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# Effects of marine protected areas under different management regimes in a hot spot of biodiversity and cumulative impacts from SW Atlantic

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## ABSTRACT

Marine protected areas (MPAs) represent a useful tool for resource management, as well as to conserve and/or restore biological communities. The level of protection is key factor influencing the marine biodiversity, where a more enforced protection is expected to drive positive outcomes. In 2008, a large MPAs network (∼11,380 km$^2$) was established in one of off the most populated and industrialized areas in the world (i.e., São Paulo State coast, southeast Brazil). Given many goods and services provided by marine ecosystems, this MPA network represents the most challenging marine conservation initiative in Brazil. Harboring areas with different socio-ecological contexts and management regimes, this MPA network provides a unique opportunity to investigate the effects of cumulative impacts. We contrasted the biomass and size structure of reef fish in three subtropical islands under different levels of enforcement. We analyzed the influence of variables as island size, benthic cover, depth, topographic complexity, wave exposure, and protection level on the biomass of reef fish assemblages. Protection level was the main attribute responsible to explain the high biomass of fish target species and small territorial herbivores. In sites sheltered from the waves, the biomass of groupers was ∼1600% higher within enforced area than that from open-access area. Beyond the idea of positive effects of enforcement on reef fish biomass and size, we add evidences that even under multiple stressors, the area-based management is still a strong tool to marine conservation.

## 1. Introduction

The last decades have been marked by alarming predictions about the future of the world's oceans, counteracted by more recent and positive expectations from the "Aichi Targets" agreement in 2010 by the parties of the Convention on Biological Diversity, as well as by UNs' Sustainable Development Goals (SDG 14) adopted in 2015 and recommitted in 2017 during the UN Ocean Conference (Pinheiro et al., 2019). However, sequential fisheries collapses, growing dead zones, invasion of exotic species, pollution, habitat destruction and impacts from climate changes are materializing globally and at an unprecedented fast pace (Jackson et al., 2001; Myers and Worm, 2003; Worm et al., 2006; Diaz and Rosemberg, 2008; Halpern et al., 2008; Jambeck et al., 2015; McCauley et al., 2015; Allison and Bassett, 2015; Pauly and Zeller, 2016). Currently (2020), 193 countries should be already "effectively and equitably" managing at least 10% of their marine areas with "effective area-based conservation measures" (Aichi Target 11), but many of them followed a wave of political opportunity and expended efforts in large marine protected areas in

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remote regions, where conflicts among resource users are scarce and relatively simple when compared with coastal zones (Giglio et al., 2018; Pinheiro et al., 2019).

Marine Protected Areas (MPAs) are the most popular area-based conservation measure and aim to manage human uses at local/regional scales to promote the recovery of overexploited marine populations, protect or restore habitats, biodiversity and food webs (Gell and Roberts, 2003; Leenhardt et al., 2015). Due to such potential, together with the overall failure of traditional fisheries management (e.g. catch restrictions), MPAs were put in the spotlight of the marine conservation as the centerpiece for ecosystem-based management (Halpern et al., 2010; Browman and Stergiou, 2004; Micheli et al., 2012; Leenhardt et al., 2015; Roberts et al., 2017). However, even with the establishment of MPAs for biodiversity conservation and fisheries management, it still remains a major planning and implementation challenges, including the assessment of their effects and effectiveness (Claudet et al., 2006; Ojeda-Martínez et al., 2011).

The increase of biomass, density, richness and size of organisms targeted by fisheries are the main direct ecological effects of MPAs, particularly in no-take areas in which extractive uses are banned (Halpern, 2003; Lester et al., 2009; Edgar et al., 2014). In general, the magnitude of such expected responses are associated to MPA management regime, age, size, isolation, and enforcement level (Claudet et al., 2008; Edgar and Stuart-Smith, 2009; Edgar et al., 2014; Gill et al., 2017). Another relevant effect of no-take MPAs is the exportation of biomass to adjacent fishing grounds via emigration of juveniles, subadults, and adults (spillover effect), thus benefiting local fisheries and strengthening support for MPA from stakeholders (Di Lorenzo et al., 2016, 2020). Indirect MPA effects have been reported less often, but include "trophic cascades" with increases in populations of large predators targeted by fisheries, coupled with decreases in their prey (see Claudet et al., 2011 for a review). However, distinct environmental characteristics and lack of data before the protection, as well as heterogeneous anthropogenic features, have represented the main sources of confounding factors to assess the differences between protected and unprotected areas (García-Charton et al., 2008; Sciberras et al., 2013). Robust experimental designs (i.e. Before–After-Control-Impact– BACI and beyond-BACI) may deal with spatial and temporal variability, but baseline data before MPA implementation (Francini-Filho and Moura, 2008a), or long-term monitoring data, are rarely available (Grorud-Colvert et al., 2011; Sciberras et al., 2013; Anderson et al., 2020).

