Sea level rise under climate change

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Sea Level Rise under Climate Change: Implications for Beach Tourism in the Caribbean

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Abstract

Sandy beaches play a significant role in the Caribbean tourism industry, which markets an attractive sea-sand-sun product, but are potentially threatened by climate change induced sea level rise. In this study we quantify the impact of climate change on sandy beaches and beach tourism losses in the region. To this end we assemble exhaustive data on sandy shorelines, beach erosion and hotel rooms for 30 Caribbean islands. Under a low CO_2 emissions pathway (RCP4.5), we predict an average 53% loss in sandy beaches, resulting in a 30% hotel room loss and thus a 38% revenue decrease by 2100. In contrast, under a higher emissions path (RCP8.5), sea level rise will cause 59, 39, and 47% reductions in beach, room, and revenue, respectively. Notably, however, there is considerable impact heterogeneity across islands. We also estimate that beach nourishment may be an affordable mitigation strategy, constituting 0.87% and 1.1% of annual tourism revenue. Our results underscore the need for the development of adaptation policies that are based on quantifying risks and losses to protect the future of Caribbean economies and their tourism sectors.

1 Introduction

Sandy beaches are an important feature of the Caribbean, capturing 6,256 km, i.e., roughly a third, of its total shoreline. These beaches are highly valued since they provide recreational opportunities, protect coastal investments from storm waves, and serve as habitat for a variety of plant and animal species (Jones, Gladstone, & Hacking, 2007). Moreover, they have played a significant role in the region's tourism industry, which markets an attractive sea-sand-sun product (Zappino, 2005; Lithgow, Martínez, Gallego-Fernández, Silva, & Ramírez-Vargas, 2019) with hotel accommodation and social activities in close proximity to sandy beaches (Castaño-Isaza, Newball, Roach, & Lau, 2015). The importance of sandy beaches to the tourism sector in the Caribbean has already been highlighted by Schuhmann et al. (2019) in that the absence of sandy beaches or even a reduction in beach width are factors that could discourage tourists from returning for vacation (Uyarra et al., 2005). Unfortunately, the value that sandy beaches bring to Caribbean economies through tourism is threatened by the impact of anthropogenic activities and climate change (Defeo et al., 2009).

While anthropogenic activities, such as coastal development and sand mining, have long been known to play a negative role (Nordstrom, 2004), the climate change impacts on shorelines have dominated the literature (Berg, 2009; Luijendijk et al., 2018; Youn & Park, 2018). This may not be surprising given the potentially substantial impacts of climate-change-induced sea level rise on beaches. As a matter of fact, some predictions indicate that a mere 30cm increase in the sea level would erode a large number of sandy beaches across the world (Schwartz, 2005), and could induce the disappearance of almost half of these globally by the end of the year 2100 (Vousdoukas et al., 2020). In the Caribbean, alarmingly, sea level rise associated with climate change is predicted to increase by up to 50cm by 2025 and 65cm by 2100 (Maul, 1993; Griggs & Noguer, 2002; Castaño-Isaza et al., 2015), where its rate of rise is expected to surpass the world's average by a factor of up to 1.4 (Tamisiea & Mitrovica, 2011). However, the loss of beaches is unlikely to be evenly distributed across the region (Schwartz, 2005). For example, research indicates that nearly 100% of beach loss is expected in Martinique if sea level continues to trend upwards (Schleupner, 2005), while for Cuba it has been estimated that 14% of the tourist destination beaches will be lost by the end of 2100 (Paneque & Finkl, 2020).

In terms of how beach loss due to sea level rise might affect the tourism industry, there are a number of studies highlighting its likely impact. In terms of supply of near beach accommodation, in the United States, a study of Florida found that over 1,300 accommodation facilities would be impacted by a 0.68m sea level rise, resulting in billions of dollars in losses by the year 2050 (Stanton, Ackerman, et al., 2007), while King, McGregor, and Whittet (2011) estimated over US$2 billion in damages by 2100 for California's beach coastal properties resulting from a sea level rise of 1.4m. In the Caribbean, Scott, Simpson, and Sim (2012) examined coastal resort properties and beach erosion for the case of a hypothetical one metre sea level rise for 19 Caribbean islands and found that 29% of resort properties could be partially or completely lost. In terms of the demand for beach tourism, a psychological study indicated significantly lower visitations to the beaches of Germany as a consequence of erosion (Braun et al., 1999), while a less than 1% decline in visits was noted for the United Kingdom coast (Coombes & Jones, 2010). The potential for lower demand by tourists was also shown for the Caribbean by Uyarra et al. (2005)'s study in that 77% of tourists in Barbados stated that they were unlikely to visit if there were severe beach erosion.

While the aforementioned literature has taken an important first step in highlighting the potential losses in beaches in the Caribbean due to sea level rise, arguably current findings are not sufficient enough to provide policy makers with enough information to consider possible mitigation strategies. More precisely, the current literature suffers from a number of weaknesses. Firstly, the sea level rise predictions, and consequent calculation of beach losses, for the region used in existing studies are generally not explicitly linked to modeling beach losses under different climate change scenarios that allow for local heterogeneity in sea level rise. For instance, Paneque and Finkl (2020) employ a rate of sea level rise that is determined directly from worldwide tide gauges and satellite altimeters data to predict future trends. Schleupner (2005) and Scott et al. (2012) both use a global level average of sea level rise to conduct their calculations, where for the latter study this is derived from the mean across several models. Secondly, the current studies on the region do not explicitly translate beach losses into usable quantitative measures that could be compared to costs involved with mitigation strategies. For example, while Scott et al. (2012) in their innovative study calculate the number of resorts within 100m of the beach that would disappear, they do not translate theses into monetary terms.

In this study we set out to address the just highlighted shortcomings of the current literature. To this end we construct an exhaustive database of sandy beaches and geo-localised tourist accommodation for all Caribbean islands. We combine these data with localised sandy beach shoreline changes generated from a global coastal erosion model under two climate change scenarios (RCP 4.5 and RCP 8.5). This data allows us to then make predictions not only with regard to sandy beach losses under climate change, but also calculate to what extent tourist accommodation near sandy beaches will be threatened, taking spatial heteregeneites in both aspects into account. We then translate the likely losses into monetary values by using available information on tourism receipts and the number of rooms of each accommodation.

A possible mitigation strategy for sandy beach losses is beach nourishment, which essentially involves adding sand to beaches reverse their erosion (National Environment and Planning Agency, 2017). This strategy has the attraction of being relatively low cost in terms of construction and maintenance, reducing storm surge damages, restoring habitats for beach organisms, and in general reducing potential revenue and job losses for the tourism industry (Leatherman, 1989; Rogers Jr et al., 2004; Houston, 2013; Vanden Eede, 2013; Alexandrakis, Manasakis, & Kampanis, 2015). Moreover, although there are other erosion mitigation strategies including hard protection measures such as groynes and breakwaters, they seem to be less preferred due to them having more of a negative impact on the beach environment

(Stronge, 2005; Neufville, 2020). Unsurprisingly then, beach nourishment is currently being employed in many regions across the globe, including Australia, China, the United States and the Middle East (Kuang et al., 2011; Cooke, Jones, Goodwin, & Bishop, 2012; Pendleton, Mohn, Vaughn, King, & Zoulas, 2012; Bitan & Zviely, 2020). However, beach nourishment is only sparingly used to combat beach erosion in the Caribbean, perhaps because government involvement is limited (Neufville, 2020). We thus also use our estimates on sandy beach losses to calculate out potential beach nourishment costs to combat the prediction erosion in the Caribbean and compare these to our implied erosion induced revenue losses. This allows us to consider beach nourishment as a possible mitigation policy for the Caribbean.

Our analysis produces a number of important findings. Under a low emissions pathway (RCP4.5) Caribbean islands are predicted to lose an average of 91 metres of beach shoreline retreat by 2050, experience a 53% loss of sandy beaches and a 30% loss of hotel rooms by 2100, although there is considerable heterogeneity across islands. If, however, a higher emissions pathway (RCP4.5) is achieved, by 2100 these losses in sandy beaches and hotel rooms are predicted to be higher by 6 and 9 percentage points, respectively, again with large differences across locations. In monetary terms the predictions under RCP8.5 translate into annual beach tourism revenue losses of 47% by 2100, whereas the corresponding estimate for the RCP4.5 scenario is 38%. In considering beach nourishment as a mitigation strategy, we find that Caribbean governments will likely have to spend only 1.09% of tourism revenues under RCP8.5 to counteract the 47% loss, whereas the corresponding figure for the 38% revenue loss will require spending of 0.87% of accommodation derived income. These findings arguably have important implications for adaptation policies across the Caribbean as islands seek to reduce the vulnerability of their tourism sectors and build climate-resilient economies.

The rest of this paper is organized as follows. Section 2 describes the data and Section 3 features the methods. The results and their discussion are provided in Section 4 and Section 5, respectively. Section 6 concludes.

2 Data

2.1 Study Region

Our study region consists of islands within the Caribbean Sea, which itself is located within the North Atlantic Ocean Basin. The total number of islands in this region is 30, of which 13 are sovereign states and the others dependent territories: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Bonaire, Saint Eustatius and Saba, British Virgin Islands, Cayman Islands, Cuba, Curacao, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Saint Barthelemy, Saint-Martin, Sint Maarten, Trinidad and Tobago, Turks and Caicos Islands, and U.S. Virgin Islands.

2.2 Sandy Shoreline

In order to identify the sandy shoreline for the Caribbean islands, we rely on the data created by Luijendijk et al. (2018). More specifically, Luijendijk et al. (2018) train a pixel-based supervised classification method on global Top of Atmosphere reflectance percentile composites based on 2016 Sentinel-2 satellite images to detect sandy beaches using the sparse beach data available from OpenStreetMap (OSM). Dividing the OSM global shoreline into 500m transects, this pixel based trained classification method is then used to identify sandy beaches across the entire shoreline for each transect. Validation through visual inspection showed a 96% detection accuracy. One should note that this method identifies as sandy beaches those with quartz and carbonate sands, as well as gravel, but does not allow one to distinguish between these types.

2.3 Beach Erosion

We use estimated local beach erosion rates from Vousdoukas et al. (2020). More specifically, Vousdoukas et al. (2020) generate probability distributions of beach erosion rates under two climate change scenarios (RCP 4.5 and RCP 8.5) and for two time periods (2050 and 2100). To this end, they model coastal erosion from two underlying components. Firstly, they determine the ambient shoreline dynamics (AC) driven by long-term hydrodynamic, geological and anthropic factors by updating the local shoreline dynamics from Luijendijk et al. (2018) and Mentaschi, Vousdoukas, Pekel, Voukouvalas, and Feyen (2018) and extending the trends into the future to estimate future shoreline dynamics. Probability density functions of these are created via Monte Carlo sampling. Secondly, they also construct future equilibrium shoreline retreat of sandy coasts due to coastal morphological adjustments to sea level rise based on Bruun's rule (Bruun, 1988), where wave dynamics are simulated using atmospheric conditions from six Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Models (GCMs). As with the AC, probability density functions of these are generated via Monte Carlo simulations. Finally, probability density functions of the two components are combined by assuming that their distributions are independent, randomly drawing from their individual distributions, and then adding these.

2.4 Hotels

Our source for tourist accommodation in the Caribbean is Delta Check's Global Accommodation Reference Database (GARD). This is believed to be a near exhaustive database of all currently known hotels, resorts, guesthouses, inns, apartments, B&B's and pensions.[1] More specifically, Delta Check takes as a starting point the accommodation register of each country's national tourism authority. These data are then further completed with information from all the 17 largest online travel agencies (ex: booking.com, hotels.com, HRS, AirBnB, etc.), as well as, where available, information from local regional authorities. For our purposes the final database provides information on the exact location (latitude and longitude) of the accommodation, as well as the number of rooms of each property.

[1] Delta Check ensure that coverage within a country is at least 95%.

