

The relationship between resilient mangroves and fish populations in the largest marine reserve in Belize: a case for conservation

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Abstract

Purpose – Mangrove forests are one of the most bio-diverse and productive wetland environments on earth. However, these unique tropical forest environments that occupy coastal areas are among the most threatened habitats globally. These threats include logging, conversion of land for agriculture and mariculture and degradation due to pollution over the past 50 years. The large population of resilient mangroves occupying the Turneffe Atoll area in Belize faces growing anthropogenic threats such as permanent clearing of land for housing, infrastructural development and pollution and natural factors (climate change). Given the few formal studies done to evaluate mangrove resilience at Turneffe Atoll, the purpose of this study was to evaluate mangrove resilience and nursery functions in the Turneffe Atoll Marine Reserve (TAMR).

Design/methodology/approach – Mangrove fish abundance and forest structure was assessed by means of a visual census and the point-centred quarter method (PCQM) for 11 sites that span across conservation and general use zones.

Findings – This study found that the more resilient mangroves (lower vulnerability ranks, higher standing biomass and higher fish biomass and abundance) exist in general use zones and warrant the need for improved mangrove conservation measures for these areas by Turneffe Atoll Sustainability Association (TASA).

Research limitations/implications – Limitations of the methods for data collection included accessibility within mangrove forests stands when establishing PCQM, observer bias among data collectors, sites without surrounding mangroves were not captured to serve as a true control group and poor visibility underwater affected the estimation of fish species and size. The timeline for this research was only three months based on available funding, and no follow-up study was done to make a true comparison.

Originality/value – The findings of this research have a guiding role in the formulation of conservation measures such as better waste management, a robust framework for mangrove management, a communication strategy to guide public awareness and long-term monitoring surveys.

Keywords Resilient mangroves, Turneffe Atoll, Fish population, Marine reserve, Conservation

Paper type Research paper

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1. Introduction

Mangroves are classified as small evergreen trees that thrive in intertidal zones of estuaries, lagoons and river deltas and dominate subtropical and tropical coastal systems (Singh, 2020). The productive nature and location of mangroves in nearshore, warm coastal waters, make them increasingly valuable targets for farming, mariculture and recreation. These activities fundamentally alter the physicochemical nature of the habitat, affecting animals such as shrimps, crabs and fishes that depend on these ecosystems for food and shelter (Jaxion-Harm, 2010; McSherry *et al.*, 2023). Habitat destruction of coastal mangroves through sea level rise by means of climate change and deforestation by means of anthropogenic activities can alter niche dynamics in these communities (Seddon *et al.*, 2011; Roy *et al.*, 2023). Mangrove forests are declining globally due to anthropogenic and natural deforestation, which has resulted in the loss of one-third of mangrove forests and associated ecosystem services worldwide over the past 50 years (Gouvêa *et al.*, 2022). Mangrove forests are important for the sustenance of fishes and invertebrates; providing coastal populations with protein sources and supporting livelihoods; shoreline protection against floods, tsunamis and typhoons; purification of water; absorption of pollutants; offsetting greenhouse gas emissions and sequestering carbon and provision of nursery habitats for fishes (McSherry *et al.*, 2023; Rull, 2023). Additionally, these vital ecological goods and services have the potential to improve mangrove resilience to climate change, storms, sea level rise and anthropogenic activities (Turschwell *et al.*, 2020; Gouvêa *et al.*, 2022).

The most common variable used to illustrate mangrove species zonation patterns is tidal inundation frequency (Ma *et al.*, 2020; Sreelekshmi *et al.*, 2020). Mangrove species zonation in Belize adheres to the pattern of *Rhizophora* typically encountered near the shoreline and inundated areas, while *Avicennia* are frequent in drier areas that are further inland and have higher soil salinities due to evaporation (Murray *et al.*, 2003; Piou *et al.*, 2006; Cherrington *et al.*, 2020). Classifying mangroves into different types provides critical information about the forest structure and facilitates the prioritisation of conservation efforts. Mangrove seedlings are individual trees <1.37 m tall, and the presence of mangrove seedlings gives an indication of the level of recruitment in a particular area (Kauffman and Donato, 2012; Ellison, 2015). Saplings are trees with a diameter at breast height (DBH) <2.5 cm, while overstory trees are defined by DBH >5 cm (Almada-Villela *et al.*, 2003; Trettin *et al.*, 2015). Relatively high growth rates are characteristic features of mangrove saplings and seedlings, and these mangrove types are capable of colonising newly created intertidal substrates and forest gaps (Numbere, 2021; Quadros *et al.*, 2021). Dwarf mangroves are trees typically <3 m tall, which are constituted by scrub categories and typically occupy areas where the environmental conditions are extreme and the vegetation is restricted to short mangroves (Romero-Mujalli and Melendez, 2023). Medium mangroves are trees approximately 3–10 m tall which thrive in locations inland that are densely populated by fringing *R. mangle*, which grow in exposed sites along the coast and on cays (Kauffman *et al.*, 2020). Tall mangroves are trees with a mean height >10 m tall, which are typically restricted to locations on the margin of rivers and estuaries that are elevated on the largest cays where the required combination of restricted salinity, high levels of sustained nutrients and stable substrate exist to sustain this stand of large trees (Kauffman *et al.*, 2020). Standing biomass gives an indication of the quantity of standing organic matter per unit area at a particular time (Thivakaran *et al.*, 2020). The quantity of standing biomass stored in a forest is a function of this ecosystem age, productivity, exportation strategies and organic matter allocation (Thivakaran *et al.*, 2020).

Mangrove ecosystems play a vital role in the Belize Barrier Reef Complex owing to the support provided for animals, from fishes to crustaceans, as well as sustaining high levels of primary production centred around the production of leaf litter, which provides a trophic subsidy for adjacent coastal waters, both near and far (Dharanirajan *et al.*, 2010; Cherrington *et al.*, 2020). Mangrove resilience refers to a measure of the persistence of mangrove

ecosystems and of their ability to absorb change and disturbance and still maintain the same relationships between populations (Seddon *et al.*, 2011; Ellison *et al.*, 2020). Further, mangroves possess considerable resilience to sea level fluctuations owing to their ability to actively modify their environment by changing processes of surface elevation and their migration ability to inland zones over consecutive generations (Ward *et al.*, 2016). This sort of migration to landward zones allows the mangrove ecosystem to absorb and recognise the effects of the stress and facilitates the maintenance of its processes, structures and functions (Numbere, 2021; Rull, 2023). Studies conducted across the Caribbean reported that mangrove species zones migrated inland where a preferred frequency of inundation, depth and period existed, since these mangroves were incapable of keeping pace with relative sea level rise (Rull, 2023). This gives an indication of the mangroves' ability to adapt to changes in sea level and remain resilient.