Brazil has 177 MPAs that cover 26.4% of its 3.5 million km $^{2}$ Exclusive Economic Zone (EEZ), but only 3.3% of this area is within no-take MPAs (CNUC-MMA, 2019). In addition, most of the country's MPAs have low enforcement levels and still lack management plans, long-term monitoring programs, and basic financial and human resources (Amaral and Jablonski, 2005; Gerhardinger et al., 2011; Oliveira-Júnior et al., 2016). This data poor scenario hinders the establishment of new MPAs and the management of the existing ones (e.g. Teixeira et al., 2017; Mills et al., 2020). The overall lack of evidence about the conditions underlying MPA effects and effectiveness is particularly important in the MPA arena, which depends on the engagement of stakeholders since the initial planning stages. Indeed, effectiveness assessments of Brazilian MPAs rely largely on qualitative management indicators (scorecard-based) (e.g. Araújo and Bernard, 2016; Oliveira-Júnior et al., 2016; Brandão et al., 2017; Giglio et al., 2019), which have a weak potential to mobilize fishers, tourism operators and visitors. Few studies have addressed the ecological effects of Brazilian MPAs, and these include one meta-analysis (Floeter et al., 2006), one large scale snapshot assessment (Morais et al., 2017), and a handful of studies focused on particular no-take MPAs and adjacent unprotected sites (Lopes et al., 2013; Anderson et al., 2014, 2018; Ilarri et al., 2017; Rolim et al., 2019). The only regional study that assessed the outcomes of a MPA network with areas under different management regimes was carried out in a tropical coral reef area (Francini-Filho and Moura, 2008b) far from the industrialized southeastern Brazil coastal zone.

Unfortunately, Brazil has been collecting examples of how the national disinterest on environmental issues may bring irreversible consequences to the marine biodiversity. Besides recent huge environmental disasters such as mining dams collapses (Cionek et al., 2019) and oil spills (Soares et al., 2020), the country suffers with chronic absence of long-term planning in basic environmental policy. For instance, 60% of the sewage production in Brazil is released untreated in the environment (Pinheiro et al., 2019). Several pharmaceuticals, including cocaine and its human metabolites, have been detected in marine coastal waters (Pereira et al., 2016) and pollution has already been pointed as a real threat to major MPAs in the world (Abessa et al., 2018; Castro et al., 2021; Nunes et al., 2021). In this context, the emerging question is how much coastal MPAs, close to metropolitan regions has been effective in conserving marine biodiversity? To address this question, the aim of this work was to compare the biomass of target and non-target fish species, considering the main habitat features and trophic and size structure of fish assemblages, in three subtropical islands at a hot spot of cumulative impacts subjected to different levels of protection.

Beyond reinforce the idea of positive effects of enforcement on reef fish biomass and size, we add evidences that even under multiple stressors influence, area-based management is still a strong tool to marine conservation being relevant to encourage states and municipalities take the lead role on regional fishing management as well as join efforts to require national leadership in issues which local initiatives are not sufficient to deal with.

## 2. Material and methods

### 2.1. Study area

São Paulo State (SP), in southeastern Brazil, comprises about 700 km of coastline between 23°18'S and 25°14'S (Fig. 1) and is among the world's most densely populated metropolitan areas, with more than 20 million people living within less than 100 km from the ocean. The "very high" human impact status of the region (Halpern et al., 2008; Magris et al., 2020) is largely due to industrial and urban pollution and habitat destruction, seaports (including south the Atlantic's largest, Santos port), industrial fisheries (including bottom trawling), marinas, and large-scale oil extraction and transportation. The coast is geomorphologically diverse, with two large estuaries (Santos and Cananéia-Iguape), mangroves, sandy beaches, rocky shores and >100 granitic coastal islands with different sizes, distance offshore and terrestrial vegetation cover (Angelo and Lino, 1989; Lamparelli, 1998). Commercial fisheries are multi-specific and include a broad spectrum between artisanal (rudimentary and family-based) and industrial arrangements. Captures of pelagic and soft-bottom resources are influenced by seasonal (summer) upwelling of cold subtropical waters, associated to alongshore winds and cyclonic vortices of the warmer, south-flowing and superficial ($<\sim$100 m) Brazil Current (Borzone et al., 1999; Vasconcellos and Gasalla, 2001; Katsuragawa et al., 2014). Reef fishes are not major commercial resources, as groupers (Epinephelidae) and snappers (Lutjanidae) annual landings averaged less than 10 tons.year$^{-1}$ between 2017 and 2019 (PMAP, 2020). On the other hand, reef fishes are the preferred targets of recreational fisheries with hook-and-line and spearguns, but these catches are unreported and poorly regulated and enforced (Freire et al.,

