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Building a mangrove ecosystem monitoring tool for managers using Sentinel-2 imagery in Google Earth Engine

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ABSTRACT

Mangroves are among the most productive ecosystems worldwide, providing numerous ecological and socio-economic co-benefits. Though highly adapted to fluctuating environmental conditions, increasing disturbances from climate change and human activities have caused significant losses. With increasing environmental uncertainties, adaptive management is necessary to monitor and evaluate changes, and to understand drivers of mangrove decline. Effective management requires access to accurate, current, and multitemporal data on mangrove cover, but such data is often lacking or inaccessible to managers. We present mangrove cover maps for Puerto Rico, the U.S. Virgin Islands, and the British Virgin Islands for the years 2020, 2021, and 2022. We used the Random Forest machine learning technique in Google Earth Engine (GEE) to classify Sentinel-2 multispectral imagery (MSI) and created mangrove vegetation maps at 10 m resolution, with classification accuracies greater than 85%. We host and present the maps in an easy-to-use GEE decision support tool (DST) for managers and policy makers that allows for evaluation of change over time. We also provide a mapping workflow fully implemented in GEE that allows for the production of subsequent maps with minimal technical expertise required. The DST and mapping workflow can help users to detect impacts of disturbances on mangrove vegetation and to monitor progress of conservation interventions such as rehabilitation or legal protection. Furthermore, our mapping approach differentiates between intact and degraded mangrove vegetation, and the increased spatial resolution of Sentinel-2 MSI imagery allowed us to capture mangrove patches that had not been previously mapped by studies using coarser resolution imagery. Our assessment of mangrove cover change between years indicated patterns of loss and recovery likely associated with disturbances, natural recovery and/or human driven restoration.

1. Introduction

Mangroves are a diverse group of halophytic plant species occurring between mean sea level and the highest spring tide mark along tropical and sub-tropical coastlines and estuaries (Tomlinson, 1994). They provide critical ecosystem services such as nursery grounds to key fisheries species (Serafy et al., 2015) that support food security and livelihoods of coastal communities (zu Ermgassen et al., 2020). They also act as a natural climate solution by providing protection to coastal communities from flood (Menéndez et al., 2020) and storm events (Das and Crépin, 2013; Del Valle et al., 2020), threats that are expected to intensify with continued climate change. Yet, mangrove ecosystems are themselves

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under continuous threats from human and environmental stressors. For example, sea-level rise (SLR) and increasing frequency of high-intensity hurricanes (Krauss et al., 2023; Jewson, 2023; Saintilan et al., 2020; Vosper et al., 2020), hydrological impairment and degradation (Jaramillo et al., 2018; López-Portillo et al., 2021), among other factors, threaten mangrove populations in the Caribbean. To facilitate adaptive management, it is critical to understand how mangroves respond to such stressors. This requires consistent, accurate and multitemporal data to assess mangrove condition (i.e., degradation and recovery) and to track cover change associated with environmental and human stressors (Simpson et al., 2021; Yando et al., 2021). On the ground monitoring can be time intensive and inefficient over extensive or inaccessible areas, but remote monitoring through unmanned aerial vehicles and satellite data offers a more efficient and cost-effective approach. Validated maps can be used for blue carbon assessments and evaluation of natural recovery and restoration success (Alexandris et al., 2013; Gatt et al., 2022; Morrissette et al., 2023). Global scale maps are useful for tracking overall trends, but frequently miss small mangrove patches (e.g., narrow fringe, small cays) and therefore may underestimate total mangrove cover (Cissell et al., 2021), an issue of relevance for small island mangrove systems, like those found in the Caribbean. Mangroves have essential roles for coastal communities in Caribbean islands (Menéndez et al., 2020; Soanes et al., 2021) despite having low percent cover (e.g., the Global Mangrove Watch estimated Puerto Rico at 82.8 km^2 in 2016). Therefore, mapping these areas at higher resolution with verified ground data is important for accuracy of mapping efforts, which can then be used to inform their management and contribute to climate adaptation and disaster risk reduction strategies.

Historical trends indicate rapid decline of mangrove cover and increased fragmentation globally, primarily associated with anthropogenic land use changes such as agriculture (Thomas et al., 2017; Bryan-Brown et al., 2020) and coastal development (e.g., human settlements, tourism) (Branoff and Martinuzzi, 2020). Environmental conditions for mangrove establishment and growth are degrading with increasing stressors from climate change such as accelerated sea-level rise (Saintilan et al., 2020), increased frequencies and intensity of tropical storms (Amaral et al., 2023), and drought (Lagomasino et al., 2021; Mafi-Gholami et al., 2020). Initial impact of storms can cause severe structural damage to mangroves (e.g., broken trunks, missing limbs, defoliation) (Doyle et al., 1995; Hernandez et al., 2020; Krauss and Osland 2020). Furthermore, storm surge sediment deposits and ponding associated with storms have been linked to delayed mangrove mortality (Lagomasino et al., 2021; Radabaugh et al., 2020; Taillie et al., 2020). Additional natural stressors such as herbivory (Rossi et al., 2020) and anthropogenic stressors such as altered hydrology (Radabaugh et al., 2020), coastal squeeze (Schuerch et al., 2018) and pollution (Lovelock et al., 2009) can impede recovery (Krauss et al., 2023). In the past decade, rates of mangrove deforestation have slowed, but future trends are uncertain (Friess et al., 2019) as the impacts of concurrent anthropogenic and climatic stressors are still under investigation. In the Caribbean, the risk of mangrove damage by tropical storms is projected to increase by 10% under global warming scenarios of 2 °C (Mo et al., 2023). Yet, the extent and patterns of current mangrove degradation have not been adequately mapped. Up-to-date maps are especially necessary to assess the extent of damage and to prioritize restoration efforts following disturbances such as storm events.

Mangrove management in the Caribbean is dominated by multi-stakeholder collaborations that include government agencies, research centers, education institutions, non-governmental organizations, and local communities, among others, actively engaged in diverse activities to promote mangrove conservation. Strategies can focus on key aspects such as the restoration and rehabilitation of ecosystems while taking a systems approach to tackling diverse and emerging challenges (Ellison et al., 2020). Research-based initiatives contribute to the development of knowledge and educational opportunities, for example about impacts of climate change (DRNA , 2017). These initiatives have contributed to mangrove conservation success and help inform policy on best management practices. Other strategies focus on community development to reduce pressure on the ecosystem by encouraging adoption of ecosystem friendly livelihood strategies. Some stakeholders have incorporated geospatial tools including remote sensing-based data for the mapping and monitoring of ecosystems (Branoff et al., 2018; DRNA, 2015). While the use of geospatial data has been useful in documenting the status and change of mangroves, the mapping is often limited to development of static habitat or zoning maps, that do not provide for continuous monitoring. Easy access to current data is necessary to detect impacts of emerging threats and to monitor progress of restoration interventions.

