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Assessment of parrotfish community structure along a fishing pressure gradient in South Sinai marine protected areas, Gulf of Aqaba, Egypt

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ABSTRACT

Herbivorous reef fishes, particularly Scaridae (parrotfishes), play many critical roles in maintaining coral reef health and resilience. As coral reefs continue to decline globally, preserving a sustainable level of parrotfish communities has become a top priority. In Egypt, the Gulf of Aqaba has been zoned into three management categories, offering varying levels of protection for coral reef fisheries, ranging from no-take to open-access fisheries. Hence, this study compared parrotfish density, biomass, and size structure across these zones to assess the effectiveness of the applied conservation measures. Our survey results indicated that *Chlorurus sordidus*, *Scarus niger*, *Hipposcarus harid*, and *Scarus ferrugineus* were the most abundant parrotfish species, accounting for 83.6% of the total density and 79.8% of the total biomass. Our study sites showed a noticeable fishing pressure gradient, where total parrotfish density (all species combined) was 1.3 and 2.3 times higher on unfished reefs than on moderately and heavily fished reefs, respectively. Similarly, the corresponding biomass values were 1.6 and 3.7 times higher on unfished reefs. Furthermore, the abundance of large-sized parrotfish individuals (>30 cm, Total Length) declined significantly from 25.9% and 17% of the total density on unfished and moderately fished reefs, respectively, to 8% on heavily fished reefs. In contrast, the abundance of small-sized individuals (10–20 cm, TL) increased with increasing fishing pressure, ranging from 18.4% on unfished reefs to 31.4% and 43.7% on moderately and heavily fished reefs, respectively. This study concluded that the present results provide important information that has management and conservation implications for artisanal fisheries in South Sinai marine protected areas (MPAs).

1. INTRODUCTION

Egypt's coral reefs in the Gulf of Aqaba (GoA) are among the world's most important biodiversity hotspots and well-developed high-latitude reefs **(Burke *et al.*, 2011)**. Also, it is of great importance to the national economy through coral reef-based tourism and artisanal fishing **(Spalding *et al.*, 2017)**. To protect and conserve these unique reefs, Egypt has established a network of three marine protectorate areas (MPAs) linked by protected coastlines to cover the entire Egyptian coast on the GoA. Fisheries management systems vary widely between South

Sinai MPAs in the GoA, resulting in different levels of protection. In Ras Mohammed and Sharm El-Sheikh, all forms of nearshore fishing are prohibited **(Pearson and Shehata, 1998; Mabrouk, 2015)**. Whereas in Nabq and Abu Galum, only local Bedouin fishermen are allowed to fish using traditional fishing methods **(Galal *et al.*, 2002)**. In Dahab, fishing is prohibited at all dive sites **(Hasler and Ott, 2008)**. In contrast, artisanal fishing is poorly regulated in the northern region of the GoA, specifically around Nuweiba and Taba **(Tilot *et al.*, 2008)**.

In the Red Sea, fishing is the most pervasive form of human activity that threatens coral reef ecosystems, with artisanal fishing being widespread **(Burke *et al.*, 2011)**. Fishing has been shown to affect coral reefs directly by reducing the abundance, biomass, and size structure of target fishes and indirectly by altering the structure of coral reef communities **(Cheal *et al.*, 2013; McClanahan *et al.*, 2016, 2021; Shantz *et al.*, 2020)**. Herbivorous fishes, including parrotfishes, play a crucial role in maintaining the health and resilience of coral reefs by controlling the biomass and distribution of faster-growing algae, allowing slower-growing coral recruits to settle **(Hughes *et al.*, 2007; Adam *et al.*, 2015)**. Parrotfishes (Scaridae) are among the most dominant families of herbivorous fishes in terms of density, biomass, and grazing rates **(Afeworki *et al.*, 2013; Mumby, 2016)**. They are also important fishery targets, particularly in tropical developing countries. Therefore, they have been severely depleted as a result of the rising demand for reef fishes as a source of food and income **(Hawkins and Roberts, 2004; Edwards *et al.*, 2014)**. Understanding the patterns of parrotfish abundance, biomass, and size structure is important for the management and conservation of coral reefs **(Bozec *et al.*, 2016; Mumby *et al.*, 2021; Nanami, 2021)**.

In the last two decades, the increased human population density and fishing pressure in different regions of the world have affected coral reef fisheries. This has resulted in reductions in the density, biomass, and average size of larger-bodied parrotfish species due to the overexploitation and selective removal of larger individuals **(Bellwood *et al.*, 2012; Edwards *et al.*, 2014)**. Accordingly, the metrics derived from parrotfish assemblages not only have the potential to provide useful information about variability in fishing effects but also provide information about the state of this important herbivore group. In the GoA, however, very few studies have investigated or compared the direct effects of fishing on parrotfish biomass and size structure **(El-Haddad *et al.*, 2021)**. Therefore, the present study intends to fill this gap by quantifying the effects of fishing on the density, biomass, and size structure of the entire parrotfish family and the most abundant four parrotfish species along a fishing pressure gradient in South Sinai MPAs. Ultimately, understanding the effects of different fisheries management systems is critical to ensuring the effective management and conservation of coral reef ecosystems in South Sinai MPAs and throughout the Egyptian Red Sea.

2. MATERIALS AND METHODS

2.1. Study area

The study area covers about 240 km of the fringing reefs on the Egyptian coast of the GoA and the northern Red Sea, representing eight regions (Ras Mohammed, Sharm El-Sheikh, Nabq, Dahab, Abu Galum, South and North Nuweiba, and Taba). Sharm El-Sheikh is under the authority of the Ras Mohammed National Park; Dahab is under the authority of the Nabq Managed Resource Protected Area (MRPA); and Nuweiba and Taba are under the authority of the Abu Galum MRPA. Noticeably, these regions are subject to different levels of protection and fishing pressure. The Egyptian GoA regions have been categorized according to **El-Haddad *et al*. (2021)** into one of three fishing pressure levels (open-access/heavily fished; gear-restricted/moderately fished; or no-take/unfished) based on many metrics for fishing pressure and, in particular, the herbivorous fish biomass (kg/500 m^2), which is widely used as an indicator of fishing pressure.

2.2. Fish survey methodology

Between April and September 2017, a series of underwater visual censuses (UVC) were conducted to quantify the density, biomass, and size structure of parrotfish assemblages at 24 reef sites across different reef zones (outer reef flat, crest, and slope) on the Egyptian coast of the GoA, spanning approximately 2° latitude, from Ras Mohammed at the southernmost tip of the Sinai Peninsula to Taba near the northern end of the GoA (Table 1 and Figure 1). Three sites were surveyed in each region, and three reef zones were censused at each site.

Table 1. Details of 24 sites surveyed along the Gulf of Aqaba, Egypt. Eight coastal regions under different levels of fishing pressure were surveyed, each comprised of three sites. Reef sites were assigned a numerical code (1-24) in order of latitude. The coordinates (in decimal degrees format) indicate survey location on reef site.

