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Predicting the impacts of sea level rise in sea turtle nesting habitat on Bioko Island, Equatorial Guinea

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Abstract

Sea level is expected to rise 44 to 74 cm by the year 2100, which may have critical, previously un-investigated implications for sea turtle nesting habitat on Bioko Island, Equatorial Guinea. This study investigates how nesting habitat will likely be lost and altered with various increases in sea level, using global sea level rise (SLR) predictions from the Intergovernmental Panel on Climate Change. Beach profiling datasets from Bioko's five southern nesting beaches were used in GIS to create models to estimate habitat loss with predicted increases in sea level by years 2046–2065 and 2081–2100. The models indicate that an average of 62% of Bioko's current nesting habitat could be lost by 2046–2065 and 87% by the years 2081–2100. Our results show that different study beaches showed different levels of vulnerability to increases in SLR. In addition, on two beaches erosion and tall vegetation berms have been documented, causing green turtles to nest uncharacteristically in front of the vegetation line. We also report that development plans are currently underway on the beach least susceptible to future increases in sea level, highlighting how anthropogenic encroachment combined with SLR can be particularly detrimental to nesting turtle populations. Identified habitat sensitivities to SLR will be used to inform the government of Equatorial Guinea to consider the vulnerability of their resident turtle populations and projected climate change implications when planning for future development. To our knowledge this is the first study to predict the impacts of SLR on a sea turtle nesting habitat in Africa.

Introduction

One of the important discussions involving climate change and sea turtle conservation is the imminent loss of sea turtle nesting habitat in relation to increasing sea level rise (SLR) [1, 2, 3]. The Intergovernmental Panel on Climate Change (IPCC) has generated four scenarios that predict SLR for years 2046–2065 and 2081–2100 [4]. The IPCC indicates that an increase of about 44 to 74 cm will be experienced globally by the year 2100, which will have previously un-

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investigated implications for the second largest nesting aggregations of leatherback (*Dermochelys coriacea)* and green sea turtles (*Chelonia mydas*) in West Africa [4–8]. Due to low elevations and limited capability for shoreline retreat, small islands are at the greatest risk from climate change [9, 10], and expected effects include increased salinity within the water table, beach erosion, and sand inundation with increased tide elevation [11, 12].

Marine reptiles have evolved with natural coastal erosive processes such as high-tide flooding, accretion, and seasonal erosion, but the extreme beach modification of the past half-century is progressing at a rate faster than the rate at which some species can adapt [1]. The Great Barrier Reef green sea turtle nesting population, the largest in the world, has experienced hatchling success reduction in the past few years, which is thought to be a result in part of a rising groundwater table [13]. It has been estimated that the most extreme SLR predictions will result in inundation of 27 percent of Great Barrier Reef green sea turtle nesting habitat [3]. Nesting habitat inundation is also expected in other nesting sites around the world, including Bonaire (26%) and Barbados (32%) with a 0.5 m rise in sea level [1, 2].

For nesting habitat that is not inundated, SLR will likely alter the potential for previous nesting beaches to continue to maintain their historic turtle reproductive output [1]. With an overall reduction in nesting habitat, if the rate of shoreline retreat continues to lag behind that of beach erosion, the density of nests will likely increase within the area of available nesting habitat. This has potential to cause decreased hatching success through increased contamination and physical disturbance of nests by co-specifics [2, 13–16]. Since sea turtle species can shift their nesting grounds when faced with unsuitable nesting habitats [17–20], it is important to also investigate multiple nesting areas within a nesting region [3]. It has been suggested that with 0.48 m SLR in the Hawaiian Islands, green sea turtle nesting localities will likely need to shift primarily from Trig, Gin, and Little Gin islands to East Island in order for historic reproductive productivity to be sustained [21]. With increasing SLR, increases in erosion rates and nests that are flooded from storms can be expected [10, 22, 23]. Effects from an increased water table due to SLR can already be observed on Raine Island, Australia, where depressions from sea turtle body pits have been observed filling with water [13, 24]. This increased nest inundation will likely cause decreases in reproductive output of all sea turtle species [13].

The 10.75 km of main sea turtle nesting beaches (Fig 1A–1E,) on the southern side of Bioko Island are critically important nesting habitat for the leatherback and green sea turtles in the West/Central African region [8, 25–27]. Further genetic analyses and internesting satellite tracking studies for green and leatherback turtles in the Gulf of Guinea are required to further understand the fidelity of turtles to Bioko Island and the potential for Bioko nesting turtles to be part of the same populations observed in Gabon and Congo [8]. On Bioko green turtles nest mostly on beaches A, B and C, and leatherback sea turtles on C, D and E [8]. Within and among species, there is variation in selection for more specific beach characteristics such as beach length, width, height, slope, orientation, and vegetation [28–31]. The various beach types where sea turtles nest combined with the specific nest-site characteristics that are selected for by each species can be altered in diverse ways by increasing sea level [1]. Green turtles prefer to nest on narrower, steeper beaches and in the area behind the vegetation line, whereas leatherback sea turtles prefer wider, flatter beaches and the area between the high tide line (HTL) and the vegetation line [32, 33]. It has been found previously that narrower beaches at lower elevations are more susceptible to SLR [1]. As the morphology of the beaches and intricate beach zoning is altered, these habitat selection differences cause species-specific SLR threats. Based on the spatial distribution of nests within each species, the threat from nest inundation could be more severe and more imminent for some species than others.