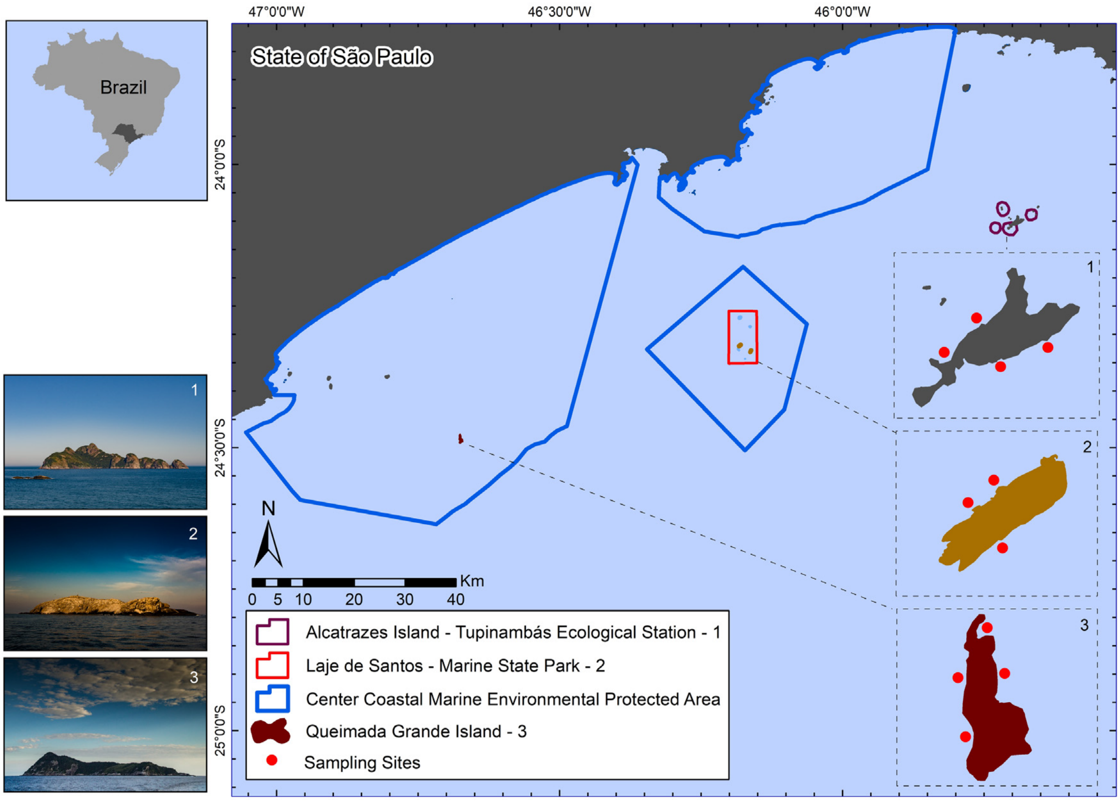

**Fig. 1.** Study area with the marine protected area network and the three islands with different enforcement levels assessed in the present study (Alcatrazes, Laje de Santos and Queimada Grande island).).

2016). Reef fish assemblages in SP islands are comprised by a mixture of tropical and subtropical species, with a relatively high numerical and biomass participation of southwestern Atlantic endemic species (Pinheiro et al., 2018). In addition, SP coast present the highest occurrence of marine threatened species in Brazil (Ceretta et al., 2020; Magris et al., 2020).

The current MPA network in SP is the largest in Brazil and was established opportunistically along two decades of *ad hoc* planning, with a strong participation of the state government, which is unusual in the country's MPA arena (e.g. Moura et al., 2013; Mills et al., 2020). The first MPAs were established by the Federal government in 1987, comprising two no-take Ecological Stations (corresponding to IUCN category I), "Tupinambás" and "Tupiniquins", which aim to protect the natural environment and to promote scientific research. The state government created the no-take Laje de Santos Marine State Park (IUCN category II) in 1993, aiming to conserve regional biodiversity and to develop SCUBA diving tourism, and followed up with the creation of three large (totaling 11,380 km $^2$) multiple-use MPAs (IUCN category V) in 2008, largely aiming to manage fisheries (Rolim and Ávila-da Silva, 2016). Although relatively large, the SP network of MPAs has only about 5.7% of its area under no-take regime. Our study encompassed three islands located at similar distances offshore (Fig. 1) and under similar oceanographic forcing, depth ranges and bottom type. On the other hand, they differ in terms of island size and protection and enforcement levels (Table 1). The Queimada Grande island (Queimada) is located within the open-access zone of one of the large multiple-use MPAs (all types of extractive uses, recreational activities and scientific research are allowed); Alcatrazes, is located within the partially and more recently enforced no-take Tupinambás Ecological Station (only scientific research is allowed); and Laje de Santos (Laje) is the best and longer-term enforced no-take MPA (only recreational scuba dive and scientific research are allowed). Although was not possible to replicate the management context of the islands, their conditions within São Paulo's MPAs network represent a unique opportunity to discuss the effect of area-based conservation in coastal regions exposed to multiple anthropogenic stressors.

### *2.2. Data collection*

Sampling was performed in March 2015. Fish abundance and biomass were estimated with a stationary visual census protocol adapted from Minte-Vera et al. (2008). Fish numbers and body sizes were recorded after listing all species within an observer-centered cylinder with 4 m radius, during five minutes. Individuals $<10$ cm (total length — TL) were counted within a 2 m radius in two size classes, $\leq 2$ cm and 2–10 cm TL, while individuals $>10$ cm TL were counted within a 4 m radius in four size classes, 10–20, 20–30, 30–40, $>40$ cm TL. Nested stationary cylinders with 2 and 4 m radius produce the most accurate density estimates for small (TL $\leq$ 10 cm), including cryptobenthic species, and large (TL $>10$ cm) reef fishes (Minte-Vera et al., 2008).

Sampling units ($n = 330$) were randomly distributed in sheltered and exposed sites and in two depth zones, 3–10 m (shallow) and 10–20 m (deep), with 15 sampling units in each stratum. Wave exposure and depth are well recognized as the most influential drivers of reef fish community structure in the shallow water rocky reefs of southeastern Brazil (Floeter et al., 2007; Gibran and Moura, 2012). In the larger islands (Alcatrazes and Queimada) we sampled two sheltered sites and two exposed sites, and in the smaller island (Laje) we sampled two sheltered sites and one exposed site.