Fishing pressure	Region/Sector	No.	Site name	Lat. (N)	Long. (E)
No fishing/unfished	Ras Mohammad	1	Yollanda Beach	27.728206	34.256730
		2	Eel Garden	27.737806	34.256753
		3	South Bareika	27.766686	34.220025
	Sharm El-Sheikh	4	Umm el-Sidd	27.852033	34.316664
		5	Sheikh Coast	27.932728	34.369997
		6	North Nasrani	27.994628	34.434483
Moderately fished	Nabq	7	Al-Gharqana	28.121594	34.441964
		8	Maria Schroder	28.189000	34.442275
		9	Ras Tantour	28.243642	34.415519
	Dahab	10	Three Pools	28.435117	34.456586
		11	Al-Island	28.477378	34.511703
		12	Al-Canyon	28.556867	34.523172
	Abu Galum	13	Al-Omayed	28.626903	34.575272
		14	Ras Mamlah	28.731942	34.625756
		15	Al-Sokhn	28.758806	34.623367
Heavily fished	South Nuweiba	16	Wadi Miran	28.805558	34.624556
		17	Hobiq north	28.895678	34.649092
		18	Al-Mazariq	28.920800	34.644264
	North Nuweiba	19	Al-Tirabin north	29.063219	34.672967
		20	Ras Shattan	29.126361	34.685983
		21	Basata	29.204842	34.735264
	Taba	22	Al-Mahash	29.325411	34.753739
		23	Morgana Beach	29.359872	34.783369
		24	Taba Heights	29.390611	34.810786

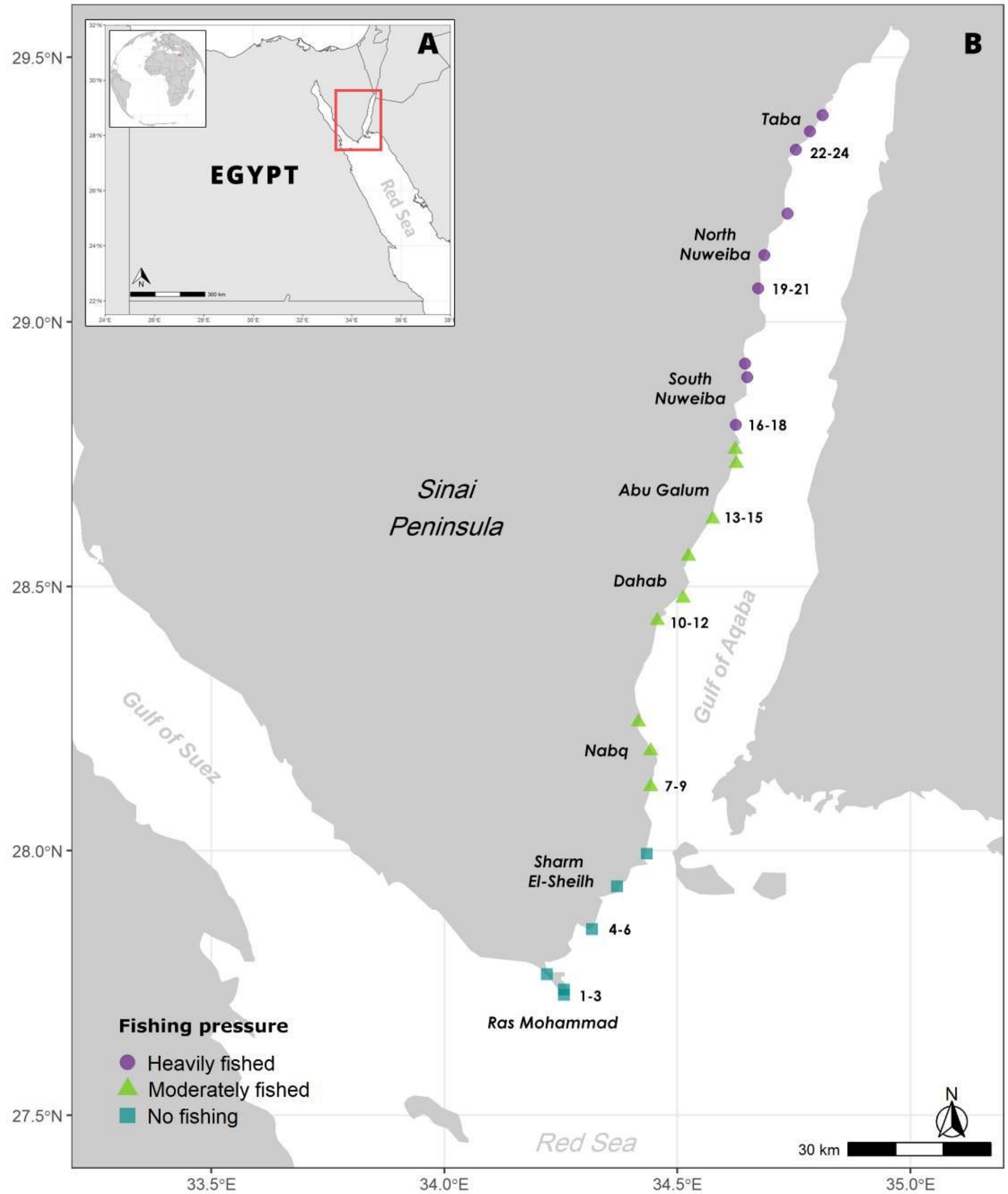

Figure 1. Map of Egypt, showing the location of the GoA **(A)**; Map of the GoA, showing locations of the 24 reef sites that represent eight coastal regions **(B)**. Different shapes represent fishing pressure levels; (square symbols) represent no fishing, (triangles) represent moderately fished, and (circles) represent heavily fished sites. Surveyed sites per region were assigned a numerical code (shown next to regions).

Four 50-meter line transects were randomly laid on each reef zone, parallel to the shoreline, and separated from one another by at least 5 m. Within each reef zone, all encountered parrotfish species greater than 10 cm total length (TL) were recorded within a 10 m wide path (5 m on each side of the transect line) that extended from the reef substratum to the surface of the water. The total length of individual fish was estimated to the nearest 5 cm. Then, body size data was grouped into three size classes: small (10–20 cm), medium (21–30 cm), and large (> 30 cm).

2.3. Fish biomass

Fish density and size estimates were converted to biomass in kg per unit area (kg.500 m^2) using the equation: W= aTL^b, where "W" is weight in kilograms, "TL" is the total length in cm (taking the midpoint of each size-class), and parameters "a" is species coefficient and "b" is species exponent, obtained from FishBase **(Froese and Pauly, 2020)**. All censuses were conducted during daylight hours between 10:00 and 17:00 at high tide conditions to ensure the counts were undertaken when the reef flat and reef crest zones are available for grazing fishes.