As the need for mangrove monitoring increases, a range of mangrove cover products at different spatial and temporal scales have proliferated in recent years. Depending on their spatial and temporal characteristics, these products have supported many mangrove assessment efforts which promote conservation and management interventions. There are several global mangrove cover maps which vary in their resolution (e.g., 10–30m), imagery used (e.g., Landsat, Sentinel-2, L-band Synthetic Aperture Radar), and classification algorithm (e.g., object-based image analysis vs Classification and Regression Tree) (Bunting et al., 2022; Giri et al., 2011; Jia et al., 2023). These global products provide a comprehensive record of mangrove cover appropriate for assessments of mangrove change at large spatial scales. At the regional and national scale, maps can provide increased accuracy and better capture regional-level heterogeneity by including local ground truth data points for model training and verification. At the national level, efforts have focused on specific countries such as Belize (Cherrington et al., 2020; Cissell et al., 2021; Murray et al., 2003) and Colombia (Murillo-Sandoval et al., 2022), among others. Local products include the benthic maps of Puerto Rico and the U.S. Virgin Islands, which includes a mangroves class, created by the NOAA National Centers for Coastal Ocean Science (Kendall et al., 2001). In many cases, assessments of mangrove cover involve merging independently generated products to obtain consistent time series data for change analysis. Merging potentially introduces uncertainties because of differences in spatial extent/resolution, period, and methodologies used. A recent study by Ximenes et al. (2023) found discrepancies among several global products in terms of their longitudinal range limits. Such discrepancies can compromise conclusions from studies trying to understand changing mangrove range limits in response to climate change. Consistent maps through time are therefore a critical requirement for effective mangrove monitoring.

To maximize the integration of science with decision-making, researchers should work in collaboration with managers and policy makers to ensure that the research is relevant and addresses current needs (Alazmi and Alazmi, 2023). Even with extensive research, a key obstacle to evidence-based conservation is the challenge in accessing and/or correctly interpreting and using research findings (Kadykalo et al., 2021). Decision support tools (DSTs) can help to incorporate knowledge generated by researchers into decisions (Schumacher et al., 2020). These tools can act as platforms to implement various frameworks such as assessment of mangrove condition, degradation, and recovery (Yando et al., 2021), tracking of cover change associated with environmental or anthropological stressors (Simpson et al., 2021), and blue carbon assessments with validated maps (Morrissette et al., 2023). However, the use of DSTs is often limited by lack of awareness and experience (Schumacher et al., 2020) among other factors. Easy-to-use DSTs are necessary to improve access to research products and facilitate data-driven ecosystem management.

In this study, we present 10m resolution mangrove cover maps for Puerto Rico, the United States Virgin Islands, and the British Virgin Islands for the years 2020, 2021, and 2022, in an easy-to-use DST for managers. The tool allows for easy access of critical management data to managers and quick assessment of mangrove cover change over time. We adapted and improved a methodology developed by Cissell et al. (2021) to map mangrove extent using Google Earth Engine (GEE) and

10m Sentinel-2 imagery, which is especially useful for enhancing the capture of mangroves on small cays and narrow fringe mangroves, that are characteristic of Caribbean islands, and that have not been extensively mapped before. Our method modifications were particularly valuable in distinguishing between intact and degraded mangrove vegetation; distinction that is necessary for tracking mangrove recovery following disturbances such as storm events. Further, we created a mangrove mapping workflow that is fully implemented in GEE and that is highly adaptable in that it allows for modification to address unique place-based mangrove characteristics such as types and species, and the integration of community/stakeholder map verification data. By adapting the workflow, users can produce subsequent maps as needed to facilitate adaptive management of mangrove ecosystems.

2. Materials and methods

2.1. Study area

The mapping was conducted for Puerto Rico (~8941.25 km^2 total land area), the United States Virgin Islands (USVI) (~346.65 km^2 total land area), and the British Virgin Islands (BVI) (~169.36 km^2 total land area), all of which are located between 64 and 67.5° W, and 17.5 and 19.0° N (Fig. 1). We selected these study areas to extend existing regional efforts of establishing consistent data for mangrove cover monitoring especially following a series of recent storm events. The area's climate is tropical with average seasonal temperatures ranging between 23 °C and 26 °C, which provides ideal conditions for mangrove growth. Rainfall patterns historically include a dry season from December–March and a wet season from April–November (Hernández Ayala and Méndez Tejeda, 2023). A sustained seasonal cycle is important for maintaining salinity balance and enhancing conditions for healthy mangrove growth (Lambs et al., 2015). The complex and mountainous terrain of these islands restricts mangroves to low-lying coastal areas. The dominant mangrove forest types are fringe, salt pond, and basin; riverine, overwash, and dwarf forests are also found in the region (Lugo and Snedaker, 1974; Krauss et al., 2023). True mangrove species in this region consist of red (*Rhizophora mangle*), black (*Avicennia germinans*), and white (*Laguncularia racemosa*), in addition to two mangrove associate species, buttonwood (*Conocarpus erectus*) and seaside mahoe (*Thespesia populnea*) (Martinuzzi et al., 2009; Buob, 2019).

2.2. Methods

Our mapping approach builds upon that of Cissell et al. (2021). We apply the random forest (Breiman, 2001) classification algorithm to Sentinel-2 multispectral imagery (MSI) in the Google Earth Engine (GEE) environment to generate mangrove cover maps for the years 2020, 2021, and 2022. We introduce modifications to the original classification scheme and show improved identification of mangrove cover, including the delineation of degraded mangrove. The current approach incorporates additional steps including extra pre-processing procedures, a new band structure that includes generated bands in addition to native Sentinel-2 bands, and spatial filtering as an additional post-processing step (Fig. 2).

2.2.1. Data preparation

To obtain a cloud free composite image, we calculated the median of all cloud free imagery obtained between January 1st and May 31st for each of the 3 years (2020, 2021, 2022) that we mapped. First, we applied a filter to eliminate images with more than 20% cloud cover. We then eliminated clouds on remaining images by evaluating bits 10 and 11 of the Sentinel-2 cloud mask setting both conditions to exclude areas with opaque and cirrus clouds. We then applied a series of masks on the cloud free composite image to exclude areas unlikely to have mangrove. Water features were excluded by applying a mask based on calculated values of the Normalized Difference Water Index (NDWI) (Gao, 1996), where values greater than zero were open water. Because mangrove vegetation occurs at low elevations mostly along the coastline in saline or brackish water, an elevation mask generated from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used to exclude high elevation areas (>20m above sea level). This resulted in a smaller image that is easier to train on and that potentially reduces classification errors. Additionally, bare, and built-up (non-vegetated) areas were masked out using Normalized Difference Vegetation Index (NDVI) with a threshold set to retain values of 0.1 and above. While NDVI values for healthy vegetation are usually higher than 0.1, we used a value of 0.1 so that degraded mangroves could be detected and included within our analyses. Such areas have the potential to recover, or regenerate over a reasonable time lag following a change in environmental conditions (Alongi, 2008; Onrizal et al., 2017; Twilley et al., 1999), depending on the severity or persistence of disturbances, and presence of surviving diaspore (Fickert, 2020). Furthermore, degraded areas remain relevant for carbon storage (Senger et al., 2021). We did not apply the Normalized Difference Mangrove Index (NDMI) mask as originally used in Cissell et al. (2021) because it excluded some areas of degraded mangroves that were of interest to the current study. However, the NDMI mask could be applied with a higher threshold that does not exclude degraded areas. All data preparation was done within the GEE environment.