The goal of this study is to characterize sea turtle nesting beaches on Bioko Island and to model the effects of SLR for use in generating targeted conservation management plans. Nest

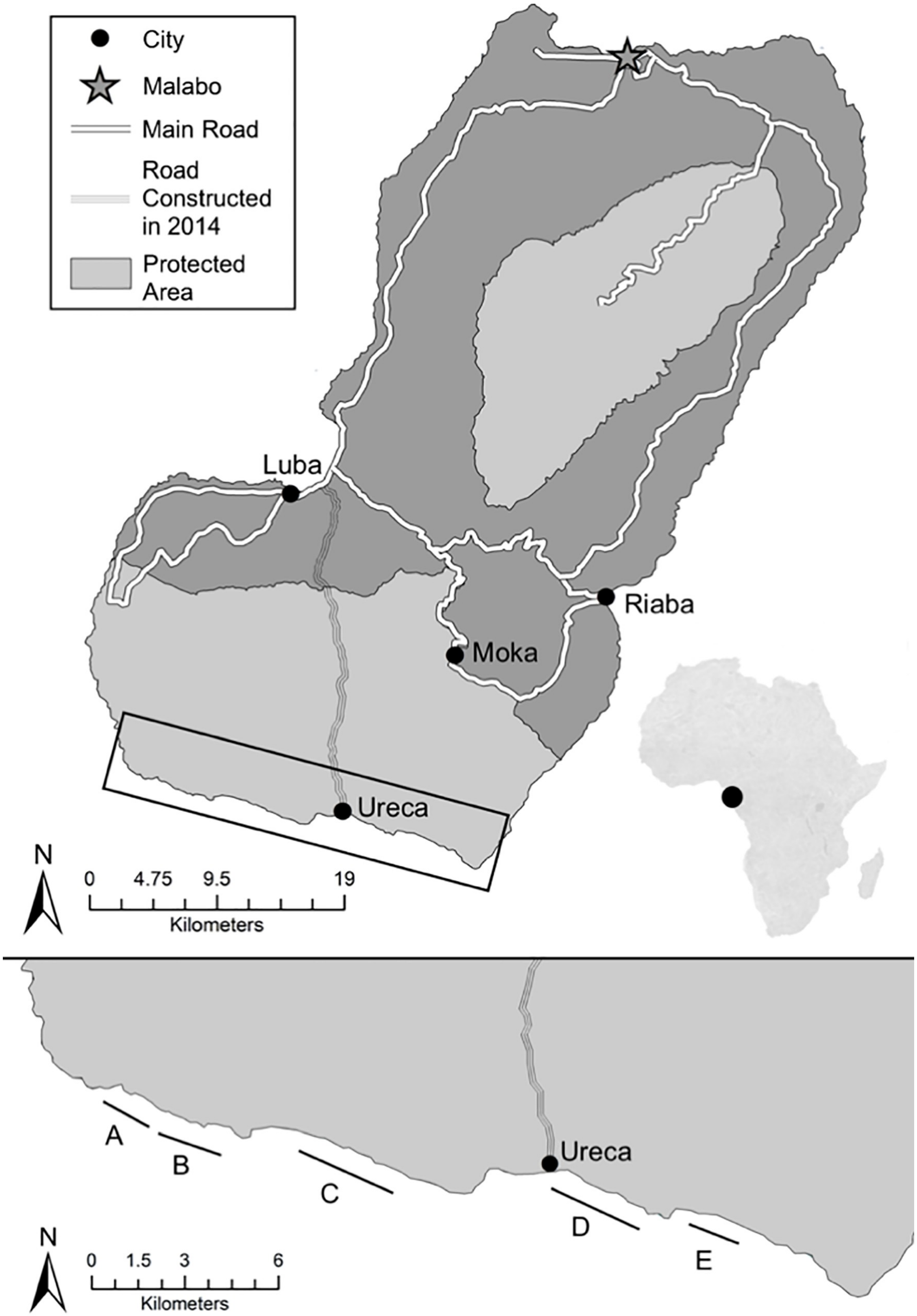

Fig 1. Bioko Island nesting beaches. The five nesting beaches are labelled with letters A–E.

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Table 1. Beach morphometrics of Bioko's five turtle nesting beaches 1.

Beach	Length (km)	Total Area (m^2)	Current Nesting Habitat (m^2) (Proportion of Total Beach Area)
A	1.7	84,914	8,852 (0.10)
B	1.9	145,350	10,350 (0.07)
C	2.9	236,784	23,946 (0.10)
D	2.65	350,564	63,592 (0.18)
E	1.6	153,110	16,217 (0.11)

Morphometrics of Bioko's five nesting beaches. Nesting habitat is defined as the area between the high tide line and vegetation line.

