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Reducing the vulnerability of coastal communities in the Caribbean through sustainable mangrove management

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ABSTRACT

The 2017 Atlantic storm season caused widespread damage to Caribbean nations including the British Virgin Islands. The winds and rainfall associated with Hurricanes Irma and Maria played their part in the destruction of infrastructure, livelihoods and the environment. With an increased interest in nature-based solutions to reduce flood risk, increasing the resilience of coastal communities and a focus on three of the most vulnerable communities in the Virgin Islands, we report on the use of flood risk vulnerability models based on remotely sensed satellite data and ecosystem services principles. Models were created with 4 primary aims to: (1) monitor the impact of storms and the recovery of mangroves, (2) assess the risk of flooding due to hurricane storm surges and extra-tropical storms (ground seas), (3) model opportunity areas for the restoration of red mangroves (*Rhizophora mangle)* and buttonwood (*Conocarpus erectus)* and (4) model and produce maps highlighting the predicted benefits that mangrove restoration will have on vulnerable coastal communities. Results highlight that between 75 and 94% of red mangroves in the three communities were negatively impacted by hurricanes in 2017. However, vulnerability models predict that even small-scale mangrove restoration initiatives can help to reduce the flood risk of homes and infrastructure up to 475 m inland. This work has provided the rationale for mangrove restoration in the Virgin Islands and presents an important tool for expansion across the wider Caribbean region that can be used to inform coastal restoration and resiliency building activities.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2013) Third Assessment Report (AR3) noted that small island states, such as those in the Caribbean, share many similarities (e.g., physical size, proneness to natural disasters and climate extremes, extreme openness of their economies, low adaptive capacity) that increase their vulnerability to climate variability and change. Additionally, the human settlements and built infrastructure of island states are predominately located in coastal areas, placing human populations at increased risk to sea-level rise, high-energy storm waves/storm surge and coastal flooding. Evidence of the damaging effects of severe hurricanes and their resulting storm surges are all too familiar in the region: Hurricanes Irma and Maria (occuring in 2017) and Hurricane Dorian (in 2019) each caused billions of dollars of damage to Caribbean island nations (ECLAC 2018). The IPCC concluded that small islands should focus their efforts on enhancing their resilience to climate-related disasters and implement appropriate adaptation measures as urgent priorities. Thus, integration of Disaster Risk Reduction (DRR) strategies into key sectoral activities should be pursued as part of the adaptation planning process for climate change. In addition to hard-infrastructure measures many island nations in the Caribbean have started to recognise the importance of healthy natural coastlines as a frontline defence to protect local communities from the effects of hurricanes (Wilson, 2017 Daigneault et al., 2016).

Mangroves are the dominant coastal vegetation of low energy coastal areas in the tropics. Salt tolerant plants that grow in or near the water's edge, mangroves provide countless benefits to nature and humans (Moore and Zaluski, 2018; Sandilyan and Kathiresan, 2012, 2015).

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Mangroves provide habitat and nursery areas for fish, thus playing an important role in global fisheries, it has been estimated mangroves support 80% of the global fish catch (Sandilyan and Kathiresan, 2012). Additionally, they support water quality by providing a catchment for upland runoff, they act as carbon sinks and they buffer storm surge, wind and waves, protecting coastlines and coastal communities, and provide additional resiliency for economically important habitats such as coral reefs. The annual global economic value of mangroves estimated by the cost of products produced and services provided is USD 200 000–900 000 ha^{-1} (Barbier, 2019). Recent estimates have also reported that globally mangroves provide flood protection benefits exceeding USD 65 billion per year and that if mangroves were lost 15 million additional people would be flooded annually (Menendez et al., 2020). Countless modelling and mathematical studies have shown that mangrove forests can attenuate wave energy (Horstman et al., 2014; Liu et al., 2013; Zhang et al., 2012).

Examples from the across the tropics highlight the protective nature of mangroves. For example, studies have shown that the flooded area produced by Hurricane Wilma in 2005 in Florida would have extended 70% further inland without the protection of the 6–30 km zone of mangroves (Liu et al., 2013; Zhang et al., 2012). The presence of mangroves was also reported to reduce the loss of human life from the 1999 cyclone that struck Orissa, India (Barbier, 2016). However, studies also indicate that the magnitude of the energy absorbed strongly depends on forest density, diameter of stems and roots, forest floor shape, bathymetry, the spectral characteristics of the incident waves, and the tidal stage at which the wave enters the forest (Alongi, 2008). Although site-specific studies are required to define specific details and limits of any protective function provided by mangroves, experts and scientists agree that coastal forest belts, if well designed and managed, have the potential to act as bioshields for the protection of people and other assets against coastal hazards (FAO, 2007). A review of 53 nature-based defence projects (including 12 mangrove projects) found that mangroves could be 2–6 times less expensive than the commonly used alternative, submerged breakwaters, at least for relatively low wave energy areas (Blankespoor et al., 2017; Narayan et al., 2016).

In recent years increased hurricane and storm activity has highlighted the extreme vulnerability of local communities, infrastructure, and the natural environment of the Virgin Islands (Fig. 1) (Moore and Zaluski, 2018). During vulnerability assessments undertaken in 2014 by Red Cross International, three coastal communities within the British Virgin Islands were prioritised as being the most vulnerable of all the Territory's communities. The reasons for their high vulnerability include a high number of homes being regularly flooded, overcrowding and high immigrant populations. Two of these communities: Sea Cows Bay and East End Long Look (from here on referred to as 'East End') are located on the southern coastline of Tortola, the third was the island of Jost Van Dyke (Fig. 2). With a view to increasing the resiliency of these three vulnerable communities we used ecologically based methods to identify areas to restore and establish mangroves with a higher rate of success by considering: wave action and exposure, topographic slope and elevations, seabed substrate, soil type, and distance from existing mangroves, seagrass, coral and wetland ecosystems. In addition, the vulnerability of the coastline and affected terrestrial land from storm surge events and annual ground sea conditions were evaluated by considering topographic elevation and slope, habitat type, fetch, and substrate type. The aim of this flood risk vulnerability modelling approach was to allow mangrove restoration work to be prioritised at the most optimum sites for planting and provided justification for local governments and communities to protect and restore the coastal habitats by highlighting the benefits of restoration in terms of reducing flood risk.

