Characteristics of Mangrove Forests in São Tomé and Príncipe and The Potential for Restoration

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Abstract

Mangrove forests in Small Island States (SIDs) have not been fully incorporated into the global mangrove atlas. Here, we present a detailed analysis of the status and conditions of mangroves located in the Republic of São Tomé and Príncipe (STP). Mapping of mangroves was carried out using remotely sensed data and GIS. This was complemented by detailed ground truthing, GPS mapping, and community appraisals in all 19 mangrove sites in STP. Sampling was conducted in 24 square plots of 100 m^2 that were randomly distributed along belt transects established perpendicular to the waterline. Within each plot, all trees with a stem diameter ≥ 2.5 cm were identified, counted, and position marked. Data on tree height (m), stem diameter (cm), and canopy cover (%) were collected, from which basal area (m^2 ha^{-1}), stocking rates (stems ha^{-1}), and biomass carbon (Mg C ha^{-1}) were derived. Mangrove forests in STP are estimated to cover approximately 180 ha, with 97.1% of these occurring on São Tomé Island and the rest on the Island of Príncipe. There are six mangrove species in STP; dominated by *Rhizophora racemosa G. Mey., R. mangle L., and Avicennia germinans (L.) L.*. The stocking rates of mangroves in STP ranged from 400 to 2,880 stems ha^{-1} (mean: 2,170.0 ± 366.0 stems ha^{-1}) with a basal area of 25.0 ± 3.9 m^2 ha^{-1} (range: 1.5 to 30.2 m^2 ha^{-1}), and standing biomass of 240.1 ± 38.3 t ha^{-1} (range: 11.1 to 315 t ha^{-1}). Together with below-ground biomass, mangroves in STP have a biomass carbon of 157.9 ± 24.9 Mg C ha^{-1}. Assuming a sediment carbon of 780.2 Mg C ha^{-1} for Central African mangroves, the total ecosystem carbon of mangroves in STP is estimated at 938.1 Mg C ha^{-1} (range: 701.1 to 1,123.2 Mg C ha^{-1}). Localized overexploitation of mangrove wood products for firewood and tannin extraction was witnessed in peri-urban mangrove sites at Praia das Conchas, Água Ize and Diogo Nunes, where natural regeneration was inadequate to support forest recovery. Other important threats to the mangroves were coastal development and waste disposal. These findings revealed spatial variation in mangrove distribution across STP, as well as identifying sites for targeted restorations. The study provides baseline data and information for exploring nature-based enterprises, including mangrove ecotourism and blue carbon.

Introduction

Mangroves are among the most productive and resilient coastal ecosystems on earth, providing habitat for fish and other wildlife, protecting shoreline from erosion, and regulating climate [1–3]. They form the interface between land and sea in tropical and subtropical regions [4] and are recognized for their capacity to deliver a wide range of ecosystem services that support local, national, and global economies [5]. Despite their relatively small global area, estimated at 13.7 million ha [6], mangroves capture and store huge stocks of carbon in both above- and below-ground components [7]. Their blue carbon values have drawn increased international attention, and mangrove countries have incorporated mangroves in their development and climate change agenda to the Paris Agreement [8–11].

In São Tomé and Príncipe (STP), mangroves are known to cover between 100 and 136 ha [12]. While they are relatively small in area and often found in the inner basins, mangroves in STP provide critical ecosystem services, including shoreline stabilization, fish spawning and feeding grounds, and climate regulation [13]. However, like elsewhere around the world, mangroves in STP are threatened by human and natural stressors, including over-exploitation of resources, conversion pressure, pollution effects, and climate change. Losses and degradation of mangroves adversely affect local biodiversity and fisheries, as well as the stability of shorelines. Protection and conservation of forests, such as mangroves, requires a clear understanding of what constitutes ecosystem health. Describing ecosystem health is fundamental in setting protection and conservation goals [14].

Until recently, there were limited field-based studies on the structure and distribution of mangrove forests in STP [12]. While resource mapping and coastal risk assessments were conducted under the West Africa Coastal Areas Management Program (WACA+), these lacked site-level ground-truthing and socio-ecological integration. Consequently, there was a need for empirical data to guide ecosystem restoration, support blue carbon initiatives, and design community-inclusive mangrove conservation programs. To our understanding, this was the first study to undertake a detailed account of mangrove forests in STP in terms of species composition, forest structure, environmental settings, degradation drivers, and socio-economic interactions. The results will inform the development plan for mangroves in STP and sites for targeted restoration.

Materials and methods

Study area

São Tomé and Príncipe is a small island developing state (SIDS) located in the Gulf of Guinea, off the western equatorial coast of Central Africa (Fig. 1). It consists of two main islands: São Tomé and Príncipe, separated by approximately 182 km, along with several smaller islets such as the Tinhosa Islands, Ilhéu das Cabras, and Ilhéu das Rolas. The country lies across the equator and features a tropical climate characterized by high temperatures and humidity year-round. The annual rainfall in STP ranges from 2,000 mm to over 7,000 mm, with long rains occurring from September to May, followed by relatively dry seasons from June to August. These climatic conditions are conducive to mangroves; however, geomorphic constraints limit the expansion of these forests in the two islands. For instance, STP experiences semidiurnal micro-tidal conditions of 0.30–1.80 m that reduce the frequency and extension of tidal inundation, thus influencing coastal and estuarine environments, including mangrove systems.