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locations from both green and leatherback turtles were used together with SLR predictions on Bioko's 5 nesting beaches to determine how each species will likely be affected in the upcoming decades by climate change. Our objectives were to (1) construct a 3D profile of 5 nesting beaches by collecting morphometric/contour data in an x, y, z dimensional space, (2) use triangulated irregular network models and digital elevation models to map landward movement of the HTL, and (3) predict how the model output will affect green and leatherback turtle nesting on Bioko Island.

Materials and methods

Data collection

Beach profiling transects were conducted on all five of Bioko's nesting beaches (A-E) (Fig 1, Tables 1 and 2). Beach characterization methods were consistent with a similar SLR prediction model for 13 beaches on the island of Bonaire, Dutch Antilles [1]. The profile of each beach was recorded at 50 m intervals along the beaches using a 60 m measuring tape. The transects on each beach were 50 m apart, perpendicular to the water line, and spanned the distance from the vegetation line to the drop off during lowest tide. A meter tape, compass and Abney level, a surveying instrument consisting of a sighting tube, movable spirit level and protractor scale, were used to create profiles of beach topography and dimensions at each change in slope along the transect [2]. Accuracy to ground truth was relative to the stake GPS point (Garmin GPSMap 64) at the start of each transect. To ensure maximum accuracy, up to 6 different waypoints for the same stake on each beach were averaged to generate an average stake reference point to be used in the following spatial analysis. During the process of beach profiling, the location of the high tide line was indicated. Three times throughout the nesting season, the high tide line of all beaches was walked to create a GPS track that could then be used in conjunction with the HTL identified during profiling to standardize the average location of the

Table 2. Beach morphometrics of Bioko's five turtle nesting beaches 2.

Beach	Max. Elevation (m)	Min. Elevation (m)	Average Elevation (m)	Max Width (m)	Min Width (m)	Mean Width (m) ±SD
A	1.78	-5.23	-2.50	100.23	16.9	49.06 ± 14.87
B	1.85	-4.51	-2.64	158.24	9.68	70.67 ± 31.03
C	1.86	-3.46	-2.40	137.14	29.44	78.80 ± 23.65
D	1.77	-2.83	-1.61	215.49	81.3	126.076 ± 31.70
E	1.30	-3.00	-2.40	154.65	59.93	94.80 ± 18.15

Morphometrics of Bioko's 5 nesting beaches based on 2017 profiling data. Averages show ± standard deviation.

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high tide line for modelling purposes. Beach D was profiled once at the beginning of the season and once at the end to better understand how seasonal fluctuations could affect SLR predictions for a single beach. The circular error probable for each stake was calculated. This work was conducted under appropriate permits from Universidad Nacional de Guinea Ecuatorial (#289/2016) and the Institutional Animal Care and Use Committee at Purdue University (IACUC protocol #1410001142).

This study was conducted from October 2016 through February 2017, coinciding with the leatherback and green sea turtle nesting season on Bioko Island. During nightly beach patrols or morning walks, nest and false crawl locations for every leatherback and green sea turtle encountered on Beach C (2.9 km) and D (2.5 km) were recorded using GPS (Garmin GPSMap 64). To understand the adaptability of sea turtle behavior in the face of changing available nesting habitat, part of the data collection throughout the nesting season included the nest abortion behavior of the females in their search to find suitable nesting habitat. At all nesting sites and every time a nesting attempt was aborted, data such as GPS point, beach zone, and distance to the high tide and vegetation lines was collected. Turtles entangled in vegetation during morning walks were freed.

Spatial analysis

A program was written in Python to generate a waypoint and elevation at each change in slope on the transects and at the present elevation of the high tide line. In ArcMap (Esri version 10.4), GPS points with their respective elevation values were entered as x, y, z data and then projected as shapefiles. All elevations were relative to the HTL, which for the purposes of this project is at an elevation of 0 m. The weighted average elevation of each beach was determined by utilizing the average elevation and length of all transect segments. The vertical error of each profile segment was determined using the generally accepted measurement error of the Abney level (4.31%) [34]. The total error of each profile was determined by adding the sequence of vertical errors along the profile in quadrature. The average vertical error of all profiles was determined to be 0.074 m ± 0.027 (standard deviation). The "points to line" feature in ArcMap was used to create five lines connecting: 1) stake GPS points, 2) HTL GPS points, 3) GPS points of the final segment of each transect, 4) GPS points for transect 1 on each beach, and 5) all points on the last transect for each beach. These lines allowed the "feature to polygon" tool to be used to create two polygons of each beach, one delineating the area between the HTL and vegetation line and another delineating the area between the final segment of each transect (at the beach dropoff visible at low tide) and the vegetation line. Total beach area was determined by calculating the area of the polygon between the vegetation line and the beach drop off at low tide. Available nesting habitat was determined by calculating the area of the polygon between the high tide line and vegetation line. The proportion of the total beach area that is available for nesting was calculated by dividing the area of available nesting habitat by the total beach area. To model sea level rise, the waypoints from all changes in slope on all transects were then used as inputs to the "topo to raster" tool to create a digital elevation model, which is an array of regularly spaced elevation values referenced horizontally. The raster dataset was then used in the creation of a triangulated irregular network model, for 3D visualizations of beach morphology and changes due to SLR [1, 3] (S1 Fig). The raster datasets were projected and reclassified to reflect the IPCC sea level rise projections (0.24, 0.25, 0.26, 0.30, 0.4, 0.48, 0.63 and 0.75 m) [4] (Tables 3 and 4). The range of one class of each raster always ended at 0 m, so the current approximate viable nesting habitat could be easily isolated. The "extract by mask" feature was then used to clip these rasters to the polygons of each beach. The count of each class along with the cell size was used to calculate the area of each beach, area of current

Table 3. Habitat loss projections on turtle nesting beaches under 4 IPCC scenarios for 2046–2065.

