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Highlights

- Sea-level rise will negatively impact sea turtle nesting ecology.
- Sea turtle species may be unevenly affected as a result of their zonal nesting preferences.
- Forecasting nest management may reduce the negative impacts associated with climate change and subsequent sea-level rise.
- Using GIS to map sea level rise can be a cost-effective methodology in supporting sea turtle conservation programs.
- Sea turtle adaptation strategies can reduce the threats of future climatic shifts, changing beach morphology and decreased hatching success.

Future Sea-Level Rise Impacts to Olive Ridley (*Lepidochelys olivacea*) and Green Sea Turtle (*Chelonia mydas*) nesting habitat on the Osa Peninsula, Costa Rica

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Abstract

Global sea turtle populations are in decline and so a global network of sea turtle nesting conservation programs have been established worldwide with the goal to protect vulnerable nesting mothers, and their clutches of eggs. Yet researchers have recently estimated that sea turtle nesting habitat is likely to suffer as a result of climate change and associated sea level rise. This study examines nest monitoring data from Costa Rica's Osa Peninsula with the aim to identify clutches located in suitable nesting habitat most susceptible to sea level rise and subsequent inundation. We analyze the impacts of six different sea level rise scenarios (from 0.25m to 2m) and discuss nesting inclinations and distributions of threatened Olive Ridley (*Lepidochelys olivacea*) and Green (*Chelonia mydas*) sea turtles on two beaches of the peninsula—known locally as Piro and Pejeperro. Sea-level rise scenarios on Piro beach indicated that 28.81% of the entire sample were likely to be inundated under a 0.25m scenario, and 16.52% on Pejeperro beach. Under a more extreme, 2m scenario, results indicated that 41.74% of nest sites on Piro and 24.55% on Pejeperro would be impacted. Results suggest that Olive Ridley turtles may be more susceptible to sea-level rise, based on their preferred nesting zones, commonly nesting closer to the tide line, as opposed to Green turtles that prefer to nest further from the tide line in vegetation zones where sea-level rise is likely to have less impact. Ultimately, the methodologies used in this study can support sea turtle conservation programs in assessing the potential effects of sea level rise and understanding nesting distributions on their nesting beaches, while also providing important insight in forecasting nest management and implementing monitoring techniques that may reduce the negative impacts associated with climate change and subsequent sea-level rise.

Keywords: Sea-level rise (SLR), Climate Change, Green sea turtle (*Chelonia mydas*), Olive Ridley (*Lepidochelys olivacea*), Osa Peninsula, Nesting Ecology

I. Introduction

In their most recent report, the Intergovernmental Panel on Climate Change (IPCC) stated that global mean sea level rise (SLR) has accelerated to $\sim 3.25\text{mm yr}^{-1}$ ($2.88\text{-}3.61\text{mm yr}^{-1}$) during the 1993-2018 period [1]. These projections indicate that sea level will continue to rise over the next century, especially with the imminent collapse of the polar ice sheets and further increases in global surface temperatures. Future SLR combined with storm surge and heavy rainfall is likely to increase compound flood risks posing existential threats to low lying coasts, and small island developing states [1,2]. As a result, important economic

areas for fisheries, agriculture and tourism are likely to be threatened, beaches and shorelines to erode, changing beach morphology and dramatically compromising beach ecosystems in the process [1,3,4,5]. With that said, habitats for threatened, endangered and endemic species inhabiting coastal areas will be at increased risk with entire ecosystems predicted to be lost or redistributed due to SLR [6]. Researchers estimate that an abundance of coastal plant species [7], coastal mammals [8], shore and seabirds [9] and reptilian species [3,4,5,10,11,12,13,14], will be amongst those likely to suffer as a consequence of increased SLR.

Currently, sea turtles are declining across their range, with six out of seven species listed as vulnerable, endangered, or critically endangered by the IUCN (International Union for Conservation of Nature) Red List [15,16,17,18,19,20]. Various direct and indirect effects are leading to declines in sea turtle populations including: bycatch (perceived to be one of the greatest threats to sea turtles), coastal development (known to create coastal squeezes to nesting habitat), poaching of nesting females and eggs for consumption and commercial purposes, light pollution, and most recently, climate change (through elevated beach surface temperatures and SLR [21,22,23,24,25,26,27]).

As sea turtles rely on both temperate and tropical beaches for nesting habitat, they are largely susceptible to SLR [4]. It has been observed that temperature, beach slope, humidity, sand particle size and density play important roles in sea turtle site selection [28,29,30]. For example, Santos et al. [31] found that the looser the sand, the more suitable the habitat. More specifically, other studies have shown that Olive Ridley (*Lepidochelys olivacea*), Leatherback (*Dermochelys coriacea*) and Loggerhead (*Caretta caretta*) turtles tend to select flat, open, and unobstructed areas and deposit their clutches in areas with low slope between the high tide line and the vegetational line [12,32]. On the other hand, Green (*Chelonia mydas*), and Hawksbill (*Eretmochelys imbricata*) turtles tend to nest at higher elevations closer to dunes and vegetation along the coastline [12,32]. In a study conducted on the Osa Peninsula, Costa Rica [34], it was suggested that the mean distance to vegetation of Olive Ridley nests was 6.5 m (n=8717), while the mean distance to vegetation of Green turtle nests was 1.5 m (n=1839). Here, there may be an ecological tradeoff for sea turtles nesting in open and unobstructed areas compared to those nesting closer to the vegetation line. Sea turtle nesting sites located in higher elevation zones may be more susceptible to increased parasite infestation rates, predation, and poachers [34,35,36]. While nesting sites located in low elevation zones characterized by low slope, closer to the high tide line, may be vulnerable to coastal erosion, increased surface temperatures, sea level rise, wave runup or clutch inundation.

Recent studies have shown that in conjunction with higher wave runup and increased storm frequency and severity, SLR is likely to dramatically reduce total sea turtle nesting habitat. For example, Fuentes et al. [3] found that about 38% of nesting habitat across all examined rookeries (n=8) for the northern Great Barrier Reef would likely be inundated as a result of SLR. They also noted that the threat to nesting habitat during storm events is likely to be much greater, with 7 out of 8 nesting grounds seeing >50% of available nesting habitat inundated by sea water due to coastal flooding [3,5,13]. As a result, high humidity within clutches may cause fungal growth, while full inundation will increase egg mortality and markedly decrease hatchling success [30,37,38]. Another example can be seen in Veelenturf et al. [5], which expects that under the most extreme scenario, up to 62% of Bioko Island's current nesting habitat could be lost by 2046–2065 and on average 87% by

the years 2081–2100 under scenarios (0.40-m, 0.48-m, 0.63-m and 0.75-m). On the other hand, Fish et al. [11] expects to see 23% of total nesting habitat under threat with a 0.5m rise in sea level and 52% lost under a 0.9m rise on the island of Bonaire. These variations are likely a result of geographical location, whose beaches will undoubtedly be impacted disproportionately by future sea level rise, as Bonaire is situated in the Caribbean Sea, and Bioko Island is located off the coast of Equatorial Guinea in Africa. In another study in Costa Rica, the probability of flooding of nest locations remains relatively stable until 2060, and then increases significantly: by a factor of two (2020 to 2070) and 3.5 (between 2030 and 2100) [12].

