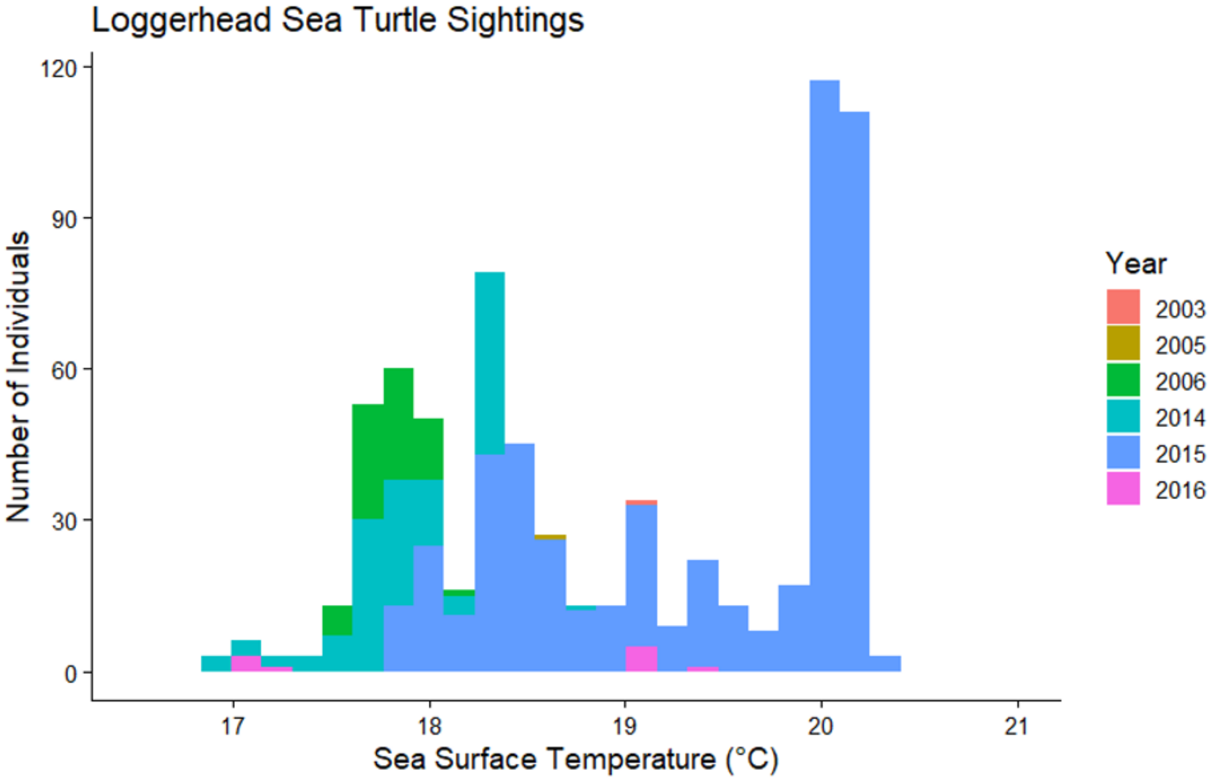


Figure 8. Relationship between sea surface temperature and loggerhead sea turtle sightings in Southern California.

The predicted probability for loggerhead sea turtle occurrence during El Niño years in Southern California is highest in the nearshore environment (Figures 8 and 12). This could be due to the non-random spatial distribution of observers, but evidence from four loggerhead turtles satellite-tracked off southern California also suggests a strong coastal affinity (Figure 5). All four satellite-tracked loggerheads were tagged from 2015–2021, with positions last recorded between 399 km to 730 km of the shore (NOAA unpublished data). Additionally, kernel density analyses highlight that loggerhead turtles are largely neritic foragers in the southern CCLME compared to juveniles in the CNP (Peckham et al. 2011; Sandoval-Lugo et al. 2020.)

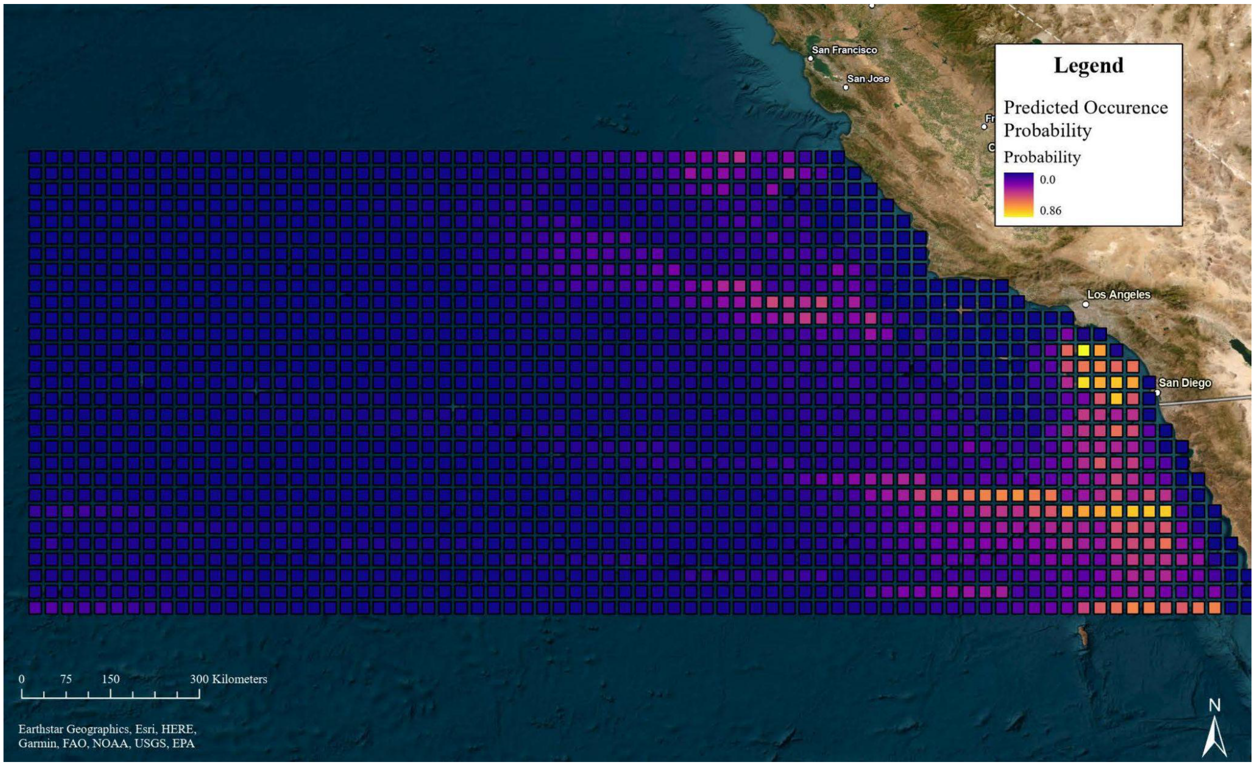


Figure 8. Generalized additive model of predicted loggerhead occurrence in Southern California during El Niño years.

MaxENT Model of Southern CCLME

In the MaxEnt model for the southern CCLME, we investigated the relationship between twelve environmental variables (chlorophyll-α, net primary productivity of carbon, extended reconstructed sea surface temperature, SST, sea surface height, magnitude of seafloor depth gradient, east-west gradient of seafloor depth, north-south gradient of seafloor depth, magnitude of wind velocity, zonal wind component, meridional wind component, particulate inorganic carbon) and North Pacific loggerhead presence. Our model of predicted loggerhead presence in winter (November–March) during El Niño year used 1397 input features and 1001 presence points and classified 879 of those 1001 points as presence (Table 5). Our model had an area under the receiver operating characteristic curve (AUC) of 0.95, indicating high performance, given a threshold of 0.5 (which is the automatic threshold for MaxEnt in ArcGIS Pro; Table 6, Figures 9 and 10).

Table 5. Winter model count of presence and background points.

	From Input Point Features	Used in Training Model	Classified as Presence
Number of Presence Points	1719	1001	879
Number of Background Points	1092	826	52

Table 6. AUC and omission rate

AUC	0.9504
Omission Rate	0.1219

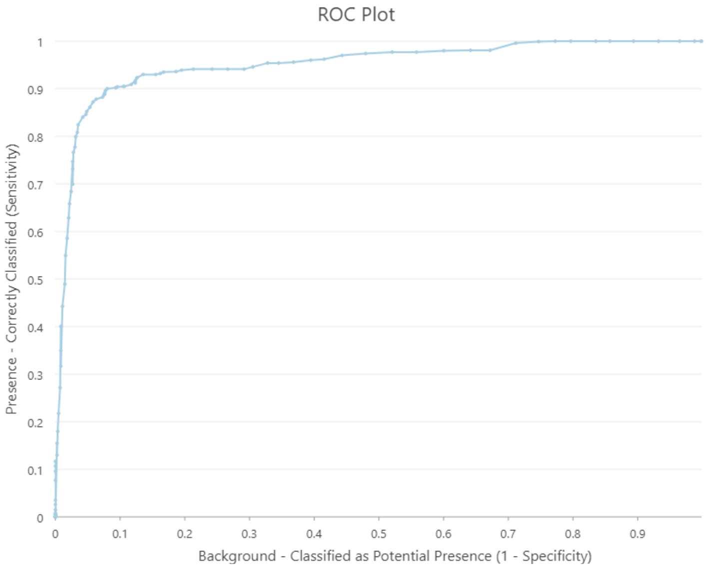


Figure 9. ROC plot of predicted loggerhead presence in winter (November–March).

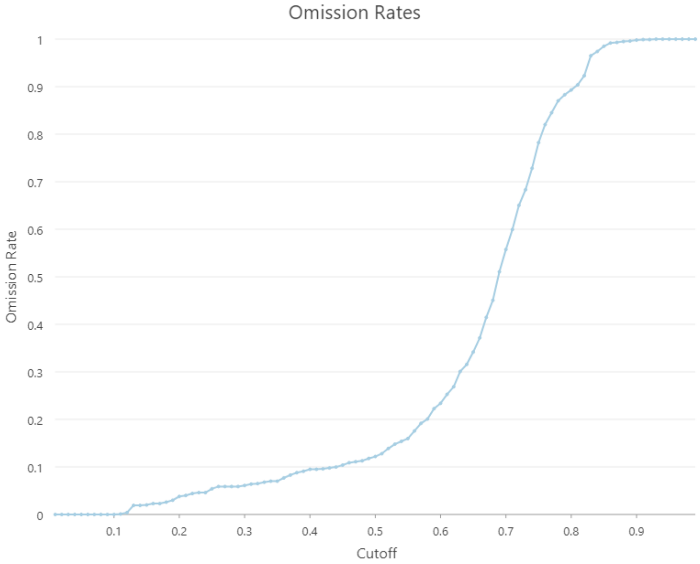


Figure 10. Omission curve of predicted loggerhead presence in winter (November–March).

Our analysis revealed a parabolic relationship between loggerhead occurrence and sea surface temperature within the southern CCLME. During El Niño years in winter (November–March), loggerhead presence was positively associated with chlorophyll-α, net primary productivity of carbon, sea surface elevation, the magnitude of seafloor depth gradient, east-west gradient of seafloor depth, magnitude of wind velocity, west-east seawind, and north-south wind component (Figure 11). Conversely, loggerhead presence during Winter in El Niño years within the southern CCLME was negatively associated with the magnitude of seafloor depth gradient, particulate inorganic carbon, and north-south gradient of seafloor depth (Figure 11). These results indicate that loggerheads are more likely to be found in the southern CCLME in relatively flat, warm (15–25°C) waters that are near-shore, highly productive, with low particulate inorganic carbon content, and high seawind speeds (Figure 11). The predicted loggerhead presence in Winter (November-March) during El Niño years is highest in the coastal areas from Southern California and the Bay of Ulloa (Figure 12). Low predicted loggerhead presence during El Niño years in Winter (November-March) occurs further offshore and in the northern portions of California (Figure 12).