2.2.2. Selection of bands

In addition to the native Sentinel-2 bands, additional layers were created and included as bands in the composite image. A histogram of

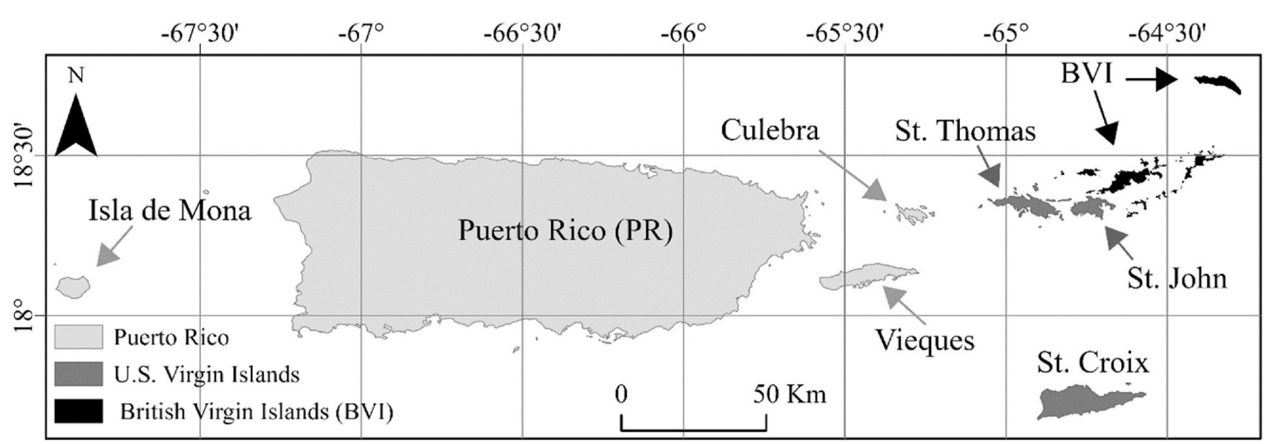

Fig. 1. Study area of Puerto Rico, the United States Virgin Islands (USVI), and the British Virgin Islands (BVI).

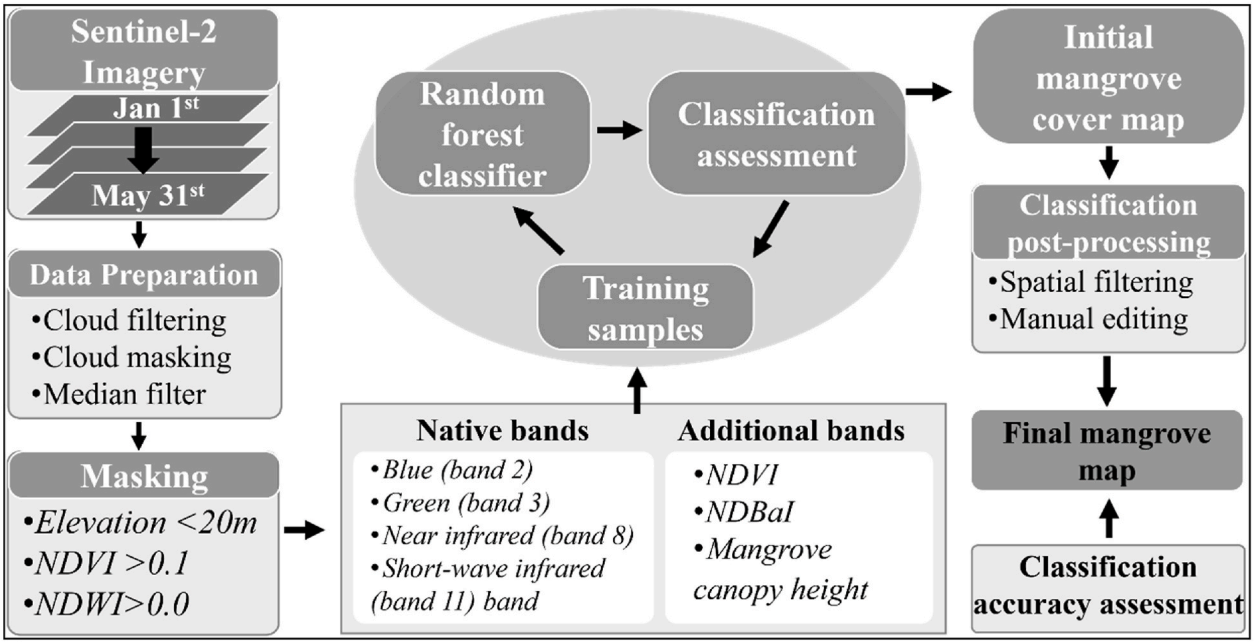

Fig. 2. Data processing and land cover classification workflow.

mangrove pixel values for each band was plotted and used to select the most appropriate bands while eliminating redundant ones. We found that the additional bands improved the identification of mangroves by increasing separability of features. Among the native Sentinel-2 bands, the blue (band 2), green (band 3), near infrared (band 8), and short-wave infrared (band 11) bands were selected for model training and image classification. NDVI, Normalized Difference Bareness Index (NDBaI) (Zhao and Chen, 2005), and mangrove canopy height were included as additional derived bands in the composite image. We calculated mangrove canopy height following the method described in Simard et al. (2019).

2.2.3. Random forest classification

Random forests consist of many relatively uncorrelated models (trees in this case) operating as an ensemble. Each tree produces a class prediction and the model's prediction becomes the class with the most votes (Breiman, 2001). The random forest approach was considered appropriate as it has been proven to have high prediction accuracy and is highly robust against overfitting (Kumari et al., 2023; Rodriguez-Galiano et al., 2012). Moreover, it was readily implemented within the GEE environment to create a standard model structure and workflow that can easily be adapted for other areas. The approach is also consistent with previous regional mangrove mapping efforts (Cissell et al., 2021) allowing for the integration and comparison of data.

An important factor to accurate model predictions is features that have actual signals which allow them to be differentiated. For this study, this required a large enough sample of high-quality training data to represent variability of mangrove conditions to allow for differentiation from other similarly vegetated areas. Training samples were created from the Sentinel-2 imagery as point features. This involved scanning the Sentinel-2 image and identifying different features based on their reflectance characteristics. The samples included three categories of cover types representing intact mangrove, degraded mangrove, and non-mangrove areas. To reduce chances for misclassification due to possible differences in mangrove characteristics, separate samples for each of the USVI and the BVI constituent islands were collected. For each site, we created a random forest classifier while setting the number of iterations/ decision trees to be equal to the number of training samples. The classifier was then applied on the multiband composite image to obtain a classification image with three classes (intact mangrove, degraded mangrove, non-mangrove). The training and classification process was iterative, each time updating the training samples to address obvious misclassifications. Within the paper we present intact and degraded mangrove cover only.