Current projections and relevant literature indicate that SLR is likely to threaten and dramatically decrease total sea turtle nesting habitat, and subsequent hatching success by 2050 and 2100. To our knowledge, previous research on the Central and South Pacific Coast of Costa Rica has primarily focused on predation, hatch frequency, and temporal and spatial distribution of sea turtle nesting [34,35,63,64]; but there has yet to be any SLR analysis conducted. With the aim to assess the potential scale of impacts of SLR to sea turtle nesting habitat on two beaches of the Osa Peninsula, Costa Rica, we: 1) Assess sea turtle nesting locations along the two beaches, 2) Identify areas that are most prevalent for nesting by beach sector, beach zone, and distance from the high tide line, and 3) Examine, under various SLR scenarios outlined in the IPCC 6th assessment report and relevant literature, the potential scale of impacts of SLR to sea turtle nesting habitat on the two beaches.

By understanding habitat usage, researchers are able to better inform sea turtle conservation decisions, ideally enabling sea turtles to adapt to rising sea levels. Specifically, by identifying and prioritizing the relocation of clutches located in suitable/preferred nesting habitat most susceptible to coastal flooding on Piro and Pejeperro beaches in the future.

II. Methods & Materials

Study Area

The Osa Peninsula, located on the southwestern coast of Costa Rica, is considered as one of the most species rich places on earth relative to its size (1093 km²) [65]. The peninsula is surrounded by the Pacific Ocean to the west, and Drake Bay to the east. The region is characterized by semi-diurnal tides with tidal fluctuations as great as ~3.1m (obtained from tide charts in the area [66]). According to Hernández Blanco et al. [67], mean sea level rise on the Osa Peninsula agrees with the global average, ~3.25mm yr⁻¹. Many of the westerly positioned beaches on the Osa Peninsula are regarded as vital habitat for nesting female sea turtles. These include: Carate, Río Oro, Piro and Pejeperro [35,63]. The primary focus of this study was centered around Piro (2 km) and Pejeperro (4.5 km - Figure 1), beaches assigned to the Osa Conservation.



Figure 1: Map of the study region. Left: (a) An arrow shows the location of Piro and Pejeperro beaches on the Osa Peninsula, Pacific coast of Costa Rica. Right: Piro (b) and Pejeperro (c) beaches, divided into the 20 and 45 sectors, respectively.

Data Collection

Data was collected on Piro beach every morning from 03:00-09:00 between June 1, 2021-March 31, 2023, and on Pejeperro beach, efforts were conducted once a week between July 4, 2021-March 31, 2023. Due to logistical complexities hindering access for the Sea Turtle Conservation Team on a daily basis, differential sampling effort on Pejeperro beach was restricted to just one day per week. During this morning census, two to four people patrolled the beach to record sea turtle tracks and locate new sea turtle clutches. Monitoring efforts were primarily conducted in the early morning, often said to maximize the chance to observe sea turtle tracks before they are washed away later that day [39], and to ensure there was no turtle emerging later that could be potentially missed during night patrols. For newly fresh nests, false crawls, and old nests, the species was identified through track identification (*Appendix A*), following the guidelines by Eckert et al. [40]. Sea turtles in this study are commonly referred to as Cm and Lo, Cm for Green turtles, and Lo for Olive Ridley.

The Sea Turtle Conservation Team recorded the beach sector, divided into 100-meter sections (*Figure 1*), and the beach zone (open, border or vegetation). If a nest was located in an open zone, it received sunlight for over 60% of the day; if a nest was located in the border zone, it received sunlight for 40-60% of the day; and if the nest was located in the vegetation zone, it received sun for less than 40% of the day (*Figure 2*). Beach zone categories were defined based on the percent sunlight exposure from sunrise to sunset and measured observationally by the Sea Turtle Conservation team. Exposure thresholds were selected to reflect increasing global surface temperature and egg incubation, where incubation temperatures determine the sex of an individual known as temperature-dependent sex determination (TSD). They were also used as an ex-situ selection criterion. On Piro beach, ~75% of the beach was composed of an open zone, ~10% was considered as a border zone, and ~15% was considered as vegetation. On the other hand, ~60% of Pejeperro beach was considered as an open zone, ~15% as a border zone, and ~25% as

vegetation. Further, the geolocation was recorded using the application Jotform downloaded from the Google Play/Apple store. Unlike recent monitoring efforts which did not use GPS coordinates to mark nests because of the known margins of error ($\sim 6\text{m}$) [34], in this study, GPS coordinates of clutches were collected using the My GPS Coordinates application downloaded from the Google Play/Apple store. My GPS Coordinates utilizes a WGS84 coordinate system. The accuracy of WGS84 (G2139) is now typically 2-5 meters [41]. Lastly, solely recorded during the 2022-2023 nesting season, this study measured the distance from the nest to the high tide line using a 30-meter measure tape. The distance from the high tide line was defined as the line on the beach dividing wet and dry sand by Ernest & Martin [42]. These authors stated that “This line represents the maximum landward extent of wave wash during the most recent high tide event”.

Data Analysis

For this research only the newly fresh nests were included in evaluation, while the false crawls, and old nests recorded were excluded from analysis. Further, only the nests with coordinates were included in ArcGIS analyses. After the coordinates were plotted into ArcGIS, miscalculated coordinates were excluded from final SLR analyses. These points were also removed from the hotspot analyses if the beach sector did not correspond with the coordinates location on the map. Yet, these points were not completely removed from the entire dataset for nesting inclination analyses: nesting seasonality (*Appendix B*), nests located by sector (*Appendix C*), nests located by beach zone, and distance from the high tide line as they were determined to still be relevant to the broader knowledge of the study. Non-parametric chi-square tests, run in R-Studio, were used to understand if sea turtle species were distributed randomly or with an undeniable preference to specific beach zones on Piro and Pejeperro beach. Chi-square tests were realized using sea turtle species observed frequencies in each beach zone, compared to their theoretical expected distributions. Sea turtle clutches were considered “randomly distributed” if their expected distributions resembled beach zone categories located on Piro: 75% open, 10% border, 15% vegetation and Pejeperro beach: 60% open, 15% border, 25% vegetation. Non-parametric Mann-Whitney tests, run in R-Studio, were used to assess the significance of the relationship between the distance from the two studied species nests to the high tide line, as well as the distance to the high tide line between the two beaches.

Hotspot Mapping

After plotting sea turtle nesting locations in ArcGIS Pro, a Geoanalytics tool “Find Hot Spots” was performed. The goal of this approach was to identify statistically significant clusters of sea turtle nests located throughout the 2021-2022 and 2022-2023 nesting seasons on Piro and Pejeperro along the beach sectors. In this analysis, hot spots were defined as locations with low p-values and high z-scores (red output features), while cold spots were defined as locations with low p-values and low z-scores (blue output features). A z-score closer to 0, therefore indicated no significant clustering. A benefit is the hotspot analysis's ability to create a less subjective end visualization, especially when compared to a simple heat map. A total of 2 outputs were created, 1 for Piro beach and 1 for Pejeperro beach, incorporating a combination of data from both the 2021-2022 and 2022-2023 nesting seasons. In consideration of the hotspot analysis conducted on Piro beach, data points were aggregated using a 19m bin size and 50m neighborhood size. To maintain this

consistency, data points on Pejeperro beach also aggregated using a 19m bin size and a 50m neighborhood size.