Mangrove cover

To understand the occurrence and distribution of mangroves in São Tomé and Principe, an unsupervised classification of the area of interest was first performed to delineate distinct spectral classes, which guided initial field validation efforts. Sentinel imagery was accessed through Google Earth Engine (GEE), and key vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), were calculated to highlight vegetated areas and distinguish mangroves from other plant types. Training samples from known mangrove and non-mangrove locations were collected, and supervised classification algorithms, specifically Random Forest and Support Vector Machine (SVM), were applied to categorize the imagery. The classification outputs were validated against detailed ground-truthing data, the Global Mangrove Watch (GMW) dataset, and high-resolution imagery from Airbus and Maxar Technologies, with overall accuracy and the kappa coefficient computed to quantify performance. To enhance map quality, spatial filters (majority filtering and edge smoothing) were applied to reduce noise. Subsequently, on-screen digitization of mangrove patch boundaries was conducted in ArcMap by visually tracing each patch on very-high-resolution imagery. Through photo-interpretation, individual polygons were manually delineated based on tonality, texture, shape, and proximity to water bodies. Mangroves typically exhibit a range of green hues, from pale to medium, depending on the image season, that contrast with the dark brown or mixed light green/brown tones of surrounding vegetation. Their characteristic sinuous perimeters with numerous inlets and proximity to water features further guided manual mapping.

Potential areas of mangrove restoration were delineated based on a set of biophysical and ecological criteria. These included soil type, hydrological conditions (regular tidal flushing and water exchange), historical presence of mangroves as indicated by old stumps and local knowledge, and absence of current land-use conflicts such as settlements or infrastructure. Areas with degraded vegetation, open mangrove areas adjacent to healthy stands, and locations showing natural regeneration potential were prioritized. This combination of qualitative indicators ensured that only sites with favorable ecological conditions and restoration feasibility were classified as potentially restorable.

Survey of mangrove forest structure

Random plots of 100 m^2 were used for the study. The number of plots varied across sites and was dependent on the extent of mangroves in the area (Table 1). In each plot, all trees with stem diameter at breast height (DBH) ≥ 2.5 cm were identified, counted, and their positions marked. The following parameters were collected: tree height (m), stem diameter at breast height (DBH) (cm), number of live/dead trees, and quality of the lead stem (categorized as either straight, semi-straight or crooked). From these data, the following vegetation attributes were derived: basal area (m^2 ha^{-1}), stocking rates (stems ha^{-1}), and standing biomass (t ha^{-1}). Vegetation cover (%) was estimated from the area of the ground that one would see if flying above the tree canopy [15]. Tree heights were estimated using a graduated pole, while stem diameters were measured at 130 cm above ground, using a diameter tape. In the case of *Rhizophora* spp., stem diameter was taken 30 cm above the highest prop root [16]. For the forked stems below 130 cm, individual branches in a clump were treated as separate stems. Patterns and conditions of natural recruitment were assessed using linear regeneration sampling, whose applications could be found in Kairo [17].

Data analysis

Graphical presentations and descriptive analysis of structural data helped to understand variations of mangroves across different sites in STP. The complexity index value for each district was determined using the approach in Holdridge et al. [18], which incorporates species composition, basal area, mean tree height, and stem density:

Complexity Index (CI) = Number of species x basal area (m^2 ha^{-1}) x mean tree height (m) x stem density (stems ha^{-1}) x 10^{-5}
Eq. 1

Biomass carbon was estimated using the general allometric equations of Komiyama et al. [16, 19]:

$$Aboveground\ Biomass\ (kg) = 0.251\rho\ D\ 2.46$$ Eq. 2

$$Belowground\ Biomass\ (kg) = 0.199\rho^{\ 0.899} \times\ D^{2.22}$$ Eq. 3

Where D = tree diameter at breast height (cm) and ρ = wood density (g cm^{-3})

Species-specific wood densities for mangroves, as reported by Howard et al. [20], were applied in this study. Biomass values were converted to carbon equivalents by multiplying with conversion factors of 0.50 and 0.39 for AGB and BGB, respectively, following procedures by Kauffman and Donato [21].

Results

Mangrove distribution in São Tomé and Príncipe

Mangroves in São Tomé and Príncipe occur in small ‘discrete pockets’ distributed in estuaries of small rivers, creeks, and coastal lagoons of the two islands. Total mangrove area in São Tomé and Príncipe was estimated at 180.0 ha, with São Tomé constituting 174.801 ha (97.1%) and Príncipe 5.2 ha (2.9%) (Table 1; Supplementary Fig. 1–3). A total of 19 mangrove sites were identified on the ground, being 14 on São Tomé and 5 on Príncipe Island. Major mangrove forests on São Tomé Island were encountered at Malanza (126.6 ha), Angolares (19.1 ha), Praia Grande (11.3 ha), Água Izé (3.7 ha), and Praia de Morro Peixe (3.2 ha) (Fig. 1; Supplementary Table 1,2). At least 6 sites reported here had never been documented before, including Praia Grande, Água Izé, Praia do Morro Peixe, Morro Peixe Comunidade, Praia Melão, and Praia Francesa, all on São Tomé Island. On Príncipe Island, Praia Burra (1.1 ha) was specifically identified as a priority site for targeted future mangrove afforestation (Fig. 2).

There are six mangrove species in São Tomé and Príncipe, dominated by *Rhizophora racemosa G. Mey., Avicennia germinans (L.) L.*, and *Rhizophora mangle L.*. Other species encountered were *Rhizophora harrisonii Leechm, Conocarpus erectus L.*, and the fern *Acrostichum aureum L.*. Although some national reports and previous studies (e.g.,[22]) indicated the presence of *Laguncularia racemosa* in São Tomé and Príncipe, its presence in all the sampled sites was not confirmed during this study. There was no obvious zonation of mangroves in STP. Several mangrove-associated tree species were also encountered in STP, including *Cocos nucifera* (coconut palm), *Hibiscus tiliaceus, Phoenix reclinata* (Senegal date palm), *Terminalia catappa* (tropical almond), and *Erythrina fusca* (coral bean), occurring in transitional ecotones.

Table 1
Summary table of mangrove distributions on São Tomé and Príncipe

Island	District	Mangrove Cover (ha)	Potential Restoration Area (ha)	Total Mangrove Area (ha)
São Tomé	Caué	144.4	12.6	157.0
	Lobata	5.3	5.8	11.1
	Cantagalo	2.7	2.9	5.6
	Mé-Zóchi	0.1	0.9	1.0
	Água Grande	0.001	0.1	0.101
	Whole of São Tomé	**152.501**	**22.3**	**174.801**
Príncipe	Pagué	2.0	3.2	5.2
Whole Country		**154.501**	**25.5**	**180.001**

Mangrove forest structure

Structural attributes of mangroves in STP are presented in Table 2. Stem density ranged from 400 ± 300 stems ha^{-1} in the Mé-Zóchi and Agua Grande districts to 2,880 ± 743.2 stems ha^{-1} in the Lobata district, with an overall mean of 2,169.6 ± 365.7 stems ha^{-1}. Structural complexity was highest in Lobata (CI = 31.7) and Cantagalo (24.2) districts, probably due to high stem densities combined with trees possessing large basal areas. Mé-Zóchi and Água Grande recorded low CI values, mostly due to human pressure. All structural attributes between the districts differed significantly except mean diameter ($F_{(4, 23)}$, f = 0.22, $p > 0.05$, $p = 0.92$). The sources of these differences, based on Tukey's post-hoc analysis, are provided in Table 2.

Table 2
Structural attributes (mean ± s.e) of mangroves in São Tomé and Príncipe

District	Species*	Stem Density (Count ha^{-1})	Mean DBH (cm)	Mean Height (m)	Basal Area (m^2 ha^{-1})	Complexity Index (CI)	Above-ground Biomass (t ha^{-1})	Below-ground Biomass (t ha^{-1})	Total Biomass (t ha^{-1})
Caué	4	1,740 ± 229.3	11.4 ± 1.5	11.3 ± 1.5	22.4 ± 3.7	17.6	227.2 ± 47.6	91.5 ± 17.5	318.7 ± 65.1
Lobata	4	2,880 ± 743.2	10.2 ± 1.1	9.1 ± 1.1	30.2 ± 7.4	31.7	266.1 ± 66.9	109.7 ± 26.4	375.8 ± 93.2
Cantagalo	3	1,850 ± 250	11.1 ± 3.3	16.7 ± 4	26.1 ± 14	24.2	315 ± 216.7	116.2 ± 71.4	431.2 ± 288.1
Mé-Zóchi & Água Grande	2	400 ± 300	10.1 ± 5.9	6.4 ± 0.7	1.5 ± 0.5	0.1	11.1 ± 5.2	5.1 ± 1.8	16.2 ± 7
Pagué	3	1,975 ± 579.3	11.4 ± 0.7	15.1 ± 1.9	26.3 ± 7.7	23.5	268.3 ± 78.1	109.1 ± 32	377.4 ± 110.1
Whole Country	**5**	**2,169.6 ± 365.7**	**10.7 ± 0.7**	**11.0 ± 0.9**	**25 ± 3.9**	**29.8**	**240.1 ± 38.3**	**97.1 ± 14.8**	**337.2 ± 53.1**
F-value	**-**	*2.79*	*0.22*	*10.46*	*3.31*		*3.04*	*3.28*	*3.10*
p-value	**-**	*0.046*	*0.92*	*0.00002*	*0.02*		*0.03*	*0.02*	*0.03*
Tukey's HSD post-hoc grouping	-	Lob ≠ Me	nsd	Paq ≠ Lob, Paq ≠ Me, Can ≠ Cau, Can ≠ Lob	Lob ≠ Me		Can ≠ Me	Paq ≠ Me, Can ≠ Me, Lob ≠ Me	Can ≠ Me

Complexity Index (CI) = Number of species x Basal area (m^2 ha^{-1}) x mean tree height (m) x stem density (stems ha^{-1}) x 10^{-5}.

Note: nsd = not significant difference (p > 0.05). Paq = Paque, Can = Cantagalo, Cau = Caue, Lob = Lobata, and Me = Mé-Zóchi & Água Grande

*Species included here are exclusive of the fern *Acrostichum aureum*

Biomass carbon

The standing biomass of mangroves in STP ranged from 7.5 to 202.8 Mg C ha^{-1} (mean: 157.9 ± 24.9 Mg ha^{-1}), with the highest and lowest mean values recorded in Cantagalo (157.5 ± 108.4) and Mé-Zóchi & Água Grande (5.6 ± 2.6 Mg C ha^{-1}) districts (Table 3). There were positive correlations between basal area and standing biomass carbon (r^2 = 0.97) as well as between stem density and biomass carbon (r^2 = 0.48), which is expected. Assuming a sediment carbon of 780.2 Mg C ha^{-1} for Central African mangroves, the total ecosystem carbon (TEC) of mangroves in STP is estimated at 938.1 Mg C ha^{-1} (range: 701.1 to 1,123.2 Mg C ha^{-1}). This translates to TEC stock of 168,858.9 Mg C for the entire mangrove system of STP (180.001 ha).

Table 3
Biomass carbon stocks of mangrove forest in São Tomé and Príncipe

District	Above-ground Carbon (Mg C ha⁻¹)	Below-ground Carbon (Mg C ha⁻¹)	Total Biomass Carbon (Mg C ha⁻¹)	Carbon dioxide Equivalent ha⁻¹
Cauê	113.6 ± 23.8	35.7 ± 6.8	149.3 ± 30.6	547.9 ± 112.4
Lobata	131.1 ± 33.5	42.8 ± 10.3	175.8 ± 43.7	645.3 ± 160.4
Cantagalo	157.5 ± 108.4	45.3 ± 27.8	202.8 ± 136.2	744.3 ± 499.9
Mé-Zóchi & Água Grande	5.6 ± 2.6	2.0 ± 0.7	7.6 ± 3.3	27.8 ± 12.2
Pagué	134.2 ± 39.1	42.6 ± 12.5	176.7 ± 51.5	648.6 ± 189.1
Whole of STP	**120.1 ± 19.2**	**37.9 ± 5.8**	**157.9 ± 24.9**	**579.6 ± 91.4**
F-value	*3.04*	*3.28*	*3.09*	*3.09*
P-value	*0.03*	*0.02*	*0.03*	*0.03*
Tukey's HSD post-hoc grouping	Can ≠ Me	Paq ≠ Me, Can ≠ Me, Lob ≠ Me	Can ≠ Me	Can ≠ Me

Carbon values were further expressed in terms of CO_2 equivalent by multiplying C stocks by 3.67, the molecular weight of C in CO_2. All attributes are significantly different ($p < 0.05$)

Harvesting pressure

Exploitation of mangrove products for building, energy, and tannin is a common feature in both rural and peri-urban areas of STP. In all the sites sampled, a mean stump count of 621.7 ± 433.7 stumps ha^{-1} was observed, with the highest cutting observed in the Lobata (1,050 ± 441.3 stumps ha^{-1}) and Cantagalo (850 ± 150 stumps ha^{-1}) districts (Fig. 3). The difference in stump density between the districts was not significantly different ($F_{(4, 23)} = 2.51$, $p > 0.05$).

Natural regeneration

The density of juveniles ranged from 0 ± 0 juveniles ha^{-1} in the Mé-Zóchi & Água Grande districts to 3,380 ± 2,374.3 juveniles ha^{-1} in the Cauê district (mean ± s.e.: 1,587 ± 648.2 juveniles ha^{-1}). There was no significant difference in the density of juveniles between the districts ($F_{(4, 23)} = 1.47$; $p > 0.05$; $p = 0.24$). The forest was dominated by Regeneration Class I juveniles (43%), followed by Regeneration Class II (41.6%)—Table 4. Although *C. erectus* was represented among the adult trees, juveniles of this species were absent in the entire forest. Regeneration ratios (for RCI: RCII: RCIII) of whole STP mangroves was 2:2:1.

Table 4
Juvenile densities (counts ha⁻¹) of mangroves in São Tomé and Príncipe

District	Regeneration Class			Total
	RCI (< 40 cm)	RCII (40–150 m)	RCIII (150.1–300 cm)	(Juveniles ha⁻¹)
Cauê	920 ± 524.8 (27.2)	2,220 ± 1,743.6 (65.7)	260 ± 188.7 (7.7)	3,380 ± 2,374.3
Lobata	920 ± 681.5 (60.9)	260 ± 98 (17.2)	330 ± 143.8 (21.9)	1,510 ± 903.4
Cantagalo	450 ± 250 (39.1)	450 ± 50 (39.1)	250 ± 50 (21.7)	1,150 ± 150
Pagué	250 ± 104.1 (45.5)	175 ± 85.4 (31.8)	125 ± 25 (22.7)	550 ± 210.2
Mé-Zóchi & Água Grande	0	0	0	0
Whole of STP	**682.6 ± 315 (43)**	**660.9 ± 315 (41.6)**	**243.5 ± 74.9 (15.3)**	**1,587 ± 648.2**
F-value	*2.72*	*2.11*	*1.40*	*1.47*
P-value	*0.58*	*0.10*	*0.26*	*0.24*
Tukey's HSD post-hoc grouping	nsd	nsd	nsd	nsd
Values in parentheses denote percentages. nsd = not significant difference. (p > 0.05)				

Mangrove restoration potential in São Tomé and Príncipe

Mangroves in STP are not pristine. They are facing a combination of human-induced and natural stressors. Direct removal of wood products and tannins remains the most significant threat, followed by pollution, land encroachment, water streams obstruction and climate change effects. Potential areas of mangrove restoration differ across sites, depending on drivers, site history, and accessibility. Total mangrove areas requiring targeted restoration in STP were estimated at 25.5 ha, with 89.8% of degraded areas occurring on São Tomé Island (Table 1). Sites like Praia das Conchas, Diogo Nunes, Praia Quinze, and Micolo, all on São Tomé Island, showed signs of historical disturbance, including altered hydrology, crab predation, and sand harvesting. These areas offer opportunities for enrichment planting with *A. germinans* and *R. mangle*. Sites threatened by increased sedimentation (like Praia da Conchas) require hydrological restoration to reconnect tidal flows and promote natural regeneration. Mangroves of Malanza, Praia Salgada, and Praia Caixão exhibited intact to moderately disturbed stands that could recover naturally. These sites are especially promising for nature-based enterprises such as ecotourism and blue carbon projects.

Discussions

Mangrove cover

Total mangrove area in São Tomé and Príncipe was estimated at 180.0 ha, with São Tomé constituting 174.801 ha and Príncipe 5.2 ha. This value is lower than earlier reports, but represents the most accurate estimate of mangrove area in São Tomé and Príncipe (Table 6).

Table 6
Mangrove area in São Tomé and Príncipe from different sources

Island	**District**	**Mangrove Area (ha)**						
		UNEP [23]	**Haroun et al. [22]**	**Global Mangrove Watch**	**Afonso [13]**	**Afonso et al., [24]**	**Machava-António et al. [12]**	**This study**
São Tomé	Caué	-	68.6	46.1	165	200	-	157.0
	Lobata	-	0.8	2.3	1	1	-	11.1
	Cantagalo	-	-	-	-	-	-	5.6
	Mé-Zóchi	-	-	-	-	-	-	1.0
	Água Grande	-	-	-	-	-	-	0.101
	Whole of São Tomé	**-**	**-**	**48.4**	**-**	**1-200**	**-**	**174.801**
Príncipe	Pagué	-	-	-	-	-	1.6	5.2
Whole Country		**140**	**-**	**-**	**-**	**-**	**100–136**	**180.001**

Detailed mangrove cover per site based on the different sources is provided in Supplementary Table 1.

The observed differences in mangrove area of STP from different sources are attributed to differences in methodologies used, the periods data were taken, as well as the definition of mangrove areas.

Forest structure

The structural attributes, such as species composition, tree height, basal area, and standing biomass, are comparable to other mangroves in the Central and West Africa region [25, 26, 4]. Mangroves in STP are dominated by *Rhizophora spp.* and *A. germinans*, which is consistent with the mangroves of the region. *Laguncularia racemosa* has been reported in West and Central African mangroves, including Guinea-Bissau, Nigeria, Gabon, and Cameroon [4, 27]. However, it was not recorded in STP during this study. Its absence may indicate historical occurrence followed by local extinction, possibly due to limited habitat extent, small and vulnerable populations, or anthropogenic pressures such as land conversion and altered hydrology. Given the islands' small and fragmented mangrove areas, the persistence of Laguncularia populations may have been ecologically constrained. Further surveys are needed to confirm whether the species is truly absent or persists in overlooked sites.

The standing biomass of mangroves in STP is estimated at 337.2 Mg ha^{-1}, which is within the range of healthy mangroves of the Atlantic–East Pacific bioregion that includes the mangroves of the Central and West Africa region (Table 7).

Table 7
Structural attributes of mangroves in São Tomé and Príncipe compared to other countries in Central Africa

Country	Structural Attribute									Source
	No. of species	Tree Density (stems ha^{-1})	Max. Height (m)	Max. Diameter (cm)	Mean Diameter (m)	Mean Basal Area (m^2 ha^{-1})	Mean AGB (Mg ha^{-1})	Mean BGB (Mg ha^{-1})	Total mean Biomass (Mg ha^{-1})	
São Tomé and Príncipe	6	2,169.6	30	44.6	10.7	25	240.1	97.1	337.2	**This study**
Cameroon	4	3,255	52	102	4.6	25.1	505	306	811	Ajonina et al., 2014[27]
Gabon	6	1,466	41	52	9.5	24.5	341	151	492	Ajonina et al., 2014[27]
Congo	2	1,666	25	58	7.7	18.8	251	122	373	Ajonina et al., 2014[27]
DRC	2	1,266	27	59	9.1	24.5	409	185	594	Ajonina et al., 2014[27]

Biomass carbon

The mangrove forests of STP exhibit moderate biomass carbon stocks, averaging 157.9 Mg C ha^{-1}, which is within the lower to mid-range compared to other regions in West and Central Africa [27]. The value is higher than the 147.5 Mg C ha^{-1} average global mangrove biomass carbon [28] but lower than the global average of 190.2 Mg C ha^{-1} [29]. Considerable spatial variability was observed, with Cantagalo supporting the highest biomass carbon (202.8 Mg C ha^{-1}), while Mé-Zóchi & Água Grande recorded severely depleted stocks (7.6 Mg C ha^{-1}), reflecting intense degradation and limited mangrove cover in urbanized districts. Districts such as Cantagalo, Lobata, and Pagué maintain relatively high carbon storage, making them priority areas for protection and integration into blue carbon initiatives. In contrast, the severely degraded sites of Mé-Zóchi and Água Grande offer opportunities for targeted restoration interventions aimed at enhancing biomass accumulation and carbon sequestration. As expected, there was a strong positive correlation between basal area and total biomass carbon ($r^2 = 0.97$), indicating that plots with larger tree sizes stored more biomass carbon. In contrast, a weak positive correlation was observed between stem density and total biomass carbon ($r^2 = 0.48$), suggesting that tree count alone was a less reliable predictor of carbon stocks compared to structural attributes like basal area.

Natural regeneration

Mangroves of STP were dominated by juvenile *Rhizophora spp*. However, the natural regeneration density, estimated at 1,587 ± 648.2 juveniles ha^{-1}, is considered insufficient to sustain forest recovery following disturbance. This value falls significantly below the minimum threshold of 2,500 seedlings ha^{-1} recommended by FAO [30] as necessary for restocking a degraded mangrove stand without replanting. An ideal regeneration ratio of RCI:RCII:RCIII = 6:3:1 is considered adequate for effective mangrove recovery [31]. In STP, the observed ratio (2:2:1) was slightly below this benchmark, indicating limited natural regeneration potential. Although juvenile densities were not significantly different among districts, the predominance of Regeneration Class I and II individuals suggests that most stands are still in early successional stages. This skewed structure highlights ongoing regeneration but also indicates limited recruitment into advanced size classes, which may constrain long-term forest stability. The absence of *C. erectus* juveniles, despite the presence of adults, points to potential regeneration bottlenecks, possibly linked to hydrological conditions, propagule availability, or species-specific ecological constraints. Districts with complete absence of juveniles may reflect intense anthropogenic pressures or degraded environmental conditions that hinder natural recruitment.

Restoration potential

Mangrove ecosystems in São Tomé and Príncipe exhibit notable potential for restoration, though levels of degradation vary across sites. Highly disturbed areas such as Praia das Conchas, Diogo Nunes, Praia Quinze, and Micolo represent prime candidates for active interventions, including enrichment planting with native mangrove species. However, successful outcomes hinge on the restoration of hydrological connectivity, a foundational step emphasized in hydrological rehabilitation frameworks [32, 33]. In contrast, relatively intact stands in Malanza, Praia Salgada, and Praia Caixão are well-suited for assisted natural regeneration (ANR) and expansion of ongoing afforestation. Studies from Southeast Asia and West Africa [34, 35] have shown that ANR, when coupled with community stewardship, yields cost-effective and ecologically robust results. These latter sites exhibit high biomass and carbon sequestration capacity, suggesting strong potential for integration into blue carbon initiatives, including carbon credit markets and Nationally Determined Contributions (NDCs) under the Paris Agreement. Restoration strategies should adopt Community-Based Ecological Mangrove Restoration (CBEMR) principles, which emphasize community involvement, ecological integrity, and long-term monitoring [36, 37]. Crab control should be considered as part of site-specific management plans, particularly in early-stage restoration plots where crab herbivory has been shown to significantly reduce seedling survival [38, 39].

Conclusion

This study provides the first comprehensive assessment of mangroves in São Tomé and Príncipe, documenting a total area of 180 ha across 19 sites, with São Tomé hosting 97.1%. Six species were recorded, dominated by *Rhizophora racemosa, Avicennia germinans*, and *R. mangle*, with smaller stands of *R. harrisonii, Conocarpus erectus*, and the fern *Acrostichum aureum*. Although limited in extent, these mangroves store an estimated 938.1 Mg C ha^{-1} (168,858.9 Mg C), underscoring their ecological and climate value. Despite this importance, they face acute pressures from unsustainable harvesting, hydrological alteration, pollution, coastal infrastructure, and settlement encroachment, with about 25.5 ha viable for restoration. Weak governance, characterized by fragmented mandates and the absence of a national mangrove policy, further constrains management. Priority restoration and afforestation sites were identified on both islands, offering opportunities for Nature-based Solutions. Interventions should emphasize hydrological rehabilitation, Community-Based Ecological Mangrove Restoration (CBEMR), nursery development, crab control, long-term monitoring, and ecotourism to support livelihoods. To secure their future, São Tomé and Príncipe must adopt a unified National Mangrove Strategy, integrate mangroves into climate commitments (e.g., NDCs, blue carbon markets), strengthen institutional coordination, and promote community co-management. Addressing knowledge gaps in biomass and soil carbon, biodiversity, and hydrology will enhance adaptive management and open access to climate finance. With decisive action and collaboration, mangroves can become a cornerstone of coastal resilience and a model of blue carbon stewardship for small island states.

Declarations

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Ethics, Consent to Participate, and Consent to Publish Declarations

Ethics approval and consent to participate: Not applicable.
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Data Availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

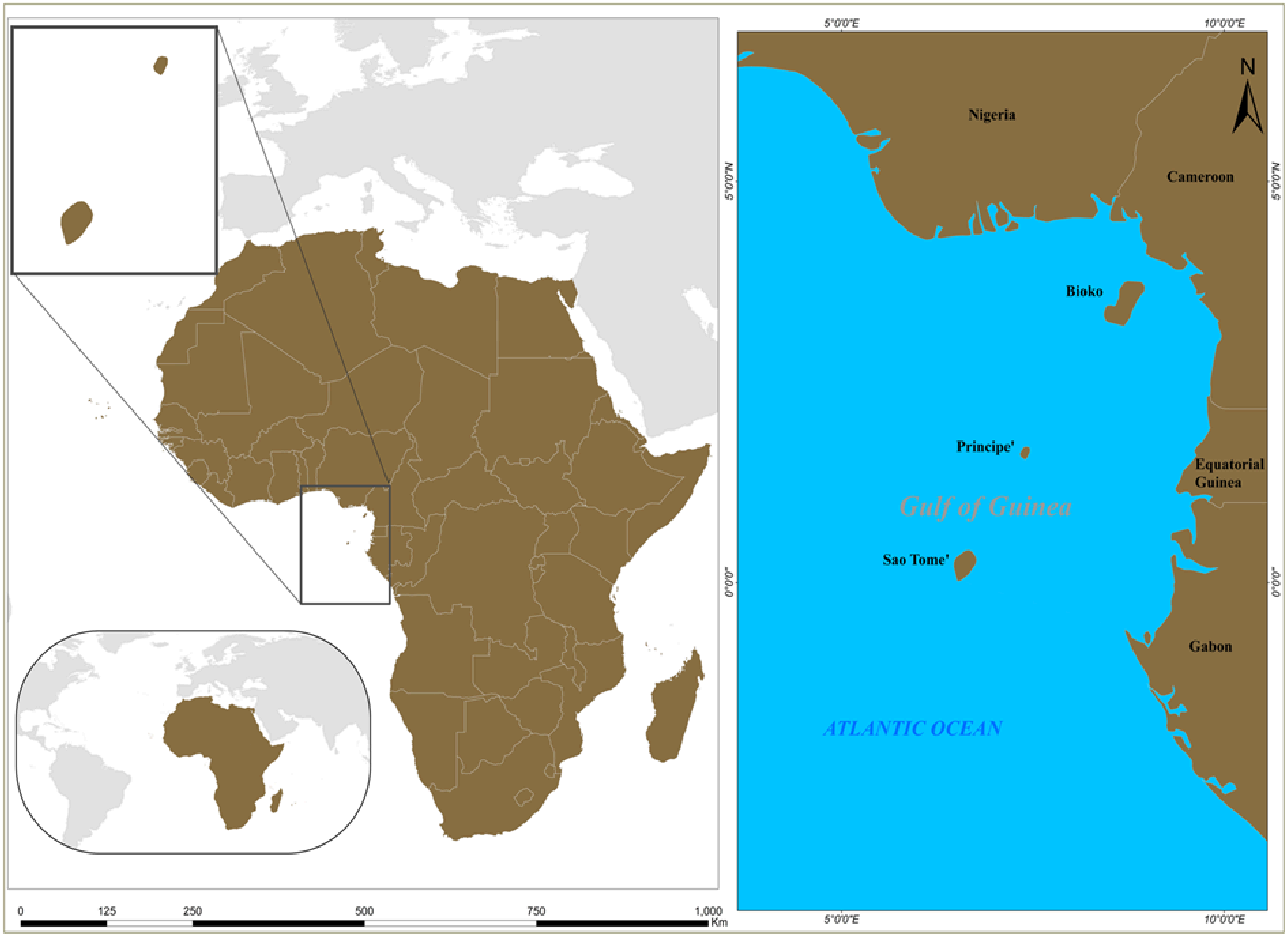

Figure 1

The locational map of São Tomé and Príncipe

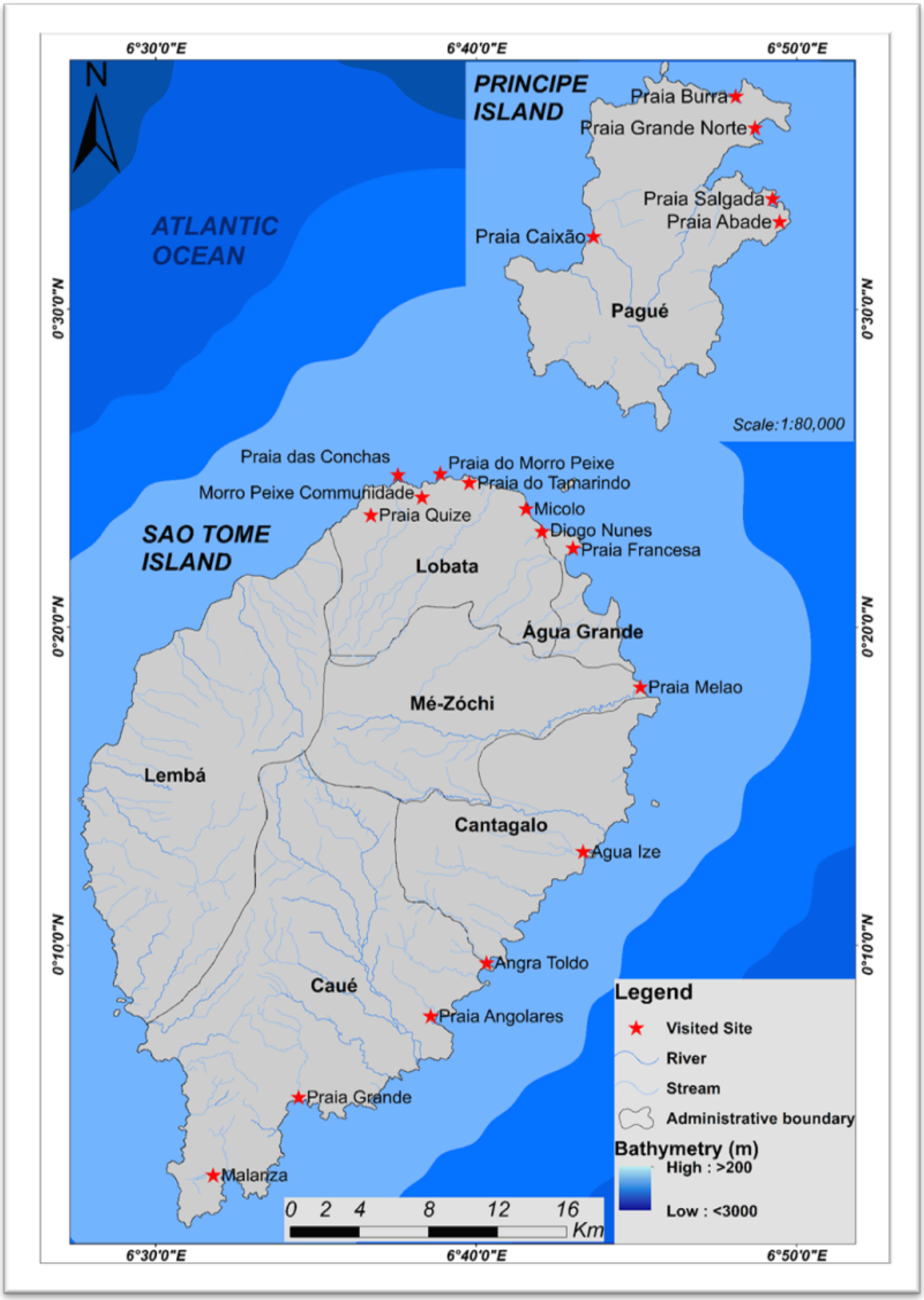

Figure 2

Mangrove sites in São Tomé and Príncipe

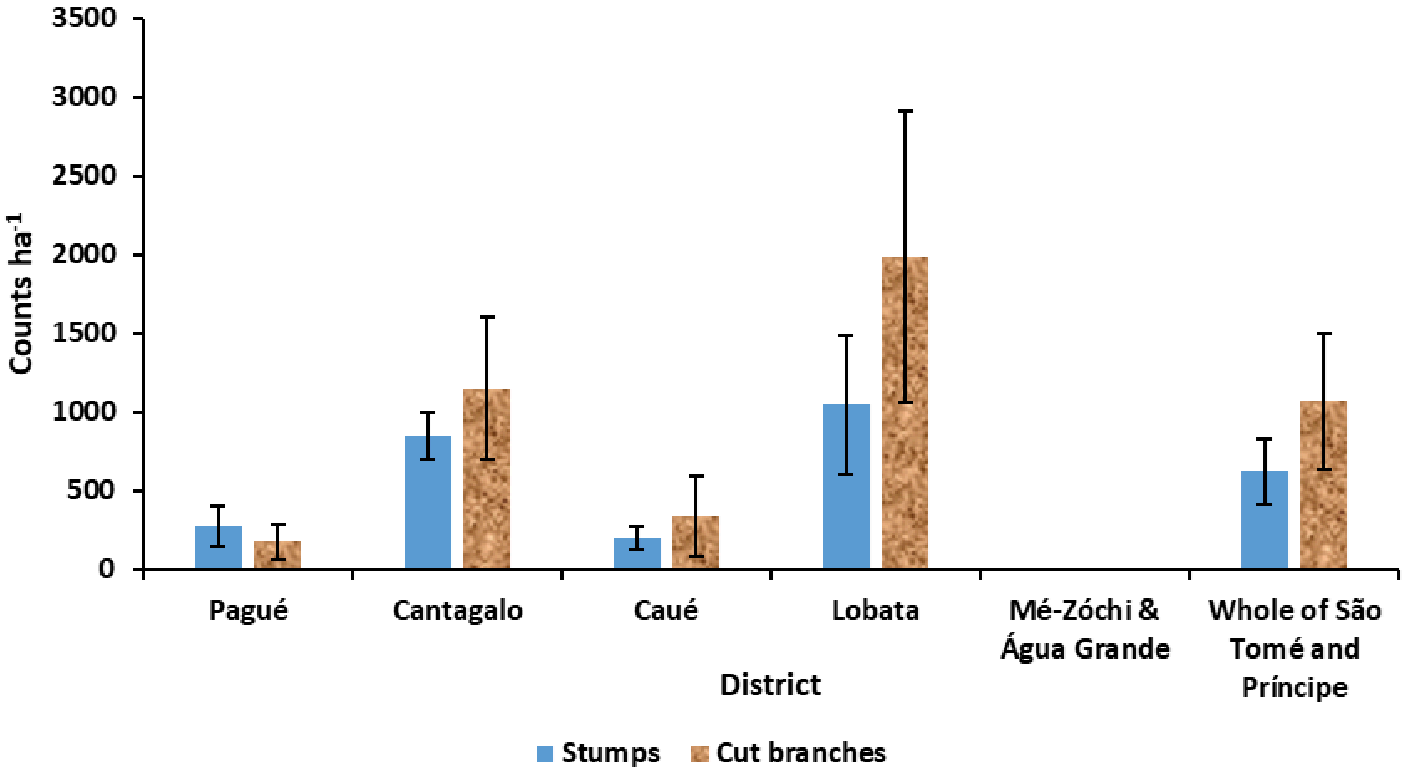

Figure 3

Stump densities (counts ha⁻¹) in mangroves of São Tomé and Príncipe

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