	Nesting Habitat Inundated (proportion of total nesting habitat)				
Beach	0.24 m	0.25 m	0.26 m	0.30 m	Mean
A	6,209 (0.70)	6,344 (0.72)	6,444 (0.73)	6,835 (0.77)	0.73
B	8,507 (0.78)	8.633 (0.79)	8,760 (0.80)	9,282 (0.85)	0.81
C	13,422 (0.50)	13,851 (0.52)	14,245 (0.53)	15,802 (0.59)	0.54
D	29,246 (0.45)	30,092 (0.46)	30,938 (0.48)	34,522 (0.53)	0.48
E	9,404 (0.50)	9,807 (0.52)	10,151 (0.53)	11,373 (0.60)	0.54

The potential area (m^2) on 5 of Bioko's nesting beaches that would be lost to sea level rise.

(SLR) under 4 scenarios for 2046–2065: 0.24, 0.25, 0.26, and 0.30 m. The average represents an average SLR loss predicted by the 4 scenarios for 2046–2065. Quantities in parentheses represent the nesting habitat inundated under each scenario as a proportion of the total nesting habitat.

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nesting habitat, and area lost and left under each SLR predation. This type of model is consistent with "bathtub" modelling and does not take into account future shoreline retreat. ArcScene (Esri version 10.4) was used to create 3D graphics of models, and ArcGIS software was used to generate all maps and basemaps. Species-specific predictions of impacts of climate change were then made based on the spatial presence (i.e. nest locations relative to vegetation and high tide lines) of each species on each beach coupled with the beach's vulnerability to SLR.

Results

The average circular error probable for the reference points was 2.43 m ± 1.44 (standard deviation), indicating that 2.43 m is the radius of a circle centered around the mean position of each reference stake that contains 50% of the reference stake GPS points. Similarly, the circular error probable was 3.85 m ± 2.51 (standard deviation) for 98% of the reference stake GPS points. Projections in GIS of the reference points and transects confirmed their proper spacing and alignment.

Beach A is the smallest beach with an average beach width of 49.06 m and a total beach area of 84,914 m^2 (Tables 1 and 2). Beach A also had the smallest area of nesting habitat in 2017, 8,852 m^2, but Beach B has the smallest percentage of nesting habitat to total beach area, 7% (Table 1). Beaches C and D were the two longest and widest nesting beaches on Bioko Island, with areas of 236,784 m^2 and 350,564 m^2, respectively (Tables 1 and 2). Beach D contained the highest percentage of nesting habitat out of all 5 beaches, 18% (Table 1). Satellite imagery and

Table 4. Habitat loss projections on turtle nesting beaches under 4 scenarios for 2081–2100 and 1 scenario for 2100.

	Nesting Habitat Inundated (proportion of total nesting habitat)				
Beach	0.4 m	0.47 m	0.48 m	0.63 m	0.75 m
A	7,544 (0.85)	7,851 (0.89)	7,887 (0.89)	8,239 (0.93)	8,396 (0.95)
B	9,576 (0.93)	9,960 (0.96)	9,996 (0.97)	10,296 (0.99)	10,338 (1)
C	18,282 (0.76)	20,052 (0.84)	20,280 (0.85)	22,494 (0.94)	23,328 (0.97)
D	42,782 (0.67)	47,314 (0.74)	47,885 (0.75)	54,761 (0.86)	58,542 (0.92)
E	12,761 (0.79)	13,723 (0.85)	13,722 (0.85)	15,313 (0.94)	15,869 (0.98)

The potential area (m^2) on 5 of Bioko's nesting beaches that would be lost to sea level rise (SLR) under 4 scenarios for 2081–2100: 0.4, 0.47, 0.48, and 0.63, and 1 scenario for 2100, 0.75 m. The mean represents an average SLR loss predicted by the 4 scenarios for 2081–2100. Quantities in parentheses represent the nesting habitat inundated under each scenario as a proportion of the total nesting habitat.

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photographs showed the evident discrepancy across nesting beaches in terms of nesting habitat available in 2017 (S2 Fig). The average elevation relative to the high tide line of Beach B was the lowest (-2.64 m) and that of Beach D the highest (-1.61 m) (Table 2). Beach A was the steepest beach with a slope of 0.086, and Beach D was the shallowest with a slope of 0.022. Beach A was the only beach that had a significantly different slope than all other beaches. The error of the elevation measurements, or the vertical error, was 0.043 m ± 0.016 (standard deviation).