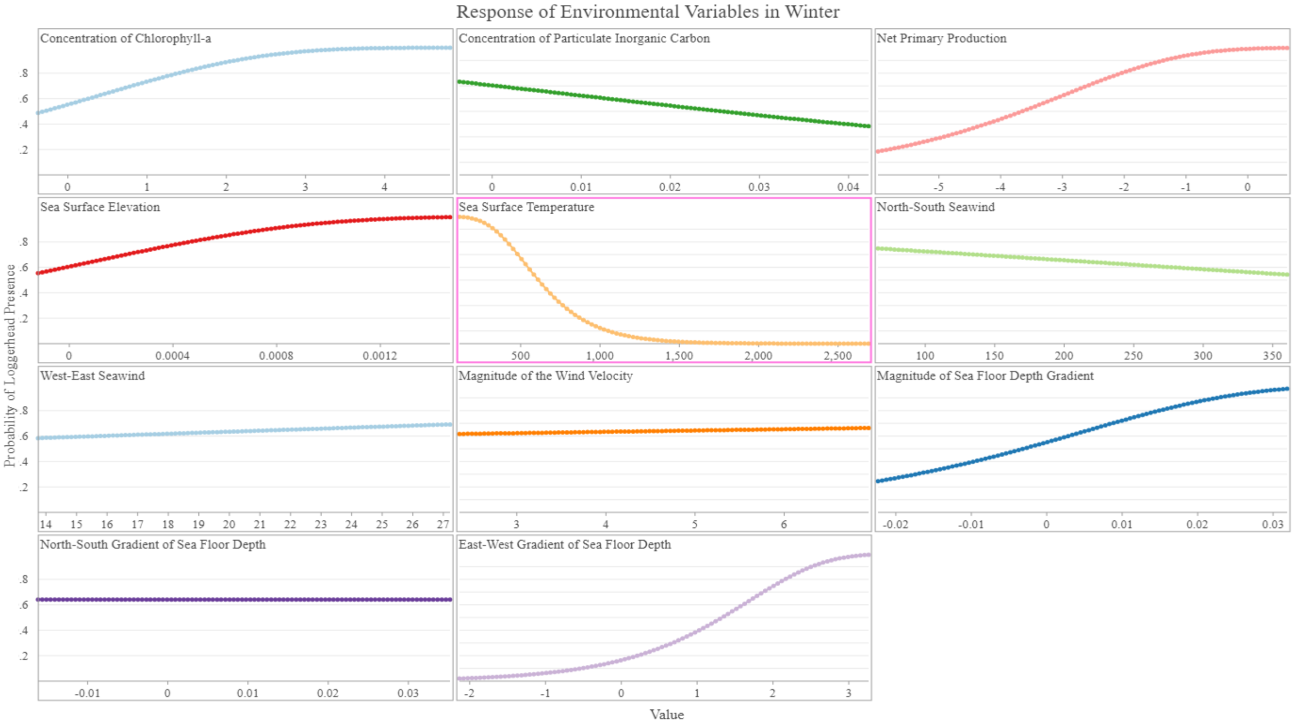


Figure 11. Response of environmental variables in the winter (November–March) During El Niño Years.

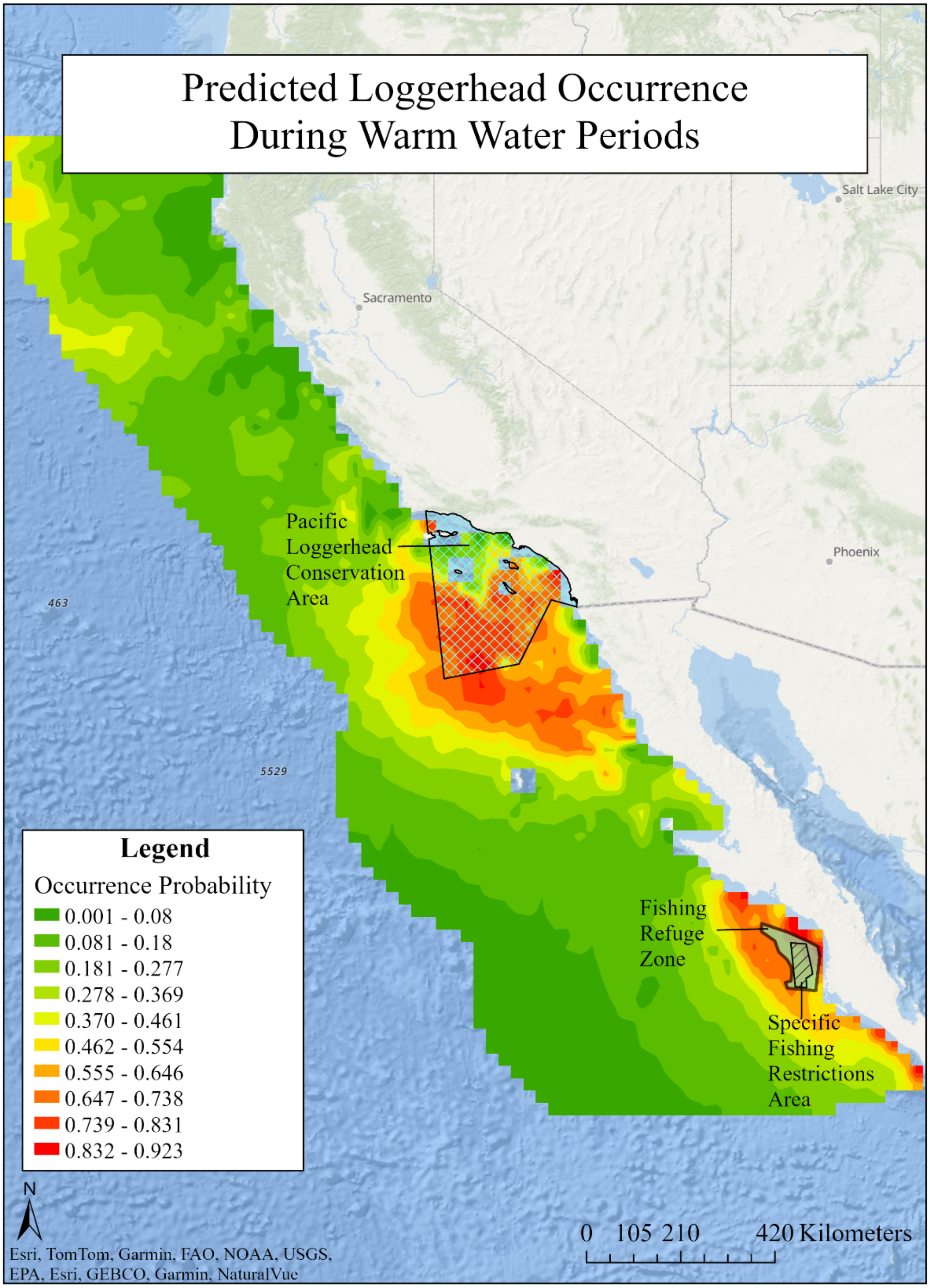


Figure 12. Predicted hotspots of North Pacific loggerhead presence (November–March) and existing conservation management areas.

DISCUSSION

To our knowledge, this is the first species distribution model for loggerheads in the eastern Pacific and one of only a few species distribution models of sea turtles globally. Our analysis revealed a noteworthy overlap between the predicted hotspots of loggerhead occurrence and two designated conservation areas: the Fishing Refuge Zone off the Gulf of Ulloa, Mexico, and the Pacific Loggerhead Conservation Area in Southern California during warm water periods. This convergence underscores the importance of these existing fishery closure areas for protecting loggerhead sea turtles from adverse fishery interactions. By identifying areas of high loggerhead occurrence that coincide with existing conservation zones, our study provides valuable guidance for conservation practitioners and policymakers. It reinforces the importance of integrating predictive modeling techniques into conservation planning and prioritization. Moreover, the overlap between predicted hotspots and designated conservation areas underscores the interconnectedness of marine ecosystems and the importance of coordinated conservation efforts across international boundaries, as this species crosses geopolitical boundaries.

In this study, we employed a two-step approach to model the species distribution of North Pacific loggerhead sea turtles off the West Coast of North America. Initially, we utilized a generalized additive model (GAM) to focus on the Southern California region. Subsequently, we employed a machine-learning technique, MaxEnt, to predict the seasonal occurrence of North Pacific loggerheads throughout the southern CCLME. We aimed to explore a range of environmental and oceanographic factors beyond sea surface temperature (SST) to describe existing patterns and inform future distributions for loggerhead presence in the southern CCLME.

Limitations of This Study

In comparing our study with previous research, it is important to acknowledge the inherent limitations of SDMs, as famously articulated by Box (1976): "All models are wrong, but some are useful." Using GAMs allowed for powerful insights into loggerhead sea turtle distribution, but it is important to recognize their potential shortcomings. GAMs may exhibit poorer predictive performance in new areas than other modeling techniques (Bahn & McGill, 2013). Our findings reveal a predictive R^2 of 36% for the GAM SDM. This level of predictive performance is consistent with similar studies, such as that by Liang et al. (2023), who also reported a predictive R^2 of 32% using a comparable methodological approach integrating satellite-tagged leatherback turtles and fisheries observations data from South American organizations to create a leatherback species distribution model. The relatively low predictive performance of GAMs in such cases can be attributed to the challenge of extrapolating coarse-scale data, such as monthly averages of environmental data we used in this study, to predict species distributions in new areas (Bahn & McGill, 2013). Despite these limitations, our study contributes valuable insights by providing a nuanced understanding of loggerhead habitat in Southern California, despite the smaller training dataset compared to the test dataset, which may have influenced predictive power while offering new insights into potential loggerhead habitat in the region.

Our SDMs did, however, employ relatively large datasets (n=1719) and were derived from several sources compared to other SDMs recently created for marine turtles. Zampollo et al. (2022) also employed MaxEnt to model Mediterranean loggerhead species distribution using 49 loggerhead turtle sightings. Liang et al. (2023) utilized 85 individual leatherback tracks to model the species distribution model of the East Pacific leatherback. More recently, Lopez et al. (2024) used boosted regression trees, a different machine-learning algorithm, to build a species distribution model of the east Pacific leatherback, inputting 1145 presence points using fisheries bycatch data.

Spatial Patterns

Temporally, our results align with the El Niño triggered implementation of the southern closure area in southern California, USA. There is a higher bycatch probability during an El Niño, but our results and other previous bycatch records in the southern CCLME demonstrate that their presence is not restricted to El Niño events (Eguchi et al., 2018; Welch et al., 2018). Our results suggest that factors other than SST influence the area's loggerhead presence. The environmental drivers identified by our MaxEnt model for loggerhead sea turtle presence in the southern CCLME during El Niño years align with previous research on the foraging ecology and habitat preferences of loggerheads in this region (Eguchi et al., 2018; Nichols et al., 2000; Polovina et al., 2000; Polovina et al., 2001; Welch et al., 2018). Our study also highlights the relationship between loggerhead habitat and several key environmental variables, such as surface chlorophyll-α concentration and aggregating prey items of loggerheads (Barceló et al., 2013). Similar to our findings, Zampollo et al. (2022) found the seasonality of loggerheads in the Mediterranean was characterized by chlorophyll-α, particulate inorganic carbon ($CaCO_3$), and SST variables, considering these environmental factors as proxies for loggerhead prey (Zampollo et al., 2022). Our findings corroborate the notion that variation among juvenile foraging strategies contributes to their ephemeral presence in southern California (NMFS and USFSWS, 2020).