Mangroves exhibit high resilience subsequent to disturbances due to their pioneering species ability, high productivity and natural regeneration capabilities (Capote-Fuentes, 2007; Ellison *et al.*, 2020). For instance, mangroves quickly re-grow subsequent to hurricanes (a disaster that Belize is prone to) and floods, but changes in temperature, hydrologic fluxes, topography and sedimentation affect mangrove forests (Rull, 2023). In the Caribbean region, hurricanes are one of the most destructive natural hazards affecting mangroves, and their occurrence has increased over the years (Rull, 2023). Certain areas of the Caribbean region with high mangrove density such as Cuba are particularly vulnerable to hurricanes compared with the South American region, which is rarely affected. Despite these disturbances, mangroves show relatively high resilience to hurricane activity and natural regeneration is common (Rull, 2023).

Mangroves' complex structure forms aquatic vegetation that provides feeding grounds and shelter for small predators and prey (Nagelkerken, 2009; Nagelkerken *et al.*, 2010; DeYoe *et al.*, 2020). For instance, in the Caribbean, there is a high abundance and diversity of estuarine, coral reef, invertebrates and juvenile fishes that shelter in mangroves, which are structure-rich habitats (Nagelkerken *et al.*, 2010; DeYoe *et al.*, 2020). High abundances of juvenile fishes in mangroves are based on these proposed hypotheses: (a) isolated location of these biotypes from off-shore waters or coral reefs and thus fewer encounters with predators; (b) copious amounts of food are provided by these biotypes for fishes, (c) predators' efficiency to forage is reduced by the relatively turbid water of the estuaries and bays and (d) extensive areas are covered by these biotopes and planktonic fish larvae may be intercepted more effectively (Nagelkerken *et al.*, 2000; DeYoe *et al.*, 2020). These hypotheses support the features of resilient mangroves, which provide nursery habitats for juvenile fishes that serve as a protein source for the Belizean population; hence, there is a need for further protection of these mangroves at Turneffe Atoll to safeguard this valuable ecosystem service.

Belize still retains large areas of mangroves (especially Turneffe Atoll, where two-thirds of the atoll's land area is occupied by mangroves) compared to many neighbouring countries due to the small population, which reduces developmental pressures and the concentration of the population in a single centre (*i.e.* Belize City) (Cherrington *et al.*, 2020). This relatively large area of mangroves should not be treated with complacency; instead, action plans should be enacted to further protect these mangroves and prolong the provision of vital ecological goods and services. Mangrove ecosystems are known for their resilience (Heumann, 2011), and studies have shown that about 94.6% of mangrove cover remains in Belize following an assessment of mangrove cover change for the period 1980 to 2017 (Cherrington *et al.*, 2020). This level of remaining mangrove cover renders the need to better understand the resilient characteristics of mangroves and propose conservation measures to protect this ecosystem and prolong the valuable goods and services provided in terms of maintaining fisheries and supporting biodiversity. The large population of resilient mangroves occupying the Turneffe

Atoll area in Belize faces growing anthropogenic threats such as permanent clearing of land for housing and infrastructural development as well as pollution and natural factors (climate change) (Cherrington *et al.*, 2010, 2020). These threats can potentially lead to irreversible losses of mangroves and therefore threaten mangroves' resiliency. To date, there have been few formal studies (Stoddart, 1963; Piou *et al.*, 2006; Cherrington *et al.*, 2010, 2020) done to evaluate mangrove-resilient features in Turneffe Atoll. Therefore, the aim of this research was to evaluate mangrove resilience to support biodiversity composition and nursery functions at Turneffe Atoll. The aim of this research was achieved through the following objectives: (1) to evaluate the resilience of mangrove ecosystems within the Turneffe Atoll, (2) to compare mangrove resilience in conservation and general use zones within the Turneffe Atoll, (3) to determine the nursery function of mangroves on fish populations and (4) to propose necessary conservation measures to further protect mangroves in the Turneffe Atoll.

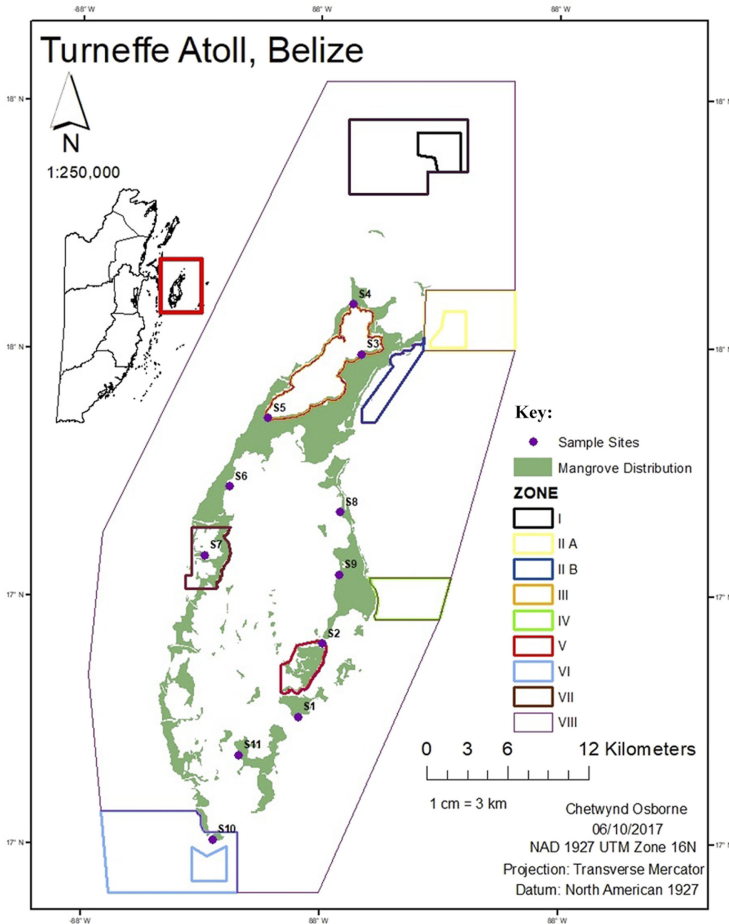
2. Materials and methods

2.1 Study area

The study was carried out in Turneffe Atoll (Figure 1), located southeast of Ambergris Caye and Caye Caulker, off the coast of Belize in Central America (17.4382°N, 87.8304°W) (Chittaro *et al.*, 2006). The Turneffe Atoll is made up of many cayes, most of which are covered with mangrove forests (covering 74.2 km²), while the perimeter of Turneffe Atoll consists of a barrier reef (Chittaro *et al.*, 2006). The sampling design tool for ArcGIS 10.4.1 (ESRI, 2016) developed by the National Oceanic and Atmospheric Administration's (NOAA) Biogeography Branch was used to select sample sites that are representative of mangrove distribution (strata) at Turneffe Atoll (Buja and Menza, 2013). Stratified random sampling was done across 11 study sites, which span across conservation zones (Long Bogue Conservation Zone [V], Caye Bokel Conservation Area [VI], Preservation Zone [VII] and General Use Zone [VIII]) at Turneffe Atoll (Wildtracks, 2011).

2.2 Resilience of mangrove ecosystems

The point-centred quarter method (PCQM) suggested by Cintrón and Novelli (1984) and also utilised by Almada-Villela *et al.* (2003) was used to assess mangrove forest structure at each mangrove site. The PCQM was done in triplicates across 11 sites in August 2017 at various distances from the shore (0–95 m, in increments of 5 m), which covered 20 sample points along each transect. Sample points for PCQM were selected within zones that were predetermined with the ArcGIS 10.4.1 tool, starting from the fringing mangroves close to the shoreline. The PCQM facilitated the measurement of the closest tree to the centre point in each quadrant according to the established transect line and perpendicular. A line was established at the zero point (at shore), and a distance of 5 m between each point was used to avoid measuring the same tree twice. Four quadrants were defined at each sampling point where the transect line and a perpendicular line cross and measurements such as distance from the sampling point to the midpoint of the nearest tree (*d*, in metres), species, diameter at breast height (DBH, in centimetres) and height (*h*, in metres) were taken from the tree closest to the sampling point. The PCQM was repeated for each of the 20 sample points, and when trees measured at the previous point were encountered, the distance between these points was extended by 2 m (Cintrón and Novelli, 1984; Almada-Villela *et al.*, 2003). The PCQM provided some community structure data about mangroves in conservation and general use zones. This sort of measurement provided an indication of mangrove composition to aid with the evaluation of how mangroves were performing within conservation zones versus the general use zone.



Note(s): Zones: I – Maugre Caye Conservation Zone, II A – Dog Flea Conservation Zone, II B – Cockroach – Grassy Caye Special Management Area, III – Vincent’s Lagoon Special Management Area, IV – Blackbird Caye Conservation Zone, V – Long Bogue Conservation Zone, VI – Caye Bokel Conservation Area, VII – Preservation Zone, VIII – General Use Zone

Source(s): Authors’ own work

Figure 1.
Map of surveyed sites

The level of mangrove recruitment, condition and basal area (m²/ha) at each site were determined by the rank criteria presented in Table 1, where 5 was high vulnerability and 1 was low, and the results were averaged to give an overall mangrove vulnerability rank (Ajonina *et al.*, 2009; Ellison, 2012):

$$\text{Vulnerability rank} = \frac{\text{Total of component rank scores}}{\text{Number of components completed}}$$

2.3 Mangrove nursery function on fish populations

Visual censuses were used to evaluate fish abundance within conservation zones compared to the general use zone, and these censuses were done during the daytime period (08.00–15.00 h) in September 2017 to ensure consistency in fish presence and activity (Nagelkerken *et al.*, 2000; Adams and Tobias, 2003; Lök *et al.*, 2008; Jaxion-Harm, 2010). Visual censuses were conducted over three days at a depth of 0–20 cm in 10 min intervals across two transects. The visual census technique (Nagelkerken *et al.*, 2000; MacDonald *et al.*, 2008) was used to estimate the fish abundance and body length of fish species in mangrove prop roots at each site. To avoid startling any fish within the two 3 × 30 m belt transects, the observers entered the water at least 20 m from each site (MacDonald *et al.*, 2008). The census was conducted by swimming slowly along the belt transects, and the best estimation by the eye of abundance and the body length of fish species was recorded. Size classes of 5 cm were used for total body length estimation, which was guided by graduation marks on the underwater slates that were used for data recording. Water clarity was good for visual censuses across all sites except for Site 5, which had poor water clarity. Site 5 (considered an outlier) was removed for statistical analysis with fish data. Fish biomass and density recorded across surveyed sites aided in the determination of mangrove nursery function on fish populations within conservation zones versus the general use zone.

2.4 Statistical analyses

All data were analysed using the statistical programme R version 3.1.0 (R Core Team, 2021) at an acceptable α -level of 0.05 (95% confidence level). The PCQM results were used to calculate tree structural variables such as (1) density per centre point:

$$\left(D = \frac{1}{d_{mean}^2} \right),$$

where D = stem density in m^2 and d_{mean} = mean distance for all trees on a transect; (2) mean DBH, (3) mean height and (4) basal area per tree:

$$\left(Basal\ area\ (cm^2) = \frac{\pi \times (DBH)^2}{4} \right),$$

where π = 3.142 and (5) standing biomass per tree:

$$\left(Biomass\ (g) = b \left[(DBH)^2 (height) \right]^m \right),$$

Table 1. Ranking criteria for mangrove vulnerability assessment results

Sensitivity components	Rank				
	1	2	3	4	5
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact
Mangrove basal area (m^2/ha)	>25	15–25	10–15	5–10	<5
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings
Source(s): Ellison (2015)					

where m and b were constants of 0.8557 and 125.9571, respectively (Cintrón and Novelli, 1984; Almada-Villela *et al.*, 2003; Piou *et al.*, 2006; Ellison, 2012). These densities, means, basal area and standing biomass provided an indication of mangrove forest structure and the health of mangrove stands. The non-parametric Kruskal–Wallis test (data did not follow a normal distribution) was used to test if there were any significant differences in mangrove height and DBH between sites in conservation and general use zones (Betts, 2006; Aschenbroich *et al.*, 2016). Height and DBH readings for sites in conservation and general use zones were compared using the Mann–Whitney test to evaluate any differences in forest structure between these locations, since they were all part of Turneffe Atoll (Betts, 2006). Non-parametric Spearman rank correlation analyses were used to evaluate the relationship between fish abundance and mangrove vulnerability rank (Jaxion-Harm, 2010).

Fish species were grouped into families, and the estimated fish abundance for the four most dominant families (Table 4) among study sites was subjected to a t -test to determine statistical differences between study sites. To control for other factors that may influence fish abundance within mangroves, sites were grouped according to low (control) and high mangrove standing biomass for comparison. This criterion for grouping was used since all surveyed areas had surrounding mangroves and the quantity of standing biomass served as a function of ecosystem productivity (Thivakaran *et al.*, 2020). The Shannon–Weiner diversity index was used to evaluate fish species diversity between study sites. Size estimates and published length-weight relationships available at FishBase (Froese and Pauly, 2017) were used to estimate fish biomass (Andradi-Brown *et al.*, 2016; AGRRA, 2017).

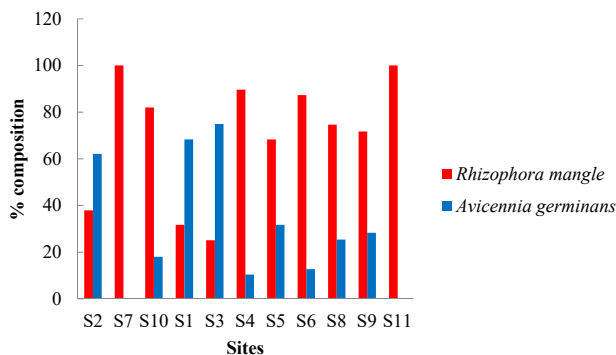
2.5 Limitations

Limitations of the methods for data collection included accessibility within mangrove forest stands when establishing PCQM, observer bias among data collectors, sites without surrounding mangroves were not captured to serve as a true control group and poor visibility underwater affected the estimation of fish species and size. The timeline for this research was only three months based on available funding and no follow-up study was done to make a true comparison.

3. Results

3.1 Mangrove ecosystem resilience within the Turneffe Atoll

Based on the 11 sites surveyed across Turneffe Atoll (Figure 1), two species of mangroves (*R. mangle* and *A. germinans*) were found across all sites, and mangrove ecosystems were dominated by *R. mangle* (Figure 2) overall. However, Site 1 (general use zone, in the central



Source(s): Authors' own work

Figure 2. Species composition in conservation and general use zones

lagoon), Site 2 (conservation zone V) and Site 3 (general use zone, close to Vincent’s Lagoon Special Management Area) were dominated by *A. germinans* (Figure 2). *L. racemosa*, one of the least common true mangroves found in Belize (Murray *et al.*, 2003), was absent from all surveyed sites. Based on the ranking criteria presented in Table 1, all sites had some components of vulnerability (Table 2). Sites S1, S2, S5, S8, S9 and S10 had ranks of 1–2, indicating current resilience for these mangrove areas, while sites S3, S4, S6, S7 and S11 had ranks of 2–4, which indicated some core vulnerability for these mangrove areas (Ellison, 2015). No statistically significant relationship ($p = 0.13$, Spearman’s correlation) existed between fish abundance and vulnerability rank, indicating that fish abundance was not strongly dependent on the vulnerability state of mangroves. Taking into consideration all sites in conservation and general use zones, higher forest structure measurements in terms of height, DBH and standing biomass were recorded for general use zone sites (Figure 3), suggesting more healthy and older mangrove stands among these sites. A statistically significant difference ($p < 0.01$, Kruskal–Wallis test) in height and DBH existed among *R. mangle* and *A. germinans*, indicating that mangrove trees of the same species differed in height and DBH among the sites.

3.2 Comparison of mangrove resilience in conservation and general use zones

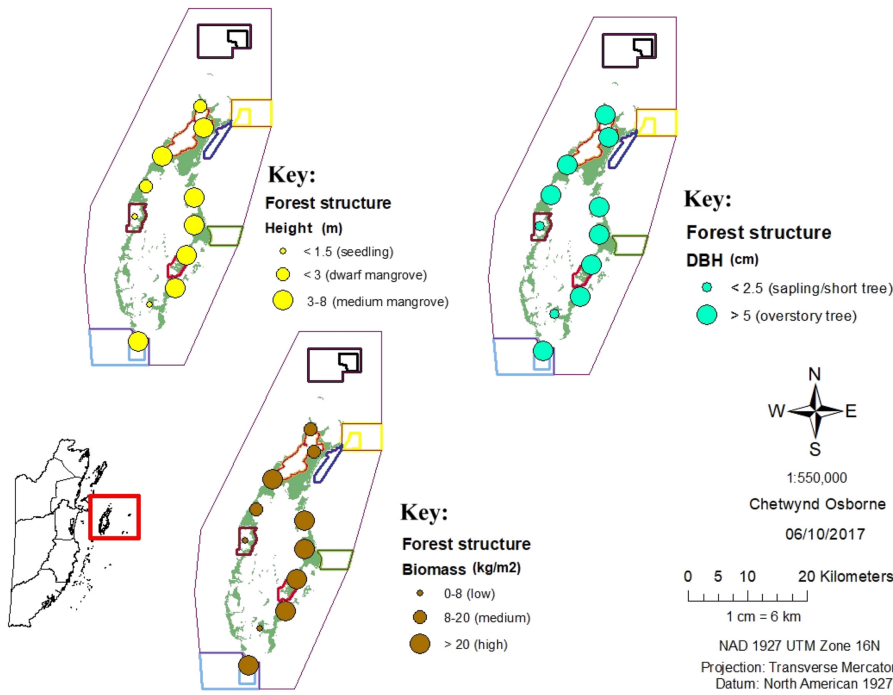
Based on the results of all trees across sites, it was evident that Site 2 (conservation zone V) and Site 8 (general use zone, close to the central lagoon) had higher mean height and DBH, suggesting that these were the most mature mangrove stands among the surveyed sites (Table 3). Site 7 (preservation zone VII) and Site 11 (general use zone, in the central lagoon) had lower mean height and DBH (Table 3), suggesting the least mature mangrove stands among the surveyed sites, and these sites were densely populated with *R. mangle* seedlings. The mean height of trees for sites 1 (general use zone, in the central lagoon), 5 (general use zone, close to the Vincent’s Lagoon Special Management Area), 9 (general use zone, close to conservation zone IV) and 10 (conservation zone VI) seemed to be similar (Table 3), possibly indicating similar maturity among these sites. No statistically significant difference in tree heights ($p = 0.32$, Mann–Whitney test) and DBH ($p = 0.76$, Mann–Whitney test) existed between the sites in conservation and general use zones. Based on mean height and DBH, tall mangrove stands were absent among the surveyed sites. Dwarf mangroves and mangrove seedlings were the least extensive, while medium mangroves were the most extensive, found at the sites in conservation and general use zones (Table 3). Mangrove standing biomass ranged from 0.11 to 95.91 kg/m² among sites surveyed (Figure 4) and Site 8 (general use zone, close to the central lagoon) had the highest standing biomass.

Sensitivity components	Conservation zone					General use zone					
	S2	S7	S10	S1	S3	S4	S5	S6	S8	S9	S11
Mangrove condition*	1	1	1	1	2	2	1	2	1	2	1
Mangrove basal area (m ² /ha)*	2	5	2	2	3	5	2	4	2	3	5
Recruitment*	1	1	1	1	2	1	1	2	1	1	1
Total	4	7	4	4	7	8	4	8	4	6	7
Number of components	3	3	3	3	3	3	3	3	3	3	3
Vulnerability rank	<i>1.3</i>	<i>2.3</i>	<i>1.3</i>	<i>1.3</i>	<i>2.3</i>	<i>2.7</i>	<i>1.3</i>	<i>2.7</i>	<i>1.3</i>	<i>2</i>	<i>2.3</i>

Note(s): *Values based on ranking criteria presented in Table 1, The last row gives averaged rank results of the overall vulnerability rank for each site (shown in italic)

Source(s): Authors’ own work

Table 2. Vulnerability assessment ranking results for sites in conservation and general use zones



Source(s): Authors' own work and Almada-Villela *et al.* (2003), Murray *et al.* (2003), Kauffman and Donato (2012), Hutchison *et al.* (2014), Trettin *et al.* (2015)

Figure 3. Mangrove forest structure across sites surveyed based on height, DBH and biomass classification

Sites	Zones	Mean DBH ± SD (cm)	Mean height ± SD (m)	Mangrove type
S1	General use	26.22 ± 15.25	4.48 ± 2.14	Medium
S2	Conservation	30.30 ± 15.30	4.99 ± 1.97	Medium
S3	General use	20.96 ± 18.81	3.46 ± 2.35	Medium
S4	General use	13.61 ± 7.97	2.90 ± 0.80	Dwarf
S5	General use	24.62 ± 15.63	4.20 ± 2.03	Medium
S6	General use	14.17 ± 10.29	2.26 ± 0.94	Dwarf
S7	Conservation	3.02 ± 4.82	1.23 ± 0.42	Seedling
S8	General use	32.61 ± 13.00	6.44 ± 1.81	Medium
S9	General use	26.08 ± 18.09	4.64 ± 1.90	Medium
S10	Conservation	27.59 ± 15.02	4.15 ± 1.81	Medium
S11	General use	1.49 ± 0.44	0.64 ± 0.11	Seedling

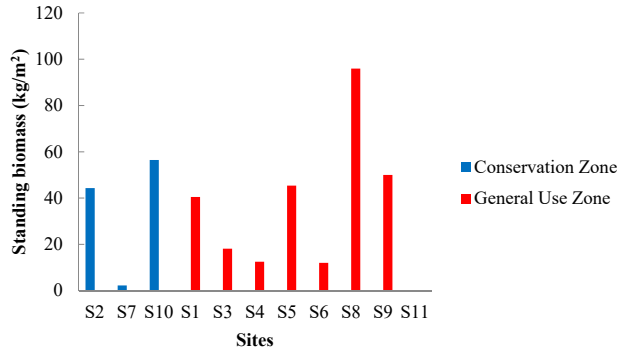
Source(s): Authors' own work and Murray *et al.* (2003) and Kauffman and Donato (2012)

Table 3. Summary of sites based on mangrove type classification scheme

3.3 Mangrove nursery function on fish populations

The surveyed sites had a rich diversity of fishes belonging to 12 families and 26 species (Table 4). The abundance and size ranges of fish by the dominant families (Haemulidae, Lutjanidae, Pomacentridae and Scaridae) (Table 4) were used to determine the nursery function of mangrove on fish populations and related to mangrove health or resilience. Site 1

Figure 4.
Comparison of
mangrove standing
biomass in
conservation and
general use zones



Source(s): Authors' own work

(general use zone, in central lagoon) had the highest Shannon–Weiner diversity index value ($H' = 2.11$), while Site 8 (general use zone, close to central lagoon) had the lowest Shannon–Weiner diversity index value ($H' = 0.18$) (Table 5). Diverse communities also existed for other sites in conservation (S2, S7 and S10) and general use (S4 and S9) zones based on Shannon–Weiner diversity index values (Table 5).

Haemulidae and Lutjanidae were the most abundant families, and high fish abundance was recorded for sites 1 (general use zone, in the central lagoon), 9 (general use zone, close to conservation zone IV) and 10 (conservation zone VI) (Figure 5). Pomacentridae and Scaridae were the least abundant families, and low abundance was recorded for sites 5 (general use zone, close to Vincent's Lagoon Special Management Area), 7 (preservation zone VII) and 11 (general use zone, in the central lagoon) (Figure 5). To control for other factors that may influence fish abundance within mangroves, sites were grouped into low (control) and high mangrove standing biomass for comparison. This comparison generally showed higher fish abundance for the dominant fish families in areas with high mangrove standing biomass (Figure 6). Based on total fish biomass for conservation and general use zones, Lutjanidae and Haemulidae had high total fish biomass, while Pomacentridae and Scaridae had low total fish biomass (Figure 7). Sites 9 (general use zone, close to conservation zone IV) and 10 had the highest total fish biomass (Figure 7). Although site one had a high fish abundance, the total fish biomass was low (Figure 7), thereby suggesting the presence of very small fishes. No statistically significant difference ($p > 0.05$, t -test) was found in the estimation of fish abundance between study sites in conservation and general use zones.

4. Discussion and conclusion

4.1 Discussion

The dominance of *R. mangle* across surveyed sites may be linked to its shade tolerant nature (DeYoe *et al.*, 2020). The dominance of *A. germinans* for sites S1, S2 and S3 may be attributed to the close location of these sites to sheltered areas such as lagoons, which provide protection from direct exposure to the striking of large waves found on the outer atoll since *A. germinans* lacks the network of prop roots present in *R. mangle* to disintegrate wave action (Chatenoux and Peduzzi, 2007; Alongi, 2008). Research has also shown that *R. mangle* along the Pacific coast of Mexico was less affected by hurricanes compared with *A. germinans* due to higher shade tolerance in *R. mangle* seedlings and saplings (DeYoe *et al.*, 2020).

The results of the vulnerability assessment ranking found that all sites had some components of vulnerability. Sites S1, S2, S5, S8, S9 and S10, with a ranking of 1–2, indicated

Family/species	Conservation zone abundance (m ²)			General use zone abundance (m ²)							
	S2	S7	S10	S1	S3	S4	S5	S6	S8	S9	S11
Acanthuridae											
<i>Acanthurus bahianus</i>						0.03					
Belonidae											
<i>Ablennes hians</i>										0.06	
Carangidae											
<i>Caranx ruber</i>	0.01										
Centropomidae											
<i>Centropomus undecimalis</i>										0.02	
Chaetodontidae											
<i>Chaetodon capistratus</i>		0.02	0.01			0.02					
Gerreidae											
<i>Gerres cinereus</i>	0.05				0.02				0.03	0.03	
Haemulidae											
<i>Haemulon flavolineatum</i>	0.24			0.03	0.01	0.03	0.01				0.04
<i>Haemulon sciurus</i>	0.01	0.02	0.19	0.15	0.03	0.04		0.01			0.1
<i>Haemulon aurolineatum</i>				0.24							
<i>Haemulon macrostomum</i>	0.12		0.08	0.03		0.17		0.04			
<i>Haemulon plumieri</i>			0.06	0.05							
<i>Haemulon carbonarium</i>			0.27					0.12			
<i>Haemulon parra</i>		0.04									0.03
Lutjanidae											
<i>Lutjanus apodus</i>	0.11	0.01	0.43	0.19	0.31	0.19		0.23	0.21	0.38	0.06
<i>Lutjanus griseus</i>		0.03		0.04	0.09			0.02		0.04	0.01
<i>Lutjanus mahogoni</i>	0.05		0.08	0.17	0.02	0.04				0.03	
<i>Lutjanus jocu</i>			0.01							0.06	
Labridae											
<i>Halichoeres bivittatus</i>	0.05		0.06			0.03					
<i>Halichoeres garnoti</i>	0.07										
Pomacentridae											
<i>Abudefduf saxatilis</i>	0.06	0.03	0.06	0.04	0.05	0.06		0.01	0.01	0.06	0.06
<i>Stegastes variabilis</i>	0.01										
<i>Stegastes adustus</i>	0.01				0.07			0.01			
Scaridae											
<i>Scarus taeniopterus</i>		0.02		0.03		0.03					
<i>Sparisoma viride</i>			0.01	0.07		0.02					0.01
<i>Scarus iserti</i>	0.04	0.01	0.1								
Sphyraenidae											
<i>Sphyraena barracuda</i>	0.02		0.07			0.03		0.02			0.01

Source(s): Authors' own work

Table 4.
Fish species observed
at study sites in
conservation and
general use zones

mangrove areas with current resilience (Ellison, 2015). Ranks of 2–4 (such as S3, S4, S6, S7 and S11) indicated mangrove areas that were prone to some core vulnerability which could be improved by targeted management (Ellison, 2015). These results further emphasise the need for the establishment of more mangrove conservation areas to better control non-climate stressors and protect mangrove areas in the general use zone. This sort of

Table 5.
Diversity of
ichthyofauna in
conservation and
general use zones

Sites	Zones	Shannon–Weiner diversity index (H')
S1	General use	2.11
S2	Conservation	1.76
S3	General use	1.43
S4	General use	1.75
S6	General use	1.31
S7	Conservation	1.84
S8	General use	0.18
S9	General use	1.60
S10	Conservation	1.88
S11	General use	1.10

Source(s): Authors' own work

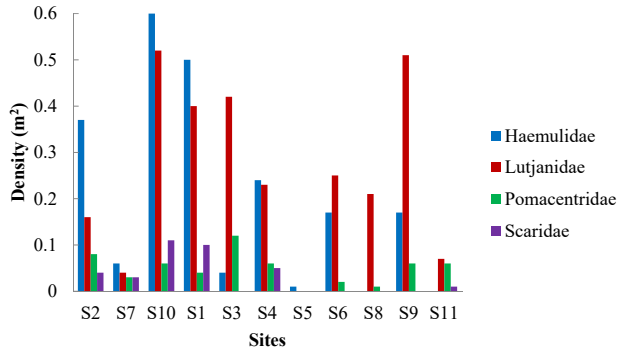


Figure 5.
Comparison of fish
abundance across
surveyed sites

Source(s): Authors' own work

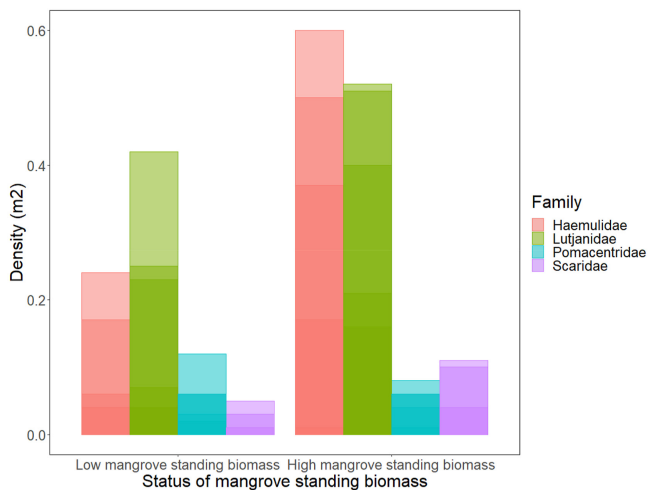
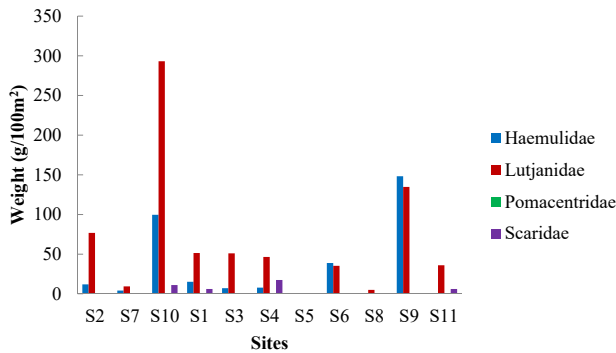


Figure 6.
Comparison of fish
abundance across sites
with low and high
mangrove standing
biomass

Source(s): Authors' own work



Source(s): Authors' own work

Figure 7.
Comparison of total fish biomass across surveyed sites

control and protection can be achieved through improved local management and reduction of human impacts (Ajonina *et al.*, 2009; Ellison, 2015), which will increase the resilience of species and mangrove habitats to the effects of climate change (Erwin, 2009; Ellison, 2015). Even though mangroves are protected under the Forests Act of Belize, foreign ownership along the coastline and recent trends in development, shifting land use, tourism (particularly the increased frequency of docking cruise ships) and wastewater management have exacerbated the pressures on mangroves (Ellison *et al.*, 2020). This sort of anthropogenic pressure was evident for some sites in the general use zone, where copious amounts of rubbish were found compared to sites in the conservation zone. The anthropogenic impact of this nature may have contributed to the inherent vulnerability in the general use zone. These findings corroborate those of Suyadi and Manullang (2020), which found that plastic debris had direct and indirect negative impacts on mangrove ecosystem in Indonesia.

Sites in conservation and general use zones were all part of the Turneffe Atoll; hence, there were similarities among the structures of mangrove communities present at these sites. A phenomenon of this nature was evident since no significant difference existed for tree height and DBH between sites in conservation and general use zones. The fairly wide distribution of DBH and high DBH measurements among sites in conservation (S2 and S10) and general use (S1, S5, S8 and S9) zones indicated uneven-aged and more mature and healthier mangrove stands (Trettin *et al.*, 2015). Additionally, the extensive distribution of overstory trees (DBH >5 cm) across surveyed sites provided more corroborating evidence about the extensive cover of old mangrove stands in the Turneffe Atoll. The nearly continuous barrier reef that runs along the coastline of Belize provides shelter for the shore, absorbs the majority of the inward wave energy and provides suitable conditions for the establishment of mangrove seedlings (Murray *et al.*, 2003; Hamylton *et al.*, 2023). A situation of this nature may partly account for the dense population of *R. mangle* seedlings present in the preservation zone (Site 7) and general use zone (Site 11) in the central lagoon. This large proportion of seedlings indicates the colonisation of forest gaps among these sites (Quadros *et al.*, 2021). Studies by Hamylton *et al.* (2023) in the Northern Great Barrier Reef suggested that significant expansion of mangrove forest over a short period is linked to changing controls within the environment such as sediment deposition and transport, natural hazard impacts and development of associated reef flat sedimentary landforms.

The results of mean DBH and height across the surveyed sites showed that dwarf mangroves (typically <3 m tall and DBH > 5 cm) were among the least extensive mangrove

types represented across the surveyed sites. Therefore, some of the sites surveyed in Turneffe Atoll lacked ideal environmental conditions, which restricted mangrove vegetation to a scattered cover of short mangroves. The presence of dwarf mangroves in certain sites indicated mangrove resilience since dwarf mangroves can survive natural disturbances such as hurricanes, which are accompanied by high water levels that cover these small individuals, preventing strong winds from blowing them down (Piou *et al.*, 2006; Romero-Mujalli and Melendez, 2023). This sort of survivability of dwarf mangroves renders them possible sources of propagules for recolonisation processes subsequent to major disturbances (Piou *et al.*, 2006). Dwarf mangrove forest is also a reflection of the plant response to environmental conditions, availability of water, pore water salinity and bioavailable nutrient limitations (Romero-Mujalli and Melendez, 2023). Medium mangroves (approximately 3–10 m tall) were the most extensive type represented across the surveyed sites, indicating that the majority of the sites surveyed were densely populated by fringing *R. mangle* growing at exposed sites along the coast and on cays (Kauffman *et al.*, 2020). Kauffman *et al.* (2020) reported that medium mangroves typically form dense stands of trees within the interior forest environments in high precipitation areas and in semiarid environments on estuarine margins.

The site with the highest standing biomass (Site 8, general use zone) can possibly be attributed to being a more productive and older mangrove ecosystem with a higher total basal area and more resilience as compared to sites with lower standing biomass (Fromard *et al.*, 1998; Thivakaran *et al.*, 2020). It is expected that the preservation zone should have good mangroves since the primary objective of this zone is to preserve an entirely natural state (Wildtracks, 2011). However, this preservation zone site had low standing biomass and was constituted mostly by young individuals with low DBH, which is a predictive variable that is frequently used for estimating mangrove forest standing biomass (Fromard *et al.*, 1998; Thivakaran *et al.*, 2020). Low standing biomass may be attributed to aridity and subsequent hypersaline conditions (Thivakaran *et al.*, 2020). Site 7 had good recruitment levels since all species were producing seedlings, indicating some amount of resilience and regeneration capabilities (McKee *et al.*, 2007; Ellison, 2015). This sort of regeneration aids in the establishment and maintenance of mangrove species zonation patterns. The range of mangrove standing biomass reported in this study was similar to that reported by Thivakaran *et al.* (2020), although tropical countries generally have higher standing biomass. It is important to note that arid and semiarid mangroves show poor structural attributes across Mexico and the Caribbean (Thivakaran *et al.*, 2020). Assessment of mangrove standing biomass could aid in addressing issues such as carbon sequestration and climate change (Thivakaran *et al.*, 2020).

Fish measurements showed differences in species diversity among sites based on Shannon–Weiner indices (H'), where high H' value was an indication of a more diverse community and even distribution of species abundance among all species recorded for that community (Bibi and Ali, 2013). Mangrove stands provide important habitats for fishes that constitute intertidal food webs (DeYoe *et al.*, 2020). Such characteristic features may account for the diverse fish communities, and this was evident in this study, since adequate food, reproductive sites and refuge are provided. Fierro-Arcos *et al.* (2021) reported high Shannon–Wiener diversity for sites sampled in the Galapagos Archipelago, highlighting the role of mangroves as a habitat for fish community composed of commercially important species. Commercial fishing is allowed in the general use zone, but not in conservation zones since a no-take regime is maintained there (Wildtracks, 2011). Therefore, it is expected that fish composition in the general use zone differs from that of conservation zones; however, this was not the case since no statistically significant difference existed for fish families' composition among conservation and general use zones ($p = 0.35$). DeYoe *et al.* (2020) indicated that *R. mangle* in the Caribbean provides cover and nutrients for many commercially important fishes (>200 species).

Higher fish abundances were recorded for sites with medium mangrove stands (S1, S9 and S10) compared to other sites with seedling and dwarf mangrove stands (S7, S11 and S4). This was possibly due to the greater shade created by medium mangrove stands (MacDonald *et al.*, 2008). These results are consistent with studies conducted by Jaxion-Harm (2010), which provided evidence of the probable positive correlation of fish abundance to shade (height of trees) and increased prop root complexity. Additionally, medium mangrove stands may have larger fringing *R. mangle* prop roots to create extensive borders around submerged habitats (DeYoe *et al.*, 2020) that serve as nursery areas to support large fish populations and hence greater productivity. Londoño *et al.* (2020) also reported causal links between fish abundance and mangrove habitat via mangrove trophic contribution. These results support the conservation of mangroves to fishery resources that the Belizean community depends on for sustenance. The high abundance of commercially important fish families such as Haemulidae and Lutjanidae for Site 10 may be attributed to greater protection and reduced impact since a no-take regime is maintained for this conservation zone site compared to sites in the general use zone where commercial fishing is allowed (Wildtracks, 2011). These findings corroborated with those of Basyuni *et al.* (2021), who found higher fish abundance in well-preserved forests compared to sites that were converted to palm oil plantations in Indonesia. This further exemplifies the close relationship between fish abundance and mangrove conservation status. Pomacentridae and Scaridae are predominantly coral reef fishes that undertake ontogenetic migrations between coral reefs, seagrass beds and mangroves, and the unique nature of Turneffe Atoll in terms of high connectivity among mangrove stands, seagrass and coral reefs creates an ideal opportunity for migration (Wildtracks, 2011; Du *et al.*, 2020). Therefore, the low fish abundance recorded across study sites for Pomacentridae and Scaridae may be attributed to the seldom utilisation of mangrove habitats for food and shelter. Fish species belonging to the family Scaridae are protected by legislated regulations under the Fisheries Department in Belize, but these species are illegally fished to support fishermen's livelihoods (Wildtracks, 2011; Ellison *et al.*, 2020). This sort of illegal fishing may in part account for the low abundance of Scaridae across surveyed sites. Fierro-Arcos *et al.* (2021) also reported Haemulidae, Lutjanidae and Pomacentridae as some of the most dominant families in the mangroves of the Galapagos. Generally, the high fish abundance recorded in this study within high mangrove standing biomass may be linked to the structural complexity of mangroves, hence the importance of mangroves as fish feeding and nursery sites (Santamaría-Damián *et al.*, 2023). Santamaría-Damián *et al.* (2023) found that mangrove sites in Mexico that were dominated by stilt root microhabitats correlated with high fish species richness, abundance and biomass. This study showed that the interaction of depth, dominance of pneumatophores, distance from the mouth of the estuary, litter production and salinity explained the patterns of fish abundance and biomass in mangroves. However, Ram *et al.* (2021) reported that even though active restoration served as a feasible option to restore mangrove standing biomass in the North Brazil Shelf, the fish population did not recover during their study period.

The smaller mode size range frequency (0–5 cm and 6–10 cm) for sites such as one, two and three may account for the low total fish biomass recorded for these sites, even though high fish abundance was recorded here. Additionally, the high total fish biomass for sites 9 and 10 may be attributed to the larger mode size range frequency (11–20 cm and 21–30 cm). The representative fish abundance and biomass recorded across surveyed sites shared some similarities with studies conducted by Kendall *et al.* (2021) on recruitment and juvenile reef fish abundance in the Caribbean, which found higher abundance among mangrove stands since these habitats are further away from the main reef and hence reduced predation. Also, factors such as natural variations in recruitment, environmental influences and hurricane disturbances may influence fish assemblage. The high fish biomass recorded for commercially important families such as Haemulidae and Lutjanidae gives an indication of

mangrove resilience to support these species (Fierro-Arcos *et al.*, 2021). Moreover, the high connectivity of mangrove stands to reef and seagrass at Turneffe Atoll provides ideal nursery habitats for commercially important juvenile fishes. Despite recent reformed and amended legislations (increased fines and stringent regulations) related to mangrove clearing laws in Belize, developers derive methods to work around these regulations and clear mangroves without permits due to poor enforcement of mangrove regulations (Ellison *et al.*, 2020). Therefore, the need exists for the establishment of more mangrove conservation areas in Turneffe Atoll to prolong these vital ecological goods and services that the Belizean population depends upon for their livelihoods.

Based on fish size class measurements, more nursery habitats were provided by *R. mangle* prop root structures across sites in conservation and general use zones for fish populations. The mixture of fish densities recorded for all size classes was consistent with evidence that some juvenile fishes primarily utilise mangroves for shelter while feeding opportunistically (MacDonald *et al.*, 2008; Kendall *et al.*, 2021). Additionally, this research was conducted during the wet season in Belize, and this season tends to correlate with high recruitment of juvenile fishes to mangrove communities since a high abundance of zooplankton exists to provide greater food abundance. Furthermore, mangrove prop roots play a critical role as habitat for juvenile fishes, and this was for studies in the Caribbean that showed the resilience of these ecosystems considering growing pressures from coastal development, fisheries and climate change (Kendall *et al.*, 2021).

Based on the results of this study, more resilient and healthier mangrove stands constituted sites (especially sites 8 and 9) in the general use zone, which are not well protected in the Turneffe Atoll Marine Reserve (TAMR). Based on the sample design for this study, the surveyed sites were selected based on mangrove distribution, and only three conservation zone sites had a representative distribution of mangroves compared to eight sites in the general use zone. Therefore, mangroves in conservation zones may be underrepresented, and future studies should look at an equal proportion of sites as well as sites without surrounding mangroves to make better comparisons. Increased protection in the general use zone is critical given the connectivity that mangroves share with other marine ecosystems to foster higher immigration rates from nursery habitats and possibly more production to support livelihoods. Site 9 is close to the Blackbird Caye conservation zone, which is privately owned and slated for further development given the major role that tourism plays in the economic development of Belize (TICAC, 2003; Ellison *et al.*, 2020). This sort of development will impact mangrove ecosystems and lead to irreversible losses of mangroves, thereby threatening mangrove resilience (Ellison *et al.*, 2020). Mangrove losses can also affect water quality since pollutants from wastewater would not be readily removed and transformed and fish abundance may decline since nursery habitats, which provide shelter for juvenile fishes are removed (Polidoro *et al.*, 2010; Wang *et al.*, 2010; Ellison *et al.*, 2020). Therefore, a more careful evaluation of conservation measures is needed for mangroves specifically. Some of these conservation measures are outlined in Table 6. Future research should focus on more long-term monitoring of mangrove forests within Turneffe Atoll to better assess the impacts of different types of disturbances over time. These long-term monitoring studies should consider sites without surrounding mangroves to capture a true control group for comparative relations. Better quantification of the structure and extent of prop roots and their correlation to fish abundance as well as combining visual censuses with unattended, continuous-recording method such as underwater video system would answer additional questions.

4.2 Conclusion

The physical and ecological characteristics of Belize are like those of other parts of the Caribbean and Central America. However, in the Caribbean region, Belize is unusual since a

Action	Resource needs	Responsibility	Timeline	Comments
Better waste management through beach cleanup and controlling pollution sources through enactment and stringent enforcement of waste management legislation	Donor and private/public financing (ca. US\$15,000) Technology transfer	Belize Coastal Zone Management Authority and Institute, Belize Association of Private Protected Areas, Belizean Mangrove Conservation Network, Government of Belize	5 years	Such actionable measures will facilitate greater elimination of non-climate stressors on mangroves such as pollution
Develop additional policies and enforcement to provide a robust framework for mangrove management and ensure the halting of mangrove forests losses in the general use zone (in keeping with Sustainable Development Goal Target 15.2.)	Public financing (ca. US\$10,000)	Government of Belize	5 years	These policy measures will aid in preventing destruction to mangrove nursery areas and reducing the impacts on other nearshore marine ecosystems. Provisions could also be made for commercial fishing in a sustainable manner since the general use zone provides fertile and valuable fishing ground
Incentivised outreach and educational programmes for landowners across Belize to promote effective mangrove conservation and restoration and foster mangrove conservation networks	Donor and private/public financing (ca. US\$50,000)	Belize Association of Private Protected Areas, Belizean Mangrove Conservation Network, Government of Belize	2 years	Active participation in mangrove management and conservation by individuals and experts who use coastal resources daily will increase understanding and awareness of the ecosystem services provided by Belize's mangroves
Robust Communication Strategy to better communicate enacted zoning policies that guide development and enforce regulations, especially to foreign property-owners	Donor and private/public financing (ca. US\$10,000)	Government of Belize, Belize Coastal Zone Management Authority and Institute, Belizean Mangrove Conservation Network	3 years	Apprise foreign property-owners in a more effective manner of domestic mangrove regulations in Belize
Long-term monitoring surveys to capture environmental drivers such as climate change, sea-level fluctuations and anthropogenic pressure on the biodiversity and evolution of mangrove ecosystems	Donor and private/public financing (ca. US\$20,000) Technology transfer	Belize Association of Private Protected Areas, Belizean Mangrove Conservation Network	10 years	The lessons learnt from these surveys may be useful to inform conservation and restoration actions

Source(s): Authors' own work and *Adger et al. (2007)*, *Gilman et al. (2008)* and *Ellison et al. (2020)*

Table 6.
Conservation
action plan

large portion of its coastline is covered by mangrove, and an extensive composition of mangrove is found at Turneffe Atoll. Mangroves in conservation zones at Turneffe Atoll are possibly underrepresented since a larger composition of resilient mangroves constitutes the general use zone. Major gaps exist in the protection of coastal and marine mangroves within Turneffe Atoll. Although the findings of this research only form a baseline, the need exists for the establishment of more mangrove conservation areas in Turneffe Atoll due to the presence of more resilient and healthier mangroves in the general use zone. The establishment of more mangrove conservation areas would better facilitate long-term, ongoing monitoring programmes.

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