During collection of training samples, we identified contentious areas that we could not decisively label as mangrove vegetation. We conducted a survey of 45 such locations in August 2021 in Puerto Rico to verify vegetation types, each time recording the vegetation types at the exact coordinate location and surrounding area. For areas confirmed to be mangrove, vegetation characteristics of tree density, overall height, and health condition were recorded. The survey data was overlaid on the Sentinel-2 image and used to guide correct labeling of training samples for the contentious locations. Another set of 49 verified sample locations collected through a field survey in St. John, St. Thomas, and St. Croix between August 2021–April 2022 were used to inform correct labeling of training samples specifically for the USVI. The data were crucial in the identification of small fringe mangroves characteristic of the islands.

2.2.4. Assessing mangrove degradation

In this study, degraded areas were defined as those consisting of dead, defoliated, or stressed mangrove vegetation. We determined the extent of mangrove degradation based on the unique spectral reflectance characteristics of vegetation in the near infrared (NIR) region of the electromagnetic spectrum. Vegetation characteristics such as the type, structure, stress, water content, and pubescence of plant leaves influence vegetation reflectance in the NIR (Glass, 2013). During photosynthesis, chlorophyl, which is plentiful in healthy leaves, reflects a high percentage of NIR light from the sun. When plants experience stress, the stomata close reducing carbon dioxide uptake and decreasing photosynthesis (Sharma et al., 2020). Unhealthy plants therefore have less chlorophyl and therefore reflect less NIR light. The difference in reflected NIR light between healthy and unhealthy plants is captured by sensors in remote sensing instruments. Additionally, the hydrologic conditions in degraded mangrove ecosystems can include poor water circulation leading to a build-up of algae and therefore increased scattering of green light, hence a high reflectance in the green band (Klemas, 2012). Collectively, these characteristics allowed us to identify samples for degraded mangroves, and hence separate degraded from intact mangrove vegetation.

2.2.5. Classification post-processing

Image classification often results in isolated pixels due to misclassification or inseparability of features in an image. A mode filter was applied using a 3 by 3 window to eliminate such pixels and smooth out the classified map. Remaining misclassifications were removed through manual edits. In GEE, this involved drawing polygons around the misclassified areas and using the polygons as a mask to exclude the misclassified areas from the mangrove map.

2.2.6. Classification accuracy assessment

To assess the accuracy of the created maps, we first generated 1000 random points (for Puerto Rico) within a 50 m buffer around identified mangrove areas (both intact and degraded). We then independently verified each point through interpretation of the Sentinel-2 imagery and high-resolution Google Earth Imagery, marking them as mangrove or non-mangrove. The verified points formed our reference data and were used to generate a confusion matrix from which an overall accuracy rate was calculated as a measure of the model's prediction performance. The overall accuracy represents the proportion of the reference points that were classified correctly. The 50 m buffer ensured enough non-mangrove samples while concurrently scanning the adjacent area for overlooked mangroves in mixed forest. For the USVI and the BVI, 200 points for each constituent island and a 20m buffer were considered sufficient given the small size of the islands and mangrove coverage.

2.2.7. Change in mangrove cover

We assessed the temporal patterns of mangrove cover change by evaluating the land area occupied by intact and degraded mangrove vegetation for each jurisdiction for the three mapped years. We then calculated the percentage change between time periods to determine relative loss/gain in mangrove cover. In addition, we assessed changes within and outside of protected areas to determine the potential effect of management (protection). To delineate protected areas, we used the world database on protected areas (UNEP-WCMC, 2019) and included only inscribed, adopted, designated, and established protected areas. We mapped spatial patterns of change to show areas of gain and loss between the time periods, and in relation to degradation and recovery of mangrove cover.

2.2.8. Data presentation for managers – Google Earth Engine Application

Using the annual mangrove cover maps, we then designed a public-facing web application in GEE to make data accessible to resource managers and community members. To enhance user-facing monitoring capabilities we developed widgets that allow users to query mangrove cover at a range of spatial (island, municipal boundaries, and protected areas) and temporal (2020–2022) scales.

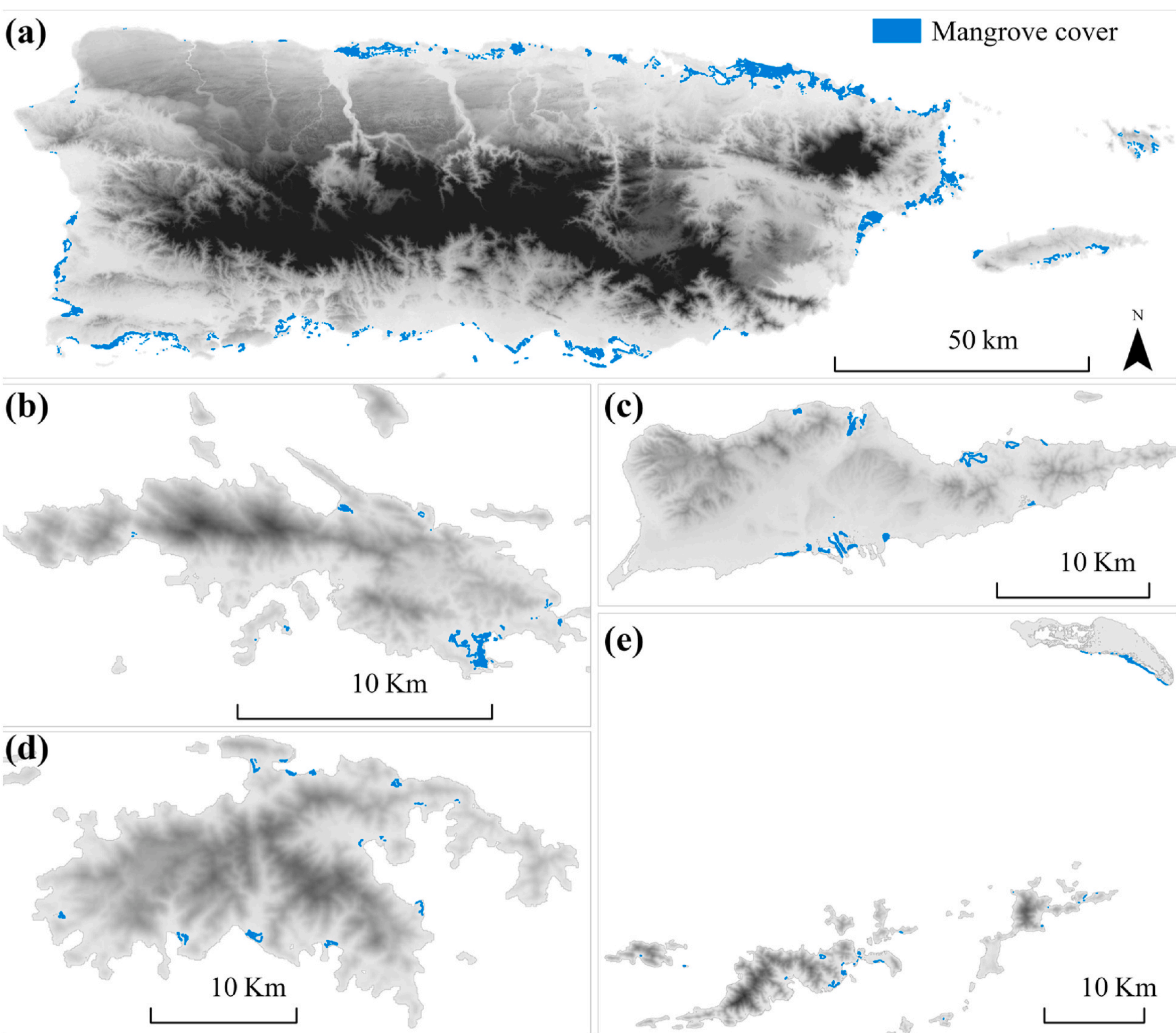

Fig. 3. Mangrove cover maps for the year 2020 for (a) Puerto Rico, the United States Virgin Islands of (b) St. Thomas, (c) St. Croix, and (d) St. John, and (e) the British Virgin Islands.