Benthic cover was characterized using photoquadrats ($25 \times 25$ cm), with 20 samples obtained at each depth stratum (totaling $n = 440$). After the divers have reached the site depth, photoquadrats were non-intentionally target in intervals

**Table 1**
Summary of characteristics and management context of studied MPAs.

| | Queimada Grande | Alcatrazes | Laje de Santos |
|---|---|---|---|
| Category IUCN[a] | V | Ia | II |
| Island area (km$^2$) | 0.78 | 1.352 | 0.0115 |
| No-take area (km$^2$) | 0 | 24.63 | 50 |
| Distance from the coast (km) | 34.8 | 33.4 | 33 |
| Declaration year | 2008 | 1987 | 1993 |
| Jurisdiction | State | Federal | State |
| Management Instruments (implementation year) | Managing Council (2008) Management Plan [b] (2021) | Management Council (2006), Establishment of a new no-take MPA[b] (2016) Management Plan[b] (2017), and Public Use Plan[b] (2017) | Management Council (2009), Fishing Exclusion Zone (2012), Emergency Plan for Public Use (2014), Management Plan[b] (2018) |
| Enforcement level | open-access (multiple-use) | Partially Enforced (no-take) | Enforced (no-take) |

[a] International Union for Conservation Nature.

[b] Management Instruments implemented after study period.

of five diver fin kicks. Percent cover was estimated with software photoQuad v1.4 (Trygonis and Sini, 2012), using 20 randomly distributed points at each quadrat. Quantitative analyses included 12 major benthic categories: crustose coralline algae (CCA), fleshy algae, coral, tunicate, zoantharia, cenocitic algae, cctocorallia, echinodermata, porifera, bivalve, hydrozoa, and turf algae. Topographic complexity was visually scored for each sampling site as follows: 1. Relatively flat sites (<45° slope) with homogeneous relief resembling rocky terraces; 2. Sites with intermediate complexity, with holes and crevices mostly presenting similar sizes; and 3. Sites with the most heterogeneous reliefs, comprised by rocks and crevices in a wider size range (see Claudet et al., 2006).

### 2.3. Data analyses

Fish species were categorized in seven trophic groups following Luiz et al. (2008) and Gibran and Moura (2012): carnivores, roving herbivores, territorial herbivores, omnivores, sessile invertivores, mobile invertivores and planktivores. Three groups preferred by local fisheries (Epinephelidae, Lutjanidae and Labridae:Scarini) were used as proxies of direct MPA effects. Territorial herbivores were also used to assess the MPA effects. Biomass was estimated with length–weight (L–W) relationships (Froese and Pauly, 2015) using W from the midpoint of each L class and the number of individuals per category, and then summing categories (Francini-Filho and Moura, 2008b). When L–W parameters were not available, biomass was calculated using those from congeners or related species from the same family.

Relationships between fish biomass and the explanatory variables (island size, benthic cover, depth, topographic complexity, wave exposure and protection level) were assessed by considering site as the lowest level of replication. A single value for each site was calculate (average) for the explanatory variables and the biomass of selected fish groups. Pairwise correlation coefficients were calculated between all explanatory variables and none of these variables displayed any collinearity ($R<0.7$; Zuur et al., 2007). The distance-based linear model (DistLM; Legendre and Anderson, 1999; McArdle and Anderson, 2001) was used to identify which set of explanatory variables best explained the variation in fish biomass. The Akaike Information Criterion (AIC) was used to select the most parsimonious model (Anderson et al., 2008). Permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001) was used to evaluate differences in biomass of target and non-target fish groups in response to depth (covariate), protection level, wave exposure (fixed factors) and interaction effects. PERMANOVA pairwise comparisons were used to assess differences in fish biomass among wave exposure and protection levels. Prior to the analysis, fish biomass and explanatory variables data were square root transformed.

## 3. Results

A total of 73 fish species (31 families) were recorded in Queimada, 77 (30 families) in Alcatrazes, and 59 (25 families) in Laje. The tomtate grunt (*Haemulon aurolineatum*) was the most abundant fish in the three islands and represented 31.2 to 34.1% of the total number of individuals (Table S1). Other five species (*Abudefduf saxatilis*, *Parablennius* spp., *Caranx crysos*, *Anisotremus virginicus* and *Stegastes fuscus*) were among the top ten most abundant fishes in the three islands (Table S1). Mobile invertivores was the most abundant trophic group in the three islands (mean ± SE = 44.5% ± 2.1), followed by territorial herbivores (21%) and omnivores (19%) in Queimada (open-access area), and by omnivores (26.8% ± 0.85) and carnivores (12.8% ± 0.04) both in Alcatrazes (partially enforced area) and Laje (enforced area) (Fig. 2).