Sea Level Rise Mapping

In this analysis, a multi-resolution digital terrain layer (“Terrain”) downloaded from Esri’s *ArcGIS Living Atlas of the World*, a collection of geographical information, including maps and data layers that provides elevation data for the entire world, was used to estimate the impact of sea level rise to sea turtle nesting sites on Piro and Pejeperro beach. As the “Terrain” raster layer encompassed the entirety of the world’s surface, the dynamic range adjustment (DRA) function was used to refine and visualize local variation in elevation values on the Osa Peninsula at a 25 m spatial resolution. Next, the “Export Raster” tool was used to export a file-based raster from the original Terrain layer, as well as clip the rest of the world outside of our area of interest. In order to map sea level rise, the “Remap” tool located under the Raster Functions pane was used to reclassify the pixel values of the exported raster and produce a new raster layer with new values. In this case, values of 1 were given to pixels impacted, whose elevation was less than the applied sea level rise scenario, while pixels that were not impacted were given values of 0. Once a new raster layer was created, the Spatial Analyst tool “Extract Values to Points” was used to sample nesting site locations on the beaches of Piro and Pejeperro, giving sites located inside pixels impacted by sea level rise a value of 1 and sites that were not located inside pixels impacted a <Null> value. Following this step, a shapefile was then created using the “Export Features” tool for RASTERVALU’s of 1, or solely current nesting sites impacted by sea level rise. Using the high tide line as a reference, sea level rise used in this analysis was considered as areas impacted under the highest high tides, where elevated sea levels were modeled to predict the impacts of different SLR scenarios on sea turtle nesting habitat. Nesting sites impacted by sea level rise were then exported for further analysis. Ultimately, this process was used and repeated to analyze the impacts of 6 different sea level scenarios (0.25m, 0.48m, 0.63m, 0.78m, 1.2m, and 2m), chosen based on the IPCC 6th assessment report (RCP2.6 & RCP8.5 GHG projections) [1,74] and relevant literature [3,4,5,10,11,12,13,14], on both Piro and Pejeperro beaches for new sea turtle nests located during the 2021-2022 and 2022-2023 nesting seasons. In this case, this study used its 0.25m sea level rise scenario to model the potential impacts to current sea turtle nests by 2050, its 0.48-0.78m scenarios to model potential impacts by 2100, and its most extreme 1.2m and 2m scenarios to model potential impacts beyond 2100.

III. Results

Nesting seasonality

During the 2021-2022 nesting season, 1189 new sea turtle nests were recorded on Piro during daily beach monitoring (187 Green, 1002 Olive Ridley) and 275 on Pejeperro during weekly beach monitoring (116 Green, 159 Olive Ridley). During the 2022-2023 nesting season, 1123 new sea turtle nests were recorded on Piro during daily beach monitoring (314 Green, 809 Olive Ridley) and 347 on Pejeperro beach during weekly beach monitoring (180 Green, 167 Olive Ridley) (*Appendix B*). Nesting seasonality observed on the beaches of Piro and Pejeperro had similar profiles (*Appendix B*). Olive Ridley sea turtles seemed to arrive in June and July, exhibiting peak nesting during the months of August and September, from which nesting slowly decreased in frequency by the end of the calendar year. However, a slightly prolonged peak nesting season on Playa Piro can be observed for

the 2021-2022 nesting season (*Appendix B-a*). Meanwhile, Green sea turtles seemed to arrive as Olive Ridley nesting decreased, beginning in November, and exhibiting peak nesting during the months of December, January, and February.

Beach Zone

Under the beach zone analyses, a total of 1881 (471 Green, 1410 Olive Ridley) nests located on Piro beach were used, while a total of 477 (259 Green, 218 Olive Ridley) nests from Pejeperro beach were used (Figure 2).



Figure 2: Top: beach zone classifications for vegetation (green), border (gray), and open (blue) zones, including expected distributions for Piro and Pejeperro beach. Bottom: proportion of sea turtle nests located by beach zone on Piro (left) and Pejeperro beach (right) over the 2021-2022 and 2022-2023 nesting seasons. Green turtles ("Cm"), Olive Ridley turtles ("Lo").

Green sea turtles seemed to avoid nesting in open beach zones, preferring to primarily nest in vegetation and border zones, or zones that received sunlight for less than 60% of the day. On the other hand, Olive Ridley avoided nesting in vegetation zones, preferring to nest in open and border zones, or zones that received sunlight for over 40% of the day. These

observations can be seen on both Piro and Pejeperro beaches for the 2021-2022 & 2022-2023 nesting seasons (*Figure 2*). Ultimately, these assumptions were confirmed with non-parametric Chi-square tests. There was an undeniable preference by Green turtles to border and vegetation zones on Piro ($\chi^2 = 823.64$, $df = 2$, $p\text{-value} < 2.2 \times 10^{-16}$) and Pejeperro beach ($\chi^2 = 270.84$, $df = 2$, $p\text{-value} < 2.2 \times 10^{-16}$), rejecting the null hypothesis due to its high significance. There was also an undeniable preference by Olive Ridley turtles to open and border zones on Piro ($\chi^2 = 179.76$, $df = 2$, $p\text{-value} < 2.2 \times 10^{-16}$) and Pejeperro beach ($\chi^2 = 44.21$, $df = 2$, $p\text{-value} = 2.506 \times 10^{-10}$). Therefore, it is safe to conclude that sea turtles were not homogeneously distributed throughout the three different beach zones located on Piro and Pejeperro beach, with clear preferences among Green and Olive Ridley turtles.

Distance from the High Tide Line

A total of 1043 (295 Green, 748 Olive Ridley) sea turtle nests located on Piro beach, and 227 (159 Green, 68 Olive Ridley) sea turtle nests located on Pejeperro beach during the 2022-2023 nesting season were used in this analysis. There was a significant difference between the median values on Piro beach (Mann-Whitney test, $W = 158624$, $p\text{-value} < 2.2 \times 10^{-16}$), indicating higher median values for Green turtles than that of Olive Ridley. On Pejeperro beach, results also indicated a significant difference between median values (Mann-Whitney test, $W = 7423.5$, $p\text{-value} = 8.283 \times 10^{-6}$), with Green turtles having higher median values between the two species (*Figure 3*). Furthermore, when comparing the distance of combined Green and Olive Ridley turtle nests from the high tide line between the two beaches, those observed on Piro beach appear further away than Pejeperro beach. This assumption was confirmed (Mann-Whitney test, $W = 133388$, $p\text{-value} = 0.003$), indicating a significant difference and higher median values on Piro beach, likely explained by differing beach morphology.