2.2.9 Strategy for continuous mangrove ecosystem monitoring: Our mapping approach includes a standard routine implemented in the GEE environment, that allows for generation of subsequent maps by users with minimal technical knowledge. We provide a mapping workflow that includes data preparation, classification and pre-processing procedures, all implemented in GEE thus facilitating quick generation of mangrove maps. To generate a map, users would need to define the desired mapping period (range of months or year) and spatial extent. Users can also use available ground validation information such as community/stakeholder reports for assessing and improving mapping accuracy. Map outputs can then be loaded into the GEE decision tool to allow comparison between mangrove covers for different periods.

3. Results

3.1. Mangrove vegetation cover maps and mapping accuracy

We generated mangrove cover maps (Fig. 3) for Puerto Rico, the USVI, and the BVI for the years 2020, 2021, and 2022, all with classification accuracies greater than 85%. In Puerto Rico, extensive areas of intact (non-degraded) mangrove vegetation occurred mostly in the south and northeastern coastal areas (Fig. 3a). In this analysis, 'intact mangrove cover' refers to the extent of healthy mangrove vegetation and 'total' is the whole extent of mangrove ecosystem including both intact and degraded. In the USVI and the BVI, most mangrove vegetation occurred in small patches along the fringes (Fig. 3b–e). Fig. 4 shows the areas of mapped mangrove vegetation, both intact and degraded.

3.2. Changes in the extent of mangrove vegetation cover

We observed a rapid increase (17.87%) of mangrove cover in Puerto Rico between 2020 and 2021, followed by a rapid decline (−13.12%) between 2021 and 2022, with an overall increase (2.41%) between 2020 and 2022 (Fig. 5a). In the USVI, changes in mangrove cover between the years varied by jurisdiction. St. Thomas showed overall increase (24.21%), St. Croix showed overall decline (−14.51%), and St. John showed a small overall decrease (−1.87%) between 2020 and 2022. In the BVI, there was an overall increase (3.68%) between 2020 and 2022.

For all locations combined, more than 75% of mangroves occurred within protected areas (PAs), and less than 25% in unprotected areas (Fig. 5b). In 2021, the proportion of mangroves inside of PAs slightly decreased, and mangroves outside of PAs slightly increased. In 2022, the proportion of mangroves inside of PAs increased, and mangroves outside of PAs decreased. As a general trend, most decreases were observed outside of PAs, and increases inside of PAs.

Mangrove change primarily occurred in small patches within the main extent of the mangrove ecosystem and along the edges of existing mangrove vegetation, with gains and losses observed between consecutive years (Fig. 6). An assessment of changed areas based on high resolution Google Earth imagery showed that most losses were associated with change in mangrove condition (defoliation/death, stress) and some were a result of human activities. Mangrove losses due to human activities occurred primarily along the edges of mangrove ecosystems due to easy access of the edges by surrounding human communities and manifested as a change in land cover to open clearings, agricultural farms, or human development (structures). Gains, on the other hand, were associated with natural recovery or restoration of mangroves in previously degraded areas.

We make two important observations regarding mangrove losses between consecutive years. The first is that change areas between 2020 and 2021 (Fig. 6a) are smaller and occur in fewer patches compared to those between 2021 and 2022 (Fig. 6b). The second is that changes involve shifts between gain and loss (and vice versa) of mangrove vegetation between time intervals, which were mostly related to degradation and recovery of mangrove vegetation. Degradation occurred in patches across the whole mapping extent (Fig. 7). Some patches, especially in Puerto Rico, were relatively extensive. With examples from three areas in Puerto Rico; Pantano Cibuco natural reserve (Fig. 7i), Punta Picua (Fig. 7ii), and Jobos Bay (Fig. 7iii), we show that the extent of the two cover types change from one year to the next as degraded mangroves recover or intact mangroves become degraded.

3.3. Monitoring tool for managers

Leveraging the cloud computing software available with GEE, we created an accessible web mapping application to share our data in a format that is readily available for decision-makers and local community members (Fig. 8). Key features of the application include annual mangrove cover layers from 2020 to 2022; extent of degraded mangrove; coastal administrative boundaries and protected areas (only

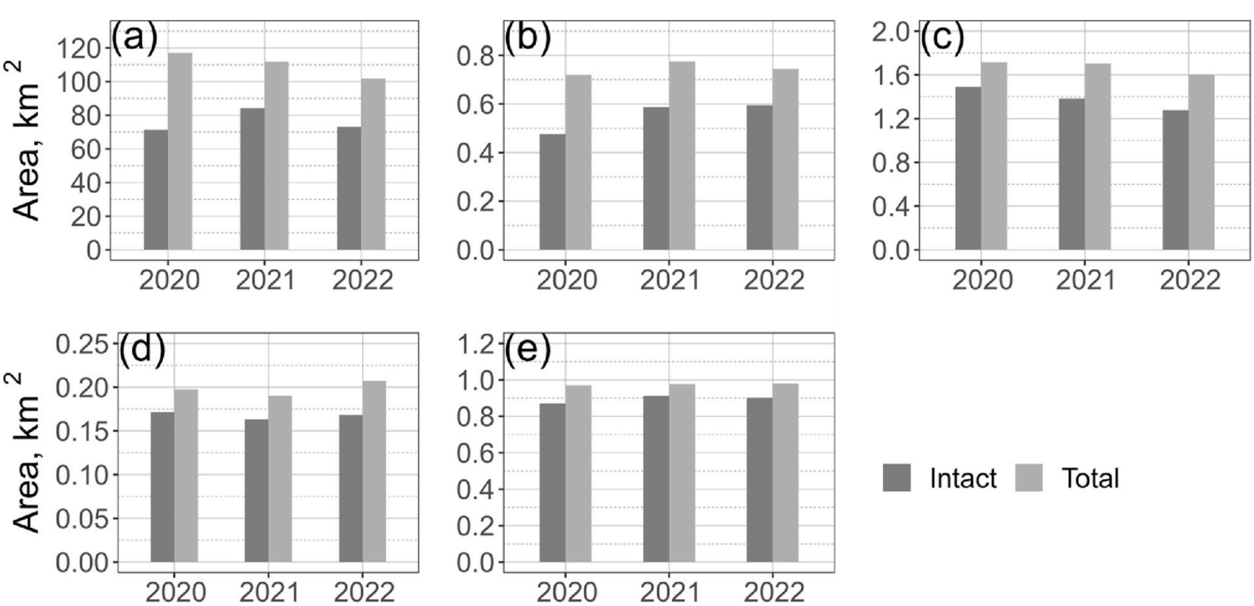

Fig. 4. Area of mapped mangrove cover. 'Intact' area refers to the total area of non-degraded mangrove vegetation, and 'total' refers to the area of the mangrove ecosystem extent including degraded mangrove. (a) Puerto Rico, the United States Virgin Islands of (b) St. Thomas, (c) St. Croix, and (d) St. John, and (e) the British Virgin Islands.