2.5 Tourism Revenue

To proxy tourism revenue, we use 2019 data on tourist spending for each island taken from World Travel & Tourism Council (2019) and World Tourism Organization (2019). Tourist spending includes only travel and passenger transport. All monetary variables are denominated in US dollars and based on 2019 real prices and exchange rates.

2.6 Beach Nourishment

To determine beach nourishment costs in the Caribbean region, we resort to data retrieved from Program for the Study of Developed Shorelines (2020) for Florida, consisting of the history of the 495 beach nourishment projects taken in the state since 1944, which then allows us to calculate the volume of sand needed and beach nourishment cost per metre (converted to 2019 real USD). Apart from the paucity of beach nourishment data for Caribbean islands, we use the state of Florida figures for two main reasons. First, islands in the Caribbean are in close proximity to Florida and thus are more likely to be similar in geographic characteristics compared to other parts of the US and the world. Second, since large waves and surges produced by storms and hurricanes are responsible for beach erosion and long-term changes in beach morphology (Birchler, Stockdon, Doran, & Thompson, 2014; Morton & Sallenger Jr, 2003), Florida, as the most hurricane-prone state in the US, also likely to relatively similar in terms of the role of this climatic factor on beach profiles.

3 Methods

3.1 Identification of Sandy Beach Hotels (Rooms)

In order to identify hotels, and thus rooms, that directly benefit from being near a sandy beach, we set the distance threshold to the nearest sandy beach to be up to 1km, and consider all hotels that are within this distance as sandy beach hotels. To calculate the distance for each hotel we simply take the Euclidean distance between the latitude and longitude of the location of the hotel and the latitude and longitude of the point in which the nearest sandy beach transect intersects the shoreline.

3.2 Sandy Beach Erosion

In order to link sandy beaches to their erosion rates across scenarios and time periods, we simply identify the nearest transect intersection point of the erosion data from Vousdoukas et al. (2020) to each transect from the sandy beach shoreline of the Luijendijk et al. (2018) data, as determined by their Eucledian distance. This provides us for each sandy beach transect erosion rates for the two climate change scenarios (RCP4.5 and RCP8.5) and two future time periods (2050 and 2100).

3.3 Sandy Beach Loss

The Luijendijk et al. (2018) data set only identifies the segments of sandy beaches along the shoreline, and does not provide a measure of beach width. As a matter of fact, currently there is no global data set on beach width. In order to identify beach loss under climate change, Vousdoukas et al. (2020) assume that beaches experiencing a shoreline retreat greater than 100m are critically eroded. However, they note that this is a rather conservative threshold and that in small islands, like the Caribbean, sandy beaches are likely to have widths below 50m. We thus assume here that a beach is 'lost', i.e., critically eroded, if it experiences retreat of at least 50m.

3.4 Revenue Losses

In determining revenue losses associated with beach erosion, we use data on international tourist expenditure and the number of hotel rooms in each country to calculate the average revenue generated by each hotel room per year. The mean value is then used to multiply the number of hotel rooms lost to beach erosion each year assuming that the number of rooms lost in 2050 and 2100 occurs on a linear scale. An important caveat is that total spending by tourists is likely underestimated since it excludes spending on other tourism-connected and non-specific tourism products, such as retail shopping goods. Another key assumption underlying our calculation of future revenue losses is that earnings per hotel room will remain stable in the future. This inherently ignores changes (possibly due in part to beach erosion) in global demand for sandy beaches as a tourism product.

3.5 Beach Nourishment Cost

We calculate beach nourishment cost in each island by multiplying the beach nourishment cost per metre by the length of eroded beaches within 1km of a hotel. Based on the data obtained from Program for the Study of Developed Shorelines (2020), we calculate the average nourishment cost per metre by dividing the 2019 real cost of nourishment by the length of nourished beaches. We determine this average cost to be US$2083.11 per metre. The volume of sand needed to nourish each metre of eroded shoreline is determined by dividing the volume of sand used by the length of shoreline nourished. Accordingly, approximately 222 cubic yards of sand are needed to nourish each metre of eroded beach. In our final calculation, we also account for the welfare distortions associated with raising funds to finance public projects via taxation by multiplying the total beach nourishment cost in each island by the marginal cost of public funds (MCF). Ballard, Shoven, and Whalley (1985) estimate that the MCF for all taxes in the US is in the range of 1.17 and 1.56. We take a more conservative approach and assume that the MCF is closer to the median, i.e., 1.3, for the Caribbean region.

4 Results

4.1 Summary Statistics

Information on the length of sandy beaches across the Caribbean are shown in the first column of Table 1. Accordingly, there are currently 6256 km of sandy beaches, which constitute around a third of the total shoreline in the region. The distribution of the sandy shoreline is, however, unevenly distributed, as depicted graphically in Figure 1. In this regard, the highest proportion is located in the Bahamas, with over 46% of the region's sandy resources, followed by Cuba (20.7%), Haiti (5.9%), Dominican Republic (5.6%), and Turks and Caicos Islands (5.0%). Thus, these five islands contain over 83% of the total region's resources in sandy beaches. One may want to note that the least endowed island in this regard is Dominica, which is home to only 2km of sandy shoreline.

The values just noted are a result of two features: namely the length of the shoreline in general, where this will depend on island size, and the composition of shorelines into their sandy and non-sandy counterparts. To explore the latter further we show the percentage of sandy shoreline in islands in the second column of Table 1. Again, the relative distribution of sandy shorelines is extremely fat tailed. More specifically, islands like Aruba and Bonaire have mostly sandy beaches (98 and 86%, respectively), while others like Grenada and Dominica (8 and 1%, respectively) are much less fortunate in terms of sandy beach resources along their coast.

The third column of Table 1 demonstrates that over 122,000 rooms in the Caribbean are located near, i.e., 1km, a sandy beach. This constitutes about 75% of all available rooms. Given that about 50% of hotels are located near the beach, this implies that these tend to be larger than those not directly benefiting from sandy beaches. In terms of the individual islands, one may want to note that while still fairly unequal, the distribution of rooms across islands is much less skewed than the distribution of sandy beach length itself. The largest share of accommodations is located in Cuba, with just over 20,000 rooms, i.e., over 16% of the region's total. Examining the share of rooms in hotels near sandy beaches compared to those further away, shows that most of the rooms (75%) are part of the latter. For some islands, this is as high as 99% (Cayman Islands), while for others this is as low as 13% (Dominica). Regardless, for all islands except Anguilla and Montserrat the share of rooms near sandy shorelines is always greater than the share of sandy beaches of the total shoreline.

We calculated the meters of sandy beach per room in the second to last column of Table 1 and show this in Figure 2. Accordingly, on average for each room there are about 3m of sandy beach located near it. This again differs across islands where the highest value is for Montserrat (167m) and Guadeloupe (20m), and the lowest for Cuba (1m) and Saint Lucia (1m). One can also calculate the per room length of sandy beach relative to the total amount of sandy shoreline available, as we do in the last column, and show in Figure 3. In this regard, the total amount of per room sandy beach length for the region increases to 51m. The highest per room ratio still is in Montserrat (5667m), followed by Haiti (523m), and the Bahamas (205m), whereas the lowest are in Saint Lucia (3m) and Saint Kitts and Nevis (7m).

4.2 Future Shoreline Retreat, Beach Loss and Room Loss Predictions

The future mean shoreline changes of sandy beaches for the Caribbean and individual islands for the two climate change scenarios and two time periods are given in Table 2 and graphically depicted in Figure 4. Accordingly, the predicted shoreline retreat in 2050 stands at an average loss of 84m for RCP4.5, with a sightly higher figure (91m) under the RCP8.5 scenario. One may want to note, however, that there is considerable uncertainty for these. For instance, the 95% confidence interval for RCP4.5 lies between a retreat of 6 and 168 meters. By 2100 the retreat increases to 91 and 223 meters under RCP4.5 and RCP8.5, respectively, but again with considerable uncertainty.

Examining the individual sandy shoreline retreats for each island, one can see there is considerable heterogeneity across islands. For instance, the estimated figures suggest that under RCP4.5, Anguilla, Aruba, Curacao, Dominica, Grenada, Guadeloupe, Martinique, Montserrat, Sint Maartin/Saint Martin, Turks and Caicos Islands all experience sandy shoreline advances. This is largest for Dominica standing at 239m in 2050 and rising to 537m in 2100 under RCP4.5, with corresponding figures of 238m and 536m, respectively, for RCP8.5. In contrast, sandy beaches in the Bahamas are predicted to retreat by 152(160)m in 2050 and 340(382)m 50 years later under RCP4.5(8.5). Other notable large sandy beach retreats are predicted to take place in Bonaire, the British Virgin Islands, Cuba, and the US Virgin Islands. More generally, one may want to note that the differences between the two scenarios are on average not very large, i.e., on average sandy shoreline is about 35m larger under the higher emission RCP8.5 scenario. However, this masks differences across islands between the predictions under the two pathways. For instance, the average shoreline retreat for Trinidad and Tobago and the Bahamas are 55m and 42m higher, respectively, under RCP8.5.

Using the threshold of shoreline retreat of 50m, we provide calculations of the % sandy beach losses in Table 3 and Figure 5. Under the RCP4.5 scenario by 2050 the Caribbean will have experienced a 39% loss in sandy beaches, with a 95% confidence that this loss will lie between 25% and 58%. By 2100 this will rise to 53%, with a 95% confidence interval of 36 and 67%. For the RCP8.5 pathway, the corresponding mean percentage losses for these two future time points will be 43 and 59%.

In terms of the individual islands, the largest loss will by 2050 be experienced by the Bahamas, where expected sandy beach loss will be 55(59)% for the RCP4.5(RCP8.5) scenario. By 2100, however, the Bahamas will be surpassed by Saint Barthelemy, where for the latter losses will rise up to 84% under both climate change scenarios. Other islands that are expected to lose substantial portions of their beaches by the end of the century are the British Virgin Islands, Cuba, Saint Lucia, and the US Virgin Islands. One may also want to note that for some islands there are large differences across the two climate change scenarios. For instance, for Sint Maarten/Saint Martin and Anguila under the higher emission path sandy beach losses will be 20 percentage points larger, followed by Puerto Rico and Trinidad and Tobago with differences of 15 and 12 percentage points, respectively. In contrast, for 14 of the islands the difference will be 5 percentage points or less.

Losses for the sub-sample of sandy beaches that are within the (1km) proximity of accommodations are depicted in Table 4 and Figure 6. Accordingly, the total sandy beach loss near accommodation is 15% in 2050 and rises to 33% by 2100 under the RCP4.5 scenario. Corresponding figures for the higher emissions RCP8.5 scenario are 19% and 41%. The uncertainty is nevertheless considerably large, as evidenced by the wide 95% confidence interval around these average figures. Additionally, these aggregate numbers mask considerable differences across islands. More specifically, under RCP4.5 the largest losses are predicted to be experienced by 2050 in Antigua and Barbuda (61%), whereas there are no losses in Anguilla, Dominica, Grenada, Haiti, and Montserrat. Under RCP8.5 in 2050 Antigua and Barbuda is still the island with the largest large ratio, and this is 11 percentage points higher than a lower emissions context. There are also only four islands (Anguilla, Dominica, Grenada, and Montserrat) that will not experience any (complete) sandy beach loss. By 2100, while losses in Anguilla and Barbuda are in relative terms still among the highest, it is Montserrat that under either pathway is the biggest loser, with expected losses of 100%, regardless of the scenario. Other islands that will be relatively significantly affected by critical beach erosion near present accommodations are Antigua and Barbuda, US Virgin Islands, Saint Barthelemy, Jamaica, Bonair, Saint Lucia, and Trinidad and Tobago.