Notably, loggerhead turtles are not confined solely to the U.S. closure area, as evidenced by their presence well south of its boundaries (Figure 12). This discovery challenges previous assumptions rooted in the spatial bias of aerial surveys and community sightings data, which primarily focused on the U.S. coastline (Eguchi et al. 2018; Seminoff et al. 2014). Moreover, findings from Briscoe et al. (2021) suggest that the Southern California Bight might serve as a crucial stopover for some loggerheads upon their arrival along the North American coast. While some individuals might proceed directly to Baja, others appear to favor the Southern California Bight initially (Briscoe et al., 2021).

Moreover, if loggerheads do indeed transition southward from the Southern California Bight to Baja, it implies the existence of a migratory corridor encompassing the area between Southern California Bight and Ulloa (Briscoe et al., 2021). This corridor would facilitate the developmental migration of loggerheads across relatively near-shore habitats between the United States and Mexico. El niño events can create a rapid influx of warm water to enter into the California current, causing nearly the entire coast of the CCLME to function as a cohesive bioregion, with new migrants in the area due to the reduced primary productivity and higher salinity during these periods (Chavez et al., 2002; Checkley & Barth, 2009). Such environmental conditions would logically encourage loggerheads to utilize the entire area as they navigate and transition between North American habitats.

In light of our findings and the existing body of literature, it is evident that loggerhead sea turtle presence in the southern CCLME during El Niño years is influenced by a complex interplay of environmental factors, including prey availability, oceanographic conditions, and geomorphological features (Eguchi et al., 2018; Welch et al., 2019; Wingfield et al., 2011).

These insights are critical for informing conservation and management strategies to protect loggerhead habitats and mitigating fishery impacts in this ecologically significant region.

Implications of Climate Change

Climate change is anticipated to lead to profound shifts in environmental conditions, altering highly migratory species' distribution and migration routes (Chen et al., 2011; Hazen et al., 2012). These changes are expected to intensify as climatic warming progresses, causing species ranges to change significantly in response to changing environmental conditions (Chen et al., 2011; Hazen et al., 2012). The North Pacific loggerhead turtle is already vulnerable to climate impacts due to its depleted status and susceptibility to other threats (Fuentes et al., 2013). Moreover, Hazen et al. (2012) projected that future loggerhead habitat will decline by over 20 percent, increasing its already tenuous status.

Anthropogenically induced SST warming is anticipated to result in more frequent and intense El Niño events (Cai et al., 2023). This heightened SST and increased frequency of strong El Niño events may increase the likelihood of loggerhead presence in Southern California. Additionally, climate change will bring warmer winters, leading to an increased “tropicalization” of coastal waters of North America, meaning we expect more sea turtles to migrate further northward than ever before (Osland et al., 2021).

Fisheries Management

The establishment of the Pacific Loggerhead Conservation Area off California was partly catalyzed by the success of TurtleWatch, one of the earliest and longest-running online tools for voluntarily mitigating sea turtle bycatch (Howell et al., 2008). TurtleWatch creates thermal habitat for loggerhead sea turtles every day in the northern Pacific (Howell et al., 2008). This online tool was created to encourage voluntary action by shallow-set pelagic longline fishers, as fishers can peruse a map depicting the likely occurrence of loggerheads north of the Hawaiian Islands (Howell et al., 2008). TurtleWatch is another example of dynamic fishery management, as Maxwell et al. (2015) estimate that this tool restricts “62 to 86 percent less time-area through its dynamic approach” than a static fishery-area closure, restricting fishing activities within a defined geographic area for a specific period, encompassing the same area.

Siders et al. (2023) evaluated the efficacy of the TurtleWatch tool and found that from April to September, tracked sea turtles, and fishery locations shifted to warmer waters, and from July to September, there was no overlap with the predictive TurtleWatch map and real fisheries interactions. This suggests that a species distribution model incorporating more environmental co-variates of loggerhead presence might increase the efficacy of time-area closures, especially in light of climate change. Assuming climate change will increase loggerhead presence in Southern California underscores the urgent need for dynamic fishery time-area closures informed by multiple variables to effectively reduce mortalities from bycatch (Osland et al., 2021).

Welch et al. (2019) created “The Temperature Observations To Avoid Loggerhead (TOTAL) tool” to further inform loggerhead thermal habitat in the Pacific Loggerhead Conservation Area. TOTAL uses monthly temperature anomalies smoothed over six months as an indicator of loggerhead presence in the Pacific Loggerhead Conservation Area and sets a threshold based on demonstrated loggerhead bycatch levels, providing a dynamic metric for guiding conservation activities (Welch et al., 2019). Expanding on this successful concept, we aim to improve species distribution models for loggerhead sea turtles by integrating additional environmental variables beyond sea surface temperature. This expansion may involve exploring the impacts of oceanographic currents, prey abundance, and habitat structure on loggerhead habitat utilization. Furthermore, ongoing refinement and validation of dynamic fishery management tools, such as TurtleWatch, could benefit from including a more comprehensive set of environmental co-variates. This enhancement would elevate the precision of time-area closures, thereby bolstering efforts to mitigate loggerhead bycatch effectively.

Management and Conservation Implications

The actions taken by both the United States and Mexico in response to the loggerhead sea turtle bycatch within their waters carry significant implications for the conservation of this species throughout the Pacific Ocean. Loggerhead sea turtles are highly migratory species, so conservation measures implemented in one country's waters can directly affect loggerhead populations in neighboring jurisdictions (Wallace et al., 2023). By aligning conservation efforts and sharing best practices, countries can collectively enhance the effectiveness of conservation measures and maximize the conservation benefits for loggerhead sea turtles.

Established over twenty years ago, the Pacific Loggerhead Conservation Area in Southern California represents a critical foraging habitat during favorable environmental conditions for loggerheads. Our findings also suggest that the Fishing Refuge Zone off the Gulf of Ulloa, Mexico, coincides with high predicted loggerhead presence, indicating it is also an important foraging ground for juvenile loggerheads. The overlap between predicted loggerhead hotspots and conservation areas underscores the value of ongoing management frameworks for promoting loggerhead population recovery.

Our analysis suggests that incorporating additional environmental variables into the time-area closure could enhance its efficacy in reducing loggerhead bycatch. The existing closure measures, triggered by sea surface temperature anomalies during El Niño years, represent an important strategy for aligning fishing activities with periods of reduced loggerhead presence offshore. However, by integrating more environmental factors, such as primary productivity, oceanographic currents, seawind speed, and prey availability, into the closure criteria and removing the closure’s dependence on an officially declared El Niño, we can further refine the spatial and temporal boundaries of the conservation area to better match loggerhead habitat use and migration patterns.

Future Research Directions

More recent telemetry data and aerial surveys are needed to update our understanding of loggerhead sea turtle movements at sea and their habitat use. Our robust dataset of aerial surveys in BCP is from over 15 years ago. Conducting new aerial surveys and telemetry studies in the BCP could provide valuable insights into changes in loggerhead distribution, behavior, and habitat preferences over time.

Future studies should expand beyond coastal areas to capture a more comprehensive view of loggerhead habitat throughout the entire Pacific Ocean. This includes examining environmental parameters in the thermal corridor area, described by Briscoe et al. (2021), which could reveal important insights into how loggerheads utilize and respond to broader oceanographic conditions. This broader perspective is crucial for understanding the full range of environmental influences on loggerhead behavior and distribution.

REFERENCES

Allen, C. D., Lemons, G. E., Eguchi, T., LeRoux, R. A., Fahy, C. C., Dutton, P. H., Peckham, S. H., & Seminoff, J. A. (2013). Stable isotope analysis reveals migratory origin of loggerhead turtles in the Southern California Bight. Marine Ecology Progress Series, 472, 275–285. https://doi.org/10.3354/meps10023

Bahn, V., & McGill, B. J. (2013). Testing the predictive performance of distribution models. Oikos, 122(3), 321–331. https://doi.org/10.1111/j.1600-0706.2012.00299.x

Balch, W. M., Gordon, H. R., Bowler, B. C., Drapeau, D. T., & Booth, E. S. (2005). Calcium carbonate measurements in the surface global ocean based on moderate-resolution imaging spectroradiometer data. Journal of Geophysical Research: Oceans, 110(C7). https://doi.org/10.1029/2004JC002560

Barbet-Massin, M., Jiguet, F., Albert, C., & Thuiller, W. (2012). Selecting pseudo-absences for species distribution models: how, where and how many? Methods in Ecology and Evolution, 3, 327–338. https://doi.org/10.1111/j.2041-210X.2011.00172

Barceló, C., Domingo, A., Miller, P., Ortega, L., Giffoni, B., Sales, G., McNaughton, L., Marcovaldi, M., Heppell, S., & Swimmer, Y. (2013). High-use areas, seasonal movements and dive patterns of juvenile loggerhead sea turtles in the southwestern Atlantic Ocean. Marine Ecology Progress Series, 479, 235–250. https://doi.org/10.3354/meps10222

Bjorndal, K.A. (1997) Foraging ecology and nutrition of sea turtles. In: Lutz, P.L. and Musick J.A., Eds., The Biology of Sea Turtles, CRC Press, Boca Raton, FL, 199-231. http://www.seaturtle.org/library/BjorndalKA_1997_InThebiologyofseaturtles_p199-231.pdf

Bowen, B. W., Abreu-Grobois, F. A., Balazs, G. H., Kamezaki, N., Limpus, C. J., & Ferl, R. J. (1995). Trans-Pacific migrations of the loggerhead turtle (*Caretta caretta*) demonstrated with mitochondrial DNA markers. Proceedings of the National Academy of Sciences, 92(9), 3731–3734. https://doi.org/10.1073/pnas.92.9.3731

Box, G. E. P. (1976). Science and statistics. Journal of the American Statistical Association, 71(356), 791–799. https://doi.org/10.1080/01621459.1976.10480949

Briscoe, D. K., Parker, D. M., Bograd, S., Hazen, E., Scales, K., Balazs, G. H., Kurita, M., Saito, T., Okamoto, H., Rice, M., Polovina, J. J., & Crowder, L. B. (2016). Multi-year tracking reveals extensive pelagic phase of juvenile loggerhead sea turtles in the North Pacific. Movement Ecology, 4(1), 23. https://doi.org/10.1186/s40462-016-0087-4

Briscoe, D. K., Turner Tomaszewicz, C. N., Seminoff, J. A., Parker, D. M., Balazs, G. H., Polovina, J. J., Kurita, M., Okamoto, H., Saito, T., Rice, M. R., & Crowder, L. B. (2021). Dynamic thermal corridor may connect endangered loggerhead sea turtles across the Pacific Ocean. Frontiers in Marine Science, 8, 630590. https://doi.org/10.3389/fmars.2021.630590

Broecker, W. S., & T.-H. Peng (1982), Tracers in the sea, 660 pp., Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York. https://www.ldeo.columbia.edu/~broecker/Home_files/TracersInTheSea_searchable.pdf

Cai, W., Ng, B., Geng, T., Jia, F., Wu, L., Wang, G., Liu, Y., Gan, B., Yang, K., Santoso, A., Lin, X., Li, Z., Liu, Y., Yang, Y., Jin, F.-F., Collins, M., & McPhaden, M. (2023). Anthropogenic impacts on twentieth-century ENSO variability changes. Nature Reviews Earth & Environment, 4. https://doi.org/10.1038/s43017-023-00427-8