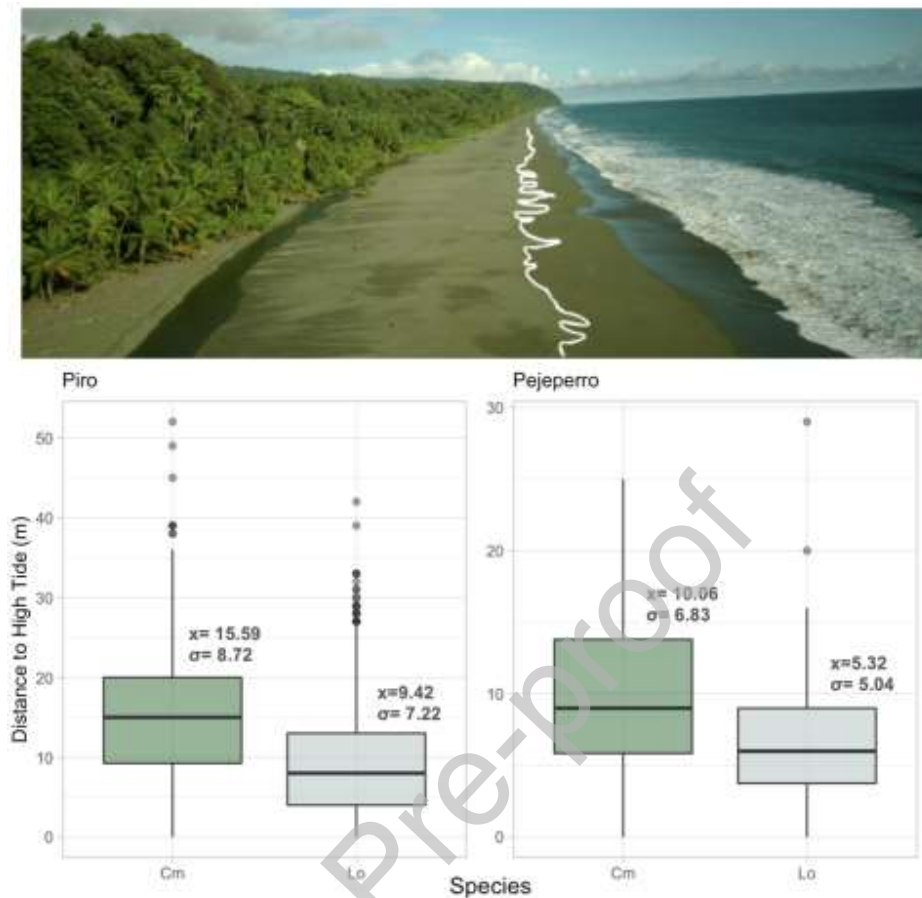


Figure 3: Top: aerial photo of Piro beach with a white line depicting the high tide line. Bottom: sea turtle nests located by species on Piro (left) and Pejeperro (right) beaches during the 2022-2023 nesting seasons.

Green turtles ("Cm", green), Olive Ridley turtles ("Lo", gray).

Hotspot Mapping

In this analysis, a total of 1694 (424 Green, 1245 Olive Ridley, 25 unidentified) new sea turtle nests were sampled on Piro beach, and 448 (237 Green, 208 Olive Ridley, 3 unidentified) new nests were sampled on Pejeperro beach. Figure 4a indicated significant hotspots between sectors 10-15 respectively on Piro beach, suggesting areas most frequented for nesting by sea turtles. Significant cold spots were identified in between sectors 3-7, suggesting sea turtles avoided nesting in these areas. Results from Figure 4b of Pejeperro beach indicated four small, isolated hotspots; these hotspots were located between sectors 2-3, 9-10, 25-27, and 31-32 respectively. No significant cold spots were identified on Pejeperro beach.



Figure 4: (a) Hotspot analysis conducted on Piro beach for the entirety of the 2021-2022 and 2022-2023 nesting seasons. (b) Hotspot analysis conducted on Pejeperro beach for the entirety of the 2021-2022 and 2022-2023 nesting seasons. Hotspots under three confidence level intervals are indicated by red output features, while cold spots are indicated by blue output features. Areas with no significant hotspots are indicated by white output features.

Sea Level Rise Analysis

Piro beach

Results of the SLR analyzes conducted on Piro beach indicated that 488 of 1694 current nests (28.81%—43 Green, 441 Olive Ridley) are likely to be impacted under the initial 0.25m SLR scenario (*Figure 5a*). Further, it seems that under the 0.48m and 0.63m scenarios, small increases in impacted nests are observed at 511 (46 Green, 461 Olive Ridley) and 516 (47 Green, 465 Olive Ridley) of the total sample (*Figure 5b* and *Figure 5c*). Under the 0.78m scenario, we begin to see more dramatic increases at 540 (51 Green, 485 Olive Ridley) or 31.88% of all nests (*Figure 5d*). Under the more extreme scenarios, 1.2m and 2m SLR, it is suggested that 594 (63 Green, 527 Olive Ridley) or 35.06%, and 707 (79 Green, 621 Olive Ridley) or 41.74% of the total sample are likely to be impacted (*Figure 5e*

and *Figure 5f*). Results also suggested that nesting sites of Olive Ridley sea turtles may be more impacted than that of Green sea turtles under all 6 SLR scenarios, encompassing over 87% of the total nests impacted in each scenario. Yet, as sea level begins to become more dramatic under more extreme scenarios, Green sea turtles nesting sites seem to be slightly more impacted. Additionally, under the 0.25m scenario, it seems that 10% of current Green turtle nests and 35% of current Olive Ridley turtle nests are likely to be impacted by 2050 (*Table 1*). While scenarios 0.48-0.78m indicated 10-13% of current Green turtle nests, and 37-39% of Olive Ridley turtle nests may be impacted by 2100. Looking beyond 2100, 15-19% Green, and 42-49% Olive Ridley turtle nests may be impacted under the 1.2 and 2m scenarios (*Table 1*).

