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An Integrated Geospatial Approach to Mangrove Forest Mapping in Trinidad and Tobago Using High-Resolution Aerial Photography and Sentinel-2 Satellite Imagery

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ABSTRACT

Mangrove forests provide a wide range of ecosystem services and socio-economic benefits globally; however, climatic and anthropogenic forces have negatively affected this unique vegetation type. Information on observed changes is useful in the development of mangrove conservation strategies. Geospatial mapping techniques can provide such information, which is key for the sustainable management of this critical resource. In Trinidad and Tobago, mangrove forests have suffered losses within recent years. This study utilised remote sensing and geographic information systems (GIS) techniques to update an existing 2007 mangrove baseline map of Trinidad and Tobago to 2014 and identify significant changes in mangrove coverage for the 7-year period. Mangrove forest boundaries were delineated using ArcGIS 10.4.1 software through an integrated approach involving visual interpretation of 2014 high-resolution, coloured aerial photography and classification of Sentinel-2 Multi-Spectral Instrument (MSI) satellite imagery. Resultant maps were verified using ground data collected between 2017 and 2019. Spatial analysis techniques were used to isolate and quantify areas of mangrove change. Results revealed that total mangrove coverage for both islands decreased from 9369.3 ha in 2007 to 9077.2 ha in 2014, a loss of 292.1 ha for the 7-year period. Solid waste pollution and land cleared for development were both observed within mangrove areas. A mangrove species map generated for the Buccoo-Bon Accord region of southwest Tobago showed that the area is dominated by red mangroves. The outputs of this study can be used in mangrove forest conservation and management strategies to promote more sustainable development practices in Trinidad and Tobago and the wider Caribbean. The geospatial approach can be implemented when developing monitoring plans.

Keywords: Mangrove mapping; Remote Sensing; Sentinel-2; Aerial photography; Trinidad and Tobago.

1.0 INTRODUCTION

1.1 Importance of mangroves

According to Moudingo et al., 2020 [1] mangroves exist on approximately 75% of tropical coastlines globally. These halophytic plants are distributed within sheltered, marine intertidal zones, between tropical and sub-tropical regions of the world [2, 3, 4]. Mangroves occupy only 0.5% of the coastal area but contribute 10-15% of the carbon storage and release 10-11% of carbon into the ocean [5]. Mangroves also support high levels of ecologic and economic productivity globally [6, 7]. Many ecosystem goods and services are provided by this essential natural reserve for the inhabitants of coastal areas [8]. The goods and services that mangroves supply can be classified into three types: provisioning, regulating, and supporting [9, 10, 11]. Mangroves produce a diverse source of food, timber, fuel, and medicine [12], contributing to basic needs for the sustenance of life. Food sovereignty and job security are fundamental functions provided by mangroves, as they remain the main source of livelihood for millions of people along the coast [13]. In addition, this natural vegetation type forms a unique ecosystem that possesses adaptive qualities capable of withstanding harsh environmental conditions [14, 15]. The distinct formation of mangrove roots forms coastal stabilisers, binding sediments to impede erosion [16, 17]. The highly complex structure of mangrove forests also alleviates coastal risk [18]. According to Spalding et al., 2014 [9] mangroves are also powerful nutrient recycling systems. Mangrove roots possess a hierarchical triple-layer structure [19], which functions as a water purification system [9]. Acting as filtering systems for seagrasses and coral reefs, the roots of mangroves prevent sediments from estuaries and inland streams from entering surrounding ecosystems [20, 21] and aid in the control of disease [9]. Other critical ecological functions provided by mangroves include providing nursery and breeding sites for mammals, birds and reptiles as well as habitat for fish and crustaceans [7, 22]. The unique ecophysiology of the ecosystem allows mangroves to host a diverse community of organisms, both terrestrial and aquatic [23].

1.2 Threats to mangroves

Threats to mangroves resulting from anthropogenic activities have increased rapidly in recent years. These include over-exploitation of resources, pollution, tourism development, reclamation for urbanisation and aquaculture farming amongst others [13, 5]. As the rise in sea level, hurricanes, storm surges and tsunamis accelerate, mangroves become more vulnerable to devastating impacts [24]. Environmental policies have had positive impacts on mangrove growth in some areas while they are still being destroyed at significant rates in others. Russi et al., 2013 [25] concluded that up to 50% of the world's total wetlands had been lost, with approximately 35% of global mangrove coverage decimated during the last twenty years [26]. Currently, 16% of the world's 70 mangrove species are at risk of disappearing altogether [26]. Factors such as climate change, sea-level rise and unplanned and unsustainable coastal development are major threats to mangrove forests globally [27, 28]. Mangroves also play a major role in the productivity of small island developing states (SIDS) [18], as most SIDS are dependent on this key flora for their food and livelihoods. Coastal communities are heavily reliant on the multiple ecosystem goods and services provided by mangroves [29], as a lack of resources still occurs on many small islands. Salvatierra, 2014 [13] noted that mangrove forests are highly productive ecosystems upon which millions of families in small islands are dependent. As islands are surrounded by water and with the majority of their populations occurring within the coastal zone [30], they become highly susceptible to natural disasters [31]. Mangrove loss in the Caribbean has been estimated to be occurring at a rate of 1.5% per annum [32, 33]. In Trinidad and Tobago, mangroves have become progressively susceptible to degradation in recent years [34].