Carretta, J. V. (2022). Estimates of marine mammal, sea turtle, and seabird bycatch in the California large-mesh drift gillnet fishery: 1990-2021. https://doi.org/10.25923/KH19-SK22

Casale, P. & Tucker, A.D. (2017). *Caretta caretta* (amended version of 2015 assessment). The IUCN Red List of Threatened Species 2017: e.T3897A119333622. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T3897A119333622.en

Chavez, F. P., Pennington, J. T., Castro, C. G., Ryan, J. P., Michisaki, R. P., Schlining, B., Walz, P., Buck, K. R., McFadyen, A., & Collins, C. A. (2002). Biological and chemical consequences of the 1997–1998 El Niño in central California waters. Progress in Oceanography, 54(1), 205–232. https://doi.org/10.1016/S0079-6611(02)00050-2

Checkley, D. M., & Barth, J. A. (2009). Patterns and processes in the California Current System. Progress in Oceanography, 83(1), 49–64. https://doi.org/10.1016/j.pocean.2009.07.028

Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. Science, 333(6045), 1024–1026. https://doi.org/10.1126/science.1206432

Christiansen, F., Putman, N. F., Farman, R., Parker, D. M., Rice, M.R., Polovina, J. J., Balazs G. H., & Hays, G.C. (2016). Spatial variation in directional swimming enables juvenile sea turtles to reach and remain in productive waters. Marine Ecology Progress Series 557:247–259. https://doi.org/10.3354/meps11874

Cliff, A.D. & Ord, J.K. (1973). Spatial autocorrelation. London: Pion—Arthur Getis, 1995. Retrieved July 26, 2023, from https://journals-sagepub-com.proxy.lib.duke.edu/doi/abs/10.1177/030913259501900205

Conant, T., Dutton, P., Eguchi, T., Epperly, S., Fahy, C., Godfrey, M., Macpherson, S., Possardt, E., Schroeder, B., Seminoff, J., Snover, M., Upite, C., & Witherington, B. (2009). Loggerhead sea turtle (*Caretta caretta*) 2009 status review under the U.S. Endangered Species Act. Report of the Loggerhead Biological Review Team to the National Marine Fisheries Service. https://www.nrc.gov/docs/ML1427/ML14279A259.pdf

Crowder, L.B. & S.S. Heppell. (2011). The decline and rise of a sea turtle: How Kemp's ridleys are recovering in the Gulf of Mexico. Solutions 2:67–73. http://www.thesolutionsjournal.com/node/859

Cuevas, E., Putman, N. F., Uribe-Martínez, A., López-Castro, M. C., Guzmán-Hernández, V., Gallegos-Fernández, S. A., Liceaga-Correa, M. de los Á., Trujillo-Córdova, J. A., González-

Díaz-Mirón, R. de J., Negrete-Phillipe, A., Acosta-Sánchez, H. H., Martínez-Portugal, R. C., López-Hernández, M., Huerta-Rodríguez, P., & Silver, J. (2020). First spatial distribution analysis of male sea turtles in the southern Gulf of Mexico. Frontiers in Marine Science, 7. https://www.frontiersin.org/articles/10.3389/fmars.2020.561846

Diario Oficial de la Federación. (June 23, 2016). ACUERDO por el que establece la zona de refugio pesquero y nuevas medidas para reducir la posible interacción de la pesca con tortugas marinas en la costa occidental de Baja California Sur. https://www.fao.org/faolex/results/details/es/c/LEX-FAOC156808/

Dunn, D. C., Maxwell, S. M., Boustany, A. M., & Halpin, P. N. (2016). Dynamic ocean management increases the efficiency and efficacy of fisheries management. Proceedings of the National Academy of Sciences, 113(3), 668–673. https://doi.org/10.1073/pnas.1513626113

Eguchi, T., McClatchie, S., Wilson, C., Benson, S. R., LeRoux, R. A., & Seminoff, J. A. (2018). Loggerhead turtles (*Caretta caretta*) in the California Current: abundance, distribution, and anomalous warming of the North Pacific. Frontiers in Marine Science, 5, 452. https://doi.org/10.3389/fmars.2018.00452

Elith, J., & Leathwick, J. (2009). Species distribution models: ecological explanation and prediction across space and time. The Annual Review of Ecology, Evolution, and Systematics, 40, 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Fuentes, M. M., Pike, D. A., Dimatteo, A., & Wallace, B. P. (2013). Resilience of marine turtle regional management units to climate change. Global Change Biology, 19:1399–1406. https://doi.org/10.1111/gcb.12138

Finkbeiner, E. M., Wallace, B. P., Moore, J. E., Lewison, R. L., Crowder, L. B., & Read, A. J. (2011). Cumulative estimates of sea turtle bycatch and mortality in USA fisheries between 1990 and 2007. Biological Conservation, 144, 2719–2727. https://doi.org/10.1016/j.biocon.2011.07.033

Gbenebor, O. P., Adeosun, S. O., Lawal, G. I., & Jun, S. (2016). Role of $CaCO_3$ in the physicochemical properties of crustacean-sourced structural polysaccharides. Materials Chemistry and Physics, 184, 203–209. https://doi.org/10.1016/j.matchemphys.2016.09.043

Gilman, E., Kobayashi, D., Swenarton, T., Brothers, N., Dalzell, P., & KinanKelly, I. (2007). Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biological Conservation, 139, 19–28. https://doi.org/10.1016/j.biocon.2007.06.002

Girerd, V. (2022). A critical assessment of the green sea turtle central west Pacific distinct population segment utilizing maxent modeling on nesting site locations [M.S., University of Southern California]. https://www.proquest.com/docview/2715834651/abstract/48AC64EE902E4A8CPQ/1

Gonzalez, S., Soto-Centeno, J., & Reed, D. (2011). Population distribution models: species distributions are better modeled using biologically relevant data partitions. BMC Ecology, 11, 20. https://doi.org/10.1186/1472-6785-11-20

Guinehut, S., Dhomps, A.-L., Larnicol, G., & Le Traon, P.-Y. (2012). High resolution 3-D temperature and salinity fields derived from in situ and satellite observations. Ocean Science, *8*(5), 845–857. https://doi.org/10.5194/os-8-845-2012

Guisan, A., & Thuiller, W. (2005). Predicting species distribution: Offering more than simple habitat models. Ecology Letters, 8(9), 993–1009. https://doi.org/10.1111/j.1461-0248.2005.00792.x

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., Regan, T. J., Brotons, L., McDonald-Madden, E., Mantyka-Pringle, C., Martin, T. G., Rhodes, J. R., Maggini, R., Setterfield, S. A., Elith, J., Schwartz, M. W., Wintle, B. A., Broennimann, O., Austin, M., Ferrier, S., Kearney, M. R., Possingham, H. P., & Buckley, Y. M. (2013). Predicting species distributions for conservation decisions. Ecology Letters, 16(12), 1424–1435. https://doi.org/10.1111/ele.12189

Hastie, T., & Tibshirani, R. (1986). Generalized additive models. Statistical Science, 1(3), 297–310. https://doi.org/10.1214/ss/1177013604

Hatase, H., Kinoshita, M., Bando, T., Kamezaki, N., Sato, K., Matsuzawa, Y., Goto, K., Omuta, K., Nakashima, Y., & Takeshita, H. (2002). Population structure of loggerhead turtles, *Caretta caretta*, nesting in Japan: bottlenecks on the Pacific population. Marine Biology, 141:299–305. https://doi.org/10.1007/s00227-002-0819-4

Havice, E., Campbell, L. M., & Braun, A. (2018). Science, scale and the frontier of governing mobile marine species. International Social Science Journal, 68(229–230), 273–289. https://doi.org/10.1111/issj.12166

Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., Shaffer, S. A., Dunne, J. P., Costa, D. P., Crowder, L. B., & Block, B. A. (2012). Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change, 3(3), 234-238. https://doi.org/10.1038/nclimate1686

Hazen, E. L., Palacios, D. M., Forney, K. A., Howell, E. A., Becker, E., Hoover, A. L., Irvine, L., DeAngelis, M., Bograd, S. J., Mate, B. R., & Bailey, H. (2017). WhaleWatch: a dynamic management tool for predicting blue whale density in the California Current. Journal of Applied Ecology, 54(5), 1415–1428. https://doi.org/10.1111/1365-2664.12820

Howell, E. A., Kobayashi, D. R., Parker, D. M., Balazs, G. H., & Polovina, J. J. (2008). TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. Endangered Species Research, 5(2–3), 267–278. https://doi.org/10.3354/esr00096

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S,. and H-M., Zhang. (2017). NOAA extended reconstructed sea surface temperature (ERSST), version 5. [sst]. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5T72FNM

IPCC. (2023). Sections in: climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate

Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, https://doi.org/10.59327/IPCC/AR6-9789291691647

Jiang, D., Chen, S., Hao, M., Fu, J., & Ding, F. (2018). Mapping the potential global codling moth (*Cydia pomonella L.*) distribution based on a machine learning method. Scientific Reports, 8(1), Article 1. https://doi.org/10.1038/s41598-018-31478-3

Kumari, M., Sarma, K., & Sharma, R. (2019). Using Moran's I and GIS to study the spatial pattern of land surface temperature in relation to land use/cover around a thermal power plant in Singrauli district, Madhya Pradesh, India. Remote Sensing Applications: Society and Environment, 15, 100239. https://doi.org/10.1016/j.rsase.2019.100239

Kobayashi, D. R., Cheng, I.-J., Parker, D. M., Polovina, J. J., Kamezaki, N., & Balazs, G. H. (2011). Loggerhead turtle (*Caretta caretta*) movement off the coast of Taiwan: characterization of a hotspot in the East China Sea and investigation of mesoscale eddies. ICES Journal of Marine Science, 68(4), 707–718. https://doi.org/10.1093/icesjms/fsq185

Lewison, R. L., Freeman, S. A., & Crowder, L. B. (2004). Quantifying the effects of fisheries on threatened species: The impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters, 7(3), 221–231. https://doi.org/10.1111/j.1461-0248.2004.00573.x

Liang, D., Bailey, H., Hoover, A. L., Eckert, S., Zarate, P., Alfaro-Shigueto, J., Mangel, J. C., Sarmiento Barturen, D., Rguez-Baron, J. M., Fahy, C., Rocaferte, A., Veelenturf, C., Abrego, M. E., & Shillinger, G. (2022). (PDF) Integrating telemetry and point observations to inform management and conservation of migratory marine species. Ecosphere. https://doi.org/10.1002/ecs2.4375

Liu, G., De La Cour, J., Heron, S., Eakin, C. M., Skirving, W., Christensen, T., Strong, A., & Li, J. (2013). NOAA technical report NESDIS 143 NOAA Coral Reef Watch 50 km satellite sea surface temperature-based decision support system for coral bleaching management. https://repository.library.noaa.gov/view/noaa/743

Lopez, J., Griffiths, S., Wallace, B. P., Cáceres, V., Rodríguez, L. H., Abrego, M., Alfaro-Shigueto, J., Andraka, S., Brito, M. J., Bustos, L. C., Cari, I., Carvajal, J. M., Clavijo, L., Cocas, L., Paz, N. de, Herrera, M., Mangel, J. C., Pérez-Huaripata, M., Piedra, R., … Zárate, P. (2024). Vulnerability of the critically endangered leatherback turtle to fisheries bycatch in the eastern Pacific Ocean. I. a machine-learning species distribution model. Endangered Species Research, 53, 271–293. https://doi.org/10.3354/esr01288