There are four scenarios from the Intergovernmental Panel on Climate Change (IPCC) that predict SLR for years 2081–2100 and for the years 2046–2065. The results presented here are calculated with average SLR under Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5 for 2081–2100, the average SLR under RCP2.6, 4.5, 6.0, and 8.5 predictions for 2046–2065, and the average SLR under the RCP8.5 prediction specifically for 2100. The RCP8.5 prediction for 2100 was included to show the most extreme extent of current IPCC predictions.

Within only 30 years, using different scenarios of SLR, these models predict changes in nesting habitat availability. Under the most extreme scenario for 2046–2065, with a 0.3 m increase in sea level, Beach D is predicted to lose the least amount of its current nesting habitat, only 53%, and Beach B is expected to lose the most with a predicted 81% nesting habitat loss (Table 3). Under the least extreme scenario, all beaches will lose at least 45% of its current nesting habitat, and Beach B is likely to lose 78% of its current available nesting habitat (Table 3). Based upon the habitat loss predictions exhibited in Table 3, the beaches where green sea turtles nest in greater quantities, A and B, will experience higher nesting habitat losses than those where leatherback sea turtles nest more often, D and E (Table 3). Under the least severe scenario, the largest proportion of current nesting habitat that would be left by 2046–2065 was 55% on Beach D, and the smallest proportion of nesting habitat that would remain on Beach B is 22% (Table 3).

Under the RCP8.5 predictions for SLR in year 2100, all beaches were predicted to lose at least 92% of their current nesting habitat (Table 4). For the average SLR across RCP2.6, 4.5, 6.0 and 8.5 scenarios for 2081–2100, no beach was predicted to lose less than 67% (Table 4). Under the most extreme scenario, Beach B is predicted to be completely inundated (Table 4). The beach expected to lose the least amount of nesting habitat is Beach D with a predicted 92% loss by the year 2100 (Table 4). Beach D is the largest and widest beach and also has the highest minimum elevation and highest average elevation of any nesting beach on the south side of the island (Tables 1 and 2). The total area across all five nesting beaches that is predicted to remain on Bioko Island for nesting under the most extreme scenario is about 6,428 m^2, which is only about 5.23% of the nesting habitat currently available. Under the least extreme scenario, approximately 31,998 m^2 of nesting habitat is likely to be viable, 26.02% of current habitat estimates (Table 4). Beaches typically characterized as green sea turtle nesting habitat (Beaches A, B, and C) face an average of 90% nesting habitat loss for 2081–2100, and those of leatherback sea turtles (Beaches C, D and E) face an average loss of 82% (average of 0.4, 0.47, 0.48, and 0.63 m predictions).

Beach D was profiled twice within the same season, and the results show how these predictions could fluctuate. The first time the analysis was conducted with the first set of data, the maximum predicted habitat loss for Beach D was 91.84%. The second analysis, conducted with the second set of data, revealed a habitat loss of 92.06%. This is a percent difference of 0.24% and is considered negligible for this study's specific objectives.

Narrower, steeper and less elevated beaches appear to be more vulnerable to climate change. Although there was a negative correlation between increasing beach elevation and average nesting habitat loss, the relationships between maximum ($F = 0.24$, $df = 1,3$, $R^2 = 0.66$, $p = 0.66$), minimum ($F = 7.23$, $df = 1,3$, $R^2 = 0.71$, $p = 0.075$) and average elevation (m) ($F = 6.13$, $df = 1,3$, $R^2 = 0.67$, $p = 0.090$) with average nesting habitat loss (proportion of current

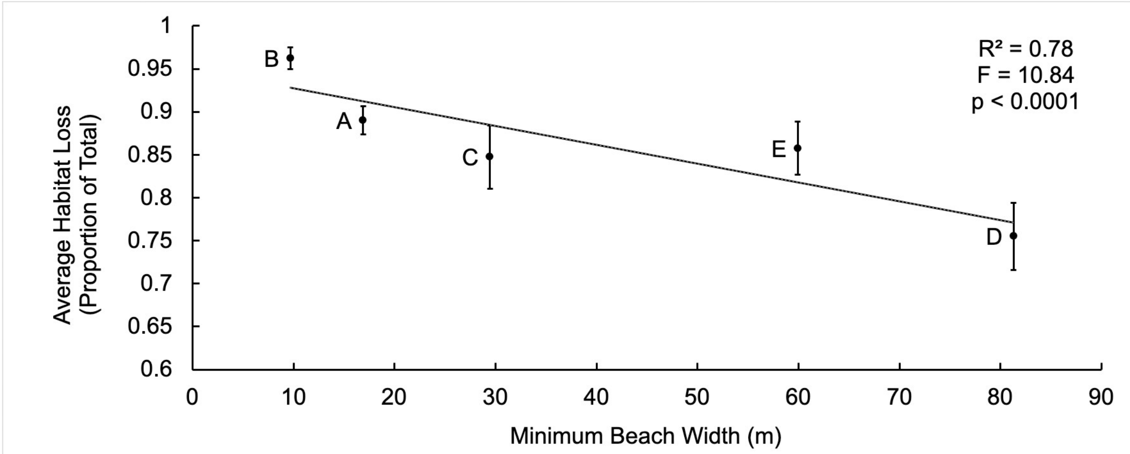

Fig 2. Minimum beach width versus average habitat loss. Relationship between minimum beach width (m) and average habitat loss (proportion of whole). Error bars are standard error from the mean.