1.3 Mapping and remote sensing

Mapping and monitoring of mangrove forests help to establish loss rates and effect protection measures [35]. It is near impossible to accomplish these mapping objectives by using only traditional field surveys, due to the logistical difficulties faced when trying to access mangrove swamps. Remote sensing technology has proven to be an effective approach for addressing this problem [36, 37]. Remote sensing data, when integrated with geographic information systems (GIS), offers numerous benefits for mapping and monitoring mangroves [38]. Remote sensing data and methods have been applied in many different regions for assessing the status of mangrove forests [37, 39]. This technological approach utilises sensors that capture data ranging from the visible to microwave wavelengths along the electromagnetic radiation (EMR) spectrum [7]. These data can be a source of up-to-date and reliable information [40], which can be used to map mangrove extent and distribution. Mangrove species distribution and extent maps also play a major role in the understanding of the overall ecology of the system [41] and can set a baseline for monitoring changes to mitigate the impacts of climate change and anthropogenic activities [42]. Hutchison et al., 2014 [43] demonstrated the importance of maintaining diverse mangrove species with varying root properties for preserving mangrove fish communities. Mangrove species mapping has been widely conducted using remote sensing techniques [44, 41, 45]. Existing satellite sensors offer a wide range of spatial, spectral, and temporal resolutions [46] that are important for specific mapping objectives.

Remotely sensed data and techniques for mangrove mapping have progressed over time [47]. In most developing countries, aerial photography is the chosen method due to its cost-effectiveness, availability, and ability to capture high-resolution photos over small areas, producing data that can be easily interpreted [48]. Aerial photos can also be compared to other lower-resolution data such as satellite imagery, to accurately classify and identify features [49]. High-resolution satellite imagery such as World View 4 and Quickbird have demonstrated good potential for mapping small mangrove areas albeit at a very high expense [50, 38], whereas no-cost, low-resolution satellite imagery such as from the moderate resolution imaging spectroradiometer (MODIS), is inadequate to map small areas [51].

The Landsat-8 Operational Land Imager (OLI) and Sentinel-2 Multi-Spectral Instrument (MSI) satellites provide free, moderate to high spatial and spectral resolution imagery at no cost. Sentinel-2 is composed of Sentinel-2A and Sentinel-2B launched in 2015 and 2017 respectively and contains wide-swath, high-resolution multispectral imagers with spatial resolutions of 10m, 20m, and 60m across 13 bands and a temporal resolution of 5 days [52]. Landsat-8 has a revisit time of 16 days, spatial resolutions ranging between 15m and 100m across 11 spectral bands, and was launched in 2013 [53]. The use of drones for mapping and studying mangroves has become ubiquitous in recent years due to the affordability and versatility of this remote sensing platform [54, 55, 56]. A critical limitation of drones, however, is the image processing requirements [56]. The primary remotely sensed data used in the development of the updated mangrove distribution and classification maps in this study was coloured aerial photography captured in May 2014. This imagery had a spatial resolution of 12.5 cm and was supplied by the Surveying and Mapping Division of the Ministry of Agriculture, Land and Fisheries of the Government of Trinidad and Tobago for use in this project.

1.4 Summary

The main objectives of this study were to 1) produce an updated map of mangrove distribution and extent in Trinidad and Tobago based on 2014 coloured aerial photography, Sentinel-2 satellite imagery, and an integrated geospatial approach; 2) compare this updated 2014 map with the 2007 baseline map produced by Juman and Ramsewak, 2013 [34] to: determine mangrove cover change over the 7-year period and; 3) produce a mangrove species distribution map of the Buccoo-Bon Accord region of Tobago based on the 2014 high-resolution aerial photography.

2.0 STUDY REGION

2.1 Site Description

The islands of Trinidad and Tobago (Figure 1) are located in the eastern region of the Lesser Antilles, farthest south in the Caribbean archipelago [34]. Situated north-east of Venezuela and adjacent to the South American continental shelf, Tobago occupies 300 km² and Trinidad 4,823 km² [34]. Similar to most Caribbean islands and other Small Island Developing States (SIDS), both islands have expansive development along one or more of their coasts and relatively large population numbers per square km [57]. The islands are bounded by the Caribbean Sea to the north and the Atlantic Ocean to the east and south. The Gulf of Paria lies to the west of Trinidad, separating it from Venezuela. The islands are characterised by a tropical climate, producing two seasons which are differentiated by distinct wet (June – November) and dry (December – May) regimes [58]. The southerly position of the islands also minimises their susceptibility to hurricanes and tropical storms [34], unlike the other Caribbean islands to the north. In Trinidad, seven species of mangroves have been identified, while only four have been observed in Tobago [34].

Figure 1. Location of Trinidad and Tobago

3.0 METHODOLOGY

3.1 Data acquisition

The primary dataset used for mangrove boundary delineation and area calculations in this study was a mosaic of coloured aerial photos with coverage for both islands, captured from a small, low flying, manned aircraft in May 2014. This 12.5 cm spatial resolution dataset was supplied by the Surveying and Mapping Division of the Ministry of Agriculture, Land and Fisheries of the Government of Trinidad and Tobago in 2016. Four images captured by the Sentinel-2 satellites, dated January 29th, 2017, April 9th, 2017, June 9th, 2017 and December 10th, 2017 were also used to support the mangrove mapping exercises. The Sentinel-2A and 2B satellites were launched in 2015 and 2017 respectively and images with low cloud interference (30% or less), acquired in 2017, were used in this study. These images, which were downloaded from the https://earthexplorer.usgs.gov/ website offered an advantage over the 2014 aerial photography for identifying potential locations of mangroves due to the spectral reflectance information they capture. Due to the comparatively low spatial resolution, however, (10m) as compared to the aerial photography (12.5 cm), Sentinel-2 imagery was not useful for quantifying mangrove gain or loss in this particular study. Verification information included global positioning systems (GPS) field data collected between 2017 and 2019 and Ikonos satellite images from Google EarthTM. A Garmin GPSMAP 78sc handheld GPS system with a horizontal accuracy of 3 m was used to acquire field coordinates. Ancillary vector layers, such as coastline polygons used in the development of the final maps, were also acquired from the Surveying and Mapping Division.

3.2 Development of the 2014 mangrove map and 2007-2014 change detection

The stepwise procedure adopted for the development of the 2014 mangrove map and subsequent 2007–2014 change analysis is outlined in Figure 2. Each dataset utilised was first georeferenced to the WGS84 UTM Zone 20N coordinate reference system before processing.

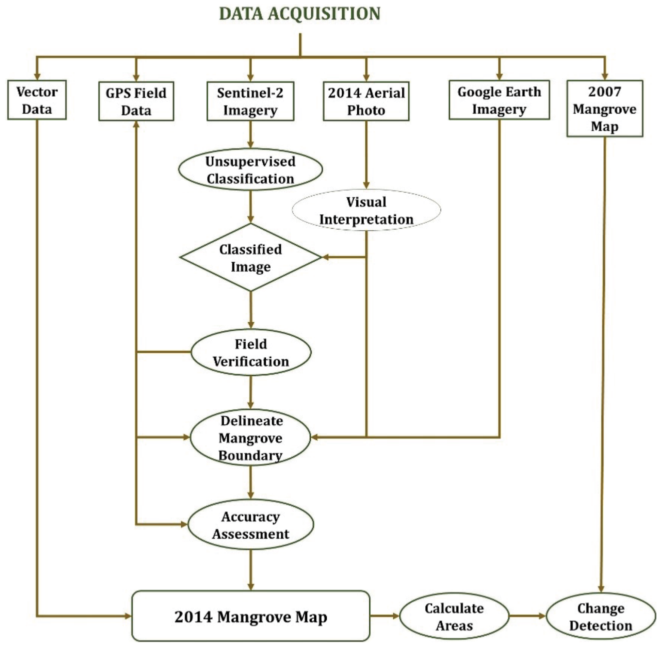

Figure 2. Flowchart for the development of the 2014 mangrove map and change analysis.

Mangrove forests were first differentiated from other vegetation types by utilising Sentinel-2 satellite imagery. Due to the spectral capabilities of satellite imagery, mangroves can be characterised visually through the use of specific three-band combinations or composites [44]. Previous studies have identified mangroves in Landsat-8 imagery based on false colour composites of Landsat-8 bands 5, 6, and 4 [59, 60]. In this study, however, improved mangrove detection was achieved using false colour composites of Sentinel-2 bands 8, 11, and 4. A comparison of Landsat-8 and Sentinel-2 composites, highlighting the enhanced performance of Sentinel-2 is given in Figure 3 A & B.

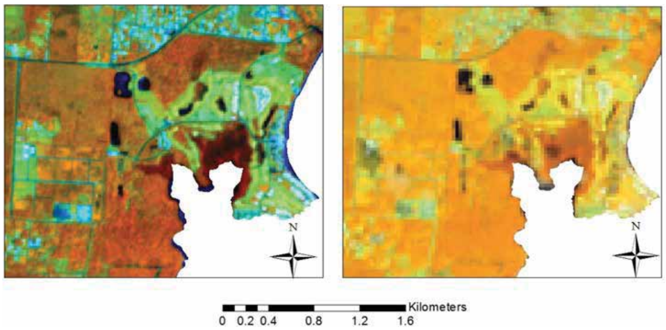

Figure 3. (A) Sentinel-2 (8-11-4) false colour composite; (B) Landsat-8 (5-6-4) false colour composite, illustrating the difference in mangrove differentiation at Petit Trou, Tobago.

Once preliminary mangrove detection in the false colour composites was achieved, an unsupervised classification of the Sentinel-2 imagery was then performed. The initial processing of the imagery was conducted in sentinel application platform (SNAP) software. All Sentinel-2 bands were first stacked and compressed to a spatial resolution of 10 m [61]. An unsupervised classification was then performed in ArcMap 10.4.1 to further separate mangrove classes from other landcover types [62]. The classification output for the southeast area of Tobago, highlighting mangrove areas in Petit Trou, is given in Figure 4. This unsupervised classification approach was subsequently used to identify the locations of all potential mangrove areas across both islands.

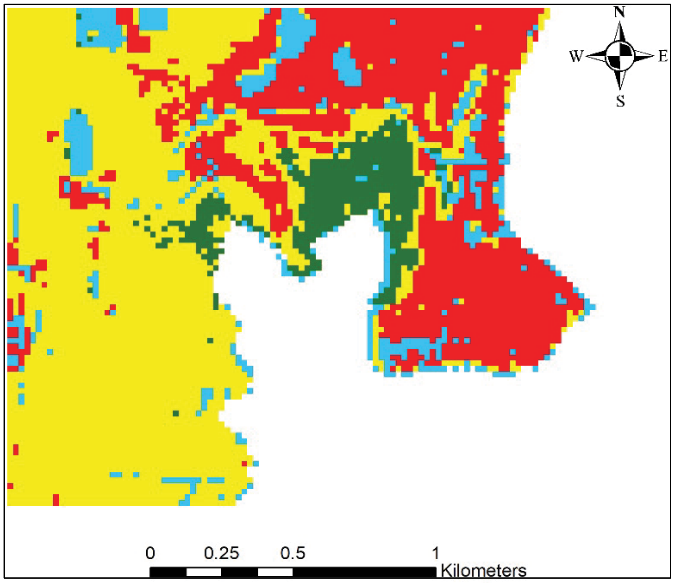

Figure 4. Unsupervised classification product of Sentinel-2 image illustrating mangrove areas at Petit Trou, Tobago

Subsequent to the identification of potential mangrove areas from the false colour composite and the unsupervised classification product, detailed mangrove polygons were then delineated from the high-resolution aerial photography. The unsupervised classification product was superimposed onto the 2014 aerial photo mosaic and the 2007 mangrove map was used as reference information. Visual interpretation of the aerial photo mosaic, based on metrics such as 'tone', 'texture', and colour [63], was then used to identify and demarcate detailed polygon boundaries representing the distribution and extent of the mangroves. The resulting 2014 mangrove polygons were then validated using GPS field data collected between 2017 and 2019. Congalton and Green, 2008 [64] recommend a minimum of 50 sample points for validating each land cover type in computer-aided image classification techniques.

In this study, 221 GPS ground sample points were used to assess the accuracy of the visually demarcated mangrove areas. A simple error matrix was created by comparing the known ground points against the demarcated mangrove areas. As a result, accuracy values of 97% for the Tobago mangrove forests map (Figure 5), 94% for the Trinidad mangrove forests map (Figure 6), and 99% for the Buccoo-Bon Accord mangrove species distribution map (Figure 8) were achieved. Hard copy maps depicting the aerial photo mosaic, the mapped mangrove polygons, and the coordinate reference system were printed and used to support the field data collection [7]. Photos of the mangrove vegetation types at each field location were also captured for further cross-referencing and validation. Due to the disparity between the date of capture of the aerial photos (May 2014) and the actual field data collection (2017-2019), Google EarthTM imagery was used as a supplementary reference dataset to support the mangrove delineation.

3.3 Mangrove species mapping in the Buccoo-Bon Accord region

Visual interpretation based on high-resolution coloured aerial photography was used to identify mangrove vegetation based on criteria such as texture, form of crowns and presence or absence of a shaded side. This approach, combined with GPS ground data, was used to delineate mangrove species in the Buccoo-Bon Accord region of Tobago. Although the mangrove forests in this region encompass a much smaller area (131.9 ha) than the Caroni Swamp mangrove forests of Trinidad (5,297.4 ha), they form part of a mangrove system located in southwestern Tobago that is the largest on the island [34].

4.0 RESULTS

4.1 Updated mangrove map and 2007-2014 change assessment for Tobago

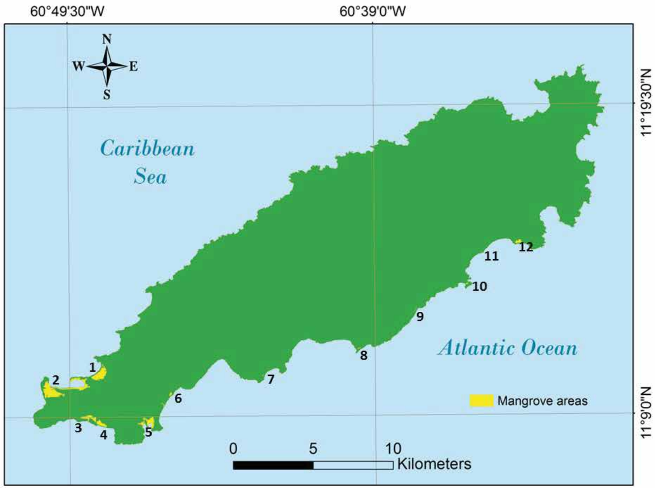

Figure 5. Mangrove forests of Tobago 2014

The 2014 mangrove distribution and extent map of Tobago produced in this study is given in Figure 5. The largest mangrove communities in Tobago persist in the southwestern region of the island. Twelve mangrove areas that were detected and mapped are listed below and numbered accordingly in Figure 5.

1. Buccoo Bay
2. Bon Accord Lagoon
3. Kilgwyn Swamp
4. Friendship Swamp
5. Petit Trou Lagoon
6. Little Rockly Bay
7. Minister Bay
8. Fort Gransby
9. Goldsborough Richmond
10. Belle Garden
11. Carapuse Bay
12. Louis d'Or

The Bon Accord Lagoon continues to be the largest mangrove stand on the island with a total area of 90.8 ha, whereas the smallest stand identified was Carapuse Bay with a coverage of only 0.2 ha (see Table 1).

Carapuse Bay was not previously detected in the 2007 mapping by Juman and Ramsewak, 2013 [34]. The integration of Sentinel-2 imagery and high-resolution aerial photography in the approach adopted by this study may have aided the detection of this small mangrove system. Basin mangrove was the dominant mangrove community observed across the island, however, both fringe and estuarine mangroves also existed. The presence of solid waste was observed in almost all areas apart from Fort Gransby. Mangrove removal was seen throughout and may be the key contributing factor to the decline of these critical habitats in Tobago. In the Bon Accord Lagoon, the change assessment revealed that there was a loss of mangroves in some areas and growth in others. The effects of climate change are causing a shift in the distribution and profusion of species globally, altering ecosystem structure and function [24]. One possibility for mangrove growth in other parts of the Bon Accord Lagoon may have been due to salt-water intrusion into the area [34]. The introduction of saltwater into inland freshwater systems inevitably contributes to the growth in mangrove areas [65]. Additionally, mangroves are capable of effectively adapting to their environment through surface elevation change processes, which allow them to grow and expand [66]. This ultimately increases their ability to migrate inland [67], which can potentially explain the increase in mangroves in the Bon Accord area. Overall, the Bon Accord Lagoon and Buccoo Bay areas remained relatively stable with a collective change in mangrove coverage of 0.4 ha.

Major mangrove losses were detected at Petit Trou, Kilgwyn Swamp, Minister Bay, and Goldsborough-Richmond (see Table 1). Mangrove expansion was identified at Fort Gransby and Friendship Swamp. These areas were less impacted by anthropogenic activities and had mangrove coverage increases of 0.1 ha and 0.6 ha respectively. Other mangrove areas in Tobago remained relatively stable with minor changes in overall coverage. The total mangrove area in Tobago calculated for 2014 was 201.4 ha. This included values for a newly mapped region (Carapuse Bay) and for Belle Garden and Louis d'Or, which were not provided in the 2007 mapping. The values for these areas were therefore excluded from the change assessment, which revealed an overall loss of 16.1 ha for comparable locations over the 7-year period (see Table 1).

Table 1. Changes in mangrove coverage in Tobago between 2007 and 2014.

Location	Approximate Size (ha) 2007	Approximate Size (ha) 2014	Change (ha)
Buccoo Bay	41.5	41.1	-0.4
Bon Accord Lagoon	90.8	90.8	0
Kilgwyn Swamp	33.9	17.4	-16.5
Friendship Swamp	11.7	12.3	0.6
Petit Trou Lagoon	34.2	26.6	-7.6
Little Rockly Bay	4.3	3.5	-0.8
Minister Bay	2.5	0.3	-2.2
Fort Gransby	0.8	0.9	0.1
Goldsborough Richmond	1.7	0.6	-1.1
Belle Garden	-	1.1	-
Carapuse Bay **	-	0.2	-
Louis d'Or	-	6.6	-

** Newly detected mangrove area
- denotes where area value not previously given

4.2 Updated mangrove map and 2007-2014 change assessment for Trinidad

The 2014 mangrove distribution and extent map of Trinidad produced in this study is given in Figure 6. The total mangrove coverage detected in 2014 was 8,875.8 ha which represents a loss of 270.6 ha from the total coverage of 9,146.4 ha reported by Juman and Ramsewak, 2013 [34].

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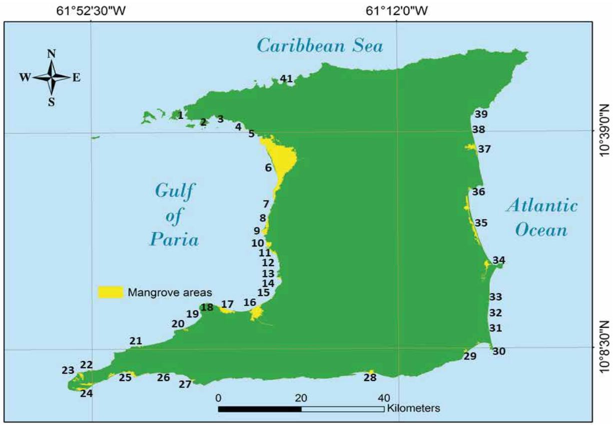
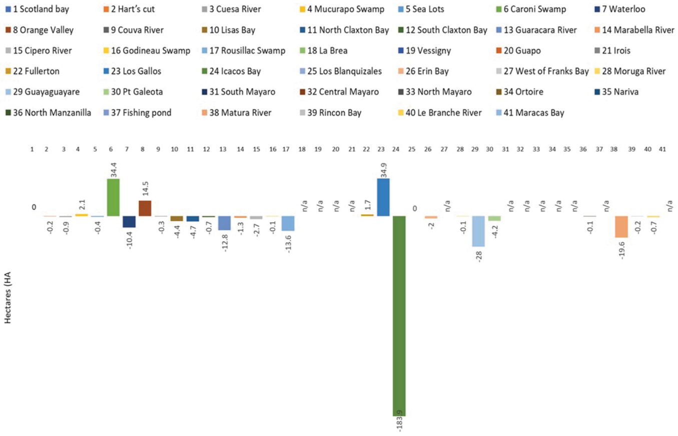


Figure 6. Mangrove forests of Trinidad 2014

An analysis of the 2007 and 2014 mangrove maps of Trinidad using ArcGIS 10.4.1, revealed greater changes in certain areas across the island and smaller changes in others. A graphical comparison of changes among all mangrove areas in Trinidad is provided in Figure 7.



n/a denotes where the change analysis was not applicable due to the lack of data in the previous study

Figure 7. A comparison of changes among all mangrove areas in Trinidad between 2007 and 2014.

The largest expansion of mangrove in Trinidad over the 7-year period was observed in the Los Gallos and Caroni Swamp regions. These locations experienced gains of 34.9 ha and 34.4 ha respectively, whereas Icacos Bay and Guayaguayare experienced the highest overall loss of mangroves on the island. These were reduced by 183.9 ha, and 28 ha respectively. A detailed quantitative account of mangrove change between 2007 and 2014, for all areas mapped in Trinidad, is given in Table 2. The biggest change occurred along the west coast mangrove regions, which experienced a comparative loss of 88.3 ha. It is important to note that areas for some mangrove regions along this coast were not reported by Juman and Ramsewak, 2013 [34], therefore the change analysis in this study excluded these regions.

Table 2. Changes in mangrove coverage in Trinidad between 2007 and 2014.

Location	Approximate Size (ha)		Change (ha)
	2007	2014	
	West Coast		
Icacos Bay	326.2	142.3	-183.9
Irois	-	16.5	-
Rousillac Swamp	338.7	325.1	-13.6
Guaracara River	45.1	32.3	-12.8
Waterloo	13.9	3.5	-10.4
Guapo	-	40	-
North Claxton Bay	88.0	83.3	-4.7
Lisas Bay	151.4	147	-4.4
Cipero River	15.4	12.7	-2.7
Marabella River	2.3	1.0	-1.3
Cuesa River	2.2	1.3	-0.9
South Claxton Bay	8.7	8.0	-0.7
Sea Lots	1.8	1.4	-0.4
Couva River	298.1	297.8	-0.3
La Brea	-	3.5	-
Hart's cut	0.7	0.5	-0.2
Godineau Swamp	765.4	765.3	-0.1
Vessigny	-	0.5	-
Fullerton	2.4	4.1	1.7
Mucurapo Swamp	9.5	11.6	2.1
Orange Valley	1.5	16.0	14.5
Caroni Swamp	5263	5297.4	34.4
Los Gallos	76.1	111.0	34.9

	South Coast		
Guayaguayare	60.3	32.3	-28
Pt Galeota	23.6	19.4	-4.2
Erin Bay	33.4	31.4	-2
West of Franks Bay	-	0.7	-
Moruga River	113.4	113.3	-0.1
Los Blanquizales	250.8	250.8	0
	East Coast		
Matura River	21.1	1.5	-19.6
Le Branche River	28.8	28.1	-0.7
Rincon Bay	0.6	0.4	-0.2
Ortoire	-	215.5	-
North Manzanilla	0.7	0.6	-0.1
Nariva	-	580.7	-
North Mayaro	-	0.5	-
Central Mayaro	-	3.3	-
South Mayaro	-	4.2	-
Fishing pond	-	269.8	-
	North Coast		
Maracas Bay	-	0.9	-
Scotland bay	0.3	0.3	0

- denotes where area value not previously given

4.3 Mangrove species distribution and extent map for the Buccoo-Bon Accord region in southwest Tobago.

The species distribution map of the Buccoo-Bon Accord mangroves derived in this study revealed that the area is dominated by red mangrove *(Rhizophora mangle)*, with total coverage of 94.2 ha (Table 3). The red mangrove was fringed by buttonwood *(Conocarpus erectus)* on the seaward side in some areas. Buttonwood had a total coverage of 4.6 ha. A detailed outline of the major mangrove types in the Buccoo-Bon Accord area is provided in Figure 8. Validation and cross-referencing of this map with GPS ground data showed that areas were accurately classified with 99% accuracy being reported.

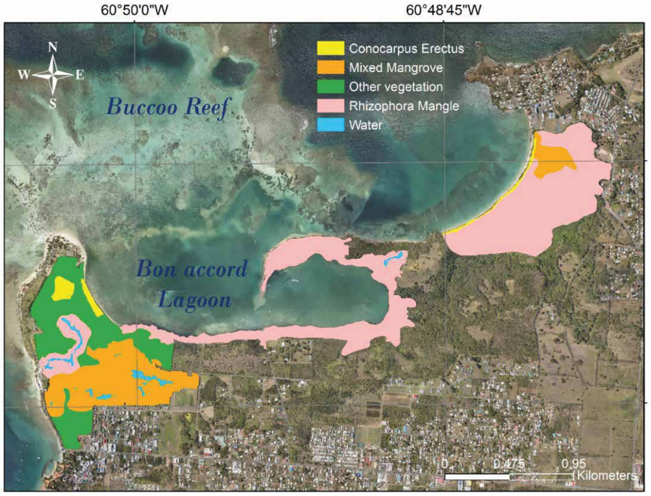


Figure 8. Mangrove species distribution and extent in the Buccoo-Bon Accord region of southwest Tobago.

Table 3. Mangrove species coverage in Buccoo-Bon Accord region of Tobago 2014.

Mangrove types	Area (ha)
Red mangrove (*Rhizophora mangle*)	94.2
Buttonwood (*Conocarpus erectus*)	4.6
Mixed mangroves	33.1

5.0 DISCUSSION

The 2007 mangrove baseline map produced by Juman and Ramsewak, 2013 [34] was the first national level mangrove mapping exercise performed in Trinidad and Tobago. This map was produced by identifying mangrove features based on visual interpretation of Ikonos satellite imagery and validation against ground reference data. One key limitation identified in the 2007 map by the authors was the temporal disparity amongst the individual satellite image tiles used to generate the base mosaic for the feature extraction. Due to the prevalence of clouds in the satellite data, a collection of 38 Ikonos images acquired during 2000-2007 was used to create the mosaic for the mapping [34].

The cloud-prone nature of the tropics usually has serious implications for inhibiting feature extraction in satellite imagery [68]. Although it appears that this was the best and most affordable data available to the researchers at the time, the 2007 map would have contained high temporal inaccuracies due to the use of imagery acquired across such a wide period. Additionally, the spatial resolution of the Ikonos imagery used for the 2007 map was 4m (in the multispectral bands) [34]. This may have been one of the reasons why some areas across both islands were misidentified as mangroves while others were not identified at all. Another simple reason why some existing mangrove areas were only detected in the 2014 mapping could have been due to an increase in the size of those particular stands between 2007 and 2014. The coloured aerial photography utilised for mangrove mapping and species discrimination in this study had a spatial resolution of 12.5 cm. This was a significant improvement upon the resolution of the Ikonos imagery used for the 2007 map. Vegetation differentiation and mapping from high-resolution imagery is based on visual assessment of the tone, texture, and colours related to morphological characteristics [63], therefore, imagery with higher spatial resolutions would facilitate improved feature extraction. Additionally, the high-resolution aerial photo dataset was acquired during the month of May in 2014. These factors allowed for very accurate and effective delineation of mangrove regions, producing mapped products with higher spatial and temporal accuracies than were achieved in the previous study. As drone technology advances and improvements in power generation and consumption, data storage, and overall cost-effectiveness take place, this remote sensing tool will become more common in mangrove mapping and change assessment studies. Also, with the recent launch of the PRISMA satellite in 2019, designed primarily for applications requiring narrow-band remote sensing [69], possibilities exist in the near future for larger-scale mangrove species mapping from this free, hyperspectral data.

The results showed that there was an expansion in mangrove coverage in certain areas. Notwithstanding this, the data revealed that overall there was a decrease in mangrove forests across both islands, primarily due to human intervention. In the Bon Accord Lagoon, for example, losses may have been as a result of beach improvements and clearing of the area for urban development [70]. The highest loss in Tobago was observed at Kilgwyn Swamp with a reduction of 16.5 ha of mangrove. Visual inspection of 2007 Ikonos imagery in Google EarthTM revealed that this vast difference was likely due to errors in interpretation of the satellite imagery in the 2007 study. The spatial resolution of the Ikonos imagery (4 m), coupled with the presence of vegetation types with similar morphological characteristics along the edges of the mangrove stands may have presented a challenge for visual interpretation and manual delineation of the mangrove boundaries. The integrated satellite image classification and high-resolution visual approach adopted in this study enabled a more effective separation of mangrove regions from other land cover types. In Trinidad, most of the mangrove forests are found along the west coast of the island, which is where many of the industrial and developmental activities are situated [34] and also where the greatest loss of mangroves was detected.

Trinidad and Tobago, and the wider Caribbean region, are directly impacted by the effects of climate change, as tropical storm and hurricane events occur more frequently each year [71]. Mangrove forests provide numerous goods and services, inclusive of protecting our coastal resources against such weather events, therefore they must be preserved and protected [12]. Restoration projects such as mangrove planting campaigns at both the governmental and non-governmental levels must be encouraged [72]. Additionally, legislation involving the preservation of mangrove ecosystems should be enforced, including laws prohibiting the cutting down and destruction of mangrove trees for industrialisation and urbanisation [73].

Mapping and monitoring are key first steps in the effective implementation of conservation strategies, therefore; the geospatial techniques applied here have significance for management and policy development. With increased climate variability expected in the future, more accurate and up-to-date data from such strategies will be required on a regular basis to inform decision-making. Settlements in Trinidad and Tobago that depend on these wetlands for work and sustenance are at higher risk [74]. The approach adopted in this study can help to reduce this risk by providing data necessary for developing enhanced management tools. Mangrove sustainability should be specifically addressed in marine spatial planning and policy frameworks. This can ultimately lead to the implementation of more effective adaptive responses for the benefit of all interested parties. In order to increase the likelihood of long-term success therefore, it is critical to include stakeholders such as the local communities and the relevant economic sectors (forestry, fisheries, tourism, aquaculture) in the policy development process [75]. Due to the similarity in nature among mangrove forests in Caribbean SIDS, this approach can be applied across the region to ensure the sustainable use of our mangrove resources.

6.0 CONCLUSION

This study utilised high-resolution, coloured aerial photography and multispectral satellite imagery in an integrated geospatial approach to produce an updated map of mangrove forests in Trinidad and Tobago, conduct an assessment of mangrove change between 2007 and 2014 and produce a mangrove species map for the Buccoo-Bon Accord region of southwest Tobago. Significant degradation of mangrove coverage was observed across both islands, with a total loss of 292.1 ha during the 7-year period. Clearing of mangroves for development and the presence of solid waste were both observed in the field. A species distribution map produced, showed that red mangrove *(Rhizophora mangle)* was the dominant species in the Buccoo-Bon Accord region of southwest Tobago with total coverage of 94.2 ha. The methodology used for detecting and delineating mangrove areas in this study generated maps with high spatial and temporal accuracies. A highly accurate mangrove species-distribution map of the Buccoo-Bon Accord region of Tobago was created through visual interpretation of aerial photography coupled with extensive ground validation. The updated mangrove forest map, mangrove change assessment, and mangrove species distribution map produced in this study can be useful inputs for the establishment of mangrove forest conservation and management strategies that promote more sustainable development practices in Trinidad and Tobago and the wider Caribbean region. With climate change and its associated anthropogenic impacts no longer at our doorstep but already over our threshold, enhanced management and policy actions need to be implemented sooner rather than later. The utilisation of information generated from advanced technological approaches and the integration of all stakeholders in the policy and planning processes will help to ensure the sustainable use of our mangroves.

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