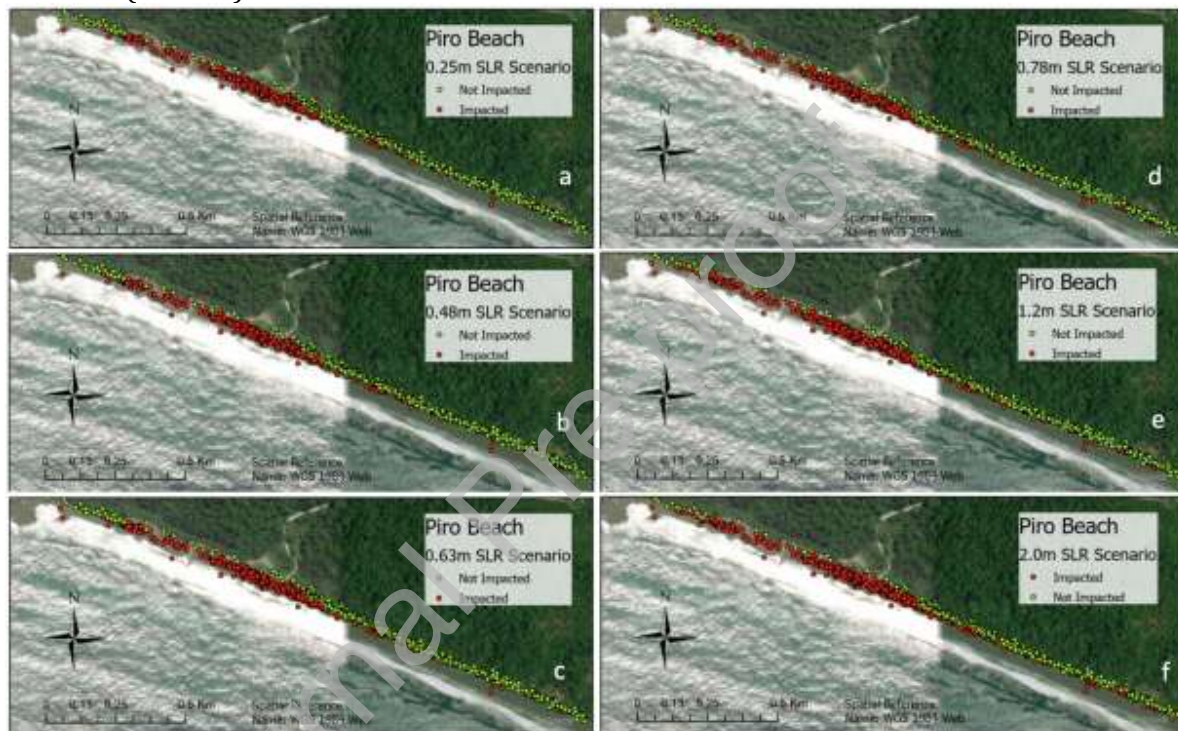


Figure 5: (a) Current nesting sites located on Piro beach impacted (red) by 0.25m SLR, or the 2050 scenario. (b,c,d) Current nesting sites located on Piro beach impacted (red) by 0.48-0.78m SLR, the three 2100 scenarios. (e,f) Current nesting sites located on Piro beach impacted (red) by 1.2m and 2.0m SLR scenarios, looking beyond the year 2100.

Pejeperro beach

Results of the SLR analyzes conducted on Pejeperro beach indicated that 74 of 448 current nests (16.52%—14 Green, 60 Olive Ridley) are likely to be impacted under the initial 0.25m SLR scenario (*Figure 6a*). It seems that under the 0.48m, 0.63m and 0.78m scenarios, slight increases were observed at 85 (15 Green, 70 Olive Ridley), 88 (15 Green, 70 Olive Ridley) and 89 (15 Green, 74 Olive Ridley) nests of the total sample impacted (*Figure 6b*, *Figure 6c*, *Figure 6d*). Under the more extreme SLR scenarios, 1.2m and 2m, it is suggested that 93 (16 Green, 77 Olive Ridley) or 20.76% and 110 (18 Green, 92 Olive Ridley) or 24.55% of nests are likely to be impacted (*Figure 6e*, *Figure 6f*). Results of this SLR analysis also suggest that Olive Ridley sea turtles are more likely to be impacted than Green sea turtles under all 6 SLR scenarios, encompassing over 81% of the total nests impacted in

each scenario. Additionally, under the 0.25m scenario, it seems that 6% of current Green turtle nests and 29% of current Olive Ridley turtle nests are likely to be impacted by 2050. While scenarios 0.48-0.78m indicated 6-7% of current Green turtle nests, and 33-35% of Olive Ridley turtle nests may be impacted by 2100. Looking beyond 2100, 7-8% Green, and 37-44% Olive Ridley nests may be impacted under the 1.2 and 2m scenarios (*Table 1*).



Figure 6: (a) Current nesting sites located on Pejeperro beach impacted (red) by 0.25m SLR, or the 2050 scenario. (b,c,d) Current nesting sites located on Pejeperro beach impacted (red) by 0.48-1.2m SLR, the three 2100 scenarios. (e,f) Current nesting sites located on Pejeperro beach impacted (red) by 1.2m and 2.0m SLR scenarios, looking beyond the year 2100.

Table 1: Number of sea turtle nests likely to be impacted by six SLR scenarios over the course of the last two nesting seasons (2021-2022 and 2022-2023) on Piro and Pejeperro beaches. A total of 1694 (424 Green, 1245 Olive Ridley) new sea turtle nests were sampled on Piro beach, and 448 (237 Green, 208 Olive Ridley) new nests were sampled on Pejeperro beach and used in this analysis. Unidentified nests were not reported here.

Piro beach: 2021-2023						
SLR Scenario	Total Nests Impacted	Nests Impacted (%)	Total Green Nests Impacted	Green Nests Impacted (%)	Total Olive Ridley Nests Impacted	Olive Ridley Nests Impacted (%)
0.25m	488	28.81%	43	10.14%	441	35.42%
0.48m	511	30.17%	46	10.85%	461	37.03%

0.63m	516	30.46%	47	11.08%	465	37.35%
0.78m	540	31.88%	51	12.03%	485	38.95%
1.2m	594	35.06%	63	14.85%	527	42.33%
2m	707	41.74%	79	18.63%	621	49.88%
Pejeperro beach: 2021-2023						
SLR Scenario	Total Nests Impacted	Nests Impacted (%)	Total Green Nests Impacted	Green Nests Impacted (%)	Total Olive Ridley Nests Impacted	Olive Ridley Nests Impacted (%)
0.25m	74	16.52%	14	5.91%	60	28.85%
0.48m	85	18.97%	15	6.33%	70	33.65%
0.63m	88	19.64%	15	6.33%	73	35.10%
0.78m	89	19.87%	15	6.33%	74	35.58%
1.2m	93	20.76%	16	6.75%	77	37.02%
2m	110	24.55%	18	7.59%	92	44.24%

IV. Discussion

Based on the sea-level rise (SLR) analyses outlined in this study, it seems that increasing sea level will have serious implications for Olive Ridley (*Lepidochelys olivacea*) and Green sea turtle (*Chelonia mydas*) populations that utilize Piro and Pejeperro beach as suitable nesting habitat. According to observation-based extrapolations using tide-gauge data in Sweet et al. [43], the most likely SLR scenarios to be met by 2050 are 0.25m or 0.48m. Results from this study propose that roughly 28.8% of sea turtle nests sampled on Piro beach and 16.5% of nests on Pejeperro beach may suffer from increased sea levels under the 0.25m SLR scenario by 2050. Yet, the SLR mapping approaches used in this research, based on current nesting sites and existing beach morphology, fail to account for complex coastal dynamics such as coastal erosion and wave-deposited sediment accumulations. This oversight could impact the manner in which the presented SLR scenarios unfold on sea turtle nesting habitat in the future as current conditions will likely change. However, Rivas et al. [12], states that even under moderate SLR scenarios, it is clear that large portions of sea turtle nesting habitats will be impacted by SLR by 2050. In many cases, results observed in this study mirror those seen in other SLR analyses. For example, Patrício et al. [13] suggests that 33.4% of the current nesting area in Poilão Island, Guinea-Bissau, West Africa will be lost under a 0.47m SLR scenario by 2050, while they expect to see up to 87.2% impacted by 2100. Another study indicated that an average of 62% of Bioko Island's nesting habitat could be lost by 2046–2065 and 87% by the end of the century, 2081–2100 [5]. Varela et al. [14], estimated that 33.2%–43.5% of the clutches under a 0.48 m SLR scenario would be impacted by inundation in Northern Cyprus. Furthermore, Katselidis et al. [4] suggested that even under the most conservative 0.2m SLR scenario, about 38% nesting habitat in Mykonos, Greece may be lost. Fish et al. [11]

explains a similar fate for Bonaire located in the Caribbean, with 32% of sea turtle nesting habitat lost under the 0.5m SLR scenario. Rivas et al. [12] explains that indications suggest sea turtle nesting habitat on islands and cays may be more susceptible to SLR, from which many studies concurred. Overall, previous literature estimated losses ranging from 23%-87% under various SLR scenarios as we enter the latter half of the century [3,4,5,10,11,12,13,14]. Results of this study, as well as those conducted previously, express the importance of adaptation strategies and ex-situ conservation efforts that aim to avoid decreased hatching successes by sea turtles on the Pacific coast. Yet, it is important to understand site-specific habitat use, to include factors that have historically driven sea turtle nesting site selection, in order to fully comprehend how sea turtles will be able to adapt to future climate uncertainties given their nesting ecology.