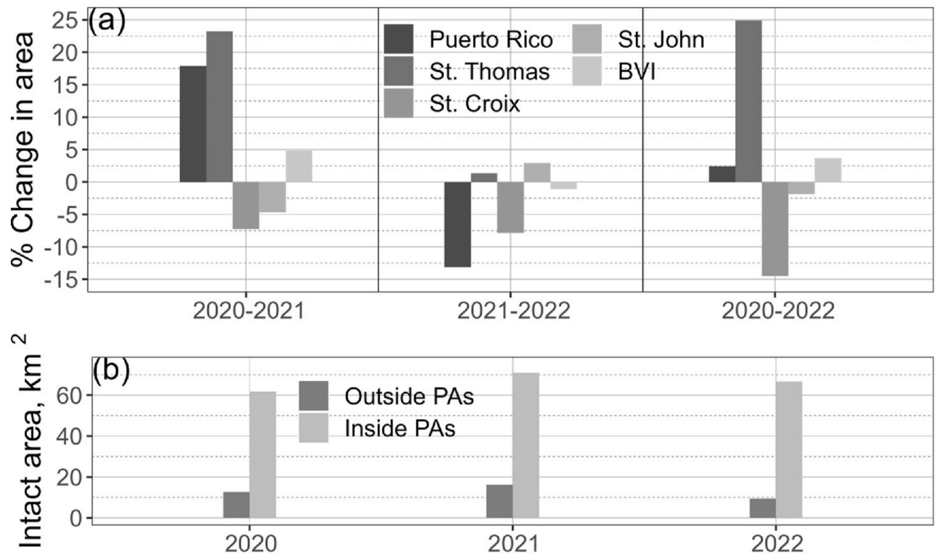

Fig. 5. Percentage change in mangrove cover area between years (a), mangrove cover inside and outside of protected areas for the years 2020, 2021, and 2022 pooled across all locations (b).

those that include mangroves); auto-generated bar charts visualizing total mangrove cover within user-selected areas; exportable CSV files with associated area calculations; and links to download the mangrove cover maps. The tool allows for easy ingestion of map layers facilitating quick assessment of change over time, and for specific geographic extents of interest.

4. Discussion

Mangrove ecosystems are highly productive, yet increasing pressure from natural and anthropogenic stressors threatens their survival and the benefits they provide to coastal communities who rely on them. Adaptive management of dynamic ecosystems requires current, accurate, and accessible data to facilitate assessment of change and guide decision making for timely intervention (Salafsky et al., 2001). Outdated, inconsistent, or inaccessible data hinder decision making. We present up-to-date, high-resolution maps of mangrove extent in a convenient GEE application, accessible to ecosystem managers. Spatial distribution maps allow the user to assess temporal mangrove cover changes to understand mangrove forest dynamics and correlate with stress events. Temporal assessments reveal overall trends and highlight potential hotspots of mangrove loss to direct management action where it is needed most. For example, patterns of loss and gain are spatially heterogeneous with some areas experiencing greater change than others, suggesting that context is important, and that site-specific management is needed.

Mangrove degradation, deforestation, and conversion to other land uses were primary causes of decreased mangrove cover over the study period. Observed mangrove degradation included intermittent defoliation and mortality within the study's timeframe. The permanence and severity of mangrove vegetation loss observed in this temporal analysis is likely related to the nature and severity of disturbance events. For example, in 2017, two major hurricanes (Irma and Maria) hit Puerto Rico, the USVI, and the BVI, ranging from category 5 to 3 as they passed the region. These storms significantly impacted mangrove vegetation (Krauss et al., 2020, Feng et al., 2020; Taillie et al., 2020; Walcker et al., 2019), and may have caused losses without vegetation recovery prior to 2020, and therefore not captured in this work. Patterns of mangrove recovery have shown variable rates across the region (Hernández et al., 2021; Xiong et al., 2022), a likely reason for the patchy patterns of recovery, and interannual variability of mangrove extent observed in this study. Mapped areas of mangrove degradation and loss highlight potential areas for restoration while increased mangrove cover may indicate natural recovery or successful restoration and/or management. This feature is useful for monitoring impacts of ongoing restoration efforts. It allows for adaptive management of mangrove ecosystems, with the caveat that full forest structural recovery, regardless of natural or assisted, requires time (Krauss et al., 2023). The ability to identify human-riven mangrove vegetation losses is useful for guiding the implementation of management policies, including the need for ecosystem protection. Furthermore, patterns of stifled or absent recovery may indicate impeding environmental conditions or may indicate where resilient or vulnerable ecosystems are located. This is particularly important for hurricane events (Amaral et al., 2023), and understanding where to prioritize management resources.

The usefulness of various map products is highly determined by their spatial and temporal resolutions and mapping accuracy. Global-scale products provide extensive coverage for high-level assessments, but they can have uncertainties associated with local variations in mangrove composition and condition (Bunting et al., 2018), and frequently use scales that do not capture the smaller, fragment forest patches characteristics of the Caribbean region. Regional and local products provide more specificity, but often lack the complete coverage necessary for comprehensive assessments of change across heterogeneous regions or across multiple timepoints. Furthermore, inconsistencies among products present a challenge for data integration. Yet, these mangrove cover products provided a basis for the training of our classification model, and this resulted in considerable overlap between our maps and existing data products. However, there were also differences: we captured small patches of unmapped fringe mangrove vegetation, typical of Caribbean islands, due to the higher resolution Sentinel-2 data. Our mapping approach also included a modified band structure including additional generated bands to improve on the identification of mangrove vegetation. In addition, we incorporated ground-validated data to improve mangrove identification for areas that we could not definitively separate between mangrove and non-mangrove vegetation based on Sentinel-2 data alone. Importantly, our validated maps can be useful in guiding global-scale mapping efforts by providing verified samples to improve accuracy for local areas.