Maxwell, S. M., Hazen, E. L., Lewison, R. L., Dunn, D. C., Bailey, H., Bograd, S. J., Briscoe, D. K., Fossette, S., Hobday, A. J., Bennett, M., Benson, S., Caldwell, M. R., Costa, D. P., Dewar, H., Eguchi, T., Hazen, L., Kohin, S., Sippel, T., & Crowder, L. B. (2015). Dynamic ocean management: defining and conceptualizing real-time management of the ocean. Marine Policy, 58, 42–50. https://doi.org/10.1016/j.marpol.2015.03.014

NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. (2014): MODIS-Aqua ocean color data. http://dx.doi.org/10.5067/AQUA/MODIS_OC.2014.0

National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA). (2000). Biological opinion. Endangered Species Act Section 7 consultation on authorization to take listed marine mammals incidental to commercial fishing operations under Section 101(a)(5)(E) of the Marine Mammal Protection Act for the California/Oregon drift gillnet fishery. Available at: http://swr.nmfs.noaa.gov/bo/lb/Drift_gillnet_ BO_2000.pdf

National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA). (April 7, 2004). Fisheries off west coast states and in the western Pacific; highly migratory species fisheries. Federal Register. https://www.federalregister.gov/documents/2004/04/07/04-7247/fisheries-off-west-coast-states-and-in-the-western-pacific-highly-migratory-species-fisheries

National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA). (June 8, 2007). Fisheries off west coast states; highly migratory species fisheries. Federal Register. https://www.federalregister.gov/documents/2007/06/08/E7-11124/fisheries-off-west-coast-states-highly-migratory-species-fisheries

National Marine Fisheries Service (NMFS) & US Fish and Wildlife Service (USFWS). (2011). Endangered and threatened species; determination of nine distinct population segments of loggerhead sea turtles as endangered. Federal Registrar, 76, 58868. https://www.fws.gov/policy/library/2011/2011-23960.html

National Marine Fisheries Service (NMFS) & US Fish and Wildlife Service (USFWS). (2020, April 6). Loggerhead sea turtle (*Caretta caretta*) North Pacific Ocean DPS 5-year review: summary and evaluation 2020. https://www.fws.gov/node/1729941

Nichols, W. J., Resendiz, A., Seminoff, J. A., & Resendiz, B. (2000). Transpacific migration of a loggerhead turtle monitored by satellite telemetry. Bulletin of Marine Science, 67, 937–947. https://www.researchgate.net/publication/233634018_Transpacific_Migration_of_a_Loggerhead_Turtle_Monitored_by_Satellite_Telemetry

Nichols, W. J. (2003). Biology and conservation of sea turtles in Baja California, Mexico. PhD Dissertation. School of Renewable Resources, University of Arizona, Tucson, AZ, USA. https://repository.arizona.edu/handle/10150/280439

NOAA National Centers for Environmental Information. (2022). ETOPO 2022 15 arc-second global relief model. NOAA National Centers for Environmental Information. DOI: 10.25921/fd45-gt74.

Okuyama, J., Kitagawa, T., Zenimoto, K., Kimura, S., Arai, N., Sasai, Y., & Sasaki H. (2011). Trans-Pacific dispersal of loggerhead turtle hatchlings inferred from numerical simulation modeling. Marine Biology 158:2055-2063 https://doi.org/10.1007/s00227-011-1712-9

Osland, M. J., Stevens, P. W., Lamont, M. M., Brusca, R. C., Hart, K. M., Waddle, J. H., Langtimm, C. A., Williams, C. M., Keim, B. D., Terando, A. J., Reyier, E. A., Marshall, K. E., Loik, M. E., Boucek, R. E., Lewis, A. B., & Seminoff, J. A. (2021). Tropicalization of temperate ecosystems in North America: The northward range expansion of tropical organisms in response to warming winter temperatures. Global Change Biology, 27(13), 3009–3034. https://doi.org/10.1111/gcb.15563

Peckham, S. H., Diaz, D. M., Walli, A., Ruiz, G., Crowder, L. B., & Nichols, W. J. (2007). Small-scale fisheries bycatch jeopardizes endangered Pacific loggerhead turtles. PLoS ONE, 2(10), e1041. https://doi.org/10.1371/journal.pone.0001041

Peckham, S. H., Maldonado-Diaz, D., Tremblay, Y., Ochoa, R., Polovina, J., Balazs, G., Dutton, P. H., & Nichols, W. J. (2011). Demographic implications of alternative foraging strategies in juvenile loggerhead turtles *Caretta caretta* of the North Pacific Ocean. Marine Ecology Progress Series, 425, 269–280. https://doi.org/10.3354/meps08995

Peckham, S. H., Lucero-Romero, J., Maldonado-Diaz, D., Rodriguez, A., Senko, J., Wojakowski, M., & Gaos, A. (2015). Buoyless nets reduce sea turtle bycatch in coastal net fisheries. Conservation Letters, 9. https://doi.org/10.1111/conl.12176

Peterson, A., & Soberón, J. (2012). Species distribution modeling and ecological niche modeling: Getting the concepts right. Natureza e Conservação, 10, 1–6. https://doi.org/10.4322/natcon.2012.019

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. Ecological Modelling, 190(3), 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Phillips, S., & Dudík, M. (2008). Modeling of species distributions with MaxEnt: new extensions and a comprehensive evaluation. Ecography, 31, 161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x

Pikesley, S. K., Maxwell, S. M., Pendoley, K., Costa, D. P., Coyne, M. S., Formia, A., Godley, B. J., Klein, W., Makanga-Bahouna, J., Maruca, S., Ngouessono, S., Parnell, R. J., Pemo-Makaya, E., & Witt, M. J. (2013). On the front line: integrated habitat mapping for olive ridley sea turtles in the southeast Atlantic. Diversity and Distributions, 19(12), 1518–1530. https://doi.org/10.1111/ddi.12118

Polovina, J. J., Kobayashi, D. R., Parker, D. M., Seki, M.P., & Balazs, G. H. (2000). Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997-1998. Fisheries Oceanography, 9, 71–82. https://doi.org/10.1046/j.1365-2419.2000.00123.x

Polovina, J. J., Howell, E. A., Kobayashia, D. R., and Seki, M.P. (2001). The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography, 49, 469–483 https://www.soest.hawaii.edu/PFRP/reprints/polovina_zone_2001.pdf

Polovina, J. J., Balazs, G. H., Howell, E. A., Parker, D. M., Seki, M. P., & Dutton, P. H. (2004). Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific Ocean. Fisheries Oceanography, 13(1), 36–51. https://doi.org/10.1046/j.1365-2419.2003.00270.x

Polovina, J. J., Uchida, I., Balazs, G. H., Howell, E. A., Parker, D. M., & Dutton, P. H. (2006). The Kuroshio Extension Bifurcation Region: a pelagic hotspot for juvenile loggerhead sea turtles. Deep Sea Research Part II: Topical Studies in Oceanography, 53(3), 326–339. https://doi.org/10.1016/j.dsr2.2006.01.006

Polovina, J. J., Howell, E. A., Kobayashi, D. R., & Seki, M. P. (2017). The Transition Zone Chlorophyll Front updated: advances from a decade of research. Progress in Oceanography, 150, 79–85. https://doi.org/10.1016/j.pocean.2015.01.006

Putman, N. F., Mansfield, K. L., He, R., Shaver, D. J., & Verley, P. (2013). Predicting the distribution of oceanic-stage Kemp's ridley sea turtles. Biology Letters, 9(5), 20130345. https://doi.org/10.1098/rsbl.2013.0345

Robinson, C., Tolentino, V., & Lopez, A. (2004). The pelagic red crab (*Pleuroncodes planipes*) related to active upwelling sites in the California Current off the west coast of Baja California. Deep Sea Research Part II: Topical Studies in Oceanography, 51, 753–766. https://doi.org/10.1016/j.dsr2.2004.05.018

Sandoval-Lugo, A. G., Espinosa-Carreón, T. L., Seminoff, J. A., Hart, C. E., Ley-Quiñónez, C. P., Aguirre, A. A., Jones, T. T., & Zavala-Norzagaray, A. A. (2020). Movements of loggerhead sea turtles (*Caretta caretta*) in the Gulf of California: Integrating satellite telemetry and remotely sensed environmental variables. Journal of the Marine Biological Association of the United Kingdom, 100(5), 817–824. https://doi.org/10.1017/S0025315420000636

Seminoff, J. A., Resendiz, A., Resendiz, B., & Nichols, W. J. (2004). Occurrence of loggerhead sea turtles (*Caretta caretta*) in the Gulf of California, Mexico: evidence of life-history variation in the Pacific Ocean. Herpetological Review, 35(1), 24–27. https://www.researchgate.net/publication/285863828_Occurrence_of_Loggerhead_Sea_Turtles_Caretta_caretta_in_the_Gulf_of_California_Mexico_Evidence_of_Life-History_Variation_in_the_Pacific_Ocean

Seminoff, J. A., Eguchi, T., J, C., Allen, C., D, P., R, R., Gilpatrick, J., Forney, K., & Peckham, S. H. (2014). Loggerhead sea turtle abundance at a foraging hotspot in the eastern Pacific Ocean: implications for at-sea conservation. Endangered Species Research, 24, 207–220. https://doi.org/10.3354/esr00601

Senko, J., Jenkins, L. D., & Peckham, S. H. (2017). At loggerheads over international bycatch: initial effects of a unilaterally imposed bycatch reduction policy. Marine Policy, 76, 200–209. https://doi.org/10.1016/j.marpol.2016.11.017

Siders, Z. A., Ahrens, R. N. M., Martin, S., Camp, E. V., Gaos, A. R., Wang, J. H., Marchetti, J., & Jones, T. T. (2023). Evaluation of a long-term information tool reveals continued suitability for identifying bycatch hotspots but little effect on fisher location choice. Biological Conservation, 279, 109912. https://doi.org/10.1016/j.biocon.2023.109912

Srivastava, V., Lafond, V., & Griess, V. C. (2019). Species distribution models (SDM): applications, benefits and challenges in invasive species management. CABI Reviews, 2019, 1–13. https://doi.org/10.1079/PAVSNNR201914020

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., Bishop, J. R. B., Marques, T. A., & Burnham, K. P. (2010). Distance software: design and analysis of distance sampling surveys for estimating population size. Journal of Applied Ecology, 47(1), 5–14. https://doi.org/10.1111/j.1365-2664.2009.01737.x

Turner Tomaszewicz, C. N., Seminoff, J. A., Avens, L., Goshe, L. R., Peckham, S. H., Rguez-Baron, J. M., Bickerman, K., & Kurle, C. M. (2015). Age and residency duration of loggerhead turtles at a North Pacific bycatch hotspot using skeletochronology. Biological Conservation, 186, 134–142. https://doi.org/10.1016/j.biocon.2015.03.015

Turner Tomaszewicz, C. N., Seminoff, J. A., Peckham, S. H., Avens, L., & Kurle, C. M. (2017). Intrapopulation variability in the timing of ontogenetic habitat shifts in sea turtles revealed using δ15 N values from bone growth rings. The Journal of Animal Ecology, 86(3), 694–704. https://doi.org/10.1111/1365-2656.12618

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, & National Marine Fisheries Service. (2007, May). Magnuson-Stevens Fishery Conservation and Management Act. https://www.fisheries.noaa.gov/resource/document/magnuson-stevens-fishery-conservation-and-management-act

U.S. Department of Commerce. (August 14, 2015). Addendum to the biennial report to congress pursuant to section 403(a) of the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006. https://media.fisheries.noaa.gov/dam-migration/addendum_to_2015report_to_congress_508.pdf