2.4. Data analysis

Parrotfish assemblages were quantified as a whole family (all species combined) and by species (for the four most abundant species) in terms of mean density (individual per 500 m^2) and mean biomass (kg per 500 m^2). Generalized linear mixed models (GLMMs) were used to test significant differences in fish density and biomass among fishing pressure levels and among reef zones. Models were conducted separately for each studied parrotfish species (*C. sordidus*, *H. harid*, *S. niger*, and *S. ferrugineus*), as well as for parrotfish family. All models included the predictors 'fishing pressure' as (fixed effect with three levels: no fishing, moderately fished, heavily fished) and 'reef zone' as (fixed effect with three levels: flat, crest, slope), while the spatial variable (site) was included as a nested random effect within the categorical fixed variable fishing pressure. Due to overdispersion, fish biomass data were modeled using a tweedie distribution, which is appropriate for positive continuous data **(Foster and Bravington, 2013)**, while fish density data were modeled using a negative binomial distribution, which is appropriate for count data **(Bolker *et al.*, 2009)**. All models were fitted with a "log" link function.

The GLMMs were run with the 'glmmTMB' package **(Brooks *et al.*, 2017)** and Pairwise Tukey's post hoc comparisons were performed with the 'emmeans' package **(Lenth, 2020)**. Model residuals were checked using the DHARMa package **(Hartig, 2020)**. Plots were made using the 'ggplot2' package **(Wickham *et al*., 2016)**. All statistical analysis and graphs were conducted in the software R v.4.1.1 **(R Core Team, 2021)**.

3. RESULTS

3.1. Parrotfish assemblage composition

A total of 6,752 adult parrotfish representing 12 species were encountered during field surveys. Of the 14 parrotfish species found in the Northern Red Sea **(Golani and Fricke, 2018)**, two species were not observed (*Leptoscarus vaigiensis* and *Scarus collana*). Across the reef-wide (all three reef zones), the estimated overall mean density of parrotfish family (all species combined) was 23.44 ± 2.34 individuals per 500 m^2 ±SE and the overall mean biomass was 7.79 ± 0.97 kg per 500 m^2 ±SE.

The four most abundant species were *C. sordidus*, *S. niger*, *H. harid*, and *S. ferrugineus*, which together comprised 83.6% of the total density and 79.8% of total biomass, respectively. Individually, *C. sordidus*, *S. niger*, *H. harid*, and *S. ferrugineus* account for 38.9%, 18.1%, 15.8%, and 10.8% of the total density, respectively, and the same species account for 26.6%, 16.9%, 21.7%, and 14.6% of the total biomass, respectively. Remarkably, the medium-sized excavator/bioeroder *C. sordidus* was the most abundant parrotfish on all reef zones (flat, crest, slope) and across all levels of fishing pressure (Table 2).

Table 2. Summary of density (individuals per 500m^{-2}) and biomass (kg per 500m^{-2}) estimates for the studied four parrotfish species and the total parrotfish family on three reef zones [reef flat (RF), reef crest (RC), reef slope (RS)] and averaged across all reef zones [reef-wide (RW)]. The numbers are mean averaged over all reef sites at each fishing pressure level (± SE; Standard Error of the Mean).

	Unfished reefs				Moderately fished reefs				Heavily fished reefs			
	RF	**RC**	**RS**	**RW**	**RF**	**RC**	**RS**	**RW**	**RF**	**RC**	**RS**	**RW**
(a) Density												
C. sordidus	11.7 ± 0.9	8.9 ± 1.4	8.9 ± 1.9	9.8 ± 0.8	11.7 ± 1.0	10.2 ± 1.0	9.3 ± 0.7	10.4 ± 0.5	8.6 ± 1.5	6.3 ± 0.5	7.2 ± 0.8	7.4 ± 0.6
H. harid	10.6 ± 2.4	8.7 ± 2.7	8.1 ± 1.8	9.1 ± 1.3	1.4 ± 0.3	2.9 ± 0.5	4.6 ± 0.9	3.0 ± 0.4	0.3 ± 0.2	0.9 ± 0.4	1.2 ± 0.3	0.8 ± 0.2
S. niger	4.1 ± 0.6	5.7 ± 0.9	5.7 ± 1.1	5.2 ± 0.5	2.9 ± 0.3	6.2 ± 0.6	5.8 ± 0.6	5.0 ± 0.3	1.1 ± 0.4	3.7 ± 0.5	3.9 ± 0.5	2.9 ± 0.3
S. ferrugineus	6.8 ± 1.3	4.2 ± 0.5	4.8 ± 0.4	5.3 ± 0.5	0.7 ± 0.4	3.4 ± 0.4	3.1 ± 0.3	2.4 ± 0.2	0.1 ± 0.1	0.9 ± 0.2	1.5 ± 0.2	0.8 ± 0.1
Parrotfish family	39.6 ± 3.7	32.0 ± 4.2	30.1 ± 3.7	33.9 ± 2.3	21.9 ± 1.7	27.6 ± 1.7	26.4 ± 1.4	25.3 ± 0.9	12.8 ± 2.2	14.7 ± 1.3	16.3 ± 1.2	14.6 ± 1.0
(b) Biomass												
C. sordidus	2.8 ± 0.3	2.2 ± 0.3	2.4 ± 0.4	2.5 ± 0.2	2.3 ± 0.2	2.3 ± 0.3	2.4 ± 0.2	2.3 ± 0.1	1.5 ± 0.3	1.6 ± 0.2	1.6 ± 0.2	1.6 ± 0.1
H. harid	4.1 ± 0.9	4.6 ± 1.9	3.5 ± 0.8	4.1 ± 0.7	0.6 ± 0.1	1.5 ± 0.3	2.4 ± 0.5	1.5 ± 0.2	0.1 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.3 ± 0.1
S. niger	1.5 ± 0.2	2.0 ± 0.4	2.2 ± 0.4	1.9 ± 0.2	0.8 ± 0.1	1.8 ± 0.2	1.9 ± 0.2	1.5 ± 0.1	0.4 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	0.8 ± 0.1
S. ferrugineus	3.1 ± 0.6	1.9 ± 0.3	2.3 ± 0.2	2.4 ± 0.2	0.4 ± 0.2	1.5 ± 0.2	1.4 ± 0.1	1.1 ± 0.1	0.1 ± 0.0	0.4 ± 0.1	0.6 ± 0.1	0.3 ± 0.0
Parrotfish family	14.2 ± 1.5	13.7 ± 2.3	12.3 ± 1.5	13.4 ± 1.0	5.2 ± 0.5	9.6 ± 0.7	9.8 ± 0.7	8.2 ± 0.4	2.3 ± 0.4	4.1 ± 0.4	4.6 ± 0.4	3.7 ± 0.3

C. sordidus = Chlorurus sordidus, H. harid = Hipposcarus harid, S. niger = Scarus niger, S. ferrugineus = Scarus ferrugineus

3.2. Parrotfish density and biomass

Our study regions showed a noticeable fishing pressure gradient, with the unfished reefs (Ras Mohamed and Sharm El-Sheikh) having the lowest fishing pressure (i.e., the highest mean biomass density), the moderately fished reefs (Nabq, Dahab, and Abu Galum) having moderate pressure, whereas heavily fished reefs (South Nuweiba, North Nuweiba, and Taba) having the highest fishing pressure (i.e., the lowest mean biomass density) (Table 2).