Fish biomass was associated with turf, coral and fleshy algae cover, level of protection, depth, island size and wave exposure (Table 2). Protection level was the most important predictor for three (out of four) analyzed fish groups (Epinephelidae, Lutjanidae and territorial herbivores), explaining 32.2–57.9% of the variation (Table 2). For the remaining target group, parrotfishes (Labridae: Scarini), coral cover was the main predictor and was associated with 18.8% of the variance (Table 2). Biomass of groupers (Epinephelidae) and snappers (Lutjanidae) were positively associated to protection level, with the exception of the single exposed site sampled in Laje (Fig. 3 and Table 3). Indeed, for exposed sites, significant differences were detected between Alcatrazes and the other two islands only for groupers (Fig. 3 and Table 3). Parrotfish biomass was equivalent in sheltered sites of the three islands and significantly higher in the exposed site of Queimada (Fig. 3). For non-target fishes, the biomass of the territorial herbivores (*Stegastes* spp.) was significantly higher in the unprotected Queimada than in Alcatrazes and Laje, in both sheltered and exposed sites (Fig. 3 and Table 3).

The size structure of target species and small territorial herbivores (prey) was also associated to management regimes (Fig. 4). Among fishes targeted by fisheries, larger groupers and snappers (>20 cm TL) were more frequent in the enforced and partially enforced no-take MPAs than in the open-access Queimada (Fig. 4). Conversely, small parrotfishes (2–30 cm TL) and territorial herbivores were more frequent in the open-access Queimada (Fig. 4), where the abundance of small groupers was minimum (Fig. 4). Small snappers (<20 cm TL) were overall absent.

## 4. Discussion

Marine Protected Areas have been implemented in the highly industrialized southeastern coast of Brazil since the 1980's, based on ad hoc consultations and without robust baselines about

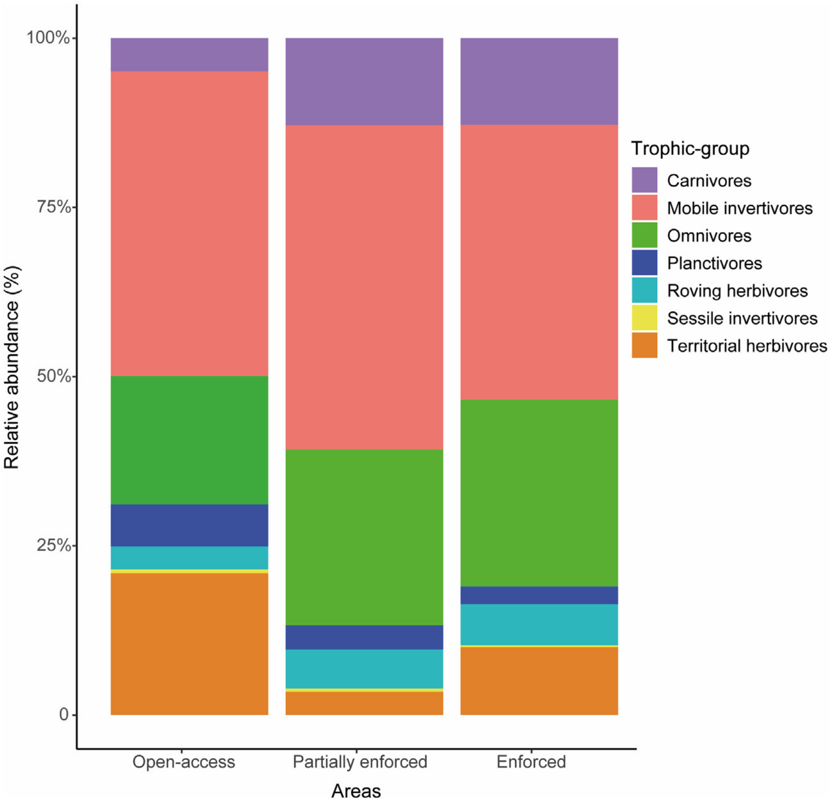

**Fig. 2.** Relative abundance of trophic groups in each MPA. Open-access (Queimada Grande Island), Partially enforced (Alcatrazes Island) and Enforced (Laje de Santos).