Our mapping approach has proven potential for being implemented for countries in Latin America and the Caribbean. It has been successfully utilized for mapping mangroves in Belize (Cissell et al., 2021), Mexico (Baloukas et al. - under review), and Panama (Viquez et al. – under review). The approach also includes tunable parameters that can

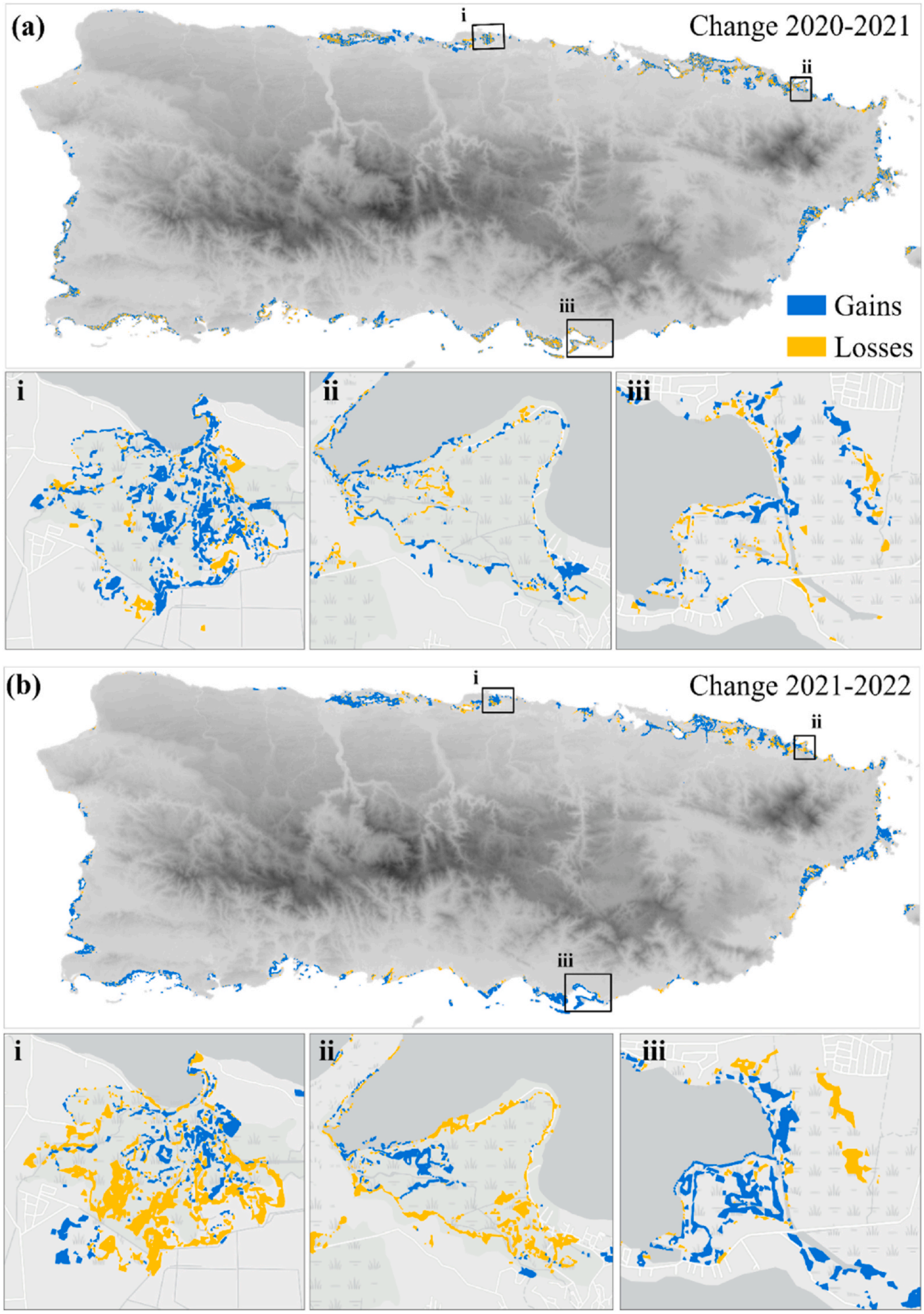

Fig. 6. Losses and gains in mangrove vegetation cover between (a) 2020–2021, and (b) 2021–2022. The data are overlaid on a gray hill shade map (derived from SRTM DEM) to enhance visibility. Insets (i) Pantano Cibuco natural reserve, (ii) near Punta Picua, and (iii) Jobos Bay, highlight some of these patterns. Both gains and losses occur within the main extent of mangrove ecosystems and along the edges.

be adjusted for better performance depending on the context and mapping purpose, and thus potentially useful for other regions. We have developed a user-friendly and accessible dashboard in GEE for exploring mangrove habitats at multiple spatial scales and time points. The dashboard provides mangrove cover maps and area estimates for annual change in mangrove extent within administrative boundaries and protected areas. It can be used for fast estimation of change for defined administrative areas allowing for assessment of management effectiveness where interventions, such as restoration projects, have been implemented, or to assess degradation following disturbances, such as hurricanes or drought. This work extends previous static mangrove cover maps into a useable tool that makes critical mangrove cover visualizations and data readily accessible to coastal land managers.

Mangroves are vital for both humans and the environment, and therefore conservation practices draw together stakeholders from