Our results confirmed that Olive Ridley preferred to nest in open and border zones, or zones that received sunlight for over 40% of the day, while Green turtles preferred to pass through open zones to nest in vegetation and border zones, or zones that received sunlight for less than 60% of the day. This observation is similar to what was observed by Ossmann [34] and was also confirmed by the high tide line analysis conducted in this study. However, it should be noted that the tendency of Olive Ridley turtles to nest in open and border zones may be simply due to accessible facilities before reaching vegetation zones. It may also be important to consider the ecological tradeoff for sea turtles nesting in open and unobstructed areas, compared to those nesting closer to the vegetation line. Sea turtle nesting sites located further from the high tide line may be more susceptible to predators, similar to those commonly seen on Costa Rican beaches (white-nosed coati (*Nasua narica*), raccoons (*Procyon* spp.), black vultures (*Coragyps atratus*), and stray dogs) [34,35,36]. They may also be more susceptible to poachers as they spend more time and energy crawling to their nesting site. While nesting sites located closer to the high tide line, may be vulnerable to coastal erosion, increased surface temperatures, sea level rise, wave runup or clutch inundation and subsequent mortality. There are several factors that may be influencing nest site selection by Green and Olive Ridley sea turtles. Heredero Saura et al. [44] explains that Green turtle nesting site selection may be a result of inherently avoiding competition with Leatherback sea turtles (*Dermochelys coriacea*), which have historically frequented Costa Rican beaches in the Pacific—Piro and Pejeperro, among others. It may also be explained as an effort to avoid erosion and changing beach morphology as a result of heavy storms, or the positive effect provided by shade or vegetation on egg development [44].

Olive Ridley and Green sea turtles' clutches may be unevenly affected as a result of their zonal nesting preferences. This may be best explained through temperature-dependent sex determination (TSD), where incubation temperatures determine the sex of individuals. In research conducted by Standora and Spotila [45] in Tortuguero, Costa Rica, researchers saw Green turtles nesting in open zones produced mainly females, while those nesting under strictly vegetation produced 94% males. Thus, Green turtles may prefer nesting in both vegetation and border zones, maintaining sex ratios, or the delicate balance between males and females within the population. It has also been suggested that by 2070 sand temperatures will reach levels above the upper thermal threshold, significantly impacting hatching success, and subsequent sea turtle populations in the process [21,46]. This idea may be most impactful to Olive Ridley sea turtles which nest more often in open zones, receiving sun for more than 60% of the day. For example, incubation temperatures in Olive

Ridley nests greater than 35°C have been associated with death during the developmental stages and failure to produce hatchlings [47]. Further, hatchlings surviving incubation temperatures 32°C and higher were mainly female [47].

Although it has also been suggested that TSD provides an advantage under warming conditions [48], climate change may warrant a shift in conservation focus to clutches located in open zones most susceptible to increasing surface temperatures. In other words, nests exposed to direct sunlight for extended periods during the day may be more important for ex-situ conservation efforts, in an effort to give sea turtles the opportunity to adapt under future climate conditions. However, it has been suggested that sea turtles may experience range shifts to climatically suitable regions by 2050 [69,70]. Yet, areas with climatically suitable habitat might be impacted by sea level rise, limiting their ability to properly adapt [70]. Sea turtles that nest in open zones, characterized by low slopes further from the vegetation lines may be more vulnerable to increased sea level, and ultimately clutch inundation. A future adaptation strategy of Olive Ridley turtles may be nesting in upper beach zones characterized by lower surface temperatures and limited wave runup, but this will result in a higher nest density and consequently, lower hatching success due to an increase in nest destruction by other nesting turtles, and predation and infestation rates [49,50]. It may also be important to mention nest-site repeatability, known to be extremely common in Green sea turtles [44]. High levels of nesting repeatability may only favor sea turtles that originally select suitable conditions for egg development and could be incredibly impactful to those that did not, especially for those exhibiting narrow nest-site selection during the nesting season [44]. Pfaller et al. [51] suggested that in some populations, more experienced females have higher nesting success than less experienced females due to an inherent ability to select more suitable nesting locations over time. Yet, populations that exhibit weak nesting site repeatability [52] and apply mixed strategies by distributing their nests over large distances may be less susceptible to beaches with varying environmental conditions, allowing some individuals to survive [44]. In some cases, they may also shift nesting to newly formed beaches [70]. These adaptation strategies may begin to reduce the threats of future climatic shifts, changing beach morphology and decreased hatching success.

Results of the nesting analyses observed in this study (*Appendix B*) mirror that of previous research exhibiting peak nesting for Olive Ridley during the months of August, September, and October (height of the rainy season), and December, January, and February for Green turtles (height of the dry season) [34,63]. This observation is also similar to beaches located north of the Osa Peninsula [53]. With that said, it may be important to consider shifting nesting seasonality under the pressure of changing climatic conditions, most notably, the impact of increasing beach surface temperatures [54] and SLR on nesting preference and suitability by Green and Olive Ridley turtles. With increased coastal erosion due to SLR, beach morphology will change, creating impassable berms similar to what has already been experienced on other nesting beaches [72], subsequently decreasing suitable nesting habitat and hatching success. Dune scarps have already been observed along many sectors on Piro and Pejeperro beaches, limiting Green turtles from accessing vegetation zones. On the Caribbean coast of Costa Rica, 18-24% of the sea turtles were unable to crawl in 20% of the beach length due to large dune scarps [12]. Beach change may be 'seasonal', or 'cyclic', but in both cases, beach morphological change is primarily due to the variability in the incident wave energy level or wave height [55]. Changes in beach morphology may

also increase beach slope making it incredibly difficult for sea turtles to enter the supratidal zone in which they prefer to nest. Natih et al. [30] states “the steeper the beach, the greater the energy needed to get to the supratidal to lay eggs, and the more difficult it is for the turtle to see objects in front of them because the turtle's eyes are only able to see well with an angle below 150°”. Piro and Pejeperro have very similar beach profiles depending on the sector. Yet, overall, Pejeperro tends to be steeper and shorter than that of Piro beach. This likely begins to explain the shorter distance to the high tide line of sea turtle clutches on Pejeperro compared to Piro beach.