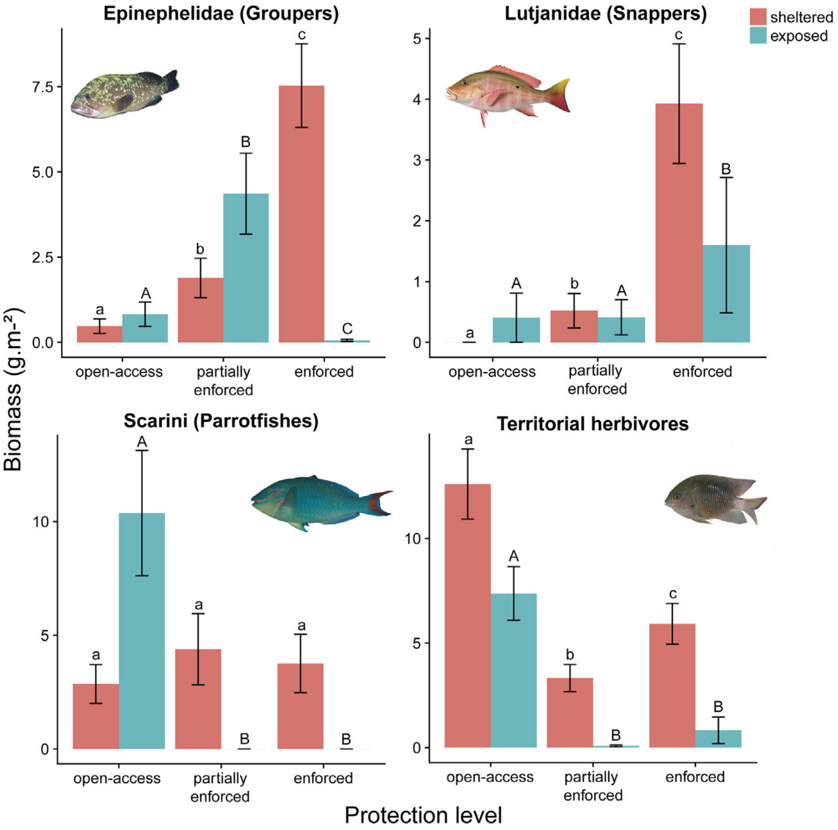

**Fig. 3.** Biomass (mean ± SE) of target (Epinephelidae, Lutjanidade and Scarini) and non-target (Territorial herbivores) fish groups in each site type (sheltered or exposed to wave exposure) and protection levels. Different letters above bars indicate pairwise results from PERMANOVA for the three MPAs. Lower case letters for sheltered and capital letters for exposed to waves. Open-access (Queimada Grande Island), Partially enforced (Alcatrazes Island) and Enforced (Laje de Santos).

**Table 2**
Results of the distance-based linear model (DistLM) for target and non-target fish groups biomass, showing the percentage of variation explained by significant explanatory variables ($P < 0.001$).

| Fish groups | AIC | $R^2$ | RSS | N° Groups | Predictors Selected (% explained) |
|---|---|---|---|---|---|
| Epinephelidae | −7.4538 | 0.54327 | 9.9511 | 4 | Turf (14.6), Protection (32.02), Exposure (5.8) |
| Lutjanidae | −24.029 | 0.6311 | 5.1303 | 2 | Turf (5.2), Protection (57.9) |
| Scarini | 12.935 | 0.37362 | 27.352 | 3 | Coral (18.8), Depth (9.6), Island size (8.96) |
| Territorial Herbivores | −8.6193 | 0.78206 | 9.4377 | 3 | Protection (40.3), Depth (27.3), Exposure (10.6) |

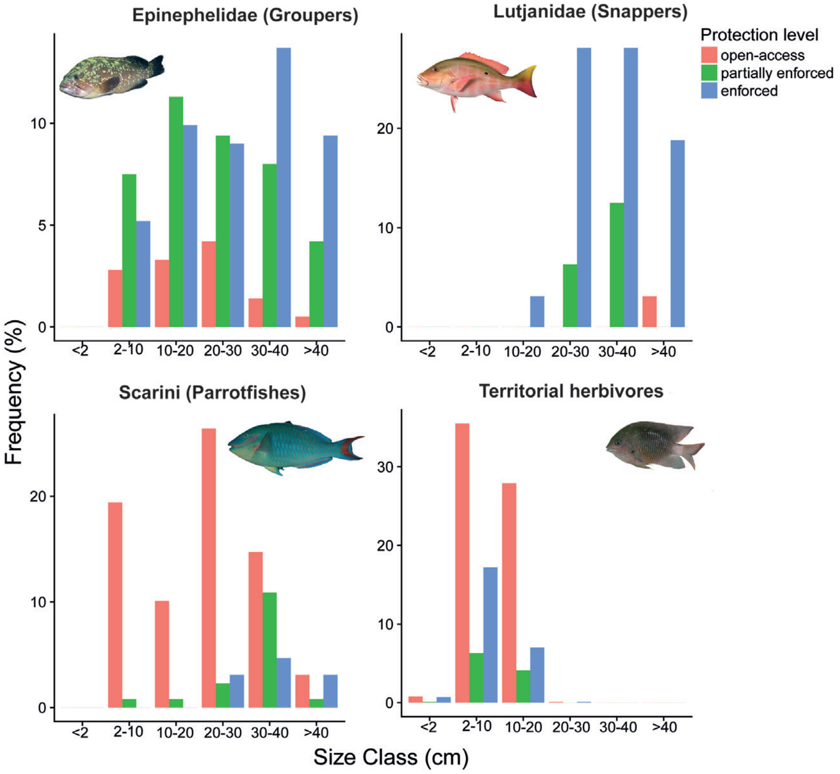

**Fig. 4.** Size frequency distribution of target (Epinephelidae, Lutjanidade and Scarini) and non-target (Territorial herbivores) fish groups in each protection level. Open-access (Queimada Grande Island), Partially enforced (Alcatrazes Island) and Enforced (Laje de Santos).

the state of the ecosystems. São Paulo (SP), Brazil's richest and most populous state, currently encompasses one of the country's largest MPA networks (≅12,055 km $^2$), with areas under Federal and State jurisdiction and different management regimes. Although such efforts had already cost millions of dollars, and affected the livelihoods of dozens of thousands of stakeholders from different sectors (e.g. fisheries, tourism), there are few studies addressing the ecological effects of the region's MPAs. Here, we present the first study comparing the biomass of rocky reef fishes in similar islands that are subjected to different contexts and management regimes. Despite the limitations derived from the lack of temporal data and replication of management contexts we show that the no-take MPAs presented significant positive effects from the protection against fisheries.

Regarding the most abundant species and the dominance of mobile invertebrate feeders, our results converge with previous studies conducted in subtropical southwestern Atlantic (Ferreira et al., 2004; Gibran and Moura, 2012; Daros et al., 2018; Rolim et al., 2019). Moreover, the higher density of territorial herbivores in open-access area as well as the higher density of carnivores in the two no-take areas can be considered as primary evidence of effects of protection.