The percentage of sandy beach losses measured in units of nearby rooms are given in Table 5 and Figure 7. For the entire region, under RCP4.5 there will be a loss of 13% in 2050 and this will rise to 30% by 2100. The level of uncertainty is relatively large, where, for example, in 2100 the estimates lie within 2% and 35% with 95% confidence. For the higher emissions scenario, the sandy beach loss is predicted to translate into the equivalent of a 15% room loss in 2050 and 39% in 2100, but again with relatively large uncertainty.

Exploring the room equivalent loss ratios across islands, first under the RCP4.5 pathway, one discovers that in 30 years the largest fraction of accommodation that can no longer avail of proximity to a sandy beach will be Trinidad and Tobago, with a loss of 66%. Other islands that are likely to be affected by critical sandy beach erosion are Antigua and Barbuda (55%), US Virgin Islands (43%), Bonair (41%), British Virgin Islands (38%), Cayman Islands (31%), and Saint Lucia (28%). In contrast, in twelve islands (Anguilla, Aruba, Barbados, Curacao, Dominica, Grenada, Guadeloupe, Haiti, Montserrat, and Saint Vincent and the Grenadines) current beach proximity hotels are not expected to be affected by sandy beach loss. By 2100 Antigua and Barbuda (79%) will be surpassed by Montserrat (100%) and US Virgin Islands (96%). Other severely affected islands are by 2100 the British Virgin Islands (72%) and Trinidad and Tobago (71%), and the Cayman Islands (46%). However, additionally, islands such Jamaica (71%) and Grenada (63%) also become relatively prominently affected.

Assuming instead a high emissions pathway (RCP8.5) implies many similar patterns, but also is characterized by some contrasting results. Overall, the total accommodation measured beach loss ratio is 2 percentage points higher than under RCP4.5 in 2050, and 9 percentage points higher in 2100. Uncertainty levels are of similar range as for the lower emission scenario. For the individual islands in 2050 front runners in terms of losses are, as under the RCP4.5 scenario, Antigua and Barbuda (63%), British Virgin Islands (72%), Saint Lucia (57%), Trinidad and Tobago (66%), and US Virgin Islands (46%), although the relative ranking of these changes. At the end of the century, in addition to Montserrat, under the RCP8.5 pathway, Antigua and Barbuda is also predicted to have all sandy beaches within in 1km hotel proximity to be critically eroded. This is nearly going to be the case for US Virgin Islands (96%), while for the British Virgin Islands only 11% of present accommodation will be within proximity of a sandy beach. Other islands with more than half of their present accommodation no longer being near a sandy beach include Jamaica (73%), Trinidad and Tobago (71%), Saint Barthelemy (54%), Dominican Republic (53%), and Saint Lucia (61%). In contrast, Aruba and Dominica are predicted to have no losses, while Guadeloupe and

Haiti will only suffer one per cent reductions.

4.3 Predicted Revenue Losses

We use the loss of nearby rooms due to beach erosion outlined in Table 6 to make predictions about future revenue losses in each country. Under the assumption of a low emissions pathway (RCP4.5), Table 6 reveals that by 2050 the decline in earnings from room losses due to beach erosion for Caribbean economies could be as much as 17% of tourism revenue per year and increase further to 38% by 2100. When we account for the uncertainty in these estimates, losses as a percentage of tourism revenue are in the range of 4% to 43% in 2050 and 22% to 54% in 2100. A closer look at individual islands shows the percentage revenue losses in 2050 being highest in countries like Trinidad and Tobago (66.8%), Antigua and Barbuda (55.1%), and the US Virgin Islands (43.6%). Anguilla, Dominica, Grenada, Haiti and Montserrat remain unaffected under this emissions pathway. For many islands, the situation looks drastically different in 2100. Montserrat, though having just a few hotels, sees its revenue stream being completely wiped out by beach erosion. This is followed by the US Virgin Islands which sees more than a two-fold increase relative to that of 2050 levels. Antigua and Barbuda (79.1%), British Virgin Islands (72.1%), and Jamaica (71.2%) complete the list of the top 5 countries with the highest projected percentage losses in revenue. Dominica is the only country that will not experience any climate-related deterioration in revenues in either period, while Aruba's revenue losses did not worsen in 2100 when compared to the 2050 period.

For the high emissions scenario (RCP8.5), Table 5 shows that the percentage of regional tourism revenue losses per year from beach erosion could increase from 19% in 2050 to 47% in 2100. Based on our confidence interval estimates, the proportion of revenue losses could increase from a minimum of 4% to a maximum of 53% in 2050. By 2100, the range of uncertainty in these revenue estimates is between 24% and 66%. Under this emissions pathway, all countries except Anguilla, Dominica, Grenada, and Montserrat remain unaffected by beach erosion until 2050. Unlike the outcome under the RCP4.5 emissions scenario, the British Virgin Islands take the lead with the proportion of revenue losses amounting to 72.1%, followed by Trinidad and Tobago (66.8%) and Antigua and Barbuda (63.7%). Similar to the results for RCP4.5, estimates of the potential revenue losses provided for 2100 under RCP8.5 shows that Montserrat is likely to be the most affected country with losses of 100%. Nonetheless, revenue losses grow the fastest for Barbados and Curacao between 2050 and 2100.

4.4 Beach Nourishment Cost Predictions

In Table 7, we present the cost of beach nourishment as a proportion of tourism revenue needed to mitigate beach losses due to beach erosion in each island. Under RCP4.5, failure to adopt early global emissions mitigation strategies could see nourishment costs as proportion of tourism revenue in the region rising from 0.4% in 2050 to about 0.9% in 2100. However, there is some considerable uncertainly associated with these estimates. For example, our 95% confidence interval estimates for the proportion of aggregate nourishment costs in 2100 lie in the range of 0.4% to 1.3%. In absolute values, nourishment costs are highest in countries like Antigua and Barbuda, Cayman Islands, and Trinidad and Tobago, as these countries experience the largest beach retreat. In general, we find the costs to be in the range of 0.14% and 13.5% for the set of islands. When we consider RCP8.5, the estimated amount that the entire Caribbean region is expected to spend to nourish its beaches will be over 0.5% of yearly tourism revenue in 2050 and approximately 1.1% in 2100. Similar to RCP4.5, Antigua and Barbuda is expected to spend the largest portion (1.6%) of its tourism revenue to nourish its beaches in 2050. By 2100 Antigua and Barbuda is expected to spend 2.2%, but it is also the case that nourishment costs now account for a larger chunk of revenues in countries like Montserrat (13.5%) and Anguilla (5%).

5 Discussion

Climate change is in its impacts indiscriminate about the valuable contribution of natural resources to economies across the world. Our analysis investigated the climate-change impact on a most treasured Caribbean asset, namely sandy beaches, which are of significant value to the tourism sector. More specifically, by 2100, we predict a sandy beach loss of 53% and 59% for lower emissions (RCP4.5) and higher emissions (RCP8.5) pathways, respectively, with corresponding proximity hotel room losses of 30% and 39%. These results suggests likely unfavourable implications for the region, including the risk of losing future tourism revenues, the need for generation of beach loss mitigation expenditures to protect earnings such as beach nourishment, finding land for hotel relocation, or possibly changing the focus of the tourism sector.

In terms of future revenue losses, under RCP4.5 beach erosion will cost Caribbean economies approximately 38% of tourism revenue by 2100. With greater increases in emissions of CO_2 (as in RCP8.5), this will increase to 47%. By 2100, under both RCP4.5 and RC8.5, the biggest revenue reductions will be felt by Montserrat (100%) and the United States Virgin Islands (97%), and for RCP8.5 Antigua and Barbuda (99.9%). However, the situation is also quite worrying for British Virgin Islands, Grenada, Jamaica and Trinidad and Tobago where losses will amount to over 70% of their revenues. On the other hand, those predicted to be least affected are Aruba (0.12%), Guadeloupe (1.1%) and Haiti (1.8%) under both RCP scenarios. In addition, Martinique, Saint Kitts and Nevis and Saint Vincent and the Grenadines also stand to lose less than 20%, which is significantly less than other countries. While there are no similar studies for the Caribbean region with which to do a direct comparison, other studies have found much larger beach erosion loss estimates than the absolute value of our estimates. For example, Alexandrakis et al. (2015) looked at the beach front of the municipality of Rethymnon in the largest of the Greek Islands, Crete, and found that expected revenue losses are likely to rise to €10.9 million in the next 20 years. In another study, Parsons and Powell (2001) showed that the cost of beach retreat in Delaware was approximately US$291 million over the next 50 years. These large differences in loss estimates when compared to our findings are largely due to the focus on land and capital losses while we only take into account losses from direct tourism spending.

Beach nourishment has become a common adaptation practice that involves adding beach material, such as sand, to re-create or recharge existing beaches in an attempt to reverse erosion (National Environment and Planning Agency, 2017) and is cited as being relatively low cost in terms of construction, maintenance and potential revenue loss in its absence (Leatherman, 1989; Alexandrakis et al., 2015). From a simple cost-benefit perspective, Caribbean economies need to only spend 1.09% of tourism revenues on beach nourishment efforts to offset hotel room revenue losses of approximately 47% under RCP8.5. If a low emissions pathway is pursued, revenue losses of 38% require spending on beach nourishment activities equivalent to 0.87% of revenues from tourism. Under both RCP4.5 and RCP8.5, by 2100, Montserrat will have highest beach nourishment costs of approximately 14% of tourism revenue while Aruba will spend the lowest, at most 0.2% of its revenue. However, the majority of countries would need to spend less than 2% of tourism revenues on beach nourishment. Importantly, we need to emphasize that our simple calculations assume constant tourism spending and time invariant and homogeneous beach nourishment costs.

Despite the evidence of the economic feasibility of beach nourishment as an effective mitigation strategy, in the Caribbean, the few projects that have been undertaken appear to have been primarily privately financed. For example, in Jamaica the government is cited as earmarking funds for breakwater construction with no consideration for beach nourishment (Neufville, 2020), so that nourishment projects are expected to be financed by the hotels affected. Conversely, in the United States, beach nourishment is funded by the government (Pendleton et al., 2012; Houston, 2013). As early as the 1920s, many beaches across the United States have benefited from increased beach width through the provision of over one half billion cubic yards of sand (Pendleton et al., 2012). There are a number of different reasons that could be motivating the use of public funds for beach nourishment. First, beaches are a leading attraction for tourists from whom the government collects taxes for beach visits (Houston, 2013). For instance, in the case of Florida it was estimated that a decline in beach tourists would reduce tax revenues by $32 million USD or 15 times the amount spent in 2013 to nourish the beaches (Houston, 2013). Second, the value of job creation and employment to the economy from maintaining sandy beaches should also be considered (Houston, 2013). In this regard, as noted by Houston (2013), there are many indirect and supply chain jobs that are generated from beach tourism, including taxi operators, producers of tourist-type goods and the associated vendors. Third, negative externalities could accrue from privately funded nourishment projects not taking into account the effect on neighboring beaches. According to Miller (2018), solving erosion at one beach can create an issue at another. As a result, coastal intervention guidelines have indicated that suitable methods must be used when nourishing beaches to avoid impacting the environmental values in neighboring areas (National Environment and Planning Agency, 2017). As suggested by Stronge (2005), governments in general should take leadership in financing beach nourishment projects, such as through subsidies. Caribbean governments thus could earn good returns from investing in beach nourishment projects through tax earnings and an overall boost to their economies (Dean & Houston, 2016).