Total density of parrotfish family across the reef-wide was ~1.3 and 2.3 times higher on unfished reefs (33.9 ± 2.7 ind./500 m^2) than on moderately fished reefs (25.3 ± 0.9 ind./500 m^2) and heavily fished reefs (14.6 ± 1.0 ind./500 m^2), (GLMM: Z = -2.49, P = 0.013; Z = -5.43, P<0.001; Table 2a and Figure 2). While the corresponding biomass value on unfished reefs (13.4 ± 1.0 kg/500 m^2) was ~1.6 and 3.7 times higher than moderately (8.2 ± 0.4 kg/500 m^2) and heavily fished reefs (3.7 ± 0.3 kg/500 m^2), (GLMM: Z = -4.05, P<0.001; Z = -7.68, P<0.001; Table 2b and Figure 2).

There was a significant interaction between the 2 factors of Fishing Pressure and Reef Zone for either density or biomass (GLMM: P<0.001 in all cases). The density of parrotfish varied about three-fold among the reef zones across fishing intensity gradients, ranging from a maximum of 39.6 ± 3.7 individuals per 500 m^2 ±SE, 32.0 ± 4.2, and 30.1 ± 3.7 at unfished reef flat, crest, and slope, respectively, to a minimum of 12.8 ± 2.2, 14.7 ± 1.3, and 16.3 ± 1.2 at heavily fished reef flat, crest, and slope, respectively (Table 2a). The corresponding values for biomass were 14.2 ± 1.5 kg per 500 m^2 ±SE, 13.7 ± 2.3, and 12.3 ± 1.5 at the unfished reef zones, and 2.3 ± 0.4, 4.1 ± 0.4, and 4.6 ± 0.4 at the heavily fished reef zones (Table 2b).

According to fishing pressure levels in the GoA, the density and biomass of the parrotfish family showed contrasting zonational patterns in relation to reef topographic features such as reef zones (reef flat, crest, and slope). In unfished reefs, the density and biomass of parrotfish were highest on the reef flat, intermediate on the reef crest, and lowest on the reef slope. In contrast, the heavily fished reefs showed the opposite trend, with the density and biomass of parrotfish being lowest on the reef flat, intermediate on the reef crest, and highest on the reef slope (Table 2, Figure 2).

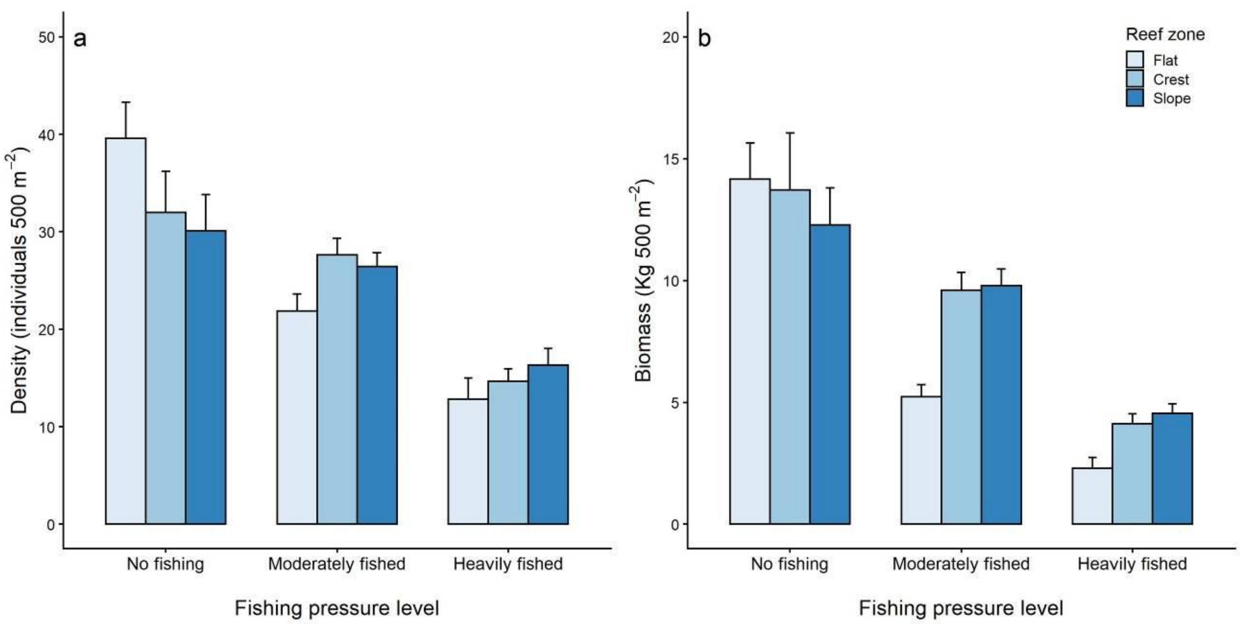

Figure 2. Patterns in the distribution of density and biomass of total parrotfish family among reef zones under different fishing pressure levels. a) Mean fish density; b) Mean fish biomass. (Bars represent mean values and standard errors).

The density and biomass of the four most abundant parrotfish species were examined across three reef zones at each fishing pressure level. Each parrotfish species had a nonuniform distribution pattern of density and biomass across reef zones (Table 2 and Figure 3). Both large-bodied scrapers, *H. harid* and *S. ferrugineus*, showed consistently significant decreasing trends in the density and biomass as fishing pressure increased (i.e., heavily fished < moderately fished < unfished), (GLMM: P<0.001 in all cases).

The large-bodied parrotfish, *H. harid*, is the most desired and targeted parrotfish species by local Bedouin in South Sinai MPAs. It represents 26.9% of the total density and 30.4% of the total biomass in unfished reefs, but their density and biomass declined significantly with increasing fishing pressure, accounting respectively for 5.5% and 8.2% in heavily fished reefs (GLMM: P<0.001 Tables 2, 3 and Figure 3). On the other hand, the density and biomass of the medium-bodied parrotfish, *C. sordidus*, and *S. niger*, were significantly higher in unfished reefs compared to heavily fished reefs (GLMM: P<0.001 in all cases). Remarkably, heavily fished reefs were dominated by small-sized individuals of *C. sordidus* and *S. niger*, representing about 70% and 65%, respectively, of the total density and biomass. Lastly, neither *C. sordidus* nor *S. niger* showed any significant differences in their densities or biomass between unfished and moderately fished reefs (Table 3).

Table 3. Post-hoc fishing pressure comparisons of density, biomass and body size for common parrotfish species and total parrotfish family from the generalized linear models using 'lsmeans'. Bold font= significant differences (P < 0.05), NS= non-significant (P > 0.05).

	Fishing pressure	*C. sordidus*	*S. niger*	*H. harid*	*S. ferrugineus*	Parrotfish family
(a) Density						
	UF x MF	NS	NS	0.04	**<.0001**	NS
Reef flat	UF x HF	NS	**0.006**	**<.0001**	**<.0001**	**<.0001**
	MF x HF	NS	**0.03**	NS	**0.05**	**0.03**
	UF x MF	NS	NS	NS	NS	NS
Reef crest	UF x HF	NS	NS	**0.002**	**0.001**	**0.03**
	MF x HF	NS	NS	NS	**0.002**	**0.02**
	UF x MF	NS	NS	NS	NS	NS
Reef slope	UF x HF	NS	NS	**0.006**	**0.01**	NS
	MF x HF	NS	NS	NS	NS	NS
(b) Biomass						
	UF x MF	NS	NS	NS	**<.0001**	**0.002**
Reef flat	UF x HF	**0.03**	**0.0007**	**<.0001**	**<.0001**	**<.0001**
	MF x HF	NS	NS	NS	**0.03**	**0.002**
	UF x MF	NS	NS	NS	NS	NS
Reef crest	UF x HF	NS	NS	**0.002**	**0.0005**	**<.0001**
	MF x HF	NS	NS	NS	**0.001**	**0.001**
	UF x MF	NS	NS	NS	NS	NS
Reef slope	UF x HF	NS	NS	**0.009**	**0.009**	**0.001**
	MF x HF	NS	NS	**0.04**	NS	**0.006**
(c) Body-size						
	UF x MF	NS	NS	NS	NS	NS
Small (10-20 cm)	UF x HF	NS	NS	NS	NS	NS
	MF x HF	NS	NS	NS	NS	NS
	UF x MF	NS	NS	NS	NS	NS
Medium (21-30 cm)	UF x HF	NS	NS	**0.009**	**0.0002**	**0.02**
	MF x HF	NS	NS	NS	NS	NS
	UF x MF	NS	NS	NS	NS	NS
Large (>30 cm)	UF x HF	NS	NS	**0.0005**	**0.005**	**<.0001**
	MF x HF	NS	NS	**0.004**	**NS**	**0.0001**

Fishing pressure levels: UF = Unfished, MF = Moderately fished, HF = Heavily fished

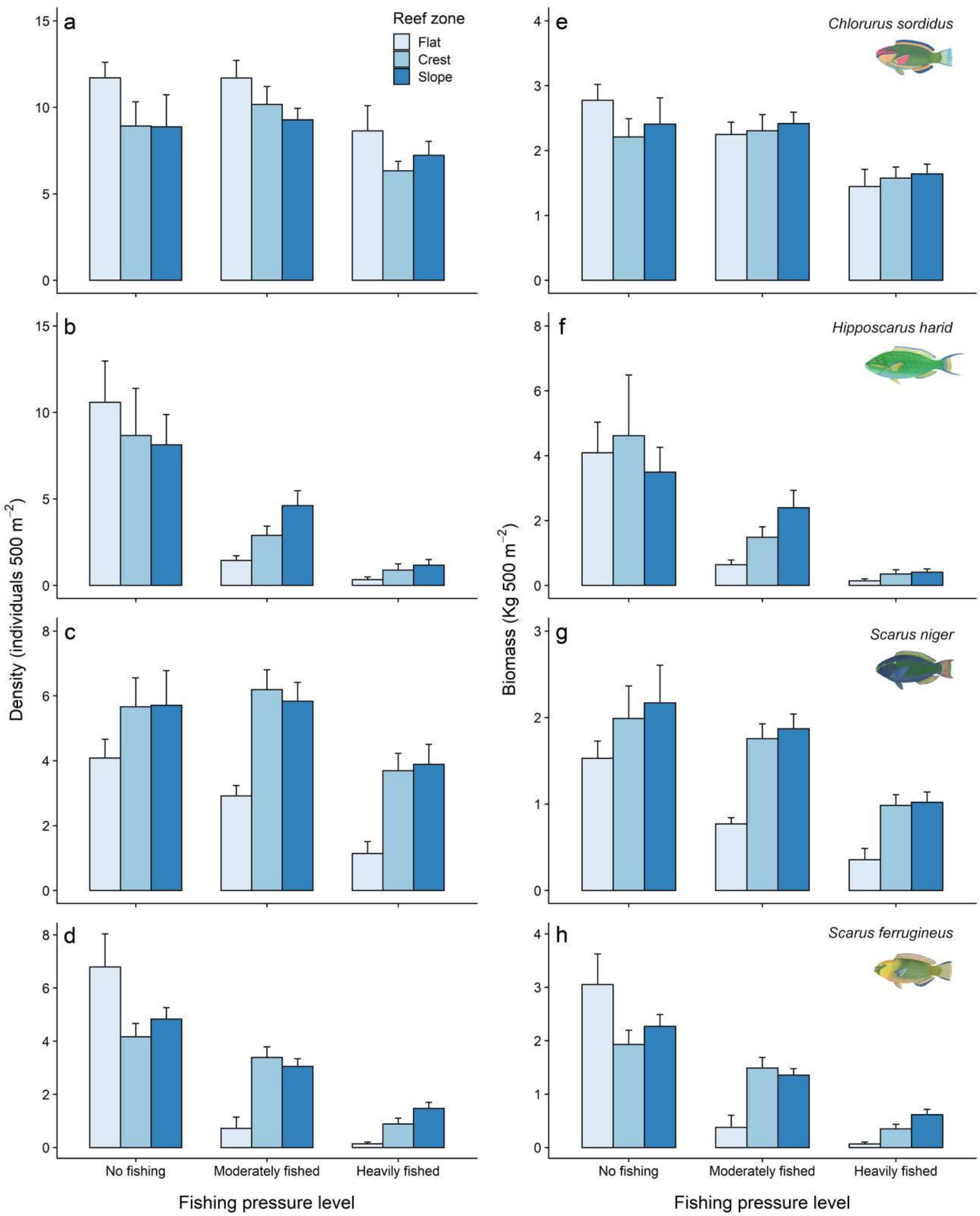

Figure 3. Patterns in the distribution of density and biomass of the four most abundant parrotfish species on three reef zones under different fishing pressure levels. Left column (a-d) shows fish density; while the right column (e-h) shows fish biomass. a) and e) *Chlorurus sordidus*; b) and f) *Hipposcarus harid*; c) and g) *Scarus niger*; d) and h) *Scarus ferrugineus*. Bars represent mean values and standard errors.

3.3. Parrotfish size structure

The size-frequency distribution of the total parrotfish family within all size classes differed according to the level of fishing pressure. Numerically, the abundance of large-sized individuals (> 30 cm, TL) decreased significantly from 25.9% and 17% on unfished and moderately fished reefs, respectively, to 8% on heavily fished reefs. In contrast, abundance of small-sized individuals (10–20 cm) increased with increasing fishing pressure, rising from 18.4% on unfished reefs to 31.4% and 43.8% on moderately and heavily fished reefs, respectively, but this increase was not statistically significant **(**GLMM: P>0.05). On unfished reefs, the abundance of medium-and large-sized parrotfish individuals was significantly higher than on heavily fished reefs (GLMM: P<0.001). Interestingly, there were no significant differences in the size distribution of all parrotfish size classes between unfished and moderately fished reefs (Tables 2c, 3 and Figure 4).

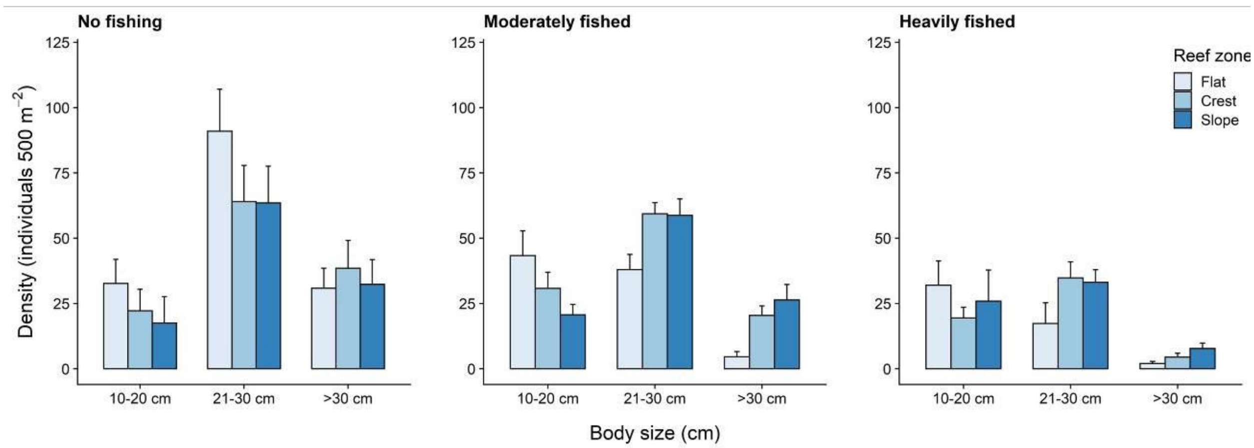

Figure 4. Abundance of total parrotfish family within three size classes in three reef zones under different fishing pressure levels. Bars represent mean values and standard errors.

For each species of the four most abundant parrotfish, Figure 5 shows the mean abundance and frequency of different size classes at each fishing pressure level. The distribution of the most abundant parrotfish species (*C. sordidus* and *S. niger*) reveals a relatively similar abundance of individuals in all size classes across all levels of fishing pressure. In contrast, the abundances of medium-and large-bodied individuals of targeted parrotfish species (*H. harid* and *S. ferrugineus*) by local Bedouin were significantly higher on unfished reefs compared to those on heavily fished reefs (GLMM: P<0.001; Tables 2c, 3). At all levels of fishing pressure, the four parrotfish species had a non-uniform distribution across the three reef zones (Table 4, Figure 5).

Table 4. Summary of body-size (length in cm per 2000 m^{-2}) estimates for the studied four parrotfish species and the total parrotfish family on three reef zones (flat, crest, slope) and averaged across all reef zones (reef-wide). The numbers are mean averaged over all reefs at each fishing pressure level (± SE; Standard Error of the Mean).

Fishing pressure	Reef zone	Fish size (cm)	*C. sordidus*	*H. harid*	*S. niger*	*S. ferrugineus*	Parrotfish family
Unfished	Flat	10-20	21.2 ± 6.5	2.7 ± 2.7	0.0 ± 0.0	1.2 ± 1.2	32.7 ± 9.2
		20-30	24.5 ± 3.3	22.2 ± 10.1	13.5 ± 4.8	17.0 ± 4.2	91.0 ± 16.0
		>30	1.3 ± 0.9	13.2 ± 4.2	2.8 ± 1.3	9.2 ± 5.0	30.8 ± 7.7
	Crest	10-20	17.0 ± 7.2	0.2 ± 0.2	2.2 ± 1.2	0.0 ± 0.0	22.2 ± 8.3
		20-30	16.7 ± 4.7	13.8 ± 8.0	16.2 ± 4.9	10.8 ± 1.6	64.0 ± 13.9
		>30	1.2 ± 0.7	20.7 ± 9.6	4.2 ± 2.8	5.8 ± 2.3	38.5 ± 10.7
	Slope	10-20	15.5 ± 10.5	0.2 ± 0.2	0.3 ± 0.3	0.3 ± 0.3	17.5 ± 10.1
		20-30	18.0 ± 5.7	12.3 ± 2.9	18.0 ± 5.7	12.0 ± 1.6	63.5 ± 14.1
		>30	2.0 ± 1.6	12.8 ± 4.9	4.5 ± 2.3	7.0 ± 2.0	32.2 ± 9.4
	Reef wide	10-20	17.9 ± 8.1	1.0 ± 1.0	0.8 ± 0.5	0.5 ± 0.5	24.1 ± 9.2
		20-30	19.7 ± 4.6	16.1 ± 7.0	15.9 ± 5.1	13.3 ± 2.5	72.8 ± 14.7
		>30	1.5 ± 1.1	15.6 ± 6.2	3.8 ± 2.1	7.3 ± 3.1	33.8 ± 9.3
Moderately fished	Flat	10-20	22.2 ± 5.2	1.3 ± 1.3	1.2 ± 0.9	0.0 ± 0.0	43.3 ± 9.4
		20-30	14.9 ± 3.4	3.6 ± 0.7	7.7 ± 1.9	0.9 ± 0.4	38.0 ± 5.8
		>30	0.0 ± 0.0	3.1 ± 1.3	0.6 ± 0.3	0.3 ± 0.2	4.6 ± 2.0
	Crest	10-20	20.6 ± 5.0	0.0 ± 0.0	6.3 ± 2.2	0.9 ± 0.6	30.8 ± 6.2
		20-30	19.4 ± 1.3	3.7 ± 0.7	16.0 ± 2.2	8.4 ± 1.8	59.3 ± 4.3
		>30	0.7 ± 0.3	7.9 ± 2.2	2.4 ± 0.8	4.2 ± 0.9	20.4 ± 3.6
	Slope	10-20	12.3 ± 2.7	1.4 ± 1.3	2.3 ± 1.5	0.1 ± 0.1	20.7 ± 4.0
		20-30	19.1 ± 3.1	5.9 ± 1.3	15.7 ± 2.9	7.3 ± 1.8	58.8 ± 6.2
		>30	2.2 ± 0.8	12.8 ± 4.5	4.2 ± 0.9	3.1 ± 0.8	26.3 ± 5.9
	Reef wide	10-20	18.4 ± 4.3	0.9 ± 0.9	3.3 ± 1.5	0.3 ± 0.2	31.6 ± 6.5
		20-30	17.8 ± 2.6	4.4 ± 0.9	13.1 ± 2.3	5.5 ± 1.3	52.0 ± 5.4
		>30	1.0 ± 0.4	7.9 ± 2.7	2.4 ± 0.7	2.5 ± 0.6	17.1 ± 3.8
Heavily fished	Flat	10-20	23.4 ± 6.5	0.0 ± 0.0	0.2 ± 0.2	0.0 ± 0.0	32.0 ± 9.3
		20-30	10.9 ± 5.4	0.7 ± 0.4	3.6 ± 2.0	0.3 ± 0.2	17.3 ± 7.9
		>30	0.2 ± 0.2	0.7 ± 0.4	0.9 ± 0.6	0.2 ± 0.2	2.0 ± 0.8
	Crest	10-20	10.4 ± 2.2	0.0 ± 0.0	4.2 ± 1.9	0.3 ± 0.2	19.4 ± 4.1
		20-30	14.2 ± 3.0	2.6 ± 1.5	9.6 ± 1.8	2.2 ± 1.2	34.8 ± 6.2
		>30	0.7 ± 0.4	1.0 ± 0.6	1.0 ± 0.4	1.0 ± 0.4	4.4 ± 1.5
	Slope	10-20	14.6 ± 6.6	0.0 ± 0.0	6.4 ± 4.3	0.6 ± 0.4	25.9 ± 11.9
		20-30	13.4 ± 2.5	3.3 ± 1.7	7.6 ± 1.3	3.3 ± 1.3	33.1 ± 4.8
		>30	0.9 ± 0.5	1.3 ± 0.7	1.6 ± 0.7	2.0 ± 0.6	7.8 ± 2.0
	Reef wide	10-20	16.1 ± 5.1	0.0 ± 0.0	3.6 ± 2.1	0.3 ± 0.2	25.8 ± 8.4
		20-30	12.8 ± 3.6	2.2 ± 1.2	6.9 ± 1.7	1.9 ± 0.9	28.4 ± 6.3
		>30	0.6 ± 0.4	1.0 ± 0.6	1.2 ± 0.6	1.1 ± 0.4	4.7 ± 1.4

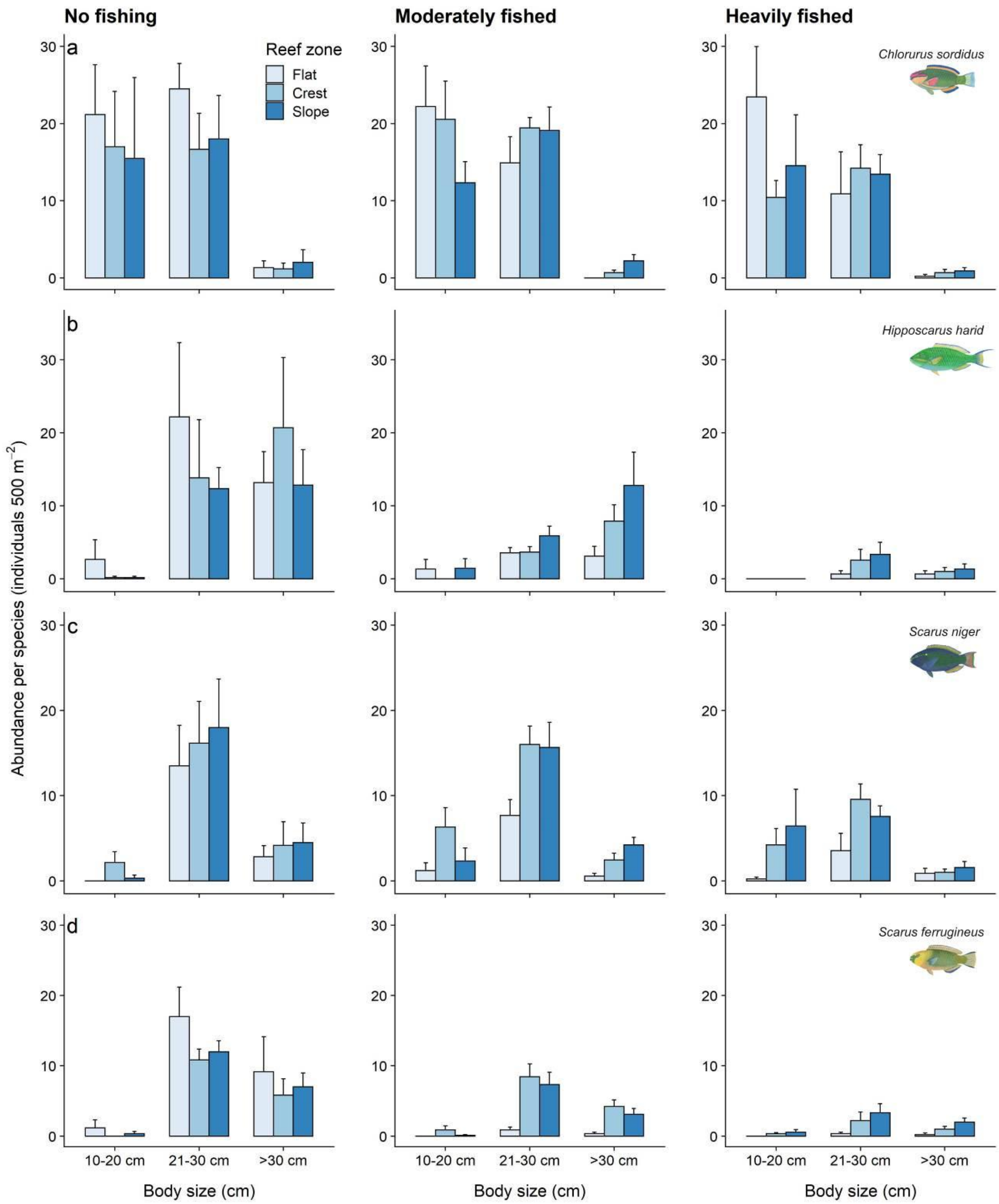

Figure 5. Abundance of **a)** *Chlorurus sordidus*, **b)** *Hipposcarus harid*, **c)** *Scarus niger*, and **d)** *Scarus ferrugineus* within three size classes in three reef zones under different fishing pressure levels. Bars represent mean values and standard errors.

4. DISCUSSION

In South Sinai (the Egyptian GoA), parrotfish communities are subject to markedly different levels of fishing pressure, ranging from virtually none in Ras Mohammed and Sharm El-Sheikh; increased in Nabq, Dahab, and Abu Galum; and reaching extremely high levels in Nuweiba and Taba. Several previous studies in South Sinai MPAs **(Galal *et al.*, 2002, 2012; Ashworth, 2004; Tilot *et al.*, 2008)** used UVC to assess the impact of fishing on coral reef fishes (including parrotfishes). However, the majority of these studies were limited to focusing on a specific geographic area or conducted only on one reef habitat. Therefore, the present study provides detailed quantification of the structure and composition of parrotfish communities across the entire Egyptian coast of the GoA. The heavily fished reefs (Nuweiba and Taba) are located in the northern GoA, where fisheries management appears to be more permissive and a variety of fishing gear (e.g., hook and line, nets, traps, spear guns) are the most commonly used. Whereas, the moderately fished reefs (Nabq, Dahab, and Abu Galum) are located in the central and southern GoA, where local artisanal fisheries are regulated (e.g., gear restrictions). Lastly, the unfished reefs (Ras Mohammed and Sharm El-Sheikh) lie around the southern tip of the Sinai Peninsula, where all forms of near-shore fishing are prohibited **(Mabrouk, 2015)**. Therefore, knowing and understanding the effects and consequences of fishing on parrotfish populations is highly needed to properly manage current levels of fishing in South Sinai MPAs.

This study has demonstrated that there were significant variations in the structure and composition of parrotfish communities among South Sinai MPAs. We found that unfished reefs support on average over 1.6 and 3.7 folds of the total parrotfish biomass, compared to moderately and heavily fished reefs, respectively. This finding is consistent with a growing number of regional and global studies that find similar patterns between unfished and fished reefs. For instance, **Edwards *et al.* (2014)** found that parrotfish biomass in unfished locations was more than twice that of fished locations. Also, **Campbell *et al.* (2018)** found the same pattern on unfished reefs, where parrotfish biomass was 46% higher than on heavily fished reefs. Comparisons of parrotfish density and biomass between unfished and heavily fished reefs across reef zones different trends. In unfished reefs, parrotfish density and biomass were highest on the reef flat, intermediate on the reef crest, and lowest on the reef slope. In contrast, the opposite trend was detected on heavily fished reefs. The majority of variation in total parrotfish density and biomass across fishing pressure levels was attributable mostly to four parrotfish species (*C. sordidus*, *S. niger*, *S. ferrugineus*, and *H. harid*).

Our findings from unfished reefs are similar to those of previous studies, which found relatively high abundances and biomass of herbivorous fishes in the shallowest zones of the reef (reef flat and crest), in both the Red Sea **(Alwany *et al.*, 2009; Afeworki *et al.*, 2013)** and the Great Barrier Reef **(Wismer *et al.*, 2009; Bellwood *et al.*, 2018)**. At the species level, our results revealed that unfished reefs support the highest density and biomass of large-sized parrotfish individuals of *H. harid* and *S. ferrugineus*. In contrast, the heavily fished reefs were characterized by the high density and biomass of small-sized parrotfish individuals of *C. sordidus* and *S. niger*. This discrepancy is largely attributable to the fact that the large-sized parrotfish species are the most desired and most targeted parrotfish by the local artisanal fishermen in the South Sinai MPAs. Several authors **(Bellwood *et al.*, 2012; Advani *et al.*, 2015; Shantz *et al.*, 2020)** found similar findings: as fishing pressure increases, the abundance of small parrotfish individuals increases.

Large-sized individuals of parrotfishes have an important and unique ecological function in maintaining the health and resilience of coral reefs **(Bozec *et al.*, 2016; Shantz *et***

***al.*, 2020)**. However, most coral reef fisheries tend to target commercially important, large-sized fishes, including parrotfishes **(Wilson *et al.*, 2010; Robinson *et al.*, 2017; Shantz *et al.*, 2020)**. Furthermore, spearfishing has become more frequently practiced by Bedouin in the last decade, in particular in the northern sector of the Egyptian GoA **(Poonian, 2020)**. This highly selective fishing method contributes to the loss of large-size classes and key herbivorous fish species, such as parrotfishes **(Frisch *et al.*, 2012; Roos *et al.*, 2016; Barbosa *et al.*, 2021)**. Our findings revealed that many of these large and medium-sized parrotfish have been overfished in the northern regions of the Egyptian GoA. Notably, large-sized parrotfish densities (> 30 cm TL) were 7.2 times higher on unfished reefs than those on heavily fished reefs. Also, the most targeted large-bodied species (*H. harid*) was either rare or absent on heavily fished reefs. This may explain the significant increases in turf algae and macroalgae cover that have been reported recently from Dahab and Nuweiba in the northern GoA **(Naumann *et al.*, 2015; Reverter *et al.*, 2020; Abdelazim, 2021)**. Our suggestion is supported by an example from the literature. **Shantz *et al.* (2020)** found that the removal of large and/or medium-sized parrotfish individuals did not affect the overall grazing rates, but resulted in 4- and 10-fold increases in algal biomass.

Our findings also confirm the expected direct effect of fishing pressure on the distribution and size structure of parrotfish communities on fished reefs. The abundance of large-sized individuals of parrotfish significantly decreased from about 26% on unfished reefs to 8% on heavily fished reefs. In contrast, the abundance of small individuals increased with increasing fishing pressure, rising from 18.4% on unfished reefs to 43.7% on heavily fished reefs. The results of the present study also examined the size-related variations in the spatial distribution of the four most abundant parrotfish species. *Chlorurus sordidus* and *Scarus niger* showed relatively similar abundances of all size classes across all levels of fishing pressure. In contrast, the abundances of medium-and large-bodied parrotfish species, *Scarus ferrugineus* and *Hipposcarus harid,* were significantly higher on unfished reefs compared to those on heavily fished reefs. Parrotfish size was identified as a useful and simple indicator of fishing effects by **Vallès *et al.* (2015)**. They investigated the effects of fishing on parrotfish assemblages by comparing three simple metrics (average individual fish size, density, and biomass). They found that the average individual fish size metric was the most strongly correlated with fishing pressure. The present study corroborates these findings by showing that there are significantly higher abundances of large-sized parrotfish individuals in unfished MPAs.

5. CONCLUSION

The status of parrotfish biomass and size structure was investigated across the entire Egyptian coast on the GoA. To our knowledge, this is the first study to evaluate the variation patterns of parrotfish biomass and size structure along a gradient of fishing pressure and on such spatial scales in the northern Red Sea and Gulf of Aqaba. Also, our findings provide important information that has management and conservation implications for artisanal fisheries in the South Sinai MPAs. Total parrotfish biomass was approximately 4 times higher in unfished (no-take) reefs than in heavily fished (open-access) reefs in the northern GoA (i.e., Nuweiba and Taba).

While fishing pressure has a clear effect on the total biomass and size structure of parrotfish family and on large-bodied parrotfish species (*Hipposcarus harid* and *Scarus ferrugineus*), there is almost no significant differences in the numerical density of medium-bodied parrotfish species (*Chlorurus sordidus* and *Scarus niger*) between fished and unfished reefs. This pattern proves that larger-sized parrotfish individuals were excessively impacted by fishing. Overall, our findings support previous studies that showed implementing adaptive management strategies, such as gear restrictions and temporary closures, provides a comparable protection benefits to parrotfishes similar to no-take MPAs. Therefore, we believe that this approach would give coral reef managers in Nuweiba and Taba a chance to recover heavily overfished parrotfish populations.

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