Although it is known that environmental variables (i.e., topographic complexity, wave exposure, benthic cover and depth) are important predictors of reef fish assemblages (Floeter et al., 2007; Gibran and Moura, 2012; Teixeira-Neves et al., 2015, 2016) and consequently sources of confounding factors to detect MPA outcomes (Claudet and Guidetti, 2010; Sciberras et al., 2013), in our results the level of protection was the most important variable to explain biomass variation of two targeted fish groups (Epinephelidae and Lutjanidae) and one non-targeted group (territorial herbivores). As expected, highly targeted fish species with higher trophic level and body size showed positive response to protection (Mosquera et al., 2000; Côté et al., 2001; Rolim et al., 2019), whereas territorial herbivores probably responded to lesser predator pressure in the open-access area. In contrast, the main predictor of biomass of the parrotfishes was coral cover followed by depth and island size. These two first factors have been recorded as important drivers of biomass of this fish group in Brazilian reefs (Cordeiro et al., 2015; Roos et al., 2019). Either way, the absence of a relationship between protection level and biomass of parrotfishes in the present study may be due its secondary importance as target of local fisheries, in this case recreational spearfishing. The environmental conditions associated with the magnitude of species' response to protection can vary by region and in function of the specific dynamics of human use (McClanahan and Arthur, 2001; Claudet et al., 2010). Moreover, the record of island size as predictor of biomass can be related to the need of parrotfishes to have large areas to foraging (Howard et al., 2013; La Mesa et al., 2012). Thus, even well-enforced no-take MPAs such as Laje may not have enough reef area to ensure a high biomass of this fish group. On the

**Table 3**
Results of PERMANOVA testing for differences in target and non-target fish groups biomass, in response to depth (covariate), level of protection, wave exposure (fixed factors) and interaction effects.

| **Epinephelidae**<br>**Source** | **df** | **SS** | **MS** | **Pseudo-F** | **P** |
|---|---|---|---|---|---|
| Depth | 1 | 7.295 | 7.295 | 4.571 | 0.0323[a] |
| Management | 2 | 65.376 | 32.688 | 20.482 | 0.0001[a] |
| Exposure | 1 | 9.732 | 9.732 | 6.098 | 0.0145[a] |
| Depth x Management | 2 | 20.928 | 10.464 | 6.557 | 0.0015[a] |
| Management x Exposure | 2 | 63.704 | 31.852 | 19.958 | 0.0001[a] |
| Residuals | 329 | 525.06 | 1.596 | | |
| Total | 337 | 692.09 | | | |
| **Lutjanidae** | | | | | |
| Depth | 1 | 1.0453 | 1.0453 | 1.126 | 0.2952 |
| Management | 2 | 35.523 | 17.762 | 19.134 | 0.0001[a] |
| Exposure | 1 | 1.3591 | 1.3591 | 1.4641 | 0.2281 |
| Management x Exposure | 2 | 8.3068 | 4.1534 | 4.4744 | 0.011[a] |
| Residuals | 331 | 307.25 | 0.92826 | | |
| Total | 337 | 353.49 | | | |
| **Scarini** | | | | | |
| Depth | 1 | 36.555 | 36.555 | 12.339 | 0.0007[a] |
| Management | 2 | 56.267 | 28.134 | 9.4962 | 0.0002[a] |
| Management x Exposure | 2 | 43.726 | 21.863 | 7.3797 | 0.0007[a] |
| Residuals | 332 | 983.6 | 2.9626 | | |
| Total | 337 | 1120.1 | | | |
| **Territorial herbivores** | | | | | |
| Depth | 1 | 171.9 | 171.9 | 105.95 | 0.0001[a] |
| Management | 2 | 230.37 | 115.18 | 70.994 | 0.0001[a] |
| Exposure | 1 | 59.551 | 59.551 | 36.705 | 0.0001[a] |
| Management x Exposure | 2 | 13.461 | 6.7305 | 4.1484 | 0.0175[a] |
| Residuals | 331 | 537.02 | 1.6224 | | |
| Total | 337 | 1012.3 | | | |

[a] Significant effect.

other hand, our observations on targeted fishes (groupers and snappers) reinforce that small-sized and well-enforced no-take MPAs produce outcomes for carnivore fish populations (Rolim et al., 2019; Rojo et al., 2019).

Groupers was the group that best responded to the different levels of protection with the biomass varying according to them, with the exception of the exposed site of Laje (enforced area), which can be explained by local features of relief and topographic complexity, a 90 degrees wall without holes and crevices. In fact, groupers are recognized for their close association with the topographic complexity of the environment and habitat conditions (Gibran, 2007; Anderson et al., 2018). The largest individuals were also more frequent in no-take MPAs, especially in Laje (enforced area). Other studies conducted in subtropical rocky reefs have shown a higher biomass and size of groupers inside no-take MPAs (Anderson et al., 2014; Morais et al., 2017; Rolim et al., 2019).