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total nesting habitat) were not significant. The five nesting beaches did not have significantly different elevations (F (4,1327) = 2.01, p = 0.092). The data shows significant negative relationships between minimum beach width (Fig 2) with average habitat loss (proportion of current total nesting habitat). As the beaches become wider, the average habitat loss decreases. A significant positive relationship between average slope and average habitat loss was observed (Fig 3). Beach D, the beach expected to lose the least of its current nesting habitat, has the flattest slope and the highest minimum elevation (Table 2). During the spring high tide during the full moon in November 2016, there was no distance between the HTL and vegetation line [31]. Green turtle nests were laid in steeper and narrower sections of the beach, whereas leatherback nests were laid in shallower and wider areas (Fig 4).

Threats of nest inundation, predation, and entanglement were identified and uncharacteristic green turtle nesting at the high tide line and in front of the vegetation line in the presence of vegetation berms was documented. With rapid beach erosion on narrow beaches, steep

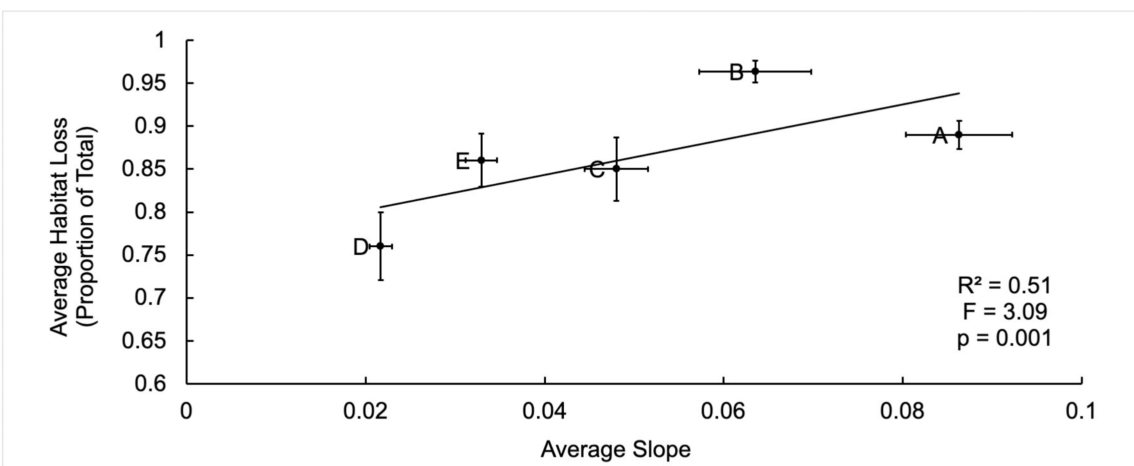

Fig 3. Average beach slope versus average habitat loss. Relationship between the average slope on beaches A, B, C, D, and E and their average expected habitat loss (expressed in proportion of whole nesting habitat currently available). The averages are for scenarios 0.4, 0.47, 0.48, and 0.63 m for years 2081–2100. Error bars are standard error from the mean.

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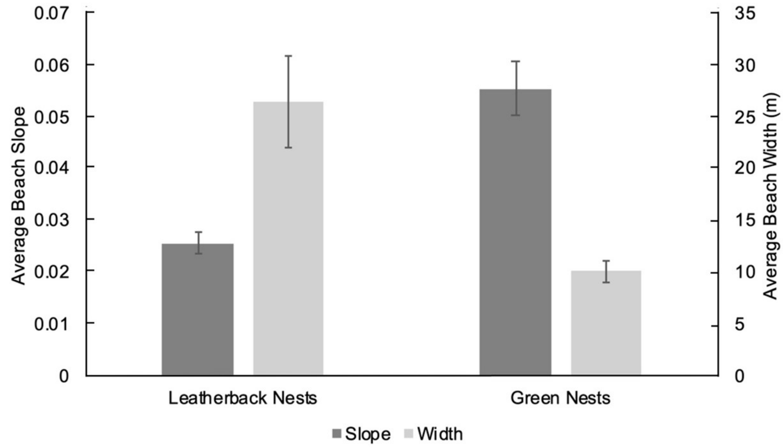

Fig 4. Leatherback and green turtle species specific nest site selection based on beach slope. Mean beach slope and width for 24 leatherback and 11 green clutches on Beaches C & D. Error bars are standard error from the mean.