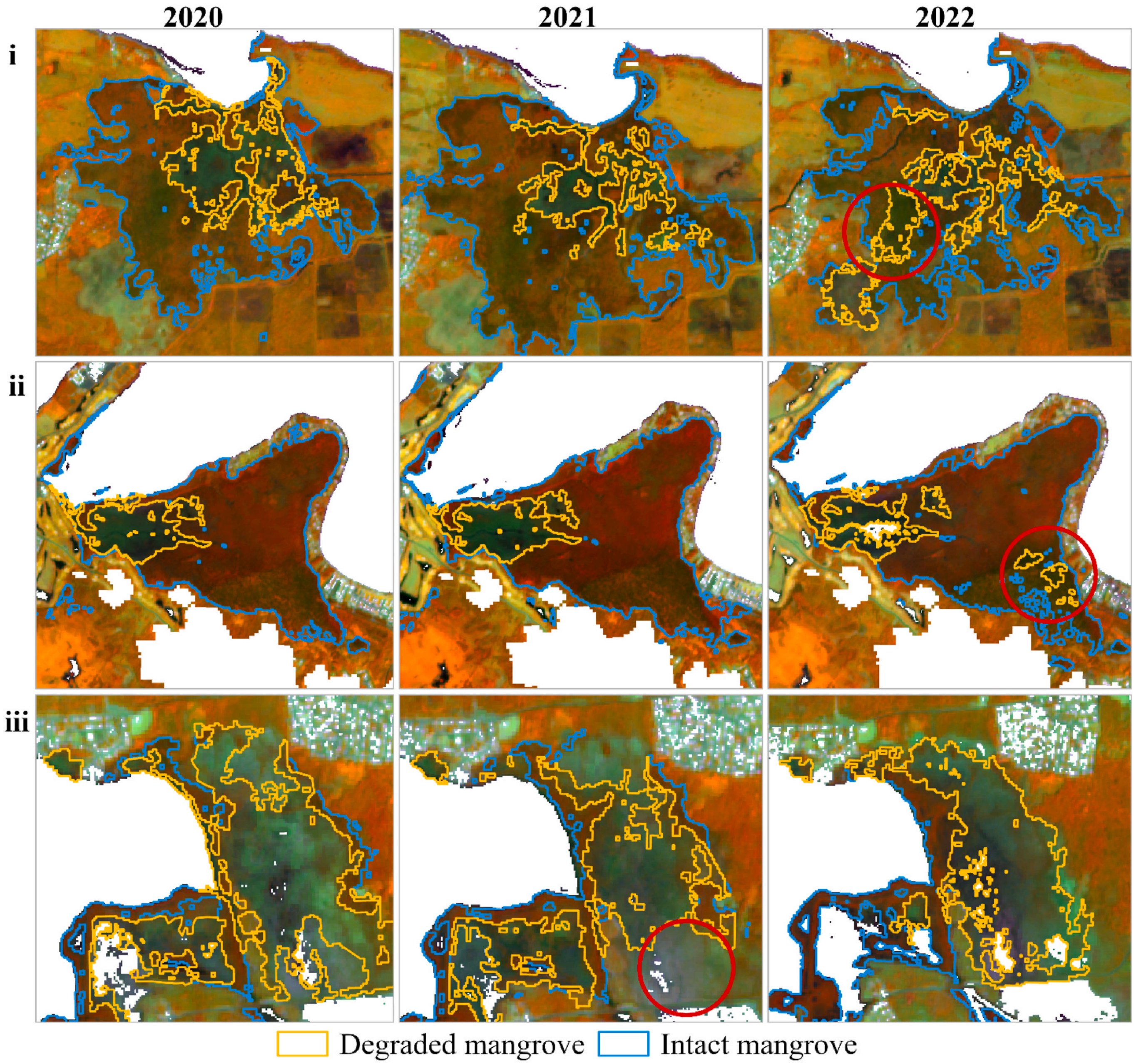

Fig. 7. Sentinel-2 MSI showing separation between intact and degraded mangrove vegetation based on reflectance characteristics in the Visible and Near Infrared (band 8), Red (band 11), and Short-Wave Infrared (band 4) bands respectively representing the red, green, and blue (RGB) colors composite. Red circles show example areas that have degraded or recovered.

diverse sectors. We presented out data to several key actors including the National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA), Commerce, and Southeast Fishery Science Center (SEFSC), during the Caribbean Fishery Management Council's meeting held on March 16th and 17th, 2022, to inform their Ecosystem-Based Fishery Management programs. Generally, common management practices involve aspects of ecosystem design where native species are planted as part of ecosystem restoration. Other practices have involved legal protection for areas identified to be ecologically suitable for mangrove development (Martinuzzi et al., 2009). A key aspect of most approaches is regular monitoring to assess effectiveness of interventions. While most of these approaches have been successful in the past, new threats have emerged in recent years following increased climate change, requiring more targeted strategies and adaptive management. In-situ monitoring techniques that are commonly used are limited to small spatial scales as they can be expensive and logistically challenging over large areas. Remote sensing-based data such as the GMW platform provides a means for monitoring mangrove extent over large areas, but it does not capture highly vulnerable areas such as mangrove on small cays or fringe mangrove. Our data was produced at high spatial resolution and therefore captures small patches of mangrove, thus facilitating local level monitoring. In addition, consistent data are key to accurately assess change over time, and it can facilitate benchmarking leading to a better understanding of mangrove response to specific threats. Easy access to current data is also necessary to detect impacts of emerging threats and to monitor progress of restoration interventions.

Furthermore, changes in mangrove habitats have implications for numerous marine species including fish and shrimps that use mangrove for nursery. The sustainable fisheries division of the National Marine

Fig. 8. Screenshot of public-facing Google Earth Engine Application. This application includes functionality for querying based on smaller administrative extents, and protected areas.

Fisheries Service (NMFS) manages these areas as essential fish habitat for commercially viable species, and therefore needs accurate and updated maps for evaluation purposes. Further, the protected resources division within the NMFS Southeast regional office manages a variety of endangered and threatened species under the Endangered Species Act (ESA) in the Southeast region of the United States, including Puerto Rico and the U.S. Virgin Islands. The ESA stipulates that a species can be listed under the act due to habitat degradation, such as mangrove lagoons and forests. In addition, the ESA requires that critical habitat be designated within a year of each species listing. Several species in the southeast such as the smalltooth sawfish (*Pristis pectinata*) rely on mangrove lagoons as critical habitat. Alterations to the essential features within these habitats are extremely impactful to the species and will greatly affect recovery efforts. Accurate and up-to-date mangrove maps can be beneficial as managers evaluate impacts to the habitat, under section 7 consultations, as well as planning efforts to recover the population throughout its range.

We recognize that a GEE based application has some inherent limitations such as difficulties in scaling up for larger areas, and limited customizability when compared to other programs (such as R Shiny) which may limit potential for implementing a wide range of ecosystem manager needs and requests. However, the tool is open-access and provides functionality for performing essential assessments of the state of mangrove vegetation. Continued collaborations with regional partners will allow for the co-development of products with a wider range of functionality. The next step in this process will be to integrate the mapping component for easy creation and ingestion of subsequent maps. This functionality will allow for continuous validation of map products which can facilitate stakeholder and community participation. The goal is to provide access to a decision support tool that is easy to use by people with limited technical expertise. Ultimately, the tool facilitates the co-creation of a living product useful for decision-making for mangrove protection and restoration.

5. Conclusions

We present high resolution time series of mangrove cover for Puerto Rico, the USVI and the BVI for the years 2020, 2021, and 2022, and a scalable mapping tool implemented in the versatile Google Earth Engine environment using freely available satellite imagery. The data documents the extent of intact and degraded mangrove vegetation allowing for assessment of change over time (loss and gain), and of the dynamics related to degradation, restoration, and recovery. These properties are especially ideal for ecosystem monitoring, making it very attractive for ecosystem managers. In addition, we provide a user-friendly GEE-based application for exploring map products to facilitate decision making by managers. Importantly, our GEE-based mapping workflow for generating subsequent maps provides a quick approach to generate up-to-date maps, a critical requirement for adaptive management of dynamic ecosystems, especially under intensifying climate change. Furthermore, consistent maps provide a means of documenting ecosystem status, monitoring change, and are a great complement to field-based monitoring protocols, as they help to prioritize actions through identification of change hotspots. In addition, consistent maps contribute to the development of a data infrastructure that researchers can use to analyze observed patterns and trends for better understanding of ongoing processes and informed management decisions. For example, the data can help to contextualize ecosystem typologies by incorporating localized risk assessments, and thus facilitate identification of at-risk ecosystems and related habitats. Such information is critical for informing the protection of critical habitats, e.g., as per the United States' Endangered Species Act stipulations. The DST can potentially be improved to include additional data layers e.g., related ecosystem and habitat maps, environmental and climate data, to support comprehensive spatial analyses of ecosystem status for identified change hotspots.

CRediT authorship contribution statement

Susan M. Kotikot: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Olivia Spencer:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Jordan R. Cissell:** Writing – review & editing, Methodology, Conceptualization. **Grant Connette:** Writing – review & editing. **Erica A.H. Smithwick:** Writing – review & editing, Supervision. **Allie Durdall:** Writing – review & editing, Validation. **Kristin W. Grimes:** Writing – review & editing, Validation. **Heather A. Stewart:** Writing – review & editing, Validation. **Orian Tzadik:** Writing – review & editing, Validation. **Steven W.J. Canty:** Writing – review & editing, Supervision, Conceptualization.

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.

Data availability

The data presented in this study are available online at https://doi.org/10.25573/serc.26483857.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107307.

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