Wallace, B. P., DiMatteo, A. D., Hurley, B. J., Finkbeiner, E. M., Bolten, A. B., Chaloupka, M. Y., Hutchinson, B. J., Abreu-Grobois, F. A., Amorocho, D., Bjorndal, K. A., Bourjea, J., Bowen, B. W., Dueñas, R. B., Casale, P., Choudhury, B. C., Costa, A., Dutton, P. H., Fallabrino, A., Girard, A., Girondot, M., Godfrey, M. H., Hamann, M., López-Mendilaharsu, M., Marcovaldi, M. A., Mortimer, J. A., Musick, J. A., Nel, R., Pilcher, N. J., Seminoff, J. A., Troëng, S., Witherington, B. & Mast, R. B. (2010). Regional management units for marine turtles: a novel framework for prioritizing conservation and research across multiple scales. PLoS ONE, 5(12), e15465. https://doi.org/10.1371/journal.pone.0015465

Wallace, B. P., DiMatteo, A. D., Bolten, A. B., Chaloupka, M. Y., Hutchinson, B. J., Abreu-Grobois, F. A., Mortimer, J. A., Seminoff, J. A., Amorocho, D., Bjorndal, K. A., Bourjea, J., Bowen, B. W., Dueñas, R. B., Casale, P., Choudhury, B. C., Costa, A., Dutton, P. H., Fallabrino, A., Finkbeiner, E. M., Girard, A., Girondot, M., Hamann, M., Hurley, B. J., López-Mendilaharsu, M., Marcovaldi, M. A., Musick, J. A., Nel, R. Pilcher, N. J., Troëng S., Witherington, B., & Mast, R. B. (2011). Global conservation priorities for marine turtles. PLoS ONE, 6(9), e24510. https://doi.org/10.1371/journal.pone.0024510

Wallace, B. P., Posnik, Z. A., Hurley, B. J., DiMatteo, A. D., Bandimere, A., Rodriguez, I., Maxwell, S. M., Meyer, L., Brenner, H., Jensen, M. P., LaCasella, E., Shamblin, B. M., Abreu-Grobois, F. A., Stewart, K. R., Dutton, P. H., Barrios-Garrido, H., Dalleau, M., Dell amico, F., Eckert, K. L., FitzSimmons, N. N., Garcia-Cruz, M., Hays, G. C., Kelez, S., Lagueux, C. J., Madden Hof, C. A., Marco, A., Martins, S. L. T., Mobaraki, A., Mortimer, J. A., Nel, R., Phillott, A. D., Pilcher, N. J., Putman, N. F., Rees, A. F., Rguez-Baron, J. M., Seminoff, J. A., Swaminathan, A., Turkozan, O., Vargas, S. M., Vernet, P. D., Vilaça, S., Whiting, S. D., Hutchinson, B. J., Casale, P., & Mast, R. B. (2023). Marine turtle regional management units

2.0: an updated framework for conservation and research of wide-ranging megafauna species. Endangered Species Research, 52, 209–223. https://doi.org/10.3354/esr01243

Watanabe, K. K., Hatase, H., Kinoshita, M., Omuta, K., Bando, T., Kamezaki, N., Sato, K., Matsuzawa, Y., Goto, K., Nakashima, Y., Takeshita, H., Aoyama, J., & Tsukamoto, K. (2011). Population structure of the loggerhead turtle *Caretta caretta*, a large marine carnivore that exhibits alternative foraging behaviors. Marine Ecology Progress Series, 424, 273–283. https://doi.org/10.3354/meps08989

Weiss, I. M., Tuross, N., Addadi, L., & Weiner, S. (2002). Mollusc larval shell formation: amorphous calcium carbonate is a precursor phase for aragonite. Journal Experimental Zoology. 1;293(5):478-91. doi: https://doi.org/10.1002/jez.90004

Welch, H., Hazen, E. L., Briscoe, D. K., Bograd, S. J., Jacox, M. G., Eguchi, T., Benson, S. R., Fahy, C. C., Garfield, T., Robinson, D., Seminoff, J. A., & Bailey, H. (2019). Environmental indicators to reduce loggerhead turtle bycatch offshore of Southern California. Ecological Indicators, 98, 657–664. https://doi.org/10.1016/j.ecolind.2018.11.001

Wingfield, D. K., Peckham, S. H., Foley, D. G., Palacios, D. M., Lavaniegos, B. E., Durazo, R., Nichols, W. J., Croll, D. A., & Bograd, S. J. (2011). The making of a productivity hotspot in the coastal ocean. PLoS ONE, 6(11), e27874. https://doi.org/10.1371/journal.pone.0027874

Winton, M. V., Fay, G., Haas, H. L., Arendt, M., Barco, S., James, M. C., Sasso, C., & Smolowitz, R. (2018). Estimating the distribution and relative density of satellite-tagged loggerhead sea turtles using geostatistical mixed effects models. Marine Ecology Progress Series, 586, 217–232. https://doi.org/10.3354/meps12396

Zaba, K. D., & Rudnick, D. L. (2016). The 2014–2015 warming anomaly in the Southern California current system observed by underwater gliders. Geophysical Research Letters, 43(3), 1241–1248. https://doi.org/10.1002/2015GL067550

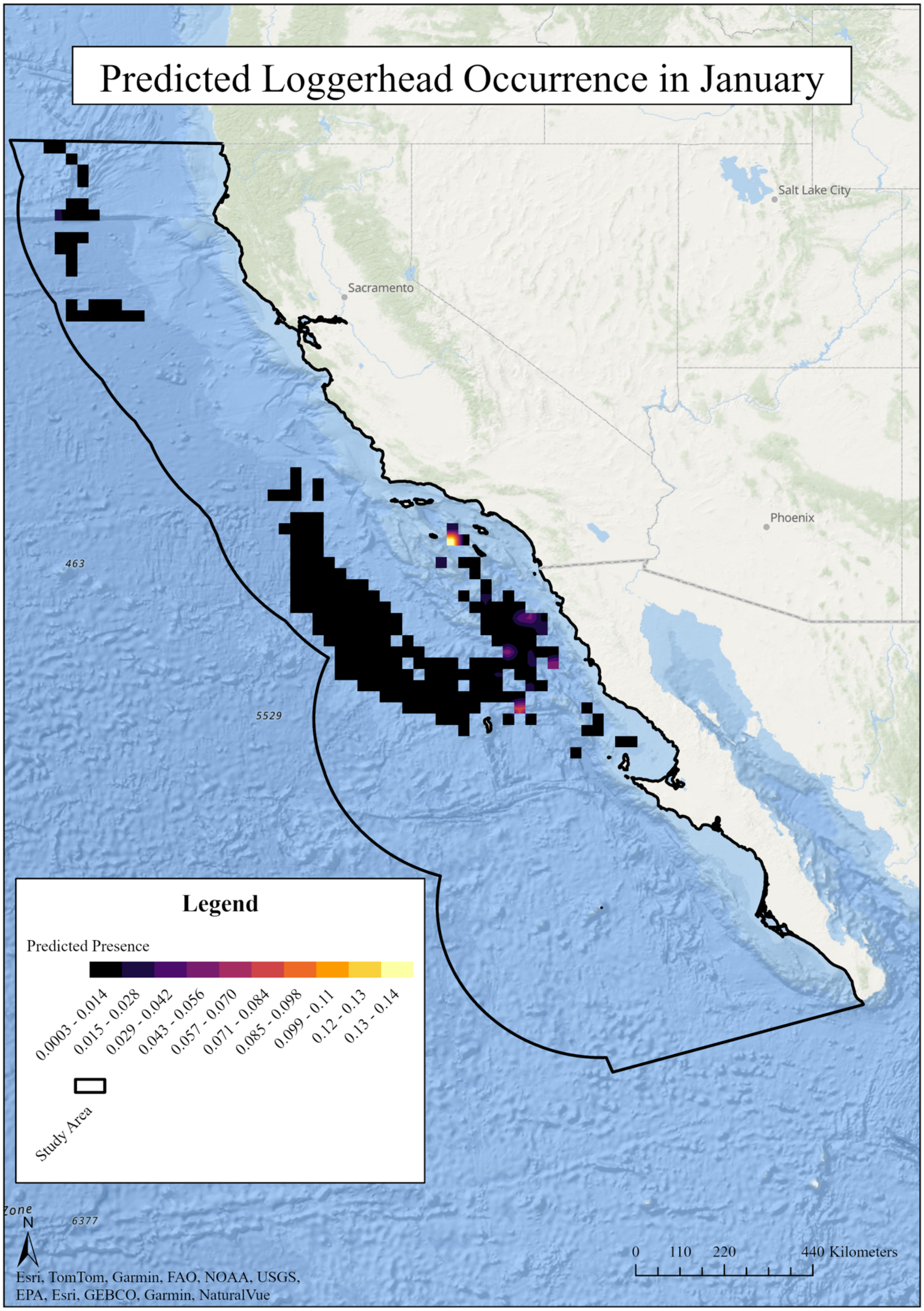
Zampollo, A., Arcangeli, A., Costantino, M., Mancino, C., Crosti, R., Pietroluongo, G., Giacoma, C., & Azzolin, M. (2022). Seasonal niche and spatial distribution modelling of the loggerhead (*Caretta caretta*) in the Adriatic and Ionian seas. Aquatic Conservation: Marine and Freshwater Ecosystems, *32*(7), 1141–1155. https://doi.org/10.1002/aqc.3815

Zaytsev, O., Cervantes-Duarte, R., Montante, O., & gallegos-garcía, A. (2003). Coastal upwelling activity on the Pacific shelf of the Baja California Peninsula. Journal of Oceanography, 59, 489–502. https://doi.org/10.1023/A:1025544700632

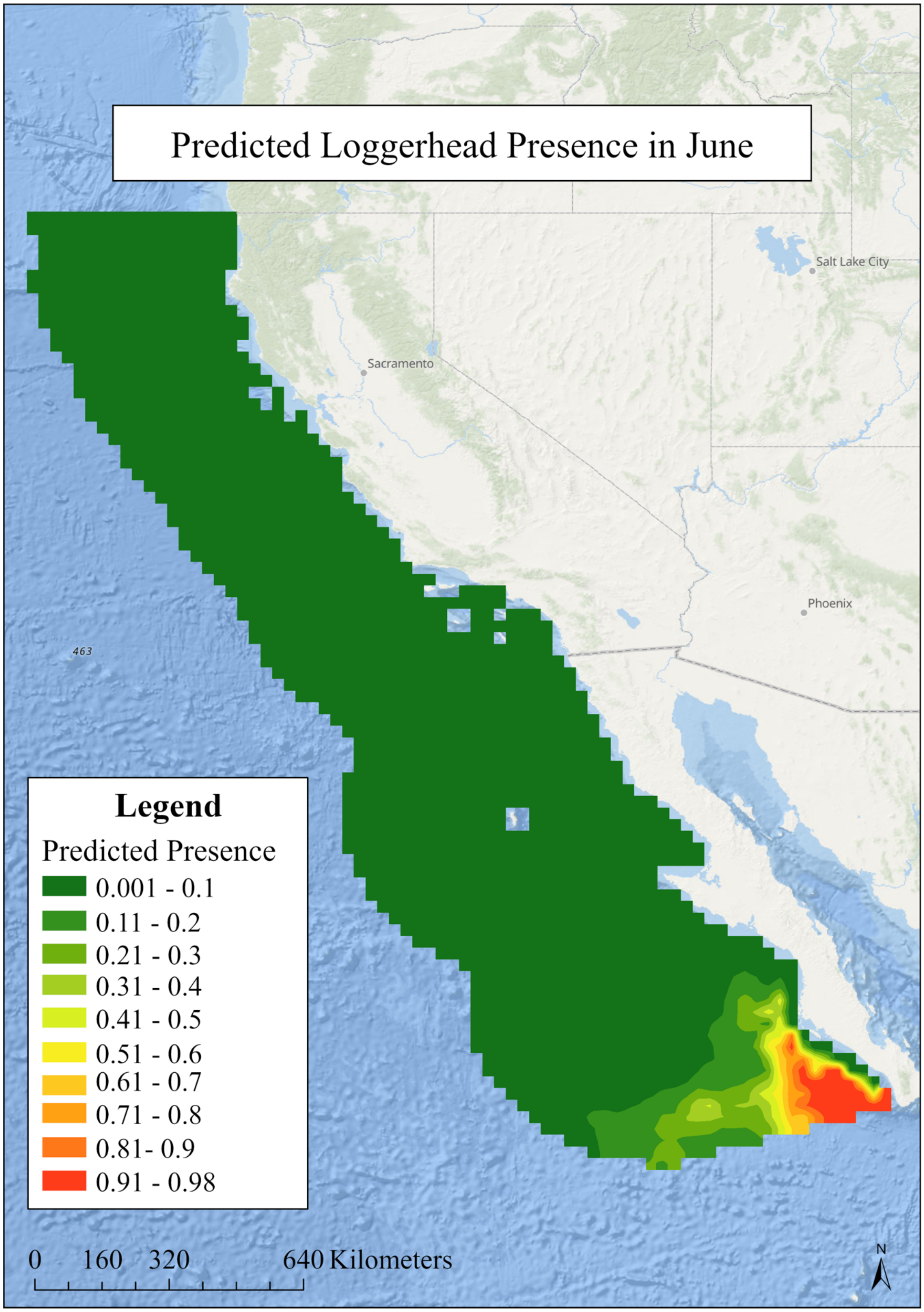
Zhang, H.-M., Bates, J. J., & Reynolds, R. W. (2006). Assessment of composite global sampling: Sea surface wind speed. Geophysical Research Letters, 33, L17714, https://doi.org/10.1029/2006GL027086