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vegetation berms, where the high tide and vegetation lines are one in the same, are left as evidence that the rate of shoreline retreat lags behind that of beach erosion. Green turtles often struggle to reach the vegetation line, as they are unable to surmount steep vegetation berms or become entangled in overhanging root systems where the sand has eroded away beneath (Beach A). Green sea turtles are being found in dangling root matrices with increasing frequency on Beaches A and B (Honarvar, *personal observations*). Instead of surmounting vegetation berms, green turtles on Beaches A and B have been observed nesting in front of the vegetation and along the high tide line, where their nests are at an increased threat from tidal inundation. In other areas scattered along Bioko's nesting beaches, classic beach zoning between the high tide line and vegetation is nonexistent but no berms are present, causing the waves to lap against the trees. In these flatter areas, more characteristic of leatherback nesting beaches, like Beaches D and E, leatherback turtles seeking dry sand to lay their eggs can be found stuck in between the trees. Furthermore, a leatherback turtle was discovered with a tree stuck in between her shoulder and neck, causing immobilization. Turtles emerge from the surf in search of dry sand to lay their eggs and instead enter the forest.

Data from standard monitoring efforts during the 2016/17 nesting season documented 284 combined night patrol and morning walk leatherback encounters and showed that 89% ($n = 26$) of the time when a leatherback was found digging her nest below the HTL and the nest filled with water, she aborted that nest to choose a drier location closer to the vegetation.

Discussion

As beaches erode, beach morphological changes produce species specific threats to sea turtles as they select for suitable sites to lay their eggs. Our results suggest there is a link between minimum beach width and average habitat loss (Fig 2, $F = 10.84$, $R^2 = 0.78$, $p<0.0001$) as well as average slope and average habitat loss (Fig 3, $F = 3.09$, $R^2 = 0.51$, $p = 0.001$) based on five data points (five beaches). More work is needed to confirm these preliminary results. The behavior of green turtles to select for narrower, steeper beaches to nest could put them at a greater risk to climate change than other turtle species, as the beaches where they characteristically nest may be morphologically predisposed to erode first based upon the data presented here. Large-scale nest inundation and increased nest conductivity, an indication of moistness due to saltwater inundation, is being observed for this species on Beaches A and B and is expected to continue [35]. Nesting in front of the vegetation line to avoid stark vegetation berms and increased nest conductivity are quantifiable changes within green nesting habitat and nest selection that require further investigation to determine their effects on hatching success and hatchling production. At this time, we expect that increased inundation risk will result in increased nest mortality, and increased sand conductivity will be a significant negative influence on hatching success [35]. At present while nesting habitat still largely remains on Bioko's nesting beaches, leatherback turtle nest site selection behavior, in nesting closer to the HTL and in front of the vegetation line, generally puts the nests of this species at a greater risk to tidal inundation regardless of the morphology of the beach they are nesting on [35]. As sea level rises and beach erosion progresses, however, potentially eroding steeper and narrower beaches first and causing unsurmountable berms along the vegetation line, green turtles may be first to lose their nesting beaches altogether.

The results presented here represent passive flooding scenarios and the threat of coastal squeeze, which occurs when beaches are obstructed from natural landward movement with increased SLR. Predictions for shoreline retreat, like the Bruun Rule, are controversial and often overly simplified [36]. Modeling shoreline retreat using a Bayesian network has been fruitful in prior studies [37]. Along with shoreline retreat, other factors will likely play a role in shaping these beaches in the future, such as the effects of long-shore drift and the corresponding reallocation of sediments across nesting beaches, wave heights, the potential net loss of offshore sediment, offshore substrate structure, ocean currents, and increased deposition of sediment materials onto current beach habitat during high tidal inundation events [21]. Complex coastal dynamic processes can be expected to alter the morphology of these beaches with some level of shoreline retreat, but these intricate processes have yet to be studied on Bioko and thus render more complex SLR predictive methods incompatible at this time. The ability of surrounding coral reef growth to correlate with increasing sea levels will likely play a key role in the level of sand accretion seen in the upcoming century [21]. IPCC RCP SLR scenarios for the mid to late 21st century are relative to the reference period of 1986–2005, meaning that the results displayed here could be an estimate applicable for at least 11 years after the official year ranges for reported projections [4]. Inconsistencies in total beach area can be attributed to rounding of proportions and slight changes in model resolution. These predictions can be viewed as the best available insight into the future effects of SLR on Bioko's five nesting beaches.

The presence of beach sections on Beaches A and B where nesting habitat between the high tide line and vegetation line has already been completely lost is evidence that even though shoreline retreat will occur over time, the rate of beach erosion is currently faster than the rate of shoreline retreat. Unsurmountable vegetation berms have been left as verification of the discrepancy between beach erosion processes and shoreline retreat. There are no anthropogenic barriers to the landward movement of Bioko's beaches, but rock walls (Beach A) and rivers (Beaches C and D) could be natural barriers [1, 2]. It is likely that a section of Beach A at least 650 m in length will eventually disappear altogether with no inland retreat due to a large rock face directly adjacent to the beach. The face is located farther and farther inland as one moves Southeast along the beach, is at least 50 m tall, and can already be considered the "vegetation line" in some areas.

Previous studies in the Caribbean and Australia conducting similar analyses have reported percent nesting habitat losses that are less than what is reported in this paper [1–3]. This can likely be attributed in part to the higher reported elevation relative to the high tide line of other studied beaches [3]. Fuentes et al. 2010 reported an intuitive decreasing trend between maximum beach elevation and percentage of predicted inundated area. Although this decreasing trend between increasing beach elevation and nesting habitat loss was also observed in the presented dataset, it was not significant. This insignificance can likely be attributed to the fact that the beaches did not have significantly different elevations. Other morphological factors such as beach width and slope did significantly influence habitat loss.