In addition, turtles that nest in areas where slope is considered too low (below 3%), can cause sea air infiltration affecting the air content in the nest [30]. As a result, it may affect the humidity and temperature of the sea turtle nest, suggesting that nests located at a slope of less than 3% may experience seawater intrusion [30]. Slope is said to have a high influence on nest site selection, perhaps because it is associated with nest elevation [71]. In one study, researchers suggested that crawl distance was negatively correlated with beach slope, and sea turtles adjusted their crawl distance to find suitable nesting elevation with reduced risk of inundation [73]. Increases or decreases in beach slope or changes in beach morphology on Piro and Pejeperro beach may therefore deter or reduce nesting success in the region. Ultimately, complex coastal dynamics are expected to change beach morphology [5], presenting an area for further research on Piro and Pejeperro beaches. It is difficult to know exactly how SLR will impact beach morphology in the future, yet Doran et al. [56] states that “seasonal and storm-induced changes in beach slope can lead to differences on the order of 1m in wave-induced water level elevation”. In Florida, Hurricane Andrew affected 90 miles of nesting beaches, where hatching success was reduced to 0% in 69% of the nests through flooding, and sea water inundation [57].

The SLR mapping methodologies outlined in this study differ from previous analyses, most commonly related to the source of the Digital Elevation (DEM) or Digital Terrain Models (DTM) used in analysis; the general ideology remained the same. For example, [14], used a custom-made quadcopter drone to take aerial photos of their nesting beaches in northern Cyprus in order to produce a georeferenced orthophoto and DTM. These layers were then imported into the ArcGIS software where elevation was extracted from each nesting site using the 3D Analyst tool. Similar to Varela et al. [14], Patrício et al. [13], created a DEM of a nesting beach in Poilão Island, Guinea-Bissau, West Africa, in Agisoft Photoscan Professional v1.3.1 (Agisoft), using aerial photos taken from a drone. This DEM was then imported into ArcGIS, where 3D Analyst Tools were used to draw out elevation from each nesting site and map sea level rise. Rivas et al. [12] states that “recent methods of satellite telemetry using high-accuracy Coastal DEMs, and Airborne-Lidar generated DEMs, drones, photogrammetry and novel GPS have been adopted to assess impacts of SLR on sea turtle populations. However, these highly accurate methodologies entail high costs (e.g. 1,500-15,000\euro per satellite image) and are time consuming”. This study was centered around the accessibility to free DEM (CoastalDEM), and DTMs (Esri's *ArcGIS Living Atlas of the World*), presenting some uncertainty in SLR analyses. Although costly when compared to the methodologies used in this research, personalized DEMs derived from aerial drones, recently applied to monitor sea turtle nesting at Osa Conservation [68], may be relevant in providing clearer, higher-resolution SLR analyses.

Thus, one limitation, briefly discussed above, is centered on the accessibility to free high-accuracy Digital Elevation Models (DEM). More specifically, access to free DEM's with

spatial resolutions of 5-10m, representing 5x5 or 10x10 meter areas of physical land. With this in mind, the higher the spatial resolution, the more accurate analyses are likely to be. Most free DEM's hold spatial resolutions at 90m (e.g., HydroSHEDS, CoastalDEM, and USGS Earth Explorer), subsequently providing weaker analyses than layers with higher resolutions. Research has suggested that the linear relationship between slope and elevation values obtained from the DEM source, HydroSHEDS (90m, 3s) provided the most accurate predictions for Costa Rica [12]. In this case, CoastalDEM and USGS EarthExplorer (<https://earthexplorer.usgs.gov/>) were proven ineffective for coastal slope analyses in this study, as the end result was too coarse. With that said, access to free DEMs would surely aid conservation organizations focused on coastal habitats and assessing their beaches under future climatic conditions, most notably, sea level rise.

Another limitation identified in this study was the accuracy provided by the GPS, *My GPS Coordinates*, the application used to record geolocations of sea turtle nests. Typically, the accuracy of a WGS84 coordinate system is 3-5m, but on cloudy or rainy days, devices took longer to reach these desirable minimums. In this case, investing in higher-quality GPS devices may eliminate geolocation errors during data collection. High-tech GPS devices may dramatically improve the number of samples viable for analysis and limit the number of samples dismayed due to inaccurate geolocations. However, this may be a substantial investment for many conservation organizations. In addition, beach monitoring programs rely heavily on students, interns, and citizen scientists with limited experience in the field, making achieving monitoring objectives difficult at times [58]. In this case, well-rounded, detailed training can aid in compliant data collection by students, interns, and citizen scientists, allowing researchers to form accurate conclusions based on the data collected.

Sea turtle hatcheries are considered as an important ex-situ conservation strategy to increase the hatching success of threatened nests laid on beaches affected by coastal erosion and SLR, among other threats. However, many studies argue that hatcheries should be the last resort, and only nests under significantly high risk warrant ex-situ conservation [59,60,61,62]. In this case, it is important to consider which sectors of the beach are most frequented for nesting and which are most susceptible to sea inundation in order to prioritize conservation efforts in these zones. This highlights the importance in pairing a hotspot analysis (*Figure 4*) that identifies statistically significant clusters of sea turtle nests, with SLR analyses. Results of this study identified hotspots located on Piro beach between sectors 10-15 respectively, just east of the Piro river mouth. Piro river morphology changes along sectors 1-9 during the rainy season, eroding the beach as it continues to exit into the sea. In these sectors, grain size is larger, which according to many studies, affects nesting success and influences sea turtle site selection [28,29,30]. More specifically, sectors 3-7 were identified as significant cold spots, indicating that sea turtles avoid nesting here. Among these sectors, beach slope is very low, and tracks are commonly washed over before they can be recorded. With that said, this study suggests that sectors most impacted on Piro beach by 0.25m SLR in the next 25 years will be sectors 3-10, in areas continuously flooded by the river mouth during heavy storms, and increased wave runup on the cusp of a large area identified as a significant hotspot for sea turtle nesting, sectors 10-15. On Pejeperro beach, under the 0.25m SLR scenarios, nests located in sectors 1-7 are most likely to suffer from sea inundation. These sectors are located near the lagoon which encompass sectors 1-11, which are most frequented by Olive Ridley turtles (*Appendix F*). In this area the vegetation is very low, mainly dominated by Dune grass (*Uniola pittieri*) and a

limited number of palm trees (*Arecaceae* sp.) dispersed throughout. The lack of shade in these sectors may not suit Green turtle nesting, which prefer nesting in vegetation zones, exposed to sunlight for less than 60% of the day. This may justify why more Green turtle nests are located in the latter sectors of Pejeperro beach, in areas less susceptible to sea level rise where the vegetation is higher and more dense. However, once again, dune scarps from changing beach morphology may limit their nesting success in these zones.

In conclusion, the results of this study suggested that Olive Ridley turtles may be more susceptible to SLR and increased surface temperatures, based on their preferred nesting zones and habits in nesting closer to the tide line, as opposed to Green turtles that prefer to nest further from the high tide line in vegetation zones where SLR and increased wave runup is likely to have less impact over time. Based on this analysis on Piro and Pejeperro beaches, ex-situ conservation efforts on Olive Ridley clutches should focus on areas more susceptible to SLR and clutch inundation, with zones characterized by minimal slope, and elevations less than 0.25m. The cost-effective methodologies used in this study can support other sea turtle conservation programs in assessing the effects of SLR and understanding nesting distributions on their nesting beaches, while also providing important insight in forecasting nest management and implementing monitoring techniques that may reduce the negative impacts associated with climate change and subsequent SLR. Future studies may include analyzing wave runup during storms, tracking increases in storm frequency, conducting a detailed slope analysis, and using aerial drone photos to study seasonal or cyclic changes in beach morphology over time (seasonally, or yearly). When paired with this study, this may give researchers and conservationists a clearer, more informed understanding as to exactly how sea turtle nesting habitat will be impacted by SLR in the coming years.