Zurell, D., Franklin, J., König, C., Bouchet, P. J., Dormann, C. F., Elith, J., Fandos, G., Feng, X., Guillera-Arroita, G., Guisan, A., Lahoz-Monfort, J. J., Leitão, P. J., Park, D. S., Peterson, A. T., Rapacciuolo, G., Schmatz, D. R., Schröder, B., Serra-Diaz, J. M., Thuiller, W., Yates, K. L., Zimmermann, N. E., & Merow, C. (2020). A standard protocol for reporting species distribution models. Ecography, 43(9), 1261–1277. https://doi.org/10.1111/ecog.04960

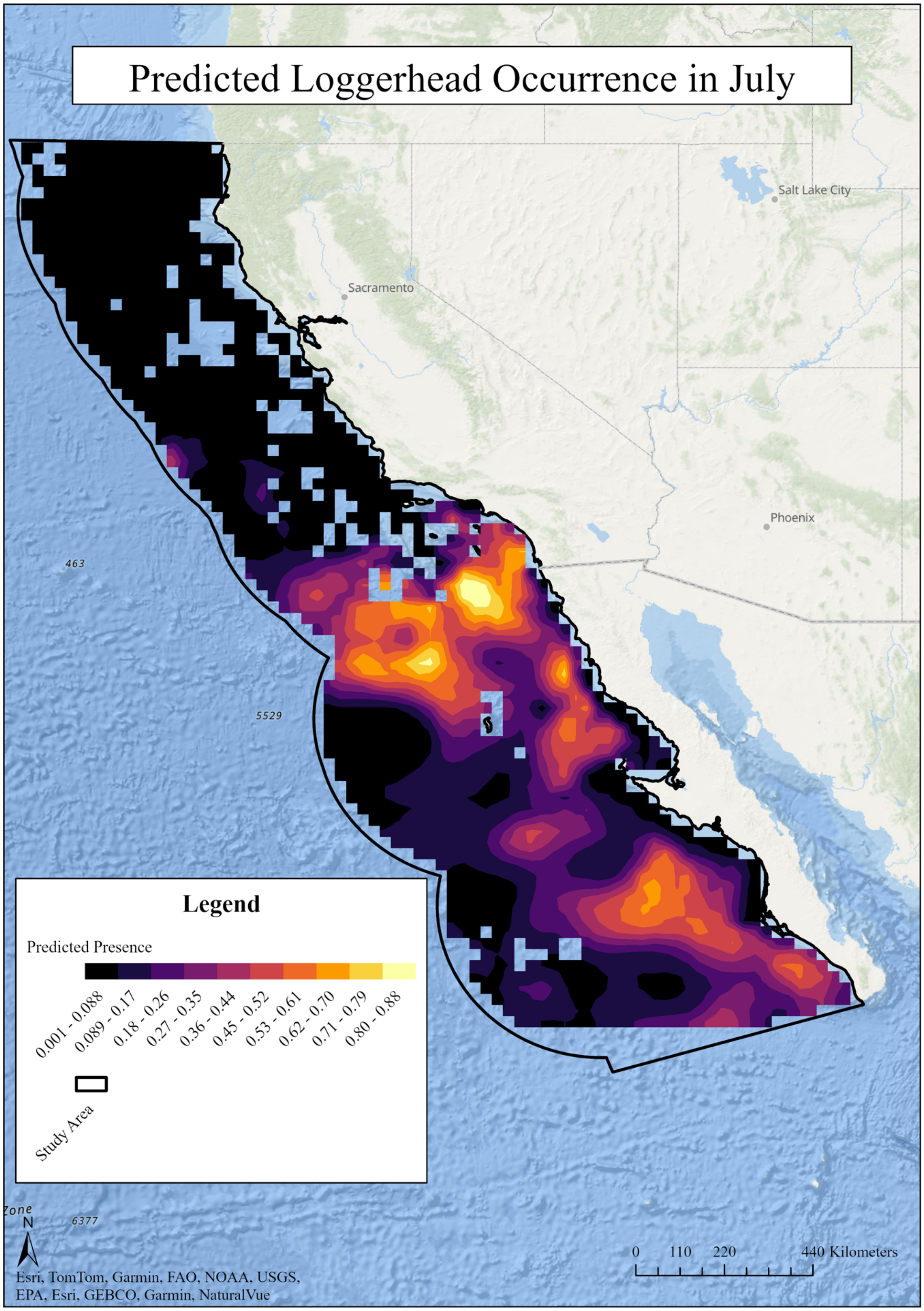
APPENDIX A


Predicted Loggerhead Occurrence in January
Salt Lake City
Sacramento
Phoenix
463
5529
6377
Zone
Legend
Predicted Presence
0.0003 - 0.014
0.015 - 0.028
0.029 - 0.042
0.043 - 0.056
0.057 - 0.070
0.071 - 0.084
0.085 - 0.098
0.099 - 0.11
0.12 - 0.13
0.13 - 0.14
Study Area
N
0
110
220
440 Kilometers
Esri, TomTom, Garmin, FAO, NOAA, USGS,
EPA, Esri, GEBCO, Garmin, NaturalVue

APPENDIX B


Predicted Loggerhead Presence in June
Salt Lake City
Sacramento
Phoenix
463
Legend
Predicted Presence
0.001 - 0.1
0.11 - 0.2
0.21 - 0.3
0.31 - 0.4
0.41 - 0.5
0.51 - 0.6
0.61 - 0.7
0.71 - 0.8
0.81- 0.9
0.91 - 0.98
0 160 320 640 Kilometers
N

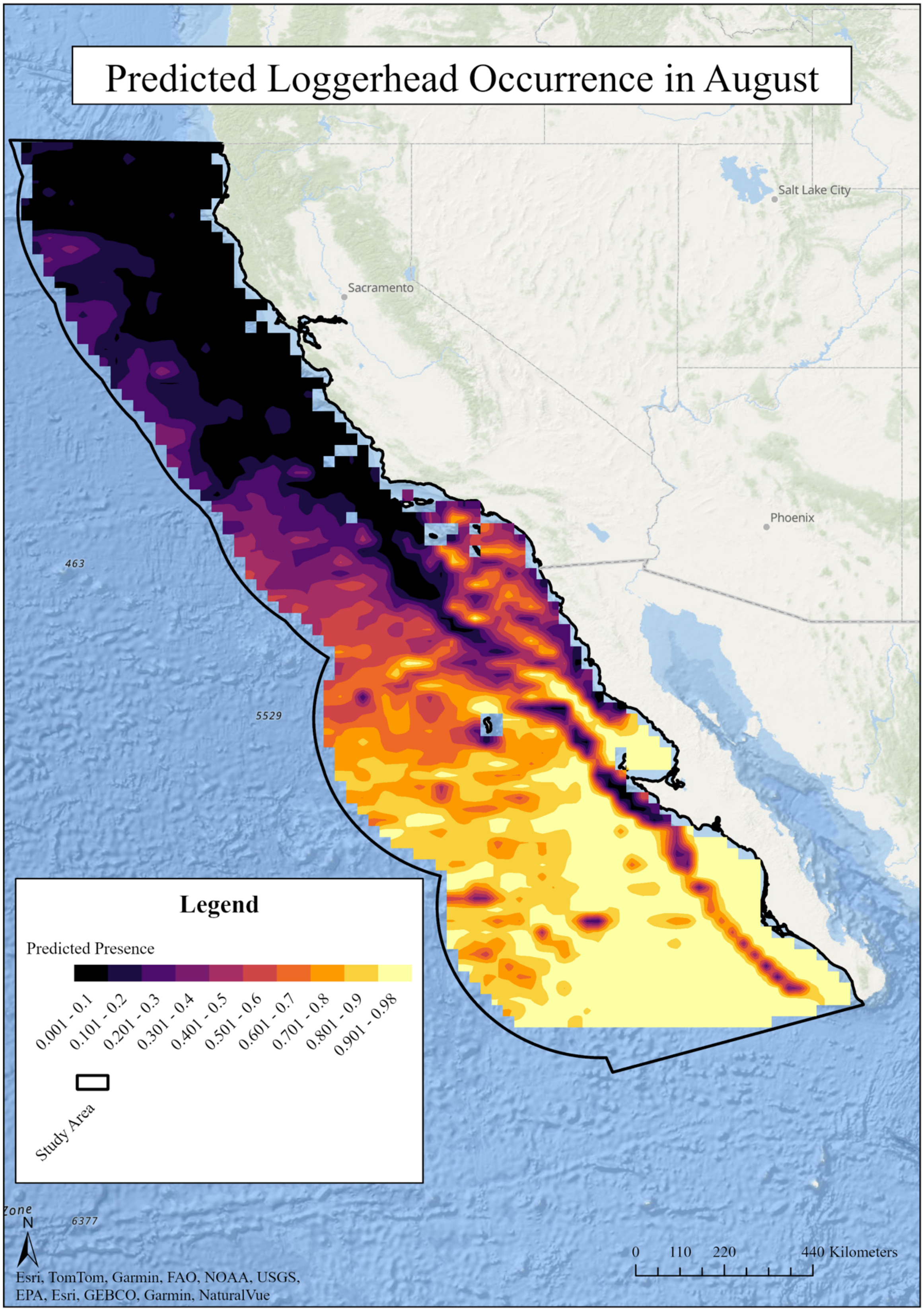
APPENDIX C



Predicted Loggerhead Occurrence in July

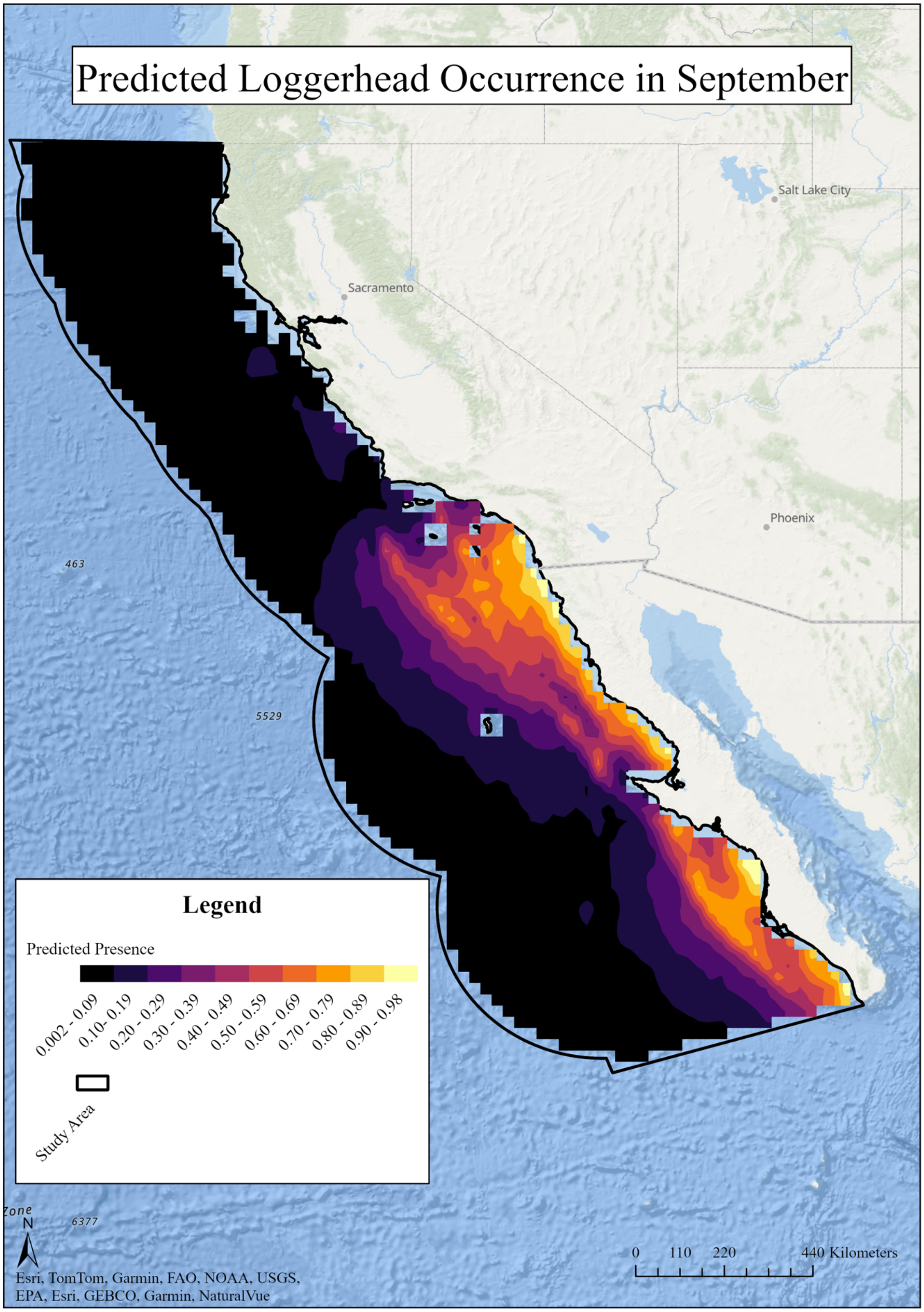
Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, Esri, GEBCO, Garmin, NaturalVue

APPENDIX D



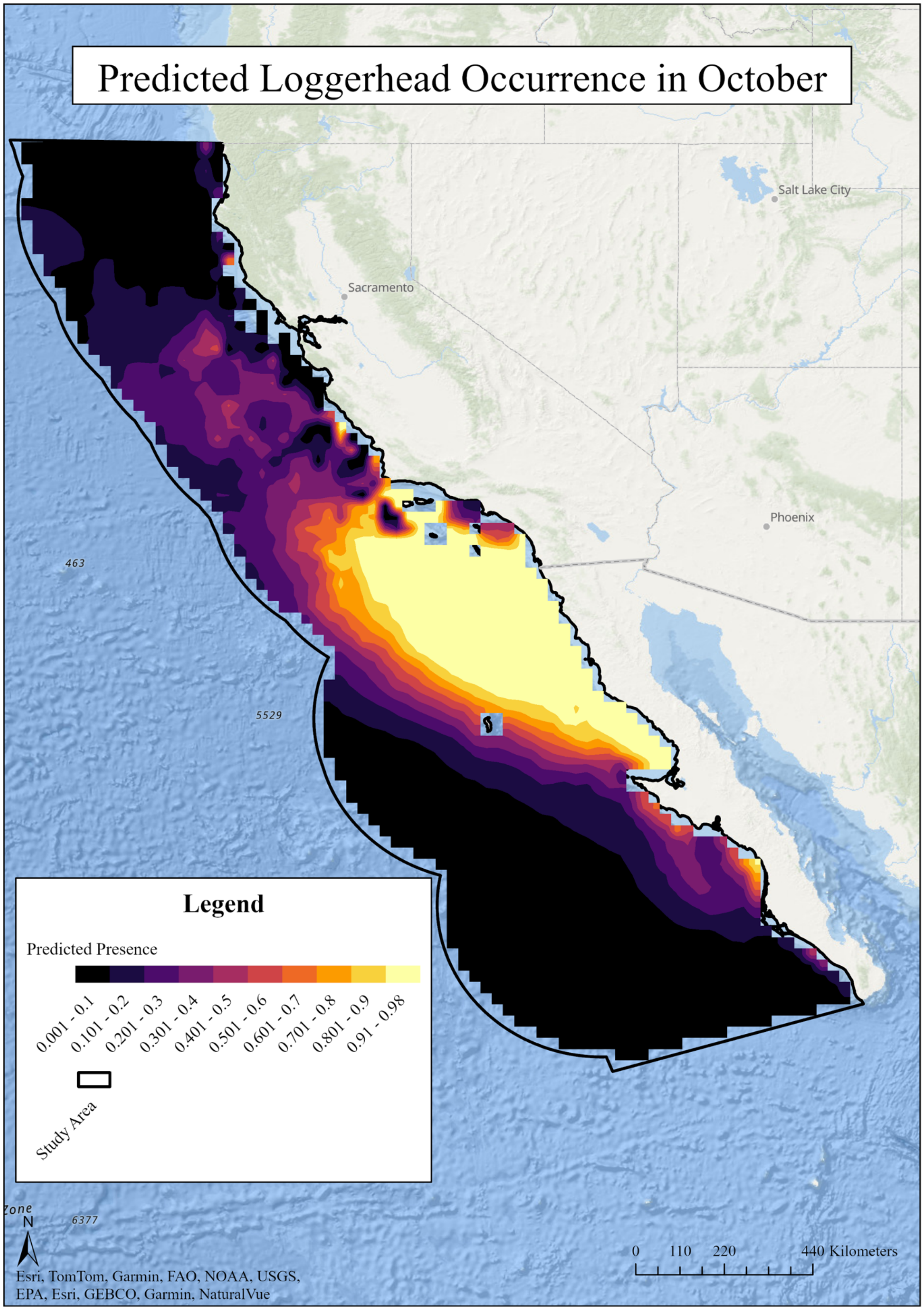
Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, Esri, GEBCO, Garmin, NaturalVue

APPENDIX E



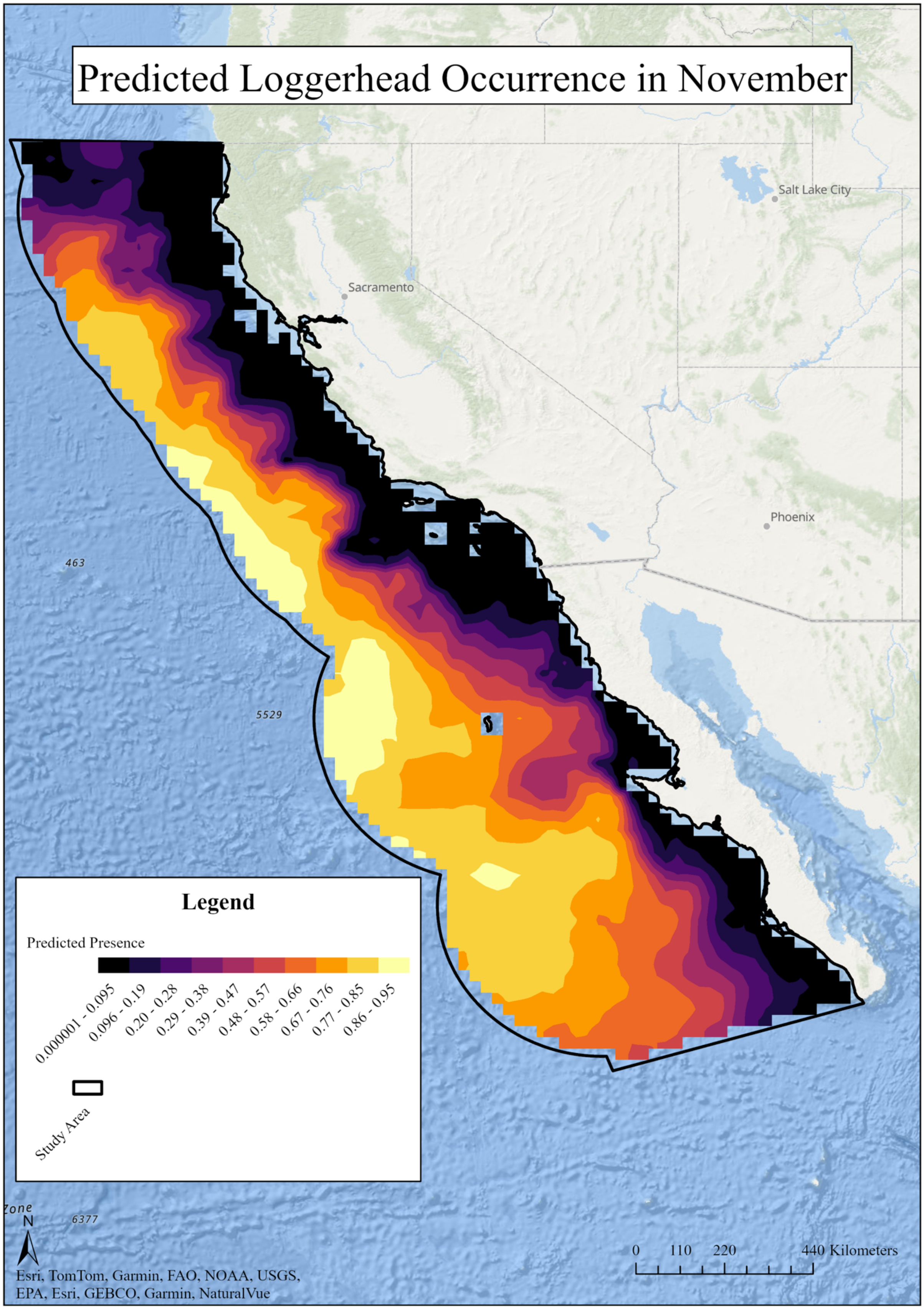
Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, Esri, GEBCO, Garmin, NaturalVue

APPENDIX F



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, Esri, GEBCO, Garmin, NaturalVue

APPENDIX G



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, Esri, GEBCO, Garmin, NaturalVue