Although snappers also responded to protection, the effects were less evident than in groupers and recorded mainly in sheltered sites of the enforced area. This lesser sensitivity to protection is likely related to the higher exposure of the snappers to fisheries. Snappers (such as *Lutjanus synagris* and *L. analis*) are usually found on sandy bottoms near to the reef, whereas groupers (especially *Epinephelus marginatus* the most abundant grouper species in the present study) are commonly observed inside, or close to their shelters (Anderson et al., 2018). In addition, some studies have estimated higher levels of exploitation of snappers as well as larger home ranges when compared to groupers (Ralston, 1987; Farmer and Ault, 2011).

Herbivores presented higher biomass in the Queimada (open-access area), with parrotfishes (target) showing higher biomass only in the exposed sites, and territorial herbivores (non-target) in sheltered and exposed sites. In both cases, this is likely due to the lower abundance of predators in the open-access area, since parrotfishes and damselfishes species have been found in the stomach contents of groupers and snappers (Randall, 1967; Moreno-Sánchez et al., 2019). Previous studies also detected a higher abundance of parrotfishes in fished areas when compared to protected sites (Floeter et al., 2006; Rolim et al., 2019). However, according to these studies, the fish body size was smaller, indicating a fishing pressure in larger body sizes. In contrast, we verified that parrotfishes were more abundant in all size classes in the open-access area. Although this difference can be related to target exploitation levels within fished areas, the abiotic habitat characteristics also can be involved since Queimada comprises a higher bottom heterogeneity, including rocky reefs associated with fringing coral reef and rhodolith beds (Pereira-Filho et al., 2019).

The biomass trends of targeted fishes observed in the present study in Alcatrazes (partially enforced) and Laje (enforced area) were inverse to those recorded by Morais et al. (2017) during a wide scale assessment using transect method. According to these authors, Alcatrazes presented one of largest fish biomass of the Brazilian reefs, including the groupers biomass, and our study Laje stood out with the highest biomass. This discrepancy may be associated to differences in the oceanographic conditions (e.g. predominant currents, temperature and local upwelling) when the studies were performed, or possibly due to particularities of visual census methods used in each study (Colvocoresses and Acosta, 2007; Pais and Cabral, 2018). In general, our results reinforce the role of local management on biomass trends of targeted fishes since the higher values were recorded in the MPA with a better enforcement due to the existence of public visitation (scuba diving) which usually reduce the risk of illegal fishing in dives sites (Steenbergen, 2013). Also, corroborating this aspect, the biomass trends of target fishes (biological indicator) recorded in the present study converged with an assessment of management effectiveness (management indicator scorecard-based) performed in Alcatrazes and Laje in the same period (Giglio et al., 2019).

In recent years, two events have the potential to improve the effectiveness of the regional MPAs network. In 2016, a new and larger no-take MPA (Alcatrazes Wildlife Refuge — 674.09 km $^2$) encompassing Alcatrazes Island was established and since December 2018 is open for public visitation through regulated recreational activities. Furthermore, in 2019 the multiple-use MPA that covers Queimada Grande Island finalized its management plan and a zone of the 19 km$^2$ around the island was defined as target of actions to making recreational uses compatible with the biodiversity conservation (Marconi et al., 2020). Therefore, the monitoring of these areas becomes crucial to quantify the effectiveness regarding fish assemblage conservation.

Spillover assessment is beyond the scope of this study. However, the first step to evaluate this process was completed here (1. ensure that biomass recovery inside MPA occurs) considering the four steps recommended by Di Lorenzo et al. (2016) that should also include: 2. home range analysis to assess whether the MPA comprises individual home ranges entirely or in part; 3. monitoring of individual movements across MPA boundaries; and 4. fishing monitoring at increasing distances from the MPA (Di Lorenzo et al., 2016). Spillover from no-take MPAs can be essential to drive the management effectiveness of adjacent multiple-use MPAs (Di Lorenzo et al., 2020), especially in the context of a MPAs network as the observed here. Furthermore, given that reef fishes are the main targets of recreational fishers, this social group is a priority to environmental information campaigns and partnership establishment aiming to support management initiatives and research on spillover process.

In view of the results presented here, MPA size, level of enforcement and open-to-visitation situation were the main attributes responsible by positive direct outcomes in the fish assemblage, with higher biomass of the main targeted fish groups, such as the Epinephelidae and Lutjanidae families. Moreover, as the MPAs network has been recently enhanced in the region, the trends of fish biomass presented here are also important baselines for future effectiveness assessments of these MPAs. This study also adds evidence that even under cumulative impacts area-based management is still a strong tool to marine conservation. We strongly suggest that local policies spheres (i.e., states and municipalities) should take the lead role on local fishery managements as well as joint efforts to require national leadership on issues which local policies are not sufficient to deal with.

## CRediT authorship contribution statement

**Fabio S. Motta:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Rodrigo L. Moura:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Leonardo M. Neves:** Formal analysis, Writing – review & editing, Visualization. **Gabriel R.S. Souza:** Investigation, Writing – review & editing. **Fernando Z. Gibran:** Methodology, Investigation, Writing – review & editing. **Carlo L. Francini:** Methodology, Investigation. **Gustavo I. Shintate:** Formal analysis, Writing – review & editing. **Fernanda A. Rolim:** Investigation, Writing – review & editing. **Marina Marconi:** Visualization, Writing – review & editing. **Vinicius J. Giglio:** Writing – review & editing. **Guilherme H. Pereira-Filho:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2021.101951.

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