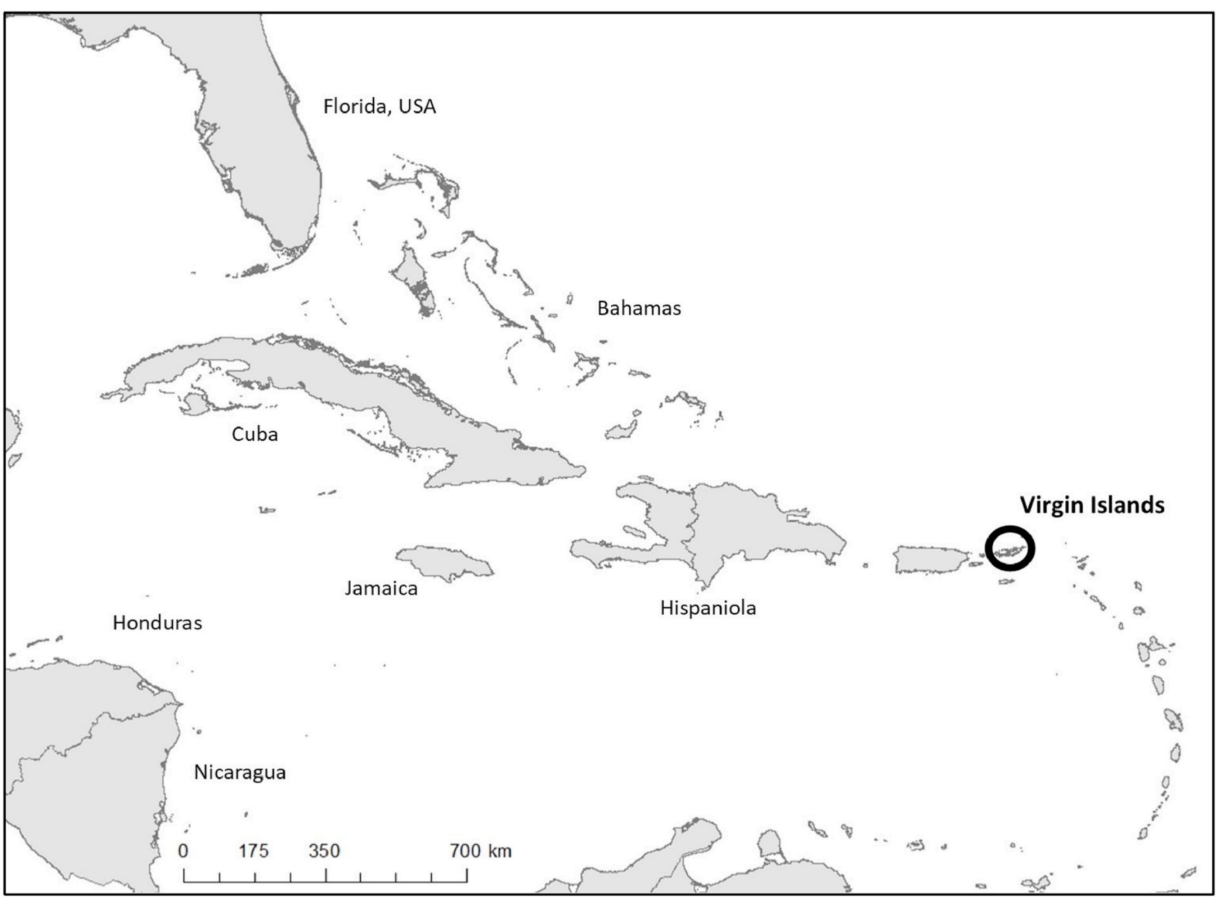

Fig. 1. Location of the Virgin Islands.

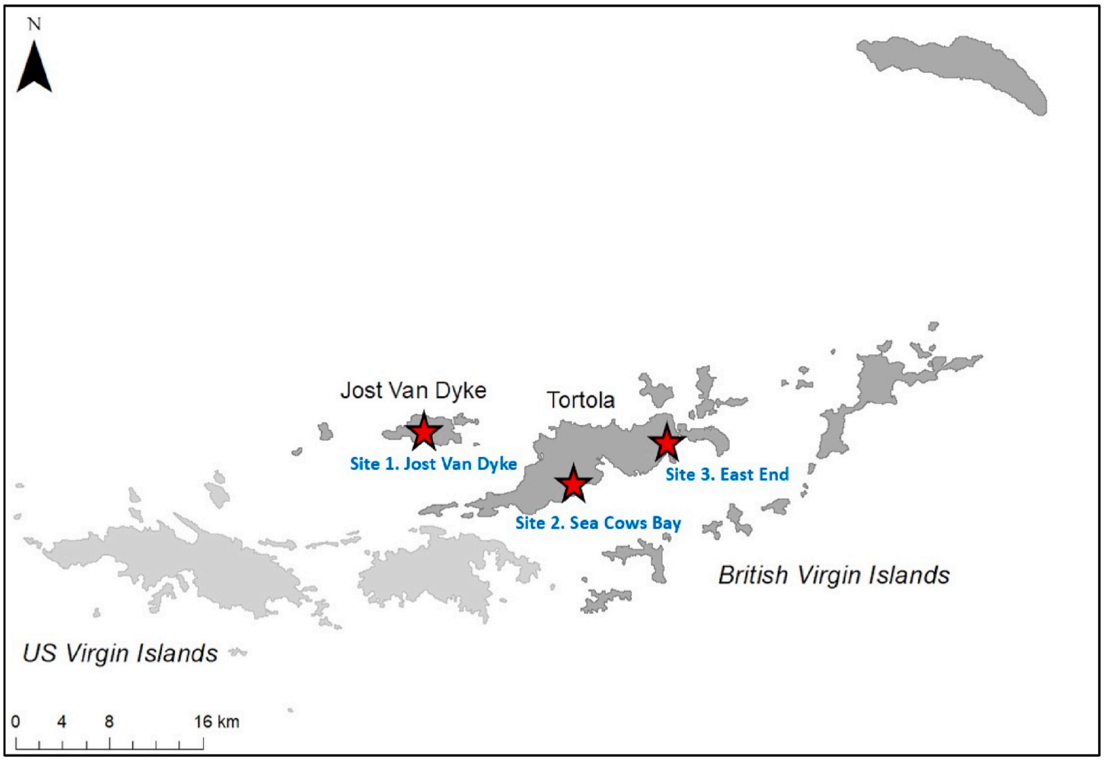

Fig. 2. Location of three of the highest ranked coastal communities in the BVI, in terms of there vulnerability.

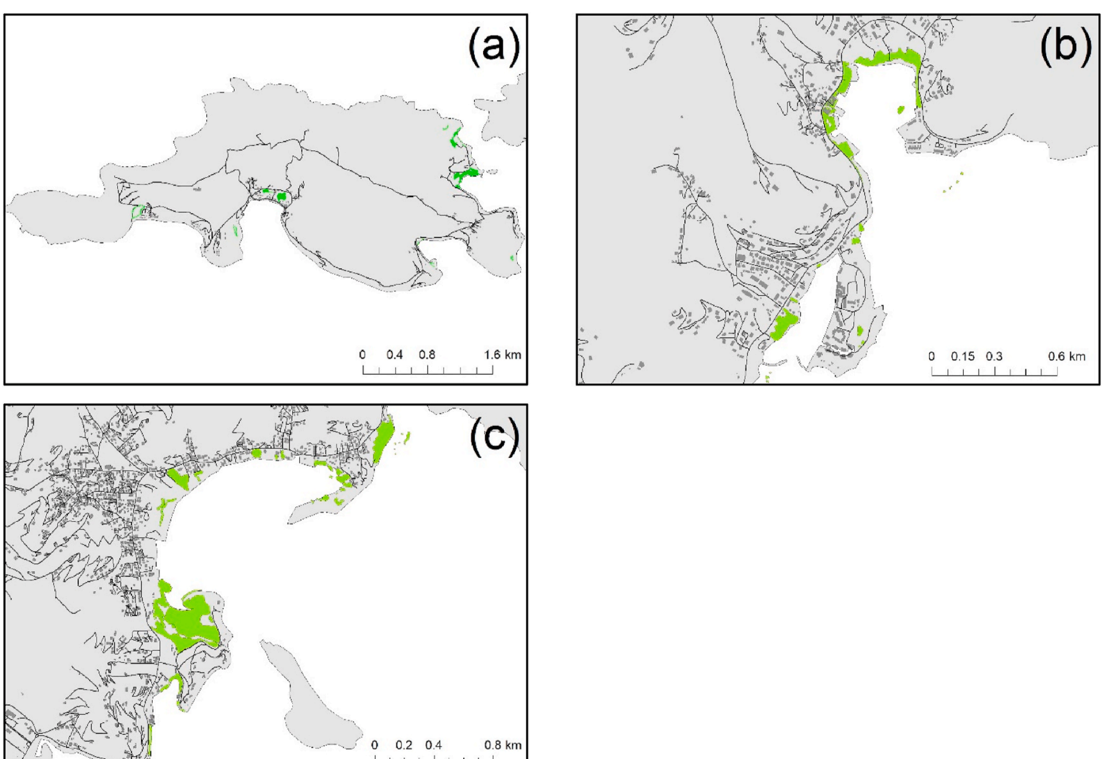

Fig. 3. Mangrove areas (highlighted in green) on (a) the island of Jost Van Dyke, (b) Sea Cows Bay and (c) East End. Roads and other infrastructure are shown in dark grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Methods

2.1. Target communities

In January 2020, the three target communities (Fig. 2) were visited and the boundaries of existing mangrove areas (composed of red mangrove *Rhizophora mangle*, white mangrove *Laguncularia racemosa*, black mangrove *Avicennia germinans* and buttonwood *Conocarpus erectus*) were recorded with a hand held GPS (Garmen etrex® 10)

2.1.1. Jost Van Dyke

The island of Jost Van Dyke has six salt ponds all with associated mangrove communities, the most extensive being those associated with the ponds at Great Harbour and Cape Wright (located on the North-East coastline). The largest mangrove area on Jost Van Dyke occurs alongside the coastline at Bakers Bay/Long Bay (Fig. 3a).

2.1.2. Sea Cows Bay

The Sea Cows Bay community is located approximately 2.6 km west of the main commercial, financial and administrative hub of Road Town, Tortola. This community ranked as the highest on the Strategic Targeting Methodology community selection tool (DDM 2014) due to the high risk of flooding and poor waste management problems. The community is also known for having an economically vulnerable population, with a high proportion of Spanish speaking members, of which many are migrants and live in vulnerable conditions (Red Cross 2019).

The mangroves within the Sea Cows Bay area are predominately restricted to fringing areas around the coastline with the most significant areas located within the Bay and around Nanny Cay Marina and hotel resort (Fig. 3b). None of the existing areas are extensive and have been significantly reduced by coastal development (Honourable Julian Fraser, pers. comm).

2.1.3. East End

The East End/Long Look community is located on the South-East coastline of Tortola. The boundaries of the community extend generally from Fat Hogs Bay in the west towards Beef Island in the east. This area ranked as one of the three highest on the Strategic Targeting Methodology community selection tool (DDM 2014) due to its low elevation, and relatively dense housing distributed in low-lying areas.

Of the three target communities, this area contains the most extensive mangrove areas, indeed the mangroves located within Fat Hogs Bay and to the North of the bay are some of the most extensive in Tortola.

2.2. Assessment of mangrove recovery at the target sites post-Irma

Remotely sensed satellite imagery (Copernicus Sentinel-2 imagery) was used to assess the recovery of mangrove sites in the BVI, using a time-series of the normalised difference vegetation index (NDVI). This index has been employed in several studies as a proxy to monitor temporal mangrove canopy as it has been shown to highly correlate with canopy closure in mangroves. As such, this measure has been used to monitor deforestation, degradation and responses to climatic disturbances, such as cyclones in mangrove forests (Long et al., 2016; Pettorelli, 2006; Satyanarayana et al., 2011). Often used as a 'greenness' index, NDVI measures the absorbance of red (visible) light by chlorophyll and the reflection of the near-infrared by the mesophyll leaf structure. NDVI exploits the contrasting characteristics of the red and near-infrared (NIR) spectral bands and is calculated using the following formula: $NDVI = (NIR - RED)/(NIR + RED)$. Output values range from -1 to $+1$, where any value below zero does not correspond to green vegetation (Long et al., 2016). Dense closed canopy tropical forests tend to produce values closer to 1, whilst sparsely vegetated areas, or open shrub tend to have lower values (0.2–0.3) (Pettorelli et al., 2005). While seasonal variations may occur a healthy dense mangrove canopy produces maximum values of approximately 0.7 (Satyanarayana et al., 2011). Following on-the ground GPS delineation of mangrove areas at the three target communities, we selected the most cloud-free Sentinel-2 imagery closest in date to September 2016 (a year before Hurricane Irma) and within 3 months following Irma, we then accessed an image from the closest date as possible to the 2017 image in 2018 and again in 2019. We calculated the response of mangroves to Hurricane Irma by first calculating a mean pre-hurricane season reference NDVI value for each mangrove polygon identified and compared this to the NDVI values post-Irma and again in 2019. Any areas experiencing a decline of >0.2 between 2016 and 2017 were identified as being seriously impacted by the Hurricane Irma (Taillie et al., 2020).

2.3. Flood risk analysis

Storm surge and ground sea vulnerability modelling was performed based on the principle of cost distance analysis, using the SENCE (Spatial Evidence for Natural Capital Evaluation) methodology (Williams et al., 2017). The model focusses on a cost distance algorithm, which estimates the difficulty of moving from one cell to another by assigning each pixel of a cost raster with an ecological resistance value (Adriaensen et al., 2003). This value denotes the difficulty for an organism or its reluctance to cross the map cell, and it is generally determined based on the substrate type it represents, thus representing the general path of least resistance of storm surges or ground sea waves. Indicators, such as topographic slope, seafloor roughness, exposure, and habitat data, are scored based on how effective they are at resisting the progression of a storm surge wave. For example, steeper slopes are scored higher than shallower slopes; red mangroves are scored higher than bare sand (Appendix 1 & 2). The individual scored datasets are combined to create a cost surface raster. Sixteen of these were created—one for each cardinal, ordinal, and inter-ordinal direction. Cost distance modelling evaluates the accumulated difficulty of moving through a space based on the values of the cost surface raster. For these models, this means that a wave that hits the shore that has only travelled across smooth, level bare substrate sand, will have a significantly easier path (and a lower cost value) than a wave that has travelled across and over rough, steep and jagged coral. Sixteen models were created, again for each direction, cardinal directions were weighted based on the predominant in-coming directions, frequency, and intensity, of historic storms passing within 100 mile radius from the BVI recorded over the past 100 years collated from International Best Track Archive for Climate Stewardship (IBTrACS) Modelling. The outputs were combined into a single vulnerability composite dataset based on the direction, frequency, and intensity of historical hurricane activity. Ground sea flood maps were created in the same way except focused on three predominant cardinal, ordinal, and inter-ordinal directions that ground seas are reported to

Table 1
The data used to create opportunity models for mangrove restoration.

Terrestrial habitat data	Distance from salt ponds
Marine habitat data	Distance from seagrass beds
Distance from dry channels	Soil type
Distance from coastline	Topographic elevation
Distance from coral reefs	Topographic slope
	International Best Track Archive for Climate Stewardship (IBTrACS) Modelling
Distance from existing mangroves	

occur in the Virgin Islands (N, NE and NNE).

2.4. Opportunity mapping

Opportunity modelling employs the SENCE methodology to ecosystem service mapping, where the contribution of each area of land to the opportunity under consideration is evaluated and scored into a simple categorisation of high, medium and low effect. Input data for these models are given in Table 1 (and ranges used in Appendix 1 & 2). The opportunity areas for replanting mangroves were modelled using two species red mangrove and buttonwood. A distinct zonation of the three Caribbean mangrove species; red mangrove, white mangrove, and black mangrove and the salt-tolerant buttonwood is observed in most Caribbean mangrove forests, with red mangrove, as the most salt tolerant, growing in and along the coast and buttonwood, being the least salt tolerant, found the furthest inland. Thus, the combined opportunity areas for both species will also encompass suitable areas for black and white mangroves, which are typically found landward of red mangrove and seaward of buttonwood. Opportunity areas will also encompass areas that already support mangrove communities.

Using this approach, each dataset attribute is scored on the basis of how easy it is to restore and/or establish red mangrove and buttonwood. For example, existing mangroves are scored very high and buildings/ roads are scored very low; close proximity of the coast/mangroves/salt ponds are scored very high; steep slopes are scored very low (Appendix 1 & 2). The scored datasets are evaluated against one another. The minimum value found across all scored datasets in the same location, is the output opportunity model value. For example, if all but one of the input datasets suggest the highest opportunity score, but the area is situated on a steep slope (i.e. has a scored value of no opportunity), then that pixel takes the value of the lowest opportunity (i.e. 0 /no opportunity).

2.5. Modelling the impact of restoring mangroves on local communities

The same input data as the baseline storm surge modelling is used with the following exception: any terrestrial/marine habitats within the focal communities that are identified as having a restoration opportunity, is scored as being red mangrove. This would mean that areas that are currently bare sand but could have mangroves established are reclassified as such and have their cost surface raster scores changed from low to very high). The cost distance modelling continues as per the baseline (see section 2.3), so that the only factor changed is the habitat cover type. The impact of restoring mangroves in opportunity areas on each community's vulnerability to storm surge is calculated by evaluating the difference between the baseline storm surge model and opportunity storm surge models (after the weightings, but before they are normalised). Therefore, small differences have lower impact, large differences have higher impact. The differences layers are normalised to values of 0 and 100 for ease of interpretation, as the output values are unitless. Areas that are predicted to receive protection from storm surges if mangroves were restored were overlaid with maps and infrastructure shapefiles to highlight the impact that mangrove restoration could have on reducing the flood risk for local communities.

3. Results

3.1. Recovery of mangroves post-Hurricane Irma

An area of approximately 0.3 km^2 of mangrove was recorded across the three priority sites (0.03 km^2 on Jost Van Dyke, 0.06 km^2 at Sea Cows Bay and 0.2 km^2 at the East End (Fig. 3). The total area experiencing impact from Hurricane Irma (i.e. mangrove areas experiencing NDVI decreases greater than or equal to 0.2 between pre-Irma and post-Irma) represented 75% of the identified mangrove area on Jost Van Dyke 79% of the area at Sea Cows Bay and 94% of the area at the East End. All sites had shown some signs of recovery one year following Irma but none had recovered to pre-Irma levels by 2019. Interestingly some areas had declined between the post-Irma analysis and 2019 –reflecting a threat other than storm damage (Fig. 4). In addition, ground surveys in 2020 identified a high presence of the invasive fast-growing seaside mahoe *Thespesia populnea* (Santos and Fabricante 2018) growing in damaged red mangrove sites, which could falsely elevate NDVI values in the remotely sensed imagery to indicate a value consistent with a dramatic or uncharacteristic recovery of mangroves that is not actually occurring.

3.2. Flood risk analysis

Flood risk analysis identified that the North-East Coast of Tortola is more prone to flooding from storm surges, while the South-East coastline is more prone to flooding by ground seas (Fig. 5). Focusing on the three priority communities, we found that Sea Cows Bay and East End

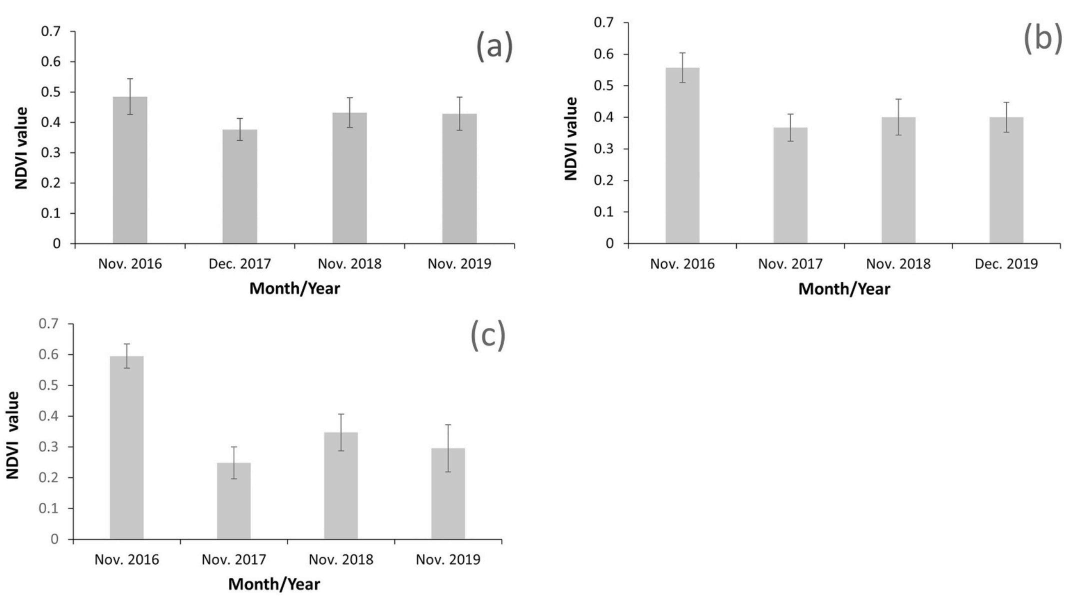

Fig. 4. Average NDVI (±SEM) values were higher pre-Hurricane Irma at mangrove sites located on (a) Jost Van Dyke, (b) Sea Cows Bay and (c) East End, none of the sites appear to have recovered to pre-Irma NDVI values even two years post-Irma. Dotted black line indicates the passing of Hurricane Irma in September 2017.

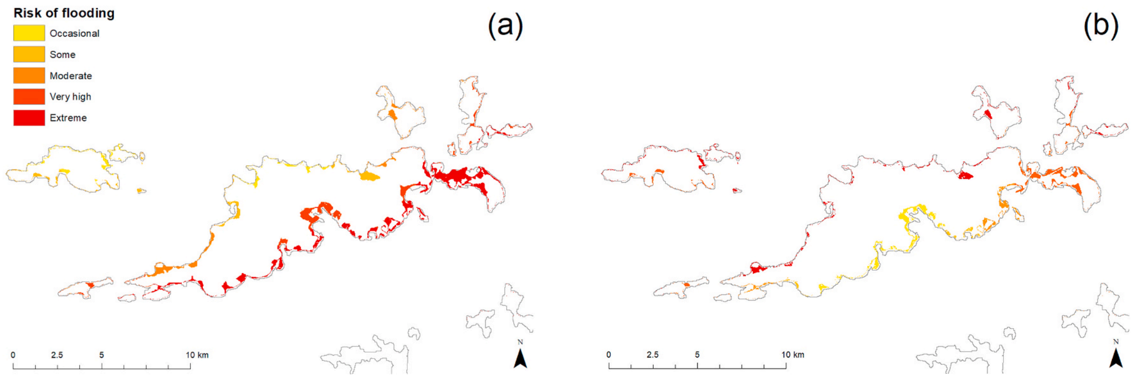

Fig. 5. Map highlighting the coastline's risk of flooding due to (a) storm surge and (b) extra-tropical storms.

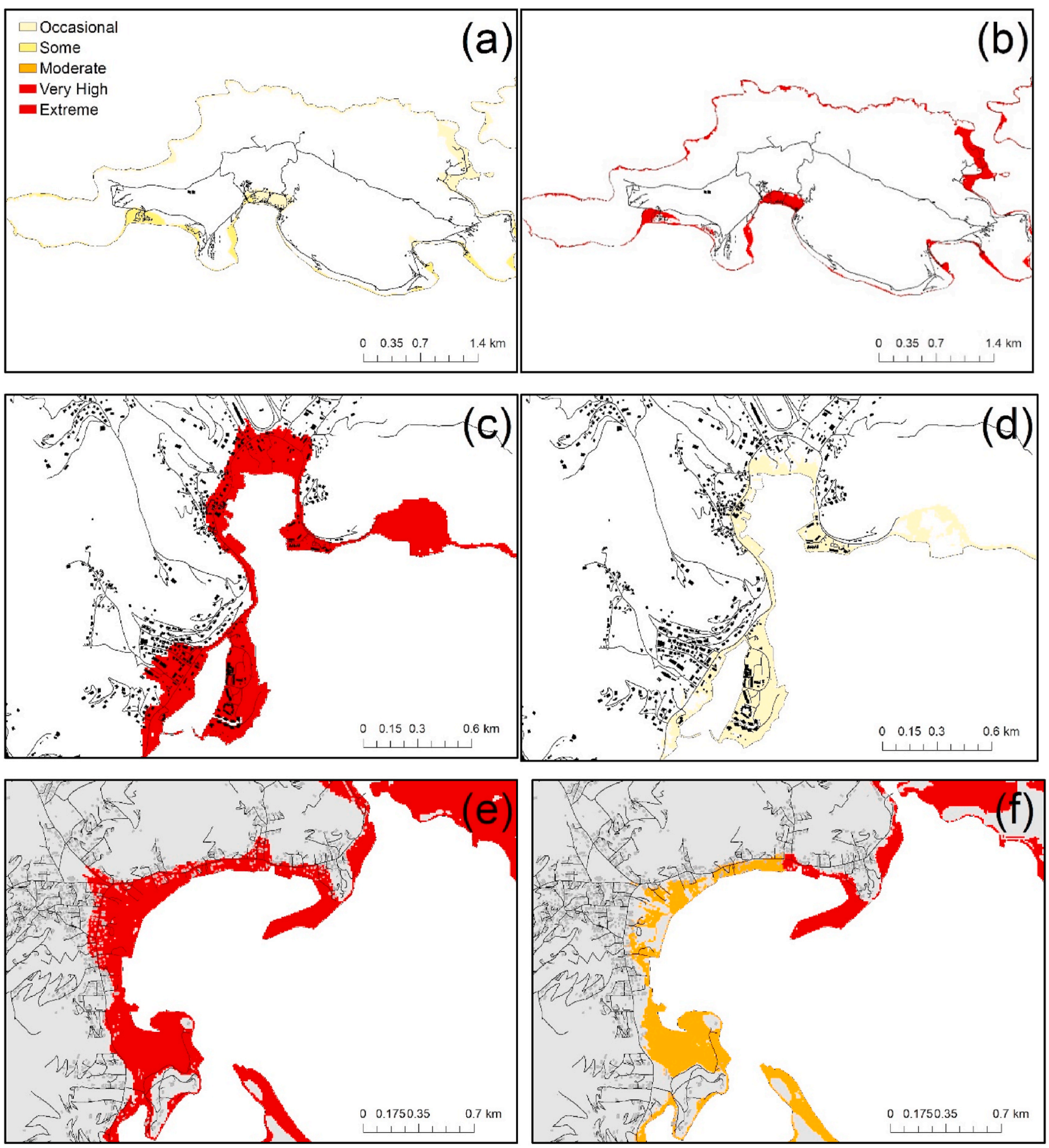

Fig. 6. Flood risk from storm surge (left hand panels) and extra-tropical storms (right-hand panels) for (a–b) Jost Van Dyke, (c–d) Sea Cows Bay and (e–f) East End.

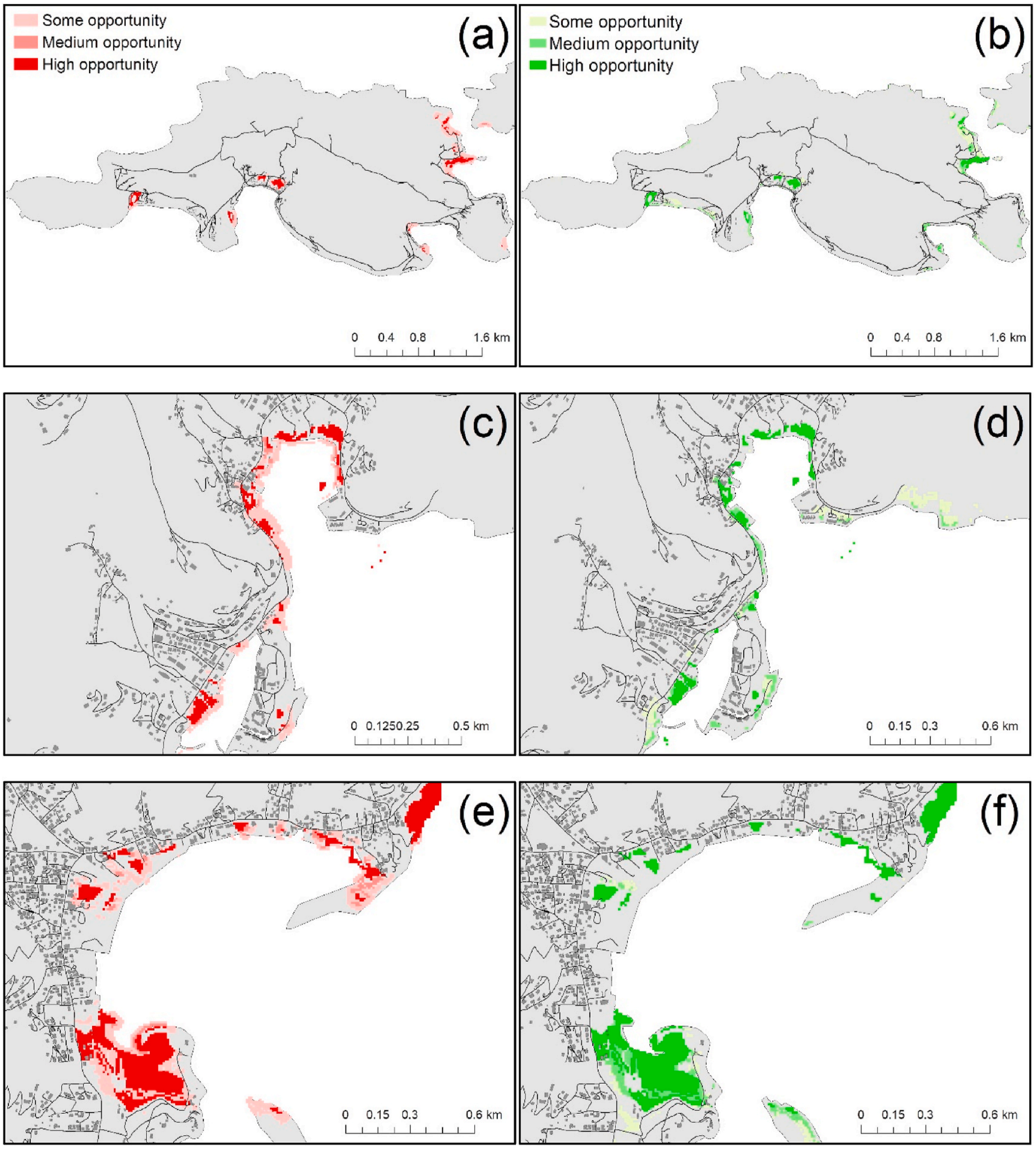

Fig. 7. Opportunity maps for red mangrove restoration (left hand panels) and buttonwood (right hand panel) on (a–b) Jost Van Dyke, (c–d) Sea Cows Bay and (d–e) East End. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

are the most vulnerable to flooding from storm surges, while Jost Van Dyke is most vulnerable to flooding from ground seas (Fig. 6).

3.3. Mangrove opportunity mapping

A total area of 2.8 km^2 was identified as being suitable for red mangrove restoration and 4.6 km^2 as being suitable for buttonwood restoration within the three priority communities. Less than 10% of the opportunity area for mangroves already contained mangrove species on Jost Van Dyke, while 76% and 55% of opportunity areas already contained mangroves at Sea Cows Bay and East End respectively (Fig. 7).

3.4. Modelling the impact of restoring mangroves on local communities

The restoration of red mangrove at identified opportunity areas has the potential to provide flood protection up to 200 m inland at the inhabited areas of Great Harbour and White Bay, Jost Van Dyke, 300 m inland at Sea Cows Bay and 475 m inland at the East End. If mangroves are restored in all identified opportunity areas at least 167 buildings located on Jost Van Dyke are predicted to receive increased protection from flooding (including a primary school, a church, water and sewage works, a police station and a fire station), while 285 buildings will benefit from a reduced flood risk in Sea Cows Bay (including a clinic, a secondary school and two places of worship) and 268 buildings receive protection at East End (including one primary school, a public library, a police station and three places of worship) (Fig. 8).

4. Discussion

Despite their importance, mangroves are globally threatened by land development, pollution, natural disasters, and the various effects of climate change. At least 35% of mangrove forest area was lost worldwide during the 1980s and 1990s alone with losses of 50–80% in some regions (Valiela et al., 2001). The unprecedented loss of mangroves will have huge impacts on biodiversity, and ecosystem services including the ability of this natural sea defence to defend our shores and coastal

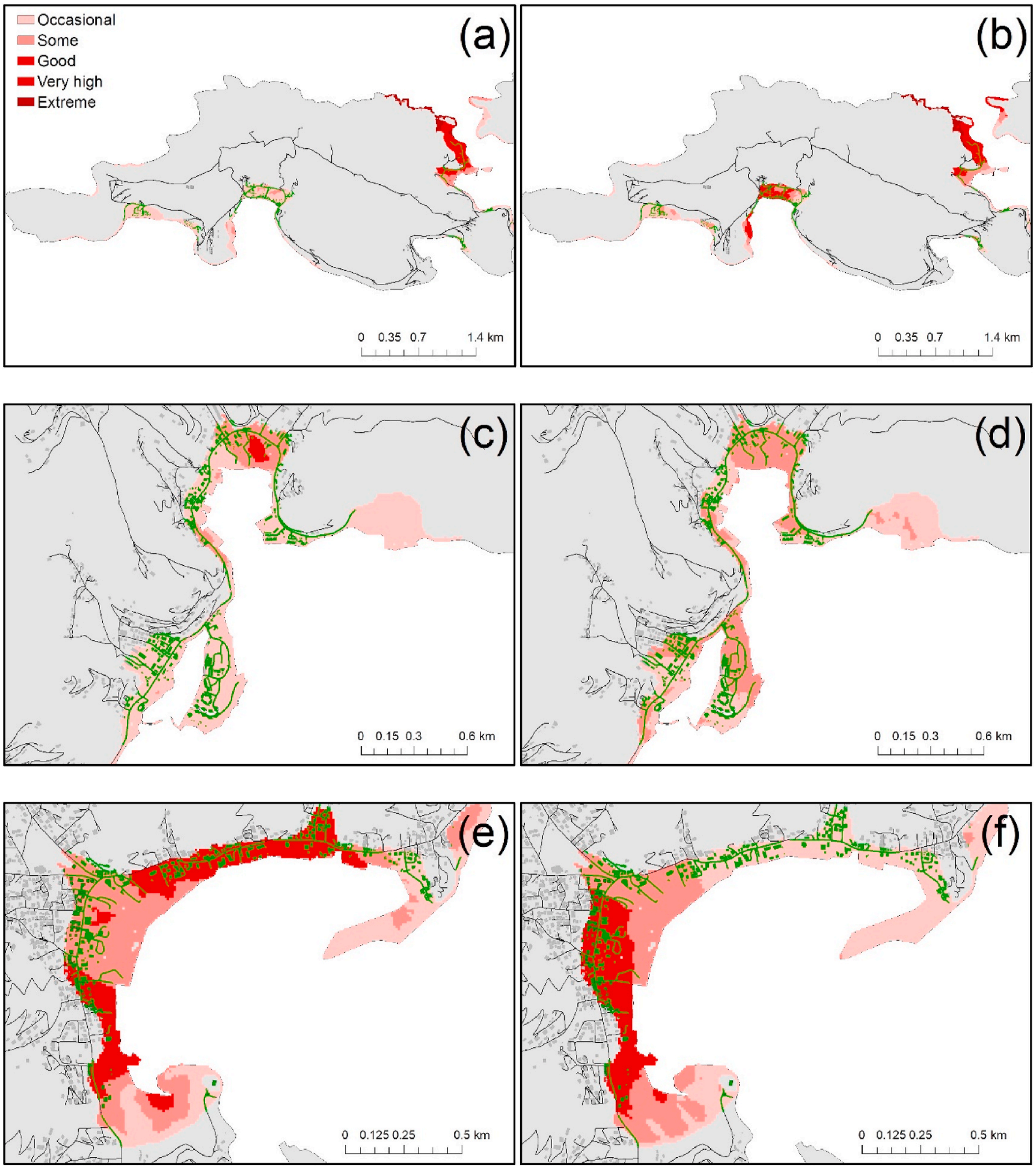

Fig. 8. Flood protection provided if red mangroves are restored at identified opportunity areas (left hand panels) and if buttonwood are restored at identified opportunity areas (right hand panel) on (a–b) Jost Van Dyke, (c–d) Sea Cows Bay and (d–e) East End. Buildings and roads are highlighted in green while shades of pink highlight the level of protection provided by mangrove restoration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

communities.

While mangroves are one of the world's most vital ecosystems – their complexity also makes them more difficult to restore than typical land-based forests (Yap, 2000). Across the globe hundreds and sometimes thousands of volunteers have been involved in mass mangrove replanting efforts that gain media attention and even earning entries into the Guinness Book of Records (IUCN, 2013). While these efforts have drawn attention to the urgent need to address the global degradation of coastal ecosystems many have failed due to lack of understanding of the complexities of the restoration sites, have focused on monospecific plantations and/or do not consider long-term monitoring and management as components of restoration. For example, a study comparing the structural development of the large-sale plantations in the Philippines compared replanted sites with adjacent natural mangrove forests and found that the 'restored' forest has significantly lower structural development and complexity that the naturally restored sites-even 60 years after restoration activities (Barnuevo et al., 2017). With often limited financial resources it is important that coastal restoration be undertaken at the most suitable sites, using the most suitable species and methods to ensure that any restoration effort can provide the most benefit in building resilience, supporting biodiversity and providing other ecosystem services.

Storms are a normal part of tropical island life, and mangroves are well adapted to respond and recover to occasional extreme weather events (Spalding et al., 2014). However, in the short-term, the natural regeneration of the Virgin Island's severely impacted mangroves is unlikely to be effective. This is due to the level of devastation that occurred during Hurricane Irma and Maria in 2017 and the lack of natural recovery recorded even after two years (Moore and Zalsuki 2018). Reasons for the observed slow/lack of recovery include the limited number of red mangrove propagules observed across the Territory, the low persistence of mangrove seeds in the soil seed banks (Harun-or-Rashid et al., 2009) and the presence of the invasive seaside mahoe. The scale of destruction caused by Hurricane Irma in 2017, with USD$290 million worth of damage to infrastructure reported (ECLAC 2018), the lack of observed mangrove recovery, coupled with reports that the Caribbean region is forecast to incur more damage than any other region from future hurricanes, has highlighted to local policy makers the urgent need to act quickly in restoring and protecting mangroves to ensure their effectiveness as buffers against future storms (Taillie et al., 2020). Thus, to assist in the restoration of mangroves, with the aim of increasing coastal resilience to future storms and flooding, immediate action should now be initiated to expedite the process of natural recovery. However, as is common in environmental management, the process of conducting restoration work or conservation action is limited by both financial and personnel restraints. In addition, any activity that uses Territory finances and personnel should be based on an approach that is likely to yield the most in terms of success. The ecologically based modelling approach presented addresses these issues by producing opportunity maps that identify areas most suitable for mangrove re-plantings. Some of the areas identified represent existing mangrove areas that should be prioritised for restoration, while other areas appear suitable for new restoration efforts. The identification of opportunity areas can also aid in the development of mangrove nurseries by providing an estimate of potential restoration areas that can be used to estimate the number of seedlings required to achieve successful restoration of sites.

Previous research has identified large land areas suitable for mangrove restoration across the globe (Worthington and Spalding, 2017); others have promoted the value of relatively large mangrove forests in providing protection against flooding. For example, re-planting of mangroves with an approximate width of 60 m reduced storm surge in coastal Bangladesh (Dasgupta et al., 2019), and a mangrove forest ranging from 6 to 30 m wide reportedly provided coastal protection from Hurricane Wilma that hit South Florida in 2005 (Zhang et al., 2012). For small islands states in the Caribbean, such large-scale restoration projects may not be viable given high levels of coastal development; however, our modelling shows that theoretically even small-scale restoration efforts of areas encompassing a few m^2 can also be effective in providing protective services for coastal populations.

The benefits of healthy coastal ecosystems in enhancing resilience of coastal communities is well reported and understood by the scientific community but is often less well understood at the community level where action must take place. While the 2017 storm season certainly made local communities in the Virgin Islands more aware of the potentially devastating effects that storm surges can have on the islands' coastlines, it is hard for most lay-people to visualise or fully comprehend the potential benefits that mitigation action can have against the risks of future storm surges and severe hurricanes. Sheppard (2005) identified several problems that are frequently encountered in the communication of climate change risks and in the promotion of environmental-based mitigation measures or in enacting local communities to take action to mitigate risks. These include (1) the available scientific data being often too complex to be understandable, (2) that most of the available information is of a biophysical nature, with few specifics on socio-economic scenarios, and (3) that often the information provided detailing risks/-threats is not usually accompanied with manageable, achievable mitigation options. The potential use of visual aids to accelerate social learning and motivate implementation of policy, technological and life-style changes has begun to be recognised. For example, Altinay and Williams (2019) suggest that visual cues can shape public understanding of coastal change and its risk to coastal communities, particularly images that refer to future environmental conditions are more likely to convey the urgency and importance of an issue. In addition, images that emphasise environmental and economic losses may be more engaging to an audience. A major output of this work is the production of flood vulnerability maps that highlight the infrastructure within each community that are likely to receive some protection from flooding even if relatively small areas of mangroves are protected/restored. This visual output has been key in engaging local government policy makers and local community stakeholders is recognising the value of coastal habitats in the Virgin Islands and will be used going forward to lobby both Government and local landowners to adopt practices that protect and restore these key sites.

5. Conclusion

Adapting to climate change is among the biggest challenges that humanity faces in the next century. An overwhelming focus of adaptation strategies to reduce climate change-related hazards has been on hard-engineering structures such as sea walls, irrigation infrastructure and dams. Closer attention to a broader spectrum of adaptation options is urgently needed. In particular, ecosystem-based adaptation approaches that provide flexible, cost-effective and broadly applicable alternatives for buffering the impacts of climate change, while overcoming many drawbacks of hard infrastructure (Jones et al., 2012). The ecologically based models used in this study to inform mangrove restoration at three of the most vulnerable communities in the Virgin Islands has informed a national mangrove restoration plan, and this work serves as a successful pilot that could be expanded throughout the region. Building on this work, it is also important to consider the 'power of three' as stated by Guannel et al. (2016) who reported on the effectiveness of a combination of healthy coral reefs, seagrass and mangrove forests in protecting coastlines from storm surges. While this study focused on the impact that mangrove restoration could have on reducing flood risk the flood risk vulnerability modelling can easily be adapted and applied to any coastal habitat. Presenting opportunity maps that highlight areas suitable for coral reef, sea grass and sand dune restoration and then the production of vulnerability maps that highlight the protective value of a healthy coastal and marine ecosystem are useful tools that can be used by natural resource managers, local communities and governments to prioritise restoration activities and advocate for the restoration and protection of coastal and marine habitats.

Declaration of competing interest

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.

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Appendix 1. Classification of terrestrial and marine habitats used to create opportunity models to highlight potential areas suitable for the restoration of red mangroves inland, in coastal areas (offshore) and buttonwood mangroves. Score of 0 = not suitable for mangrove restoration; Score of 1 = optimum habitat for establishing mangroves, score of −1 = mangroves already present

Habitat Type	Red Mangrove, Inland	Red Mangrove, Offshore	Buttonwood Mangrove
Coral rock	0	0	0
Algae	1	1	0
Soft coral	0	0	0
Other coral	0	0	0
Mangrove	−1	−1	−1
Beach rock	1	1	0
Montastrea	0	0	0
Sand	1	1	0
Terriginous rock	1	1	0
Mud	3	3	0
Acropora	0	0	0
Seagrass	1	1	0
Channel	0	0	0
Mangrove, red	−1	−1	−1
Coastal grassland	1	1	1
Herbaceous agriculture/cultivated land	0	0	0
Road	0	0	0
Coastal evergreen shrubland	1	1	2
Open water	3	3	0
Disturbed ground	0	0	0
Coastal sand and rock	1	1	2
Building	0	0	0
Other developed land	0	0	0
Buttonwood	1	1	−1
Mangrove, white	−1	−1	−1
Mangrove	−1	−1	−1
Semi-deciduous forest	0	0	0
Drought deciduous dry forest	0	0	0
Shrubland	0	0	0
Gallery forest	0	0	0
Upland evergreen forest	0	0	0
Mangrove, black	−1	−1	−1
Salt pond	3	3	0
Salt Pond	3	3	0
Cliff	0	0	0
Infrastructure	0	0	0
Sand	1	1	2
Mineral Soil	2	2	2
Stoney Beach	1	1	1
Derelict coral	1	1	1

Appendix 2. Model parameters used to create opportunity maps that highlight areas where red mangroves could be established at both inland, and coastal areas and also where buttonwoods could be established

For example, we scored areas 0–10-m from a freshwater channel as the most suitable (optimum sites) for the restoration of red mangroves, while those more than 70-m from a channel were considered unsuitable.

	Parameter thresholds for red mangrove restoration at coastal sites			
	Not suitable	Low suitability	Moderately suitable	Optimum conditions
Distance to freshwater channel	70+ m	30–70m	10–30 m	0–10m
Distance to ponds/existing mangroves	40+ m	20–40m	0–20	−10-0
Elevation	1m +	0.3–1m	-1 to −0.3m	−0.3-0.3m
Slope	5°	–	3–5°	0–3°
	Parameter thresholds for red mangrove restoration at inland sites			
	Not suitable	Low suitability	Moderately suitable	Optimum conditions
Distance to reef	20+ m	–	–	0–20 m
Distance to land	20+ m	–	10–20 m	1–10 m
Distance to ponds/existing mangroves	40+ m	20–40 m	0–20 m	−10 - 0
Distance to seagrass	20+ m	–	–	0–20m
Elevation	1m+	0.3–1m	-1 to −0.3m	−0.3- 0.3m
Slope (degrees)	5°		3–5°	0–3°
	Parameter thresholds for buttonwood mangroves			
	Not suitable	Low suitability	Moderately suitable	Optimum conditions
Distance to ponds/existing mangroves	100+ m	–	30–100m	0–30m

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