With increasing SLR, increases in the amount of erosion and flooded nests are expected [10] and have been observed already on Bioko [35]. If rains increase in the West African region with climate change, as is suggested with low to medium confidence [38], these beaches are particularly susceptible to increased inundation risk due to rising water tables from both landward and seaward sides. Specific predictions include an increase in the quantity of days experiencing extreme rainfall in West Africa and increased frequency and intensity of rainfall events in the Guinea Highlands and Cameroon Mountains [39–42]. Bioko Island, one of the wettest places in Africa [43], is made up of a complex network of rivers, waterfalls, and lagoons that intersect the beaches at countless points along the shoreline. The fate of one inundated leatherback nest on Beach D is attributable to the high-water table, resulting from a waterfall located directly behind this particular portion of the beach [35].

Creating a hatchery could be an important conservation measure undertaken to protect nests that are likely to be saturated by the tides or rising water tables. Hatcheries have increased the hatching success of sea turtle species on beaches where various anthropogenic and natural threats have made successful in-situ incubation unlikely [44–47]. Although translocating nests can negatively affect embryo development [48, 49], the relocation of otherwise doomed eggs to a hatchery can result in a net gain in hatchlings produced over time [50].

Increased nest inundation will likely cause decreases in the reproductive output of sea turtles [13]. Preliminary predictions that can be made about species-specific vulnerability with increasing SLR are imperative in understanding which species are at greater impending risks with continued climate change. The data suggest that Beach D will be the beach to maintain the largest amount of nesting habitat for the longest period of time, making it theoretically the most vital beach to protect on the entire island. Unfortunately, it is also the beach that is most threatened by the road built in 2014 and corresponding increase in construction planning, tourists, and illegal egg and adult turtle take [8]. Recommendations have been made to the government of Equatorial Guinea to protect Bioko's nesting beaches, and especially Beach D, by minimizing development in the Grand Caldera and Southern Highlands Scientific Reserve and the southern beaches, investing in increased tourist environmental awareness campaigns, and increasing enforcement of existing regulations. With minimal development, natural shoreline retreat will have a chance to preserve intricate beach zoning as the sea level rises. By reporting our findings that the beach that is the least vulnerable to future increases in sea level is also the most vulnerable to anthropogenic encroachment, Beach D, the government of Equatorial Guinea can make more informed decisions about the protection of their endangered wildlife.

Similar studies that deploy this basic modelling technique can be useful globally in identifying priority areas for conservation of sea turtle nesting habitat. In areas where compromises need to be made between conservation and coastal development, basic sea level rise modelling can help authorities know which beaches or areas will be the most viable for sea turtles for the longest period of time. These areas can be prioritized for preservation. This type of site-specific modelling can also be helpful in determining the best areas to focus mitigation efforts, such as the placement of a hatchery, to decrease threats related to sea level rise and beach erosion.

Basic adaptive capabilities of sea turtles to change their behavior and choose locations further up the beach is supported in this study by the statistic that 89% (n = 26) of the time when a leatherback was found digging her nest below the HTL and the nest filled with water, she aborted that nest to choose a drier location closer to the vegetation. As turtle species can shift their nesting grounds when faced with unsuitable nesting habitats [17–20], it is possible that turtles could begin to nest on Beach D more frequently, as the other surrounding beaches experience more nesting habitat loss. This possibility highlights the importance of protecting Beach D from future development. As Bioko hosts the second largest nesting aggregations of leatherback and green turtles in West Africa [8], the reproductive output of these beach habitats is vitally important to the health of the nesting stocks. Losing this nesting habitat to sea level rise would either remove or displace hundreds of individuals of each species [8]. Internesting satellite tracking and genetic studies in the Gulf of Guinea could provide more insight into the nest site fidelity of Bioko's nesting turtles and their potential adaptability to other nesting grounds.

To our knowledge this is the first study to predict the impacts of SLR on sea turtle nesting habitat in Africa and one of the first for a critically important leatherback nesting aggregation worldwide. In the future, advances in modeling methods and increased knowledge of complex coastal processes could be used to improve presented estimates of SLR. These present findings provide a baseline for continued coastal change and habitat use modeling. This study will call attention to the fragility of sea turtle nesting habitat globally and the findings will be valuable to the government of Equatorial Guinea in future developmental planning.

Supporting information

S1 Dataset. Nesting beach profiles.
(XLSX)

S1 Fig. Triangulated irregular network model example. A screenshot of the triangulated irregular network model for Beach D. Displayed are the projected increases in sea level predicted for 2046–2065 scenarios of 0.24, 0.25, 0.26, and 0.3 m and the 2081–2100 scenarios of 0.47, 0.48, 0.63, and 0.75 m.
(PNG)

S2 Fig. Nesting beach satellite and ground images. This figure illustrates the visible space in between the HTL and vegetation line, the current nesting habitat, on Beaches D, C and B. HTL shown in blue and vegetation line shown in green.
(PNG)

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