Regardless of the source of funding, the success of beach nourishment as a mitigation strategy is not a certainty due to a number of reasons, such as sand availability, the cost of acquiring it, and the placed sand being washed away by hurricanes (North Carolina Department of Environmental Quality, 2016; Banton, Warner, Smith, & Morin, 2017; National Environment and Planning Agency, 2017). Nevertheless, beach nourishment arguably provides benefits beyond revenue protection for beach tourism. For example, it reduces storm damage of beachfront properties and other infrastructure arising from storm surge (Pompe & Rinehart, 1995; Rogers Jr et al., 2004). In this regard Pompe and Rinehart (1995) estimate $63.8 million USD in benefits from beach nourishment that accumulate to property owners in South Carolina, United States. Nourishment also restores and maintains the beach ecosystem that facilitates the nesting and spawning activities of certain species, as well as habitat protection (Botton, 2009; Vanden Eede, 2013; North Carolina Department of Environmental Quality, 2016; Hawai'i Department Land & Natural Resources, 2020). As has been observed in New York, United States, beach nourishment protects the habitat of the horseshoe crab whose reproductive activities increased, albeit slowly (Botton et al., 2018). In addition, nourishment increased the nesting of the endangered beach tiger beetle and overall beetle numbers in Virginia, United States (Fenster, Knisley, & Reed, 2006). However, at the same time some nourishment projects may be damaging to or disturb the habitat for species, such as sea turtles (North Carolina Department of Environmental Quality, 2016).

Although we only discussed beach nourishment as an adaptation technique for the Caribbean based on its relatively low cost, there are other measures that can be used to protect against beach loss due to sea level rise. In fact, beach nourishment is a type of soft measure, categorized as such because of its low environmental impact (Parab et al., 2011). Another soft measure is beach drainage which involves putting in place strip drains to lower the beach water table in order to allow for increased sand deposits and reduced sand extraction or retrieval by significant wave movements (Parab et al., 2011). This technique has been successful in Australia and even in Japan, where the drained beaches have shown greater stability than the undrained areas (Davis, Hanslow, Hibbert, & Nielsen, 1993; Katoh, Yanagishima, Nakamura, & Fukuta, 1994). However, more recent studies on beach drainage experiments have either not been able to document any success, such as in Italy (Ciavola, Vicinanza, & Fontana, 2009), or note that improvements are limited, for example, in Germany (Contestabile, Aristodemo, Vicinanza, & Ciavola, 2012). Other measures, generally categorized as hard defenses or engineered structures, including groynes, breakwaters, revetments, seawalls, and jetties are cited as being more expensive than softer measures (Parab et al., 2011; National Environment and Planning Agency, 2017). Despite the expense, such defenses appear to be widely used even though they have proven ineffective in some countries (for example, seawalls and groynes in Colombia, (Rangel-Buitrago, Anfuso, & Williams, 2015); and breakwaters and groynes in Taiwan, (Yang, Wu, Hwung, Liou, & Shugan, 2010)). In some instances, some have suggested combining soft and hard measures to combat beach erosion (see for example, Yang et al. (2010) and Masria, Iskander, and Negm (2015). Despite the protection from hard defenses, they appear to be the less preferred measures since their implementation reduces recreational beach space and habitats for beach organisms (Stronge, 2005; Neufville, 2020).

Beach nourishment and the other protective measures highlighted above are not the only options to deal with the consequences of beach erosion. Building new hotels away from the coast could prevent room losses for the hotel industry. In Barbados, for instance, new buildings are required to be located at least 30 metres away from areas that are deemed at risk from erosion (Mycoo, 2014). As a matter of fact, building further inland is considered as a cost effective alternative to shoreline protection methods including seawalls (Zhu, Linham, & Nicholls, 2010). However, building hotels inland may increase the competition for other land-use options, such as forest conservation. For example, in Gambia forested areas are generally cleared to construct hotels, an action which has been cited as focused on the economic benefits rather than the environmental implications (Food & Agriculture Organization of United Nations, 2016). It is perhaps with economic benefits in mind that land-use efficiency studies indicate that hotels can be designed to utilize less ground floor area per bed and become a significant contributor to factor income (Kytzia, Walz, & Wegmann, 2011).

Of course an alternative adaptation strategy for Caribbean islands to be considered is for them to increase their engagement in more non-beach tourism, such as ecotourism. Ecotourism has been estimated to contribute approximately 4.6% of Caribbean Gross Domestic Product (Wilson, Shellyanne and Sagewan-Alli, Indera and Calatayud, Agustina , 2014). Although some islands have promoted nature-based activities such as mountainous excursions, bird watching and kayaking (Wilson, Shellyanne and Sagewan-Alli, Indera and Calatayud, Agustina , 2014), evidence from Martinique, where only 3% of tourists engage in activities relating to the preserved natural environment, shows that there is room for more investment (Schleupner, 2005). However, this may prove to be challenging in the long term since other non-sandy beach aspects of an island's natural environment may also be negatively impacted by climate change (Jamaliah & Powell, 2018).

Finally, we need to point out a number of limitations of our analysis. For instance, our quantitative predictions regarding the impact of sea level rise on sandy beaches rests on the assumptions of a specific beach width across the region, i.e., a complete loss of beaches rather than reduced quality due to narrower width, a constant revenue per room, a constant beach nourishment price, an unlimited supply of sand, and an abstraction from the fact that nourishment of a beach needs to be done with a similar type of sand. In addition, we do not take into account the building of new hotels and the positive and negative spillovers of beach nourishment to the rest of the economy and the environment. Incorporating these aspects, which would require currently unavailable data, would serve to provide greater precision to our findings and subsequent conclusions.

6 Conclusion

Given the importance of sandy beaches to the tourism industry in the Caribbean and the threat that climate change poses to them, we examined the likely future status of sandy beaches and sandy beach hotel rooms under two climate change scenarios, RCP4.5 and RCP8.5. Using our estimates, we also predicted future tourism revenue losses and calculated necessary mitigation beach nourishment costs for the island in the region. The results derived from this study set the stage for designing policies that are based on quantified beach loss risk and monetary losses. Many countries across the Caribbean have climate change adaption plans, policies, and visions, which, worryingly, generally do not contain quantified risk assessments of sandy beach losses due to climate change, despite this natural resource forming part of the backbone of tourism in most of the region. But, policies formulated in the absence of such estimated future losses may be unsuccessful in efficiently combating the impact of climate change on the tourism sector. Our findings here suggest that, despite the likely considerable sandy beach losses and large subsequent losses in tourism revenue, a mitigation strategy such as beach nourishment may be an effective mitigation strategy, or at least part of a strategy combined with other measures, such as hard engineering techniques.

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Figure 1: Current Sandy Beach Length (km)

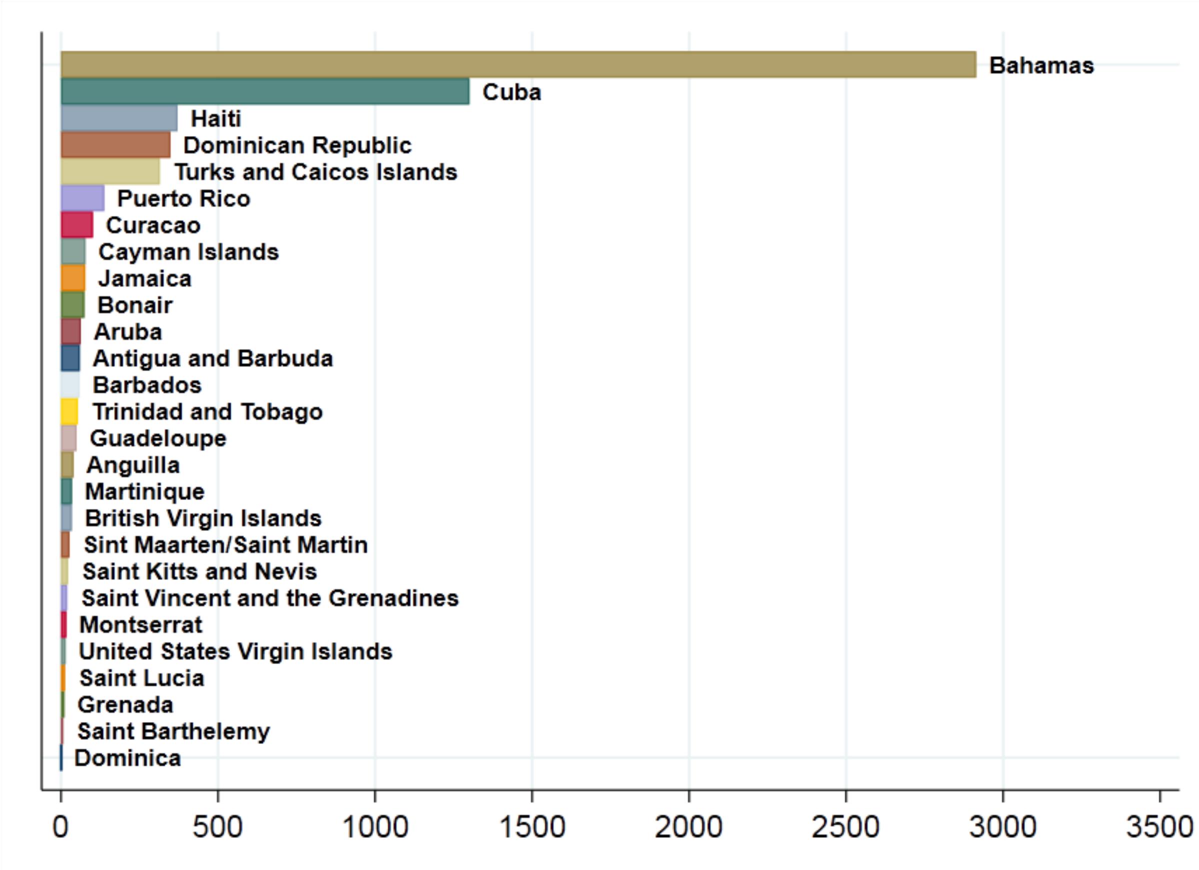


Figure 2: Sandy Beach per Beach Hotel Room (m)

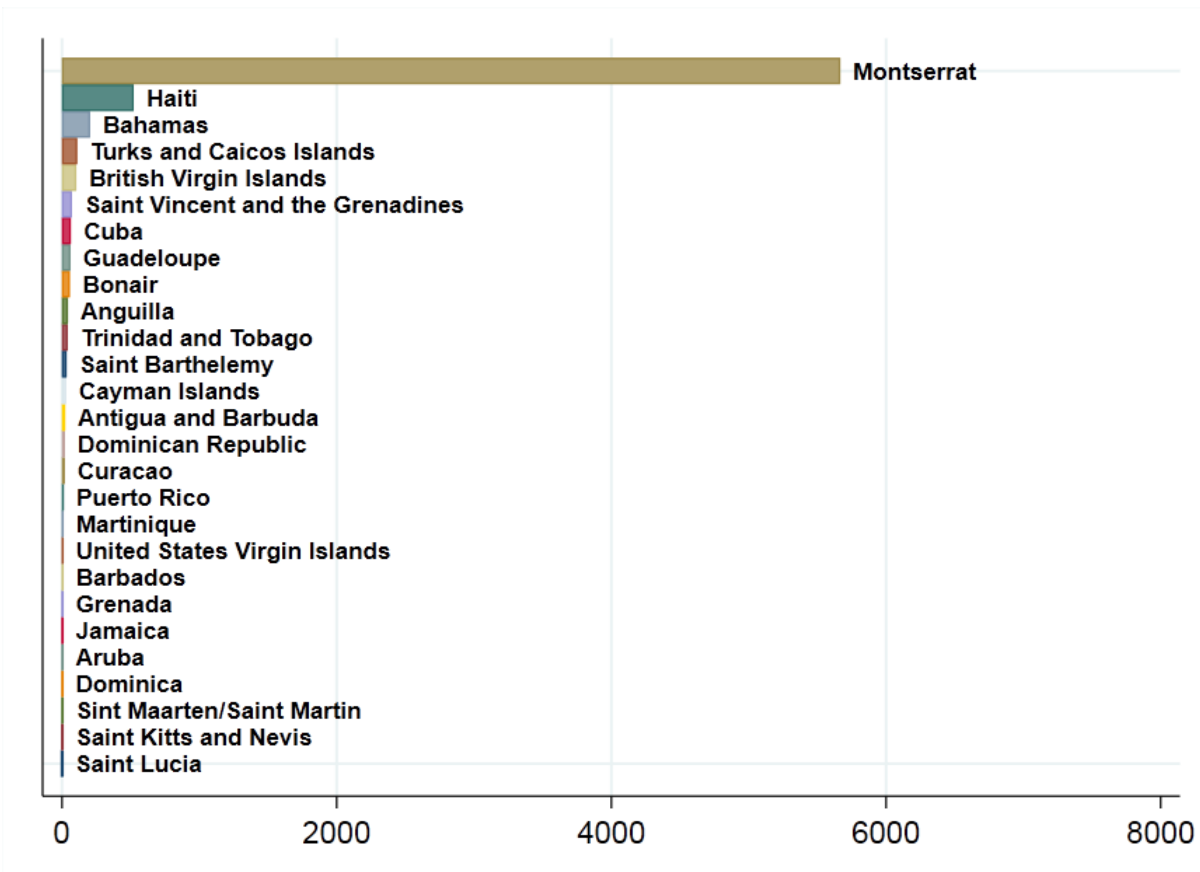


Figure 3: Hotel Sandy Beach per Beach Hotel Room (m)

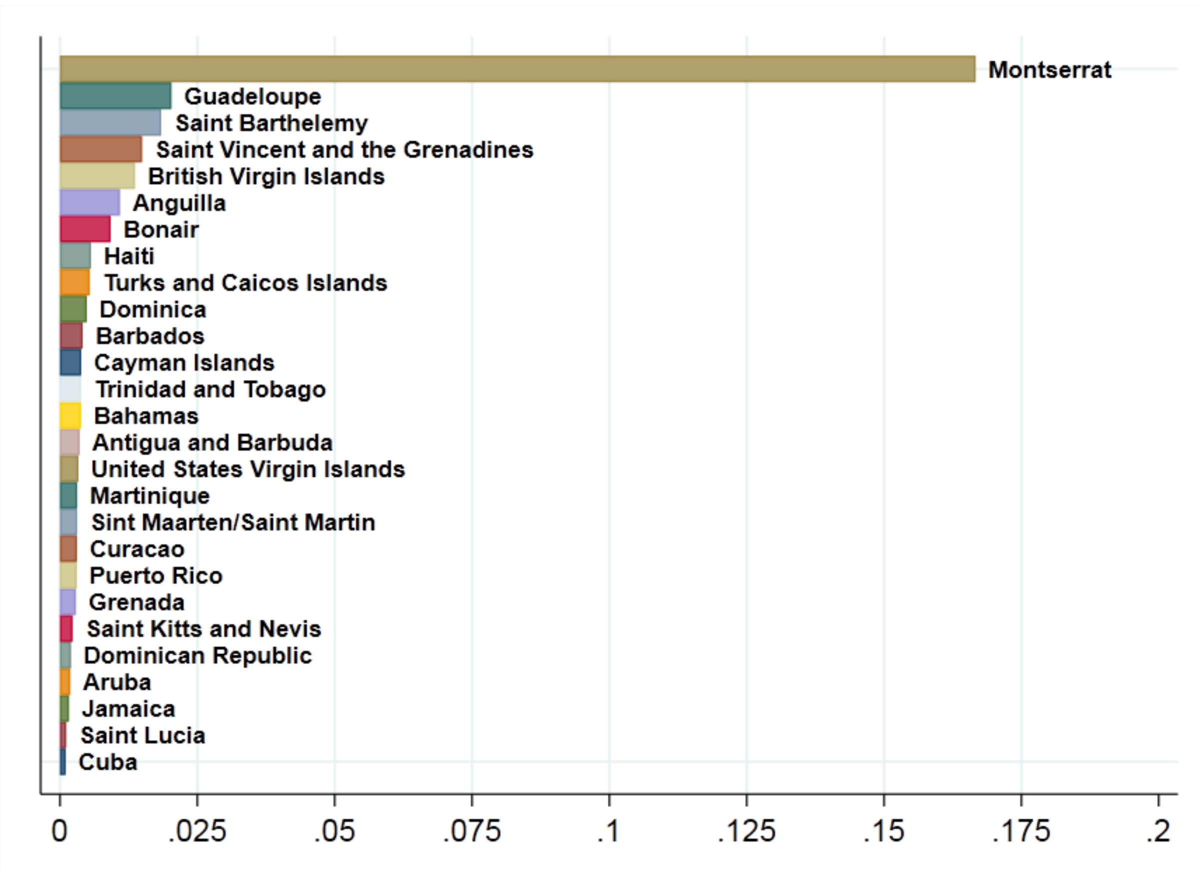
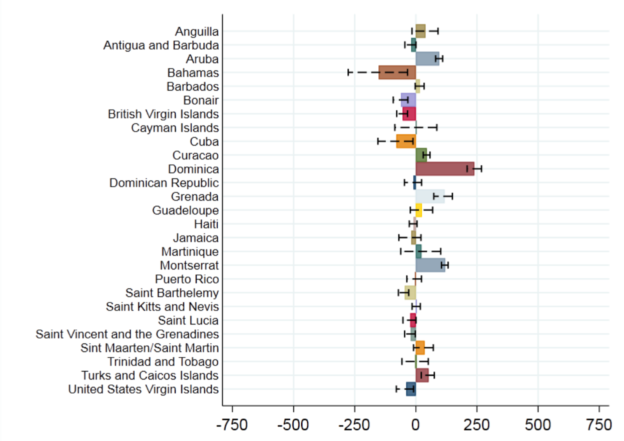
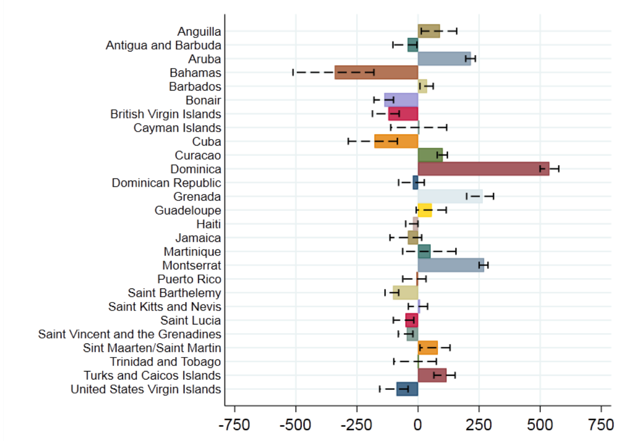


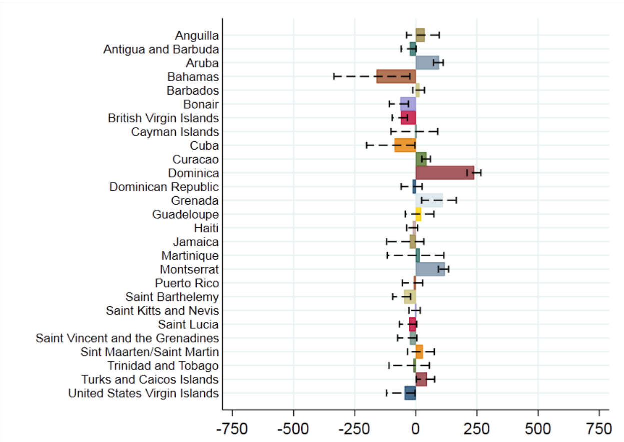
Figure 4: Shoreline Change (m) on Sandy Beaches



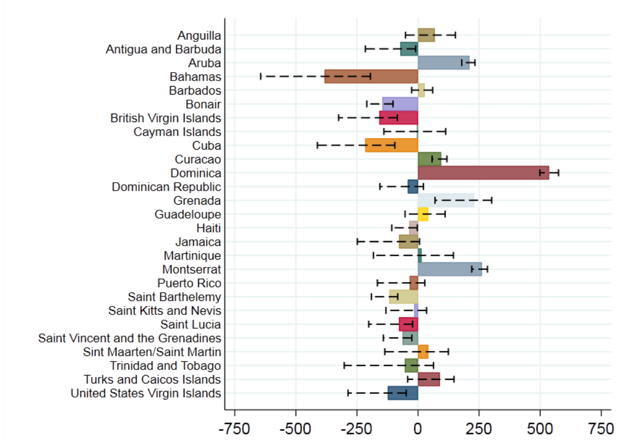
(a) RCP 4.5 - 2050



(b) RCP 4.5 - 2100

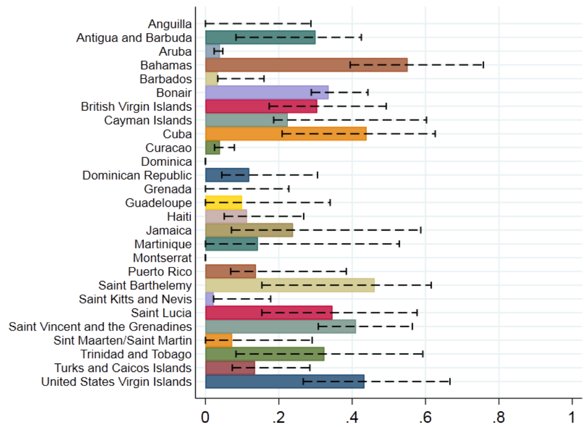


(c) RCP 8.5 - 2050

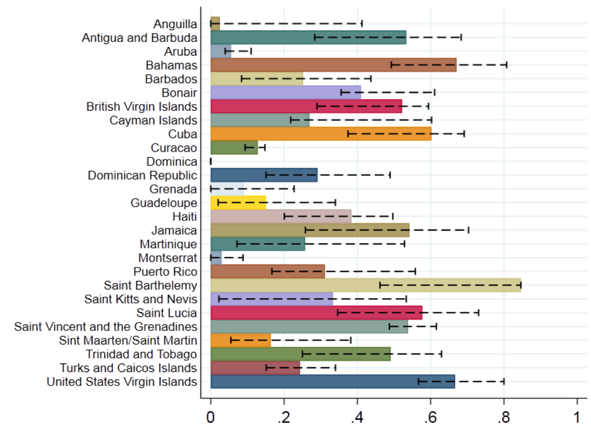


(d) RCP 8.5 - 2100

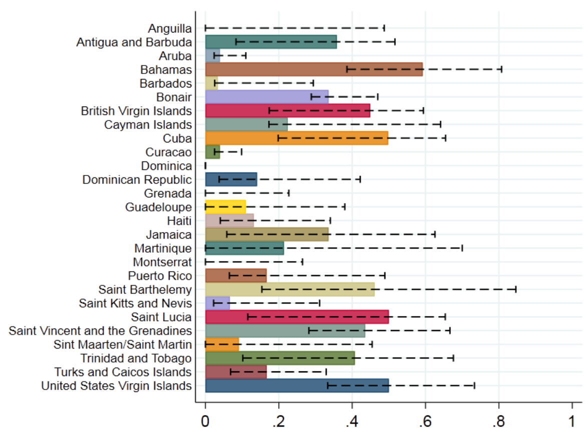
Figure 5: Sandy Beach Loss (%)



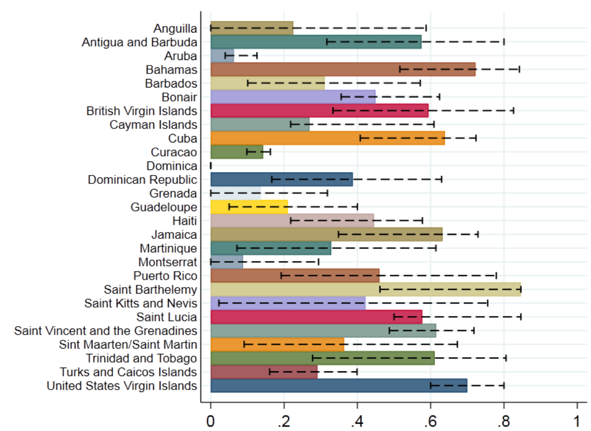
(a) RCP 4.5 - 2050



(b) RCP 4.5 - 2100

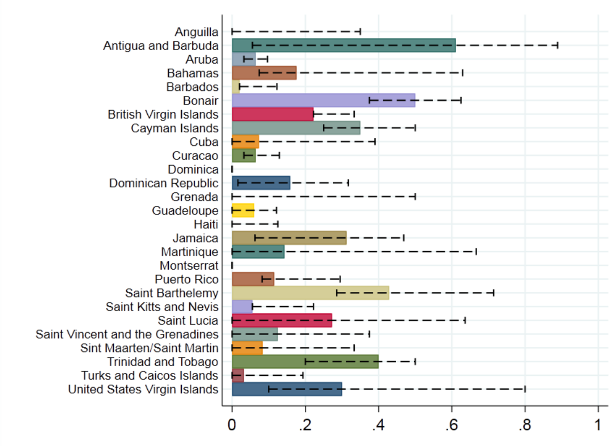


(c) RCP 8.5 - 2050

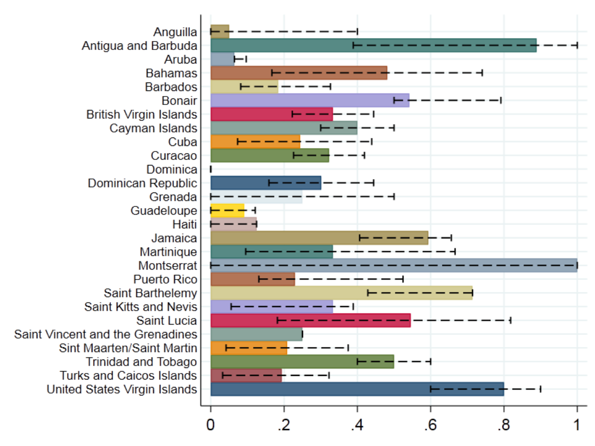


(d) RCP 8.5 - 2100

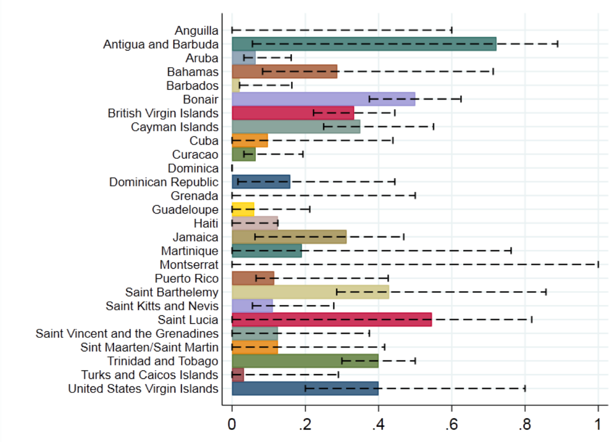
Figure 6: Hotel Sandy Beach Loss (%)



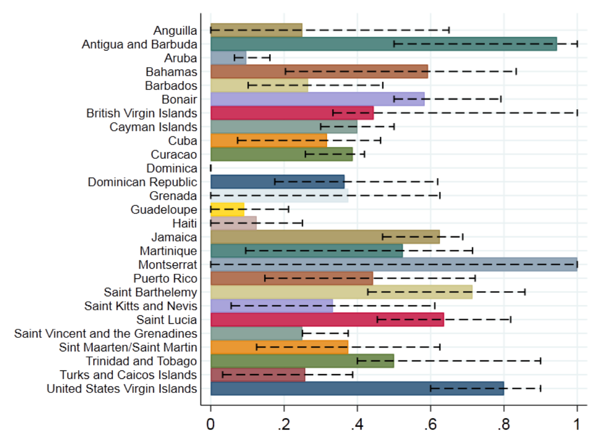
(a) RCP 4.5 - 2050



(b) RCP 4.5 - 2100

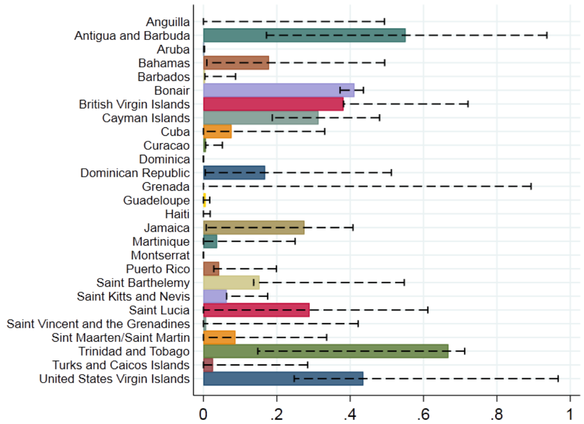


(c) RCP 8.5 - 2050

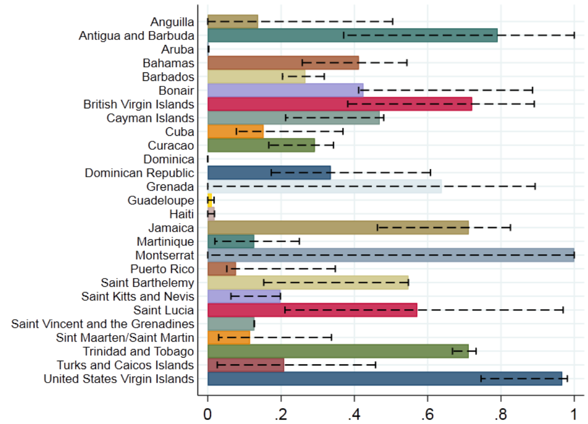


(d) RCP 8.5 - 2100

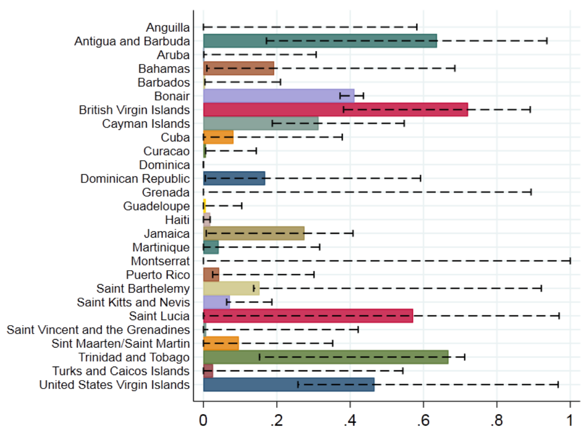
Figure 7: Hotel Beach Room Loss (%)



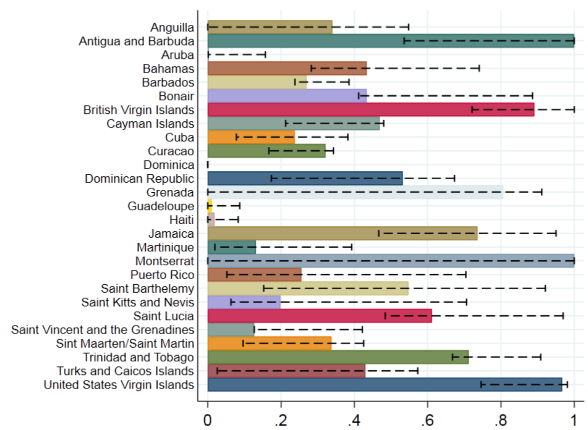
(a) RCP 4.5 - 2050



(b) RCP 4.5 - 2100



(c) RCP 8.5 - 2050



(d) RCP 8.5 - 2100

Table 1: Summary Statistics

Island	$SBeach(km)$	$SBeach(\%)$	$Rooms(\#)$	$Rooms(\%)$	$\frac{SBeach}{Rooms}(m)$	$\frac{ABeach}{Rooms}(m)$
Anguilla	40	0.5	918	0.4	11	44
Antigua and Barbuda	60	0.4	2526	0.7	4	24
Aruba	64	1.0	8276	0.9	2	8
Bahamas	2914	0.6	14 226	0.9	4	205
Barbados	60	0.7	5921	0.9	4	10
Bonair	75	0.9	1300	1.0	9	57
British Virgin Islands	35	0.1	330	0.2	14	105
Cayman Islands	78	0.5	2589	1.0	4	30
Cuba	1301	0.2	20 038	0.9	1	65
Curacao	102	0.7	4999	0.9	3	20
Dominica	2	0.0	205	0.1	5	7
Dominican Republic	349	0.3	15 983	0.7	2	22
Grenada	11	0.1	1385	0.5	3	8
Guadeloupe	50	0.1	814	0.6	20	61
Haiti	372	0.3	711	0.3	6	523
Jamaica	78	0.1	9831	0.6	2	8
Martinique	35	0.1	3359	0.8	3	10
Montserrat	17	0.4	3	0.2	167	5667
Puerto Rico	138	0.2	10 036	0.8	3	14
Saint Barthelemy	7	0.3	190	0.5	18	34
Saint Kitts and Nevis	23	0.2	3984	0.9	2	6
Saint Lucia	13	0.1	4935	0.7	1	3
Saint Vincent and the Grenadines	20	0.2	268	0.2	15	73
Sint Maarten/Saint Martin	28	0.6	3840	1.0	3	7
Trinidad and Tobago	54	0.1	1303	0.4	4	41
Turks and Caicos Islands	315	0.8	2855	0.9	5	110
United States Virgin Islands	15	0.1	1491	0.4	3	10
ALL	6256	0.3	122 316	0.8	3	51

Notes: (a) *SBeach*: Sandy beaches (b) *ABeach*: All beaches

Table 2: Average Shoreline Retreat (m)

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	39.00	(90,-15)	89.00	(158,13)	35.00	(95,-38)	68.00	(152,-51)
Antigua and Barbuda	-19.00	(0.00,-45)	-42.00	(-4,-102)	-24.00	(0.00,-59)	-72.00	(-9,-215)
Aruba	95.00	(109,80)	215.00	(234,195)	94.00	(111,72)	210.00	(232,178)
Bahamas	-152.00	(-33,-276)	-340.00	(-180,-511)	-160.00	(-24,-334)	-382.00	(-194,-643)
Barbados	16.00	(33,-2)	37.00	(62,7)	14.00	(35,-12)	27.00	(59,-26)
Bonair	-61.00	(-32,-92)	-138.00	(-100,-180)	-62.00	(-30,-108)	-146.00	(-102,-209)
British Virgin Islands	-54.00	(-33,-78)	-121.00	(-77,-186)	-61.00	(-34,-96)	-158.00	(-84,-325)
Cayman Islands	2.00	(85,-86)	5.00	(117,-111)	0.00	(89,-101)	-5.00	(113,-139)
Cuba	-79.00	(-11,-155)	-178.00	(-84,-285)	-87.00	(-3,-201)	-216.00	(-94,-412)
Curacao	44.00	(57,29)	100.00	(120,78)	43.00	(59,24)	94.00	(118,57)
Dominica	239.00	(268,209)	537.00	(576,499)	238.00	(265,209)	536.00	(574,498)
Dominican Republic	-9.00	(23,-46)	-21.00	(25,-79)	-13.00	(25,-59)	-41.00	(21,-156)
Grenada	117.00	(149,73)	264.00	(308,198)	110.00	(165,23)	229.00	(301,69)
Guadeloupe	24.00	(68,-22)	56.00	(115,-7)	22.00	(73,-42)	41.00	(111,-53)
Haiti	-9.00	(4,-26)	-20.00	(0.00,-50)	-12.00	(7,-37)	-35.00	(-2,-107)
Jamaica	-18.00	(20,-69)	-41.00	(14,-114)	-25.00	(32,-119)	-77.00	(6,-248)
Martinique	22.00	(101,-61)	51.00	(155,-62)	15.00	(114,-116)	14.00	(144,-182)
Montserrat	120.00	(131,104)	270.00	(286,250)	118.00	(133,92)	262.00	(284,219)
Puerto Rico	-3.00	(23,-36)	-6.00	(32,-62)	-8.00	(27,-55)	-34.00	(27,-166)
Saint Barthelemy	-45.00	(-29,-71)	-102.00	(-79,-134)	-48.00	(-21,-94)	-117.00	(-83,-190)
Saint Kitts and Nevis	3.00	(18,-15)	8.00	(38,-39)	-1.00	(17,-27)	-16.00	(34,-131)
Saint Lucia	-22.00	(0.00,-52)	-51.00	(-17,-100)	-27.00	(3,-67)	-78.00	(-21,-201)
Saint Vincent and the Grenadines	-20.00	(-2,-45)	-46.00	(-20,-80)	-24.00	(4,-74)	-63.00	(-25,-141)
Sint Maarten/Saint Martin	35.00	(71,-9)	81.00	(130,7)	28.00	(75,-33)	42.00	(124,-136)
Trinidad and Tobago	0.00	(50,-57)	1.00	(74,-99)	-9.00	(55,-109)	-54.00	(63,-302)
Turks and Caicos Islands	52.00	(75,22)	116.00	(151,64)	45.00	(76,1)	89.00	(147,-42)
United States Virgin Islands	-39.00	(-9,-79)	-88.00	(-40,-156)	-46.00	(-3,-119)	-123.00	(-48,-286)
ALL	-84.00	(-6,-168)	-188.00	(-81,-308)	-91.00	(0.00,-211)	-223.00	(-91,-421)

Notes: 95% confidence band in parentheses

Table 3: % Sandy Beach Loss

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	0.00	(0.00,0.28)	0.02	(0.00,0.41)	0.00	(0.00,0.48)	0.22	(0.00,0.58)
Antigua and Barbuda	0.30	(0.08,0.42)	0.53	(0.28,0.68)	0.35	(0.08,0.51)	0.57	(0.31,0.8)
Aruba	0.03	(0.02,0.04)	0.05	(0.03,0.11)	0.03	(0.02,0.11)	0.06	(0.03,0.12)
Bahamas	0.55	(0.39,0.75)	0.67	(0.49,0.8)	0.59	(0.38,0.8)	0.72	(0.51,0.84)
Barbados	0.03	(0.03,0.15)	0.25	(0.08,0.43)	0.03	(0.02,0.29)	0.31	(0.1,0.57)
Bonair	0.33	(0.28,0.44)	0.40	(0.35,0.61)	0.33	(0.28,0.46)	0.44	(0.35,0.62)
British Virgin Islands	0.30	(0.17,0.49)	0.52	(0.28,0.59)	0.44	(0.17,0.59)	0.59	(0.33,0.82)
Cayman Islands	0.22	(0.18,0.6)	0.26	(0.21,0.6)	0.22	(0.17,0.64)	0.26	(0.21,0.6)
Cuba	0.43	(0.2,0.62)	0.60	(0.37,0.69)	0.49	(0.19,0.65)	0.63	(0.4,0.72)
Curacao	0.03	(0.02,0.07)	0.12	(0.09,0.14)	0.03	(0.02,0.09)	0.14	(0.09,0.16)
Dominica	0.00	(0.00,0.00)	0.00	(0.00,0.00)	0.00	(0.00,0.00)	0.00	(0.00,0.00)
Dominican Republic	0.11	(0.04,0.3)	0.29	(0.15,0.48)	0.14	(0.03,0.42)	0.38	(0.16,0.62)
Grenada	0.00	(0.00,0.22)	0.09	(0.00,0.22)	0.00	(0.00,0.22)	0.13	(0.00,0.31)
Guadeloupe	0.09	(0.00,0.34)	0.15	(0.02,0.34)	0.10	(0.00,0.38)	0.20	(0.05,0.4)
Haiti	0.11	(0.05,0.26)	0.38	(0.2,0.49)	0.13	(0.04,0.34)	0.44	(0.21,0.57)
Jamaica	0.23	(0.07,0.58)	0.54	(0.25,0.7)	0.33	(0.05,0.62)	0.63	(0.34,0.72)
Martinique	0.14	(0.00,0.52)	0.25	(0.07,0.52)	0.21	(0.00,0.7)	0.32	(0.07,0.61)
Montserrat	0.00	(0.00,0.00)	0.02	(0.00,0.08)	0.00	(0.00,0.26)	0.08	(0.00,0.29)
Puerto Rico	0.13	(0.06,0.38)	0.31	(0.16,0.55)	0.16	(0.06,0.48)	0.46	(0.19,0.77)
Saint Barthelemy	0.46	(0.15,0.61)	0.84	(0.46,0.84)	0.46	(0.15,0.84)	0.84	(0.46,0.84)
Saint Kitts and Nevis	0.02	(0.02,0.17)	0.33	(0.02,0.53)	0.06	(0.02,0.31)	0.42	(0.02,0.75)
Saint Lucia	0.34	(0.15,0.57)	0.57	(0.34,0.73)	0.50	(0.11,0.65)	0.57	(0.5,0.84)
Saint Vincent and the Grenadines	0.41	(0.3,0.56)	0.53	(0.48,0.61)	0.43	(0.28,0.66)	0.61	(0.48,0.71)
Sint Maarten/Saint Martin	0.07	(0.00,0.29)	0.16	(0.05,0.38)	0.09	(0.00,0.45)	0.36	(0.09,0.67)
Trinidad and Tobago	0.32	(0.08,0.59)	0.49	(0.25,0.62)	0.40	(0.1,0.67)	0.61	(0.27,0.8)
Turks and Caicos Islands	0.13	(0.07,0.28)	0.24	(0.15,0.34)	0.16	(0.06,0.32)	0.29	(0.16,0.39)
United States Virgin Islands	0.43	(0.26,0.66)	0.66	(0.56,0.8)	0.50	(0.33,0.73)	0.70	(0.6,0.8)
ALL	0.39	(0.25,0.58)	0.53	(0.36,0.67)	0.43	(0.24,0.64)	0.59	(0.38,0.72)

Notes: 95% confidence band in parentheses

Table 4: % Sandy Beach Near Beach Hotel Loss

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	0	(0.00,0.35)	0.0500	(0.00,0.4)	0	(0.00,0.6)	0.250	(0.00,0.65)
Antigua and Barbuda	0.610	(0.05,0.88)	0.880	(0.38,1)	0.720	(0.05,0.88)	0.940	(0.5,1)
Aruba	0.0600	(0.03,0.09)	0.0600	(0.06,0.09)	0.0600	(0.03,0.16)	0.0900	(0.06,0.16)
Bahamas	0.170	(0.07,0.62)	0.480	(0.16,0.74)	0.280	(0.08,0.71)	0.590	(0.2,0.83)
Barbados	0.0200	(0.02,0.12)	0.180	(0.08,0.32)	0.0200	(0.02,0.16)	0.260	(0.1,0.46)
Bonair	0.500	(0.37,0.62)	0.540	(0.5,0.79)	0.500	(0.37,0.62)	0.580	(0.5,0.79)
British Virgin Islands	0.220	(0.22,0.33)	0.330	(0.22,0.44)	0.330	(0.22,0.44)	0.440	(0.33,1)
Cayman Islands	0.350	(0.25,0.5)	0.400	(0.3,0.5)	0.350	(0.25,0.55)	0.400	(0.3,0.5)
Cuba	0.0700	(0.00,0.39)	0.240	(0.07,0.43)	0.0900	(0.00,0.43)	0.310	(0.07,0.46)
Curacao	0.0600	(0.03,0.12)	0.320	(0.22,0.41)	0.0600	(0.03,0.19)	0.380	(0.25,0.41)
Dominica	0	(0.00,0.00)	0	(0.00,0.00)	0	(0.00,0.00)	0	(0.00,0.00)
Dominican Republic	0.150	(0.01,0.31)	0.300	(0.15,0.44)	0.150	(0.01,0.44)	0.360	(0.17,0.61)
Grenada	0	(0.00,0.5)	0.250	(0.00,0.5)	0	(0.00,0.5)	0.370	(0.00,0.62)
Guadeloupe	0.0600	(0.00,0.12)	0.0900	(0.00,0.12)	0.0600	(0.00,0.21)	0.0900	(0.00,0.21)
Haiti	0	(0.00,0.12)	0.120	(0.00,0.12)	0.120	(0.00,0.12)	0.120	(0.00,0.25)
Jamaica	0.310	(0.06,0.46)	0.590	(0.4,0.65)	0.310	(0.06,0.46)	0.620	(0.46,0.68)
Martinique	0.140	(0.00,0.66)	0.330	(0.09,0.66)	0.190	(0.00,0.76)	0.520	(0.09,0.71)
Montserrat	0	(0.00,0.00)	1	(0.00,1)	0	(0.00,1)	1	(0.00,1)
Puerto Rico	0.110	(0.08,0.29)	0.220	(0.13,0.52)	0.110	(0.06,0.42)	0.440	(0.14,0.72)
Saint Barthelemy	0.420	(0.28,0.71)	0.710	(0.42,0.71)	0.420	(0.28,0.85)	0.710	(0.42,0.85)
Saint Kitts and Nevis	0.0500	(0.05,0.22)	0.330	(0.05,0.38)	0.110	(0.05,0.27)	0.330	(0.05,0.61)
Saint Lucia	0.270	(0.00,0.63)	0.540	(0.18,0.81)	0.540	(0.00,0.81)	0.630	(0.45,0.81)
Saint Vincent and the Grenadines	0.120	(0.00,0.37)	0.250	(0.25,0.25)	0.120	(0.00,0.37)	0.250	(0.25,0.37)
Sint Maarten/Saint Martin	0.0800	(0.00,0.33)	0.200	(0.04,0.37)	0.120	(0.00,0.41)	0.370	(0.12,0.62)
Trinidad and Tobago	0.400	(0.19,0.5)	0.500	(0.4,0.6)	0.400	(0.3,0.5)	0.500	(0.4,0.9)
Turks and Caicos Islands	0.0300	(0.00,0.19)	0.190	(0.03,0.32)	0.0300	(0.00,0.29)	0.250	(0.03,0.38)
United States Virgin Islands	0.300	(0.09,0.8)	0.800	(0.6,0.9)	0.400	(0.19,0.8)	0.800	(0.6,0.9)
ALL	0.150	(0.06,0.38)	0.330	(0.16,0.5)	0.190	(0.06,0.46)	0.410	(0.18,0.61)

Notes: 95% confidence band in parentheses

Table 5: % Sandy Beach Room Loss

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	0	(0.00,0.49)	0.130	(0.00,0.5)	0	(0.00,0.58)	0.330	(0.00,0.54)
Antigua and Barbuda	0.550	(0.17,0.93)	0.790	(0.37,1)	0.630	(0.17,0.93)	0.990	(0.53,1)
Aruba	0	(0.00,0.00)	0	(0.00,0.00)	0	(0.00,0.3)	0	(0.00,0.15)
Bahamas	0.170	(0.00,0.49)	0.410	(0.25,0.54)	0.190	(0.00,0.68)	0.430	(0.28,0.74)
Barbados	0	(0.00,0.08)	0.260	(0.2,0.31)	0	(0.00,0.2)	0.260	(0.23,0.38)
Bonair	0.410	(0.37,0.43)	0.420	(0.41,0.88)	0.410	(0.37,0.43)	0.430	(0.41,0.88)
British Virgin Islands	0.380	(0.38,0.72)	0.720	(0.38,0.89)	0.720	(0.38,0.89)	0.890	(0.72,1)
Cayman Islands	0.310	(0.18,0.48)	0.460	(0.21,0.48)	0.310	(0.18,0.54)	0.460	(0.21,0.48)
Cuba	0.0700	(0.00,0.33)	0.150	(0.07,0.36)	0.0800	(0.00,0.37)	0.230	(0.07,0.38)
Curacao	0	(0.00,0.05)	0.290	(0.16,0.34)	0	(0.00,0.14)	0.320	(0.16,0.34)
Dominica	0	(0.00,0.00)	0	(0.00,0.00)	0	(0.00,0.00)	0	(0.00,0.00)
Dominican Republic	0.160	(0.00,0.51)	0.330	(0.17,0.6)	0.160	(0.00,0.59)	0.530	(0.17,0.67)
Grenada	0	(0.00,0.89)	0.630	(0.00,0.89)	0	(0.00,0.89)	0.800	(0.00,0.91)
Guadeloupe	0	(0.00,0.01)	0.0100	(0.00,0.01)	0	(0.00,0.1)	0.0100	(0.00,0.08)
Haiti	0	(0.00,0.01)	0.0100	(0.00,0.01)	0.0100	(0.00,0.01)	0.0100	(0.00,0.08)
Jamaica	0.270	(0.00,0.4)	0.710	(0.46,0.82)	0.270	(0.00,0.4)	0.730	(0.46,0.95)
Martinique	0.0300	(0.00,0.24)	0.120	(0.01,0.24)	0.0400	(0.00,0.31)	0.130	(0.01,0.39)
Montserrat	0	(0.00,0.00)	1	(0.00,1)	0	(0.00,1)	1	(0.00,1)
Puerto Rico	0.0400	(0.02,0.19)	0.0700	(0.05,0.34)	0.0400	(0.02,0.3)	0.250	(0.05,0.7)
Saint Barthelemy	0.150	(0.13,0.54)	0.540	(0.15,0.54)	0.150	(0.13,0.92)	0.540	(0.15,0.92)
Saint Kitts and Nevis	0.0600	(0.06,0.17)	0.190	(0.06,0.19)	0.0700	(0.06,0.18)	0.190	(0.06,0.7)
Saint Lucia	0.280	(0.00,0.61)	0.570	(0.21,0.96)	0.570	(0.00,0.96)	0.610	(0.48,0.96)
Saint Vincent and the Grenadines	0	(0.00,0.42)	0.120	(0.12,0.12)	0	(0.00,0.42)	0.120	(0.12,0.42)
Sint Maarten/Saint Martin	0.0800	(0.00,0.33)	0.110	(0.02,0.33)	0.0900	(0.00,0.35)	0.330	(0.09,0.42)
Trinidad and Tobago	0.660	(0.14,0.71)	0.710	(0.66,0.73)	0.660	(0.15,0.71)	0.710	(0.66,0.9)
Turks and Caicos Islands	0.0200	(0.00,0.28)	0.200	(0.02,0.45)	0.0200	(0.00,0.54)	0.430	(0.02,0.57)
United States Virgin Islands	0.430	(0.24,0.96)	0.960	(0.74,0.98)	0.460	(0.25,0.96)	0.960	(0.74,0.98)
ALL	0.130	(0.02,0.35)	0.300	(0.17,0.47)	0.150	(0.02,0.46)	0.390	(0.19,0.59)

Notes: 95% confidence band in parentheses

Table 6: % Revenue Loss

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	0.0	(0.0, 49.4)	13.7	(0.0, 50.4)	0.0	(0.0, 58.2)	34.0	(0.0, 54.8)
Antigua and Barbuda	55.1	(17.2, 93.6)	79.1	(37.1, 100.0)	63.7	(17.2, 93.6)	100.0	(53.6, 100.0)
Aruba	0.1	(0.1, 0.3)	0.1	(0.1, 0.3)	0.1	(0.1, 30.7)	0.3	(0.1, 15.7)
Bahamas	17.9	(0.9, 49.4)	41.2	(25.8, 54.3)	19.3	(0.9, 68.5)	43.4	(28.2, 74.1)
Barbados	0.4	(0.4, 8.8)	26.6	(20.4, 31.8)	0.4	(0.4, 21.0)	27.0	(23.8, 38.5)
British Virgin Islands	38.2	(38.2, 72.1)	72.1	(38.2, 89.1)	72.1	(38.2, 89.1)	89.1	(72.1, 100.0)
Cayman Islands	31.4	(18.8, 48.0)	46.9	(21.2, 48.0)	31.4	(18.8, 54.7)	46.9	(21.2, 48.0)
Cuba	7.7	(0.0, 33.1)	15.2	(7.8, 36.9)	8.2	(0.0, 37.8)	23.7	(7.8, 38.2)
Curacao	0.7	(0.6, 5.2)	29.2	(16.6, 34.3)	0.7	(0.6, 14.4)	32.2	(16.7, 34.3)
Dominica	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)
Dominican Republic	16.8	(0.5, 51.2)	33.6	(17.3, 60.8)	16.8	(0.5, 59.2)	53.2	(17.4, 67.3)
Grenada	0.0	(0.0, 89.3)	63.8	(0.0, 89.3)	0.0	(0.0, 89.3)	80.6	(0.0, 91.1)
Guadeloupe	0.6	(0.0, 1.7)	1.1	(0.0, 1.7)	0.6	(0.0, 10.4)	1.1	(0.0, 8.7)
Haiti	0.0	(0.0, 1.8)	1.8	(0.0, 1.8)	1.8	(0.0, 1.8)	1.8	(0.0, 8.3)
Jamaica	27.6	(0.8, 40.8)	71.2	(46.3, 82.6)	27.6	(0.8, 40.8)	73.6	(46.7, 95.0)
Martinique	3.7	(0.0, 25.0)	12.7	(1.9, 25.0)	4.1	(0.0, 31.7)	13.2	(1.9, 39.3)
Montserrat	0.0	(0.0, 0.0)	100.0	(0.0, 100.0)	0.0	(0.0, 100.0)	100.0	(0.0, 100.0)
Puerto Rico	4.3	(2.8, 19.9)	7.7	(5.2, 34.8)	4.3	(2.5, 30.1)	25.5	(5.2, 70.4)
Saint Kitts and Nevis	6.3	(6.3, 17.5)	19.8	(6.3, 19.8)	7.2	(6.3, 18.7)	19.8	(6.3, 70.6)
Saint Lucia	28.9	(0.0, 61.2)	57.2	(21.1, 97.0)	57.2	(0.0, 97.0)	61.2	(48.4, 97.0)
Saint Vincent and the Grenadines	0.8	(0.0, 42.2)	12.7	(12.7, 12.7)	0.8	(0.0, 42.2)	12.7	(12.7, 42.2)
Sint Maarten/Saint Martin	8.7	(0.0, 33.6)	11.5	(3.0, 33.8)	9.6	(0.0, 35.2)	33.8	(9.6, 42.5)
Trinidad and Tobago	66.8	(14.8, 71.2)	71.2	(66.8, 73.2)	66.8	(15.3, 71.2)	71.2	(66.8, 90.9)
Turks and Caicos Islands	2.6	(0.0, 28.4)	20.8	(2.6, 45.8)	2.6	(0.0, 54.4)	43.0	(2.6, 57.3)
United States Virgin Islands	43.6	(24.8, 96.7)	96.7	(74.6, 98.1)	46.6	(25.8, 96.7)	96.7	(74.6, 98.1)
ALL	17.1	(4.0, 42.8)	37.5	(22.0, 54.4)	19.2	(4.1, 52.5)	46.9	(24.3, 66.0)

Notes: Baseline data are not available for Bonair and Saint Barthelemy. Losses calculated as a proportion of tourism revenue in 2019. 95% confidence band in parentheses.

Table 7: % Beach Nourishment Costs

Island	RCP4.5 [2050]		RCP4.5 [2100]		RCP8.5 [2050]		RCP8.5 [2100]	
Anguilla	0.0	(0.0, 7.0)	1.0	(0.0, 8.0)	0.0	(0.0, 12.0)	5.0	(0.0, 13.1)
Antigua and Barbuda	1.4	(0.1, 2.0)	2.0	(0.9, 2.3)	1.6	(0.1, 2.0)	2.2	(1.1, 2.3)
Aruba	0.1	(0.1, 0.2)	0.1	(0.1, 0.2)	0.1	(0.1, 0.3)	0.2	(0.1, 0.3)
Bahamas	0.7	(0.3, 2.5)	1.9	(0.7, 2.9)	1.1	(0.3, 2.8)	2.4	(0.8, 3.3)
Barbados	0.1	(0.1, 0.7)	1.0	(0.4, 1.7)	0.1	(0.1, 0.9)	1.4	(0.5, 2.5)
British Virgin Islands	0.5	(0.5, 0.7)	0.7	(0.5, 1.0)	0.7	(0.5, 1.0)	1.0	(0.7, 2.1)
Cayman Islands	1.3	(1.0, 1.9)	1.5	(1.1, 1.9)	1.3	(1.0, 2.1)	1.5	(1.1, 1.9)
Cuba	0.1	(0.0, 0.7)	0.4	(0.1, 0.8)	0.2	(0.0, 0.8)	0.6	(0.1, 0.8)
Curacao	0.5	(0.2, 0.9)	2.3	(1.6, 3.0)	0.5	(0.2, 1.4)	2.7	(1.8, 3.0)
Dominica	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)	0.0	(0.0, 0.0)
Dominican Republic	0.2	(0.0, 0.3)	0.3	(0.2, 0.5)	0.2	(0.0, 0.5)	0.4	(0.2, 0.7)
Grenada	0.0	(0.0, 1.2)	0.6	(0.0, 1.2)	0.0	(0.0, 1.2)	0.9	(0.0, 1.5)
Guadeloupe	0.5	(0.0, 1.1)	0.8	(0.0, 1.1)	0.5	(0.0, 1.9)	0.8	(0.0, 1.9)
Haiti	0.0	(0.0, 0.3)	0.3	(0.0, 0.3)	0.3	(0.0, 0.3)	0.3	(0.0, 0.6)
Jamaica	0.4	(0.1, 0.6)	0.7	(0.5, 0.8)	0.4	(0.1, 0.6)	0.8	(0.6, 0.9)
Martinique	1.0	(0.0, 4.8)	2.4	(0.7, 4.8)	1.4	(0.0, 5.4)	3.7	(0.7, 5.1)
Montserrat	0.0	(0.0, 0.0)	13.5	(0.0, 13.5)	0.0	(0.0, 13.5)	13.5	(0.0, 13.5)
Puerto Rico	0.3	(0.2, 0.6)	0.5	(0.3, 1.1)	0.3	(0.1, 0.9)	1.0	(0.3, 1.6)
Saint Kitts and Nevis	0.3	(0.3, 1.3)	1.9	(0.3, 2.2)	0.6	(0.3, 1.6)	1.9	(0.3, 3.5)
Saint Lucia	0.4	(0.0, 0.9)	0.8	(0.3, 1.2)	0.8	(0.0, 1.2)	0.9	(0.7, 1.2)
Saint Vincent and the Grenadines	0.5	(0.0, 1.5)	1.0	(1.0, 1.0)	0.5	(0.0, 1.5)	1.0	(1.0, 1.5)
Sint Maarten/Saint Martin	0.6	(0.0, 2.4)	1.5	(0.3, 2.7)	0.9	(0.0, 3.0)	2.7	(0.9, 4.5)
Trinidad and Tobago	1.1	(0.5, 1.4)	1.4	(1.1, 1.6)	1.1	(0.8, 1.4)	1.4	(1.1, 2.5)
Turks and Caicos Islands	0.2	(0.0, 1.0)	1.0	(0.2, 1.7)	0.2	(0.0, 1.6)	1.4	(0.2, 2.1)
United States Virgin Islands	0.2	(0.1, 0.4)	0.4	(0.3, 0.5)	0.2	(0.1, 0.4)	0.4	(0.3, 0.5)
ALL	0.4	(0.2, 1.0)	0.9	(0.4, 1.3)	0.5	(0.2, 1.2)	1.1	(0.5, 1.6)

Notes: Baseline data are not available for Bonair and Saint Barthelemy. Cost calculated as a proportion of tourism revenue in 2019 for sandy beaches within 1km of hotels. Cost of welfare distortions are also accounted for in beach nourishment costs. 95% confidence band in parentheses.