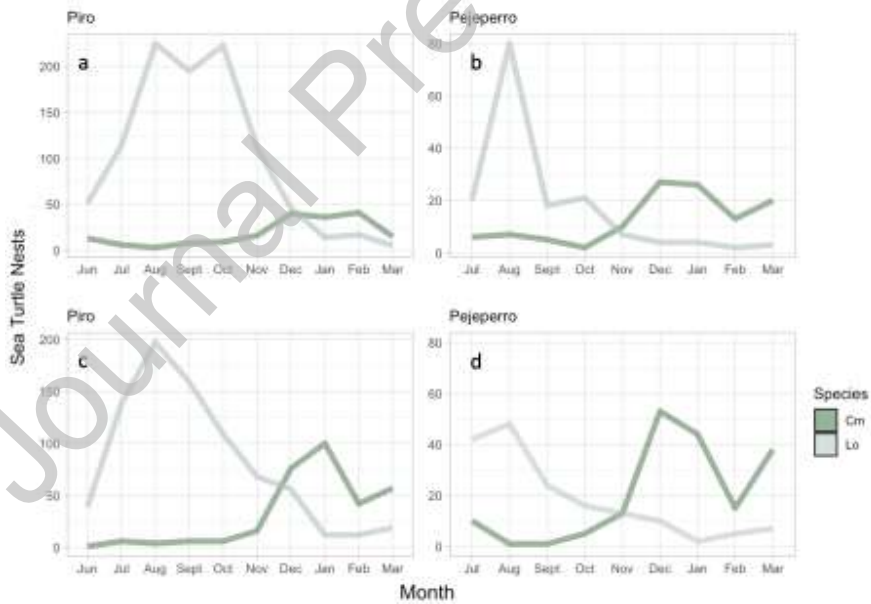
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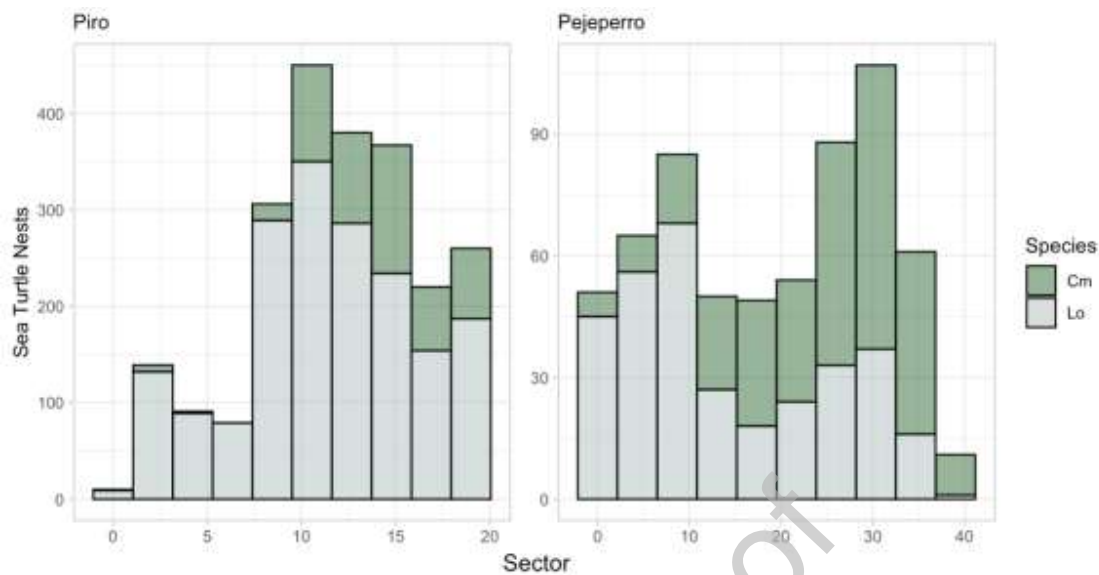
Appendices



Appendix A: Green beach crawl (a), Olive Ridley beach crawl (b)



Appendix B: Sea turtle nesting seasonality on: (a) Piro beach during the 2021-2022 season, (b) Pejeperro beach during the 2021-2022 season, (c) Piro beach during the 2022-2023 season, (d) Pejeperro beach during the 2022-2023 season. Green turtles ("Cm", green), Olive Ridley turtles ("Lo", gray).



Appendix C: Sea turtle nests located by sector on Piro (left) and Pejeperro (right) beach during the 2021-2022 and 2022-2023 nesting seasons. Green turtles (“Cm”, green), Olive Ridley turtles (“Lo”, gray).

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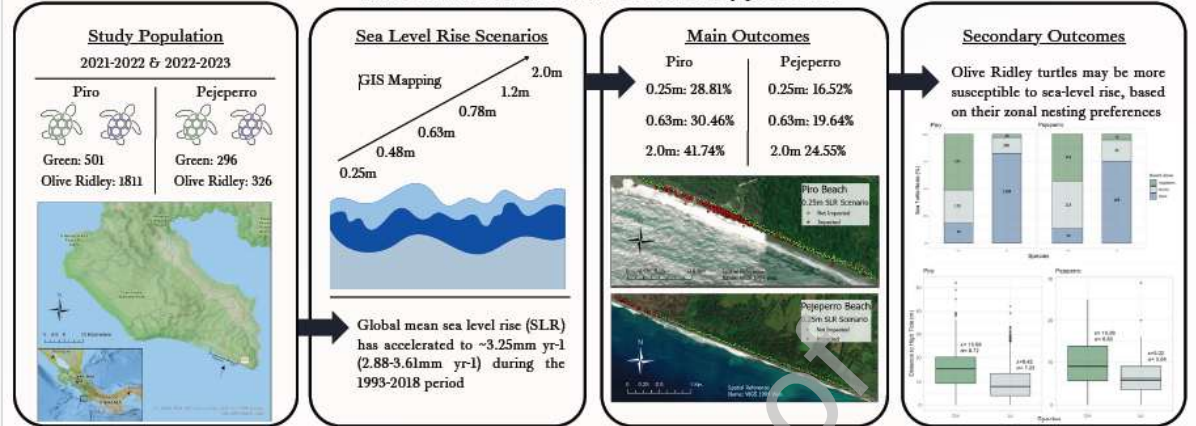
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Graphical abstract

Future Sea Level Rise Impacts to Olive Ridley (*Lepidochelys olivacea*) and Green Sea Turtle (*Chelonia mydas*) nesting habitat on the Osa Peninsula, Costa Rica

Sea turtle nesting habitat will likely suffer from sea water intrusion by 2050; 28.81% of the entire sample may be inundated under a 0.25m scenario on Piro Beach, and 16.52% on Pejeperro Beach



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Declaration of interests

- ☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- ☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: