Marine Policy 88 (2018) 204–212

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Evaluating the effectiveness of coastal no-take zones of the Galapagos Marine Reserve for the red spiny lobster, *Panulirus penicillatus*

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ABSTRACT

Monitoring and assessing the effectiveness of no-take zones (NTZs) is critical, not just for the effective management of marine resources, but also for informing and gaining support from community stakeholders. The Galapagos Marine Reserve (GMR) established a network of coastal NTZs in 2001, yet, to date no study has investigated their effectiveness in protecting and enabling key species to recover. Using data from the Galapagos National Park Directorate annual Lobster Population Monitoring Program from 2012 to 2014, this study evaluated the recovery of the commercially valuable red spiny lobster (*Panulirus penicillatus*) inside NTZs in the GMR. It was hypothesized that NTZs would present higher lobster abundances or sizes when compared with adjacent fished zones. However, the study found no significant differences in these comparisons. Overall the findings indicate that > 11 years of protection has had no appreciable effect on lobster abundances or sizes inside the NTZs. This paper explores possible reasons for the lack of response in NTZs, and concluded that non-compliance and shortcomings within the enforcement framework of the GMR are the key factors limiting the functionality of these NTZs. Additionally, it also evaluates the limitations of the current monitoring program and highlights the need for a more comprehensive and long-term program to be implemented. As the new zoning scheme for NTZs in the GMR that began in 2016 is still to be determined, this information should be considered by decision makers to improve the effectiveness of NTZs and sustainable management of the GRM's coastal resources.

1. Introduction

In the last four decades governments worldwide have been creating marine protected areas (MPAs) with the main goal of preserving biodiversity and populations of ecologically and/or economically important species [1–5]. No-take zones (NTZs) are MPAs, or zones within an MPA, where all types of resource extraction are prohibited, and are regarded as key tools for conservation and fisheries management [5–7]. There is now an extensive body of empirical evidence confirming the benefits of NTZs for fisheries, which include increases in abundance, biomass, average size, and spawning potential, which in turn can ultimately lead to larval and adult spill-over into adjacent fishing areas [3,8–13]. This has especially been the case for commercially important lobsters species, which have been shown to respond rapidly to protection as they have rapid growth rates, reach sexual maturity at an early age, and tend to show high degrees of site fidelity [9,12,14–17].

However, not all MPAs deliver positive ecological outcomes, often referred to as "paper parks" [5,18–20]. Many MPAs fail to meet their management objectives due to inadequate human and financial resources, ineffective enforcement, and poor acceptance by local communities [4,21,22]. According to a recent global meta-analysis study on the response of exploited fish species in MPAs [5], the five key characteristics of effective MPAs that they are: no-take, enforced, old (> 10 years), large (> 100 km^2) and isolated (based on habitat discontinuities). The majority of MPAs assessed in the study that only had one or two of these five key features showed little to no response levels among populations of commercial fish species. Furthermore, another major problem MPAs feature is that they are often created to meet unspecified conservation goals, rather than verifiable management objectives, and lack targeted monitoring programs to evaluate their

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https://doi.org/10.1016/j.marpol.2017.11.028
Received 7 September 2017; Received in revised form 25 November 2017; Accepted 27 November 2017

effectiveness [18,23,24].

Creating and managing MPAs, especially with NTZs, is costly and time-intensive [25], and often negatively perceived by local communities as they initially limit their resource extraction [26,27]. Thus, assessing the effectiveness of NTZs is critical [28,29], not only for supporting sound decision making for MPA management, but also for demonstrating long-term positive impacts on biodiversity and society [30]. For instance, evidence of positive responses of commercial fisheries can increase NTZ management legitimacy and improve stakeholder acceptance and compliance among local communities [21]. For a clearer understanding of whether protection measures work in practice, temporal trends in the recovery of exploited species should thus be evaluated [31]. Ideally, evaluation studies would use a before–after control-impact (BACI) design to obtain data from replicates in NTZs and control sites both before and after zonation [28,32].

The Galapagos Marine Reserve, created in 1998, is a multi-use MPA, covering an area of ~138,000 km^2 where industrial fishing is banned, while artisanal fishing remains permitted for ~1200 Galapagos residents [33,34]. To reduce ongoing conflict between the fishing, tourism, and conservation sectors at the time, a temporary zoning scheme, led by a consensus-based participatory process, was implemented in 2001 [35,36]. As a result of this process 22% of the coastline (that extends 2 nautical miles seawards) became designated as either conservation or tourism zones, while artisanal fishing remained permitted along the remaining coastline and open water (Fig. 1). In both the conservation and tourism zones, all types of extraction are prohibited, therefore in this study both are considered as NTZs. In total, there are 78 named NTZ sites across the GMR coastline, that range from 0.01 to 91 km^2 in size [33,34]. According to the Galapagos National Park Directorate (DPNG, initials for name in Spanish) management plan, the objective of the NTZs is to protect biodiversity, ecosystem services, and promote sustainable tourism and fishing [37]. Currently, the DPNGs management plan of the GMR has no evaluation framework in place to assess the effectiveness of its NTZs [36].

In 2015, the DPNG initiated a re-zoning scheme for the NTZ network in the GMR. Yet no published study to date has investigated the effectiveness of the 2001 NTZs to conserve biodiversity and enable populations of valuable commercial species to recover. Over 70 marine species are exploited by artisanal fishermen in the GMR [38]. Among these fisheries, some have collapsed, like the sea cucumber fishery (*Isostichopus fuscus*) in 2002 [39], others have been on the edge of collapse, e.g. lobster fishery (*Panulirus gracillis,* and *P. penicillatus*) [40] and many are being unsustainably overexploited, in particular serranids such as the regionally endemic Galapagos sailfin grouper (*Mycteroperca olfax*) [41,42]. Increasing current understanding about whether the GMR zoning of NTZs is supporting the recovery of commercially valuable and fragile fisheries is thus paramount.

The only long-term species-specific population monitoring programs across the GMR have been carried under the Monitoring of Fisheries Resources Plan [37], which for now includes sea cucumber (*Isostichopus fuscus*) and the commercial lobster species *P. penicillatus, P. gracilis* and *Scyllarides astori* [42]. Using data collected from the DPNG's Lobster Population Monitoring Program, the aim of this study was to evaluate the efficacy of the GMR's NTZs by assessing the response of the populations of spiny lobsters *P. penicillatus* inside and outside NTZs.

2. Methods

2.1. Study area

The Galapagos Archipelago is located in the Eastern Tropical Pacific, ~1200 km west of mainland Ecuador, and constitutes 13 major islands and over 100 smaller islands and islets that altogether total 1667 km of predominantly rocky coastline [43]. The abundance and distribution of marine species and habitats is strongly influenced by the convergence of three major current systems: the Peru (from the southeast), the Cromwell (from the west), and the North Equatorial (from the northeast) as well as by natural environmental variability, such as "El Niño" [44]. The only inhabited islands are Baltra, Santa Cruz, San Cristóbal, Isabela, and Floreana, where approximately 25,000 people live permanently as of 2015 [45]. As of 2016 there were 1105 fishermen with fishing-licenses and 468 vessels actively registered by the DPNG, even though only ~40% of fishermen were active full-time or part-time [46,47].

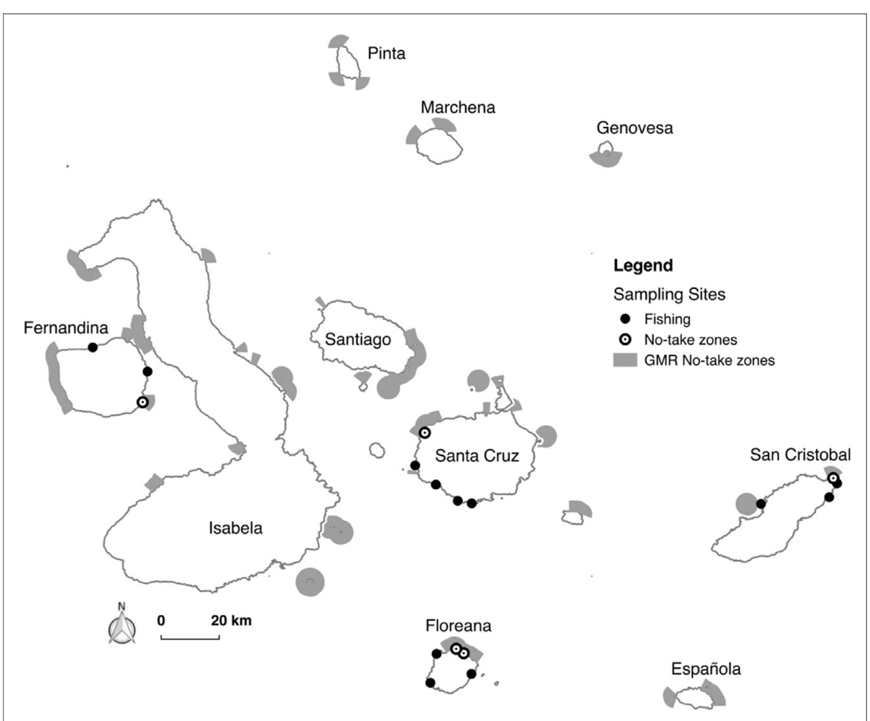

Fig. 1. Map of Galapagos Islands, excluding the far northern islands Darwin and Wolf, showing sampling sites and layer of no-take zone network implemented in 2001 (Moity, unpublished data).

Table 1
No-Take Zones (NTZ) and adjacent fishing zones sampled for *P. penicillatus* in the Galapagos Marine Reserve from 2012 to 2014.

Island	Site name	Year surveyed	Zone	Lat	Long	Size of NTZ (Km^2)
Fernandina	Punta Mangle	2013	NTZ	−0.46401	−91.39689	19.5
	Punta Gavilanez	2014	Fishing	−0.3662	−91.37739	
	Punta Espinoza	2014	Fishing	−0.29135	−91.54723	
Floreana	Las Cuevas	2012–2013	NTZ	−1.27756	−90.35254	28.9
	Punta Cormorant	2012–2013	NTZ	−1.22517	−90.42045	16.8
	La Montura	2012–2014	Fishing	−1.33048	−90.50056	
	Piedras Amarillas	2012	Fishing	−1.30308	−90.37328	
	Punta Cormorant	2014	Fishing	−1.22029	−90.42413	
San Cristobal	Punta Pitt	2012, 2014	NTZ	−0.6967	−89.25169	18.4
	Punta Pitt	2012	Fishing	−0.71267	−89.2403	
	Puerto las Tablas	2014	Fishing	−0.7556	−89.2644	
	Cerro Brujo	2012	Fishing	−0.77268	−89.46652	
Santa Cruz	El Eden	2012–2013	NTZ	−0.55611	−90.51767	47.3
	La Fe	2012–2013	Fishing	−0.76693	−90.41563	
	La Torta	2013	Fishing	−0.77475	−90.37234	
	Las Palmas	2012–2013	Fishing	−0.65798	−90.54496	
	Cerro Gallina	2012–2013	Fishing	−0.716684	−90.483367	

2.1.1. The Galapagos Spiny Lobster Fishery and P. penicillatus

Lobster fishing on the Galapagos has taken place since the archipelago was first colonized in the late 19th century (Reck 1983). During the 1960s, spiny lobster fishing transformed from subsistence to a commercial operation, becoming an export-oriented business (Murillo et al., 2012). Currently it is the most lucrative local fishery with a gross value above USD $2 million annually based on 2016 landings of red (*P. penicillatus*) and green (*P. gracilis*) spiny lobsters [48]. By the early 2000s, concerns about the overexploitation of the lobster fishery grew following reports of the absence of spiny lobsters in shallow intertidal zones, and steady decline in catches and mean lobster sizes [40]. In 2003, the DPNG implemented a moratorium restricting spiny lobster fishing to a 4-month fishing calendar, and prohibited the catch of lobsters < 26 cm in length and berried (carrying eggs) females [48]. Recent increases in lobster catch yields, improved revenues per unit effort and the apparent stabilization of fishing effort since 2012 suggest a potential recovery of the fishery [46,49]. Such positive trends are believed to be an outcome of a combination of factors, including the moratorium, climate variability, market forces, and inactivity by > 50% of licensed fishermen [47].

Globally, *P. penicillatus* is distributed across the Tropical Pacific, Indian Ocean and Red Sea [50]. Locally, this species has been reported across all the islands of the Archipelago, and is the most abundant, representing ~75% of the annual total catch [39]. Given their high commercial value, *P. penicillatus* are among the few marine species in the GMR whose life history [40,51,52] and population dynamics [49,53] are relatively well understood. In the Galapagos this species sexually matures between 4 and 5 years of age (21–22 cm), and are known to reproduce year-round, though abundance of berried females appear to be highest between January-June [54]. The maximum size *P. penicillatus* in the GMR is ~40 cm, but overall population mean size is between 24 and 26 cm [55], which used to be ~ 28–31 cm in the 1980s before the intensification of the lobster fishery [40,56]. Like in other parts of the world, Galapagos *P. penicillatus* forage mostly at night, are gregarious, prefer shallow exposed rocky reefs between 1 and 5 m in depth, and have small home ranges, as they are not known to migrate distances > 5 km [52]. Currently little is known about *P. penicillatus* larval supply, dispersal and recruitment patters within the GMR. However, given the species archipelago wide distribution and long larval duration (> 300 days) [57], it is assumed that the larval pool disperses across the entire GMR.

2.1.2. Lobster population monitoring program

In 2012, the DPNG in collaboration with local fishing co-operatives and NGOs (Charles Darwin Foundation, WWF and Conservation International) developed a participatory monitoring program to assess the state of the population of the three commercially important lobster species (*P. penicillatus, P. gracilis* and *Scyllarides astori*). The Lobster Population Monitoring Program's objective is to provide demographic indicators to inform the sustainable management of the lobster fishing industry in the GMR [55]. A secondary objective has been to evaluate the effectiveness of the provisional zoning of NTZs in the GMR in supporting the recovery of lobster populations.

Since 2012 surveys have been conducted by the DPNG and experienced lobster fishermen selected by the local fishing co-operatives accompanied by independent observers. The fishermen were selected based on the criteria that they had their fishing permits up to date, they were familiar with the monitoring sites and had boats fitted with a hookah system. Annually, ~55 sites were sampled along the rocky coastlines of Isabela, Santa Cruz, San Cristobal, Floreana, Fernandina and Española (DPNG 2016b). Sampling sites were chosen based on: (a) having a historically high catch per unit effort (CPUE), (b) being proposed by fishermen, and (c) being regularly visited by DPNG as part of other fisheries programs to maximize limited resources [46].

Table 2
Mean CPUE and length (± Standard Deviation) for *P. penicillatus* collected in surveys between 2012 and 2014 inside NTZ and fishing zone (FZ) of the Galapagos Marine Reserve.

Island	Zone	No. of sites (dives)	dive time (hrs)	No. of lobsters	Mean CPUE (ind./h dive^{-1})	Mean TL(cm)
Fernandina	NTZ	1(4)	0.7	12	19.5 (± 35.3)	30.1 (± 5.0)
	FZ	2(2)	1.9	34	10.83 (-)	28.3 (± 5.3)
Floreana	NTZ	2 (7)	6.2	135	31.0 (± 23.5)	26.0 (± 3.3)
	FZ	4 (9)	5.9	275	50.8 (± 32.1)	25.7 (± 4.2)
San Cristobal	NTZ	1 (2)	1.3	16	13.0 (-)	25.9 (± 2.5)
	FZ	3 (6)	4.7	105	23.3 (± 14.6)	25.0 (± 3.8)
Santa Cruz	NTZ	1 (5)	1.9	136	74.8 (± 19.6)	25.5 (± 3.0)
	FZ	4 (14)	9.3	357	37.6 (± 19.8)	25.1 (± 3.8)

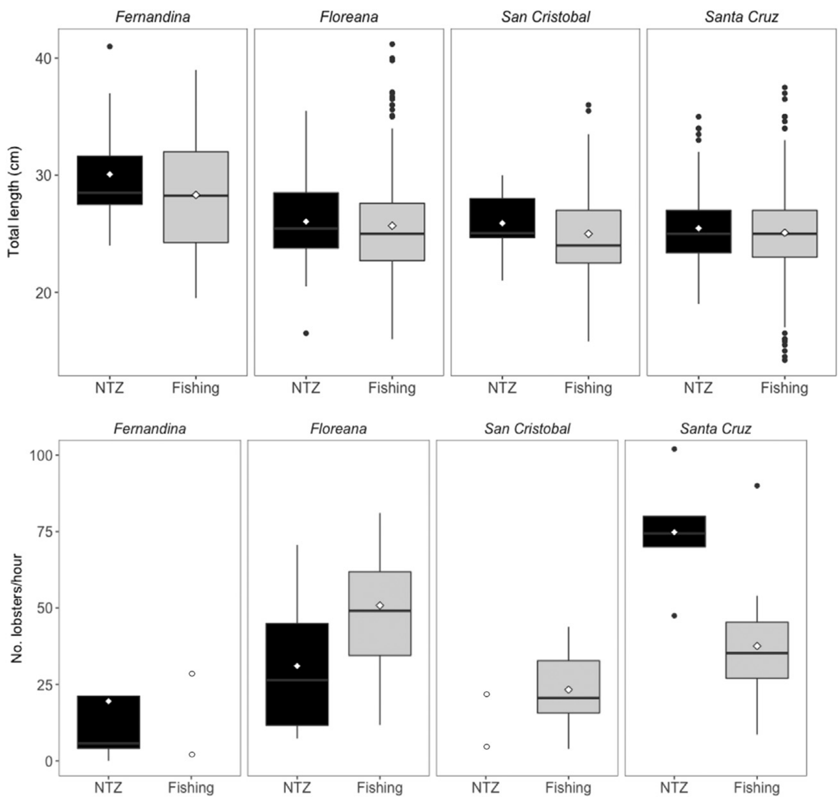

Fig. 2. Size (TL) and CPUE (No. of lobster caught/hour^{-1}) for *P. penicillatus* inside NTZs and fishing zones in the four islands of the Galapagos Marine Reserve between 2012 and 2014. Boxes plots are medians and represent data falling between the 25th and 75th percentiles, whiskers indicate data falling between the 1.5 times the interquartile range. Outliers are represented by filled circles, and means by white diamonds. At Fernandina and San Cristobal CPUEs samples size was < 3, so only data points could be added (white circles).

2.2. Data collection

Population data for *P. penicillatus* from the annual Lobster Population Monitoring Program were used, which were collected between 2012 and 2014 inside five NTZs and in adjacent fishing zones (Table 1, Fig. 1). No data were available for 2015 and 2016 as no surveys were conducted inside NTZs during those years. Sampling was conducted by fishermen on hookah dives of a maximum duration of 2 h and took place exclusively at night-time. Divers aimed to hand collect as many lobsters as possible between depths of 1–17 m. On the vessels, dive times were logged and the lobster total length (TL, cm) of cephalothorax and tail were measured and recorded. Additionally, each lobster was sexed, and the presence or absence of egg masses recorded. All individuals were then returned to their site of capture.

2.3. Data analysis

Sites were not consistently re-sampled throughout the three years (2012–2014), thus it was not possible to assess temporal changes. Consequently, data collected in different years were pooled per site after determining that CPUE and mean lengths did not vary annually (ANOVA and post-hoc Tuckey tests, $p > 0.05$). Due to the small sample sizes inside NTZs, sexes were not analysed separately, and were pooled instead. To estimate the relative abundance of lobsters among zones, CPUE was calculated based on the number of lobsters caught per diver per hour. Differences inside and outside NTZs were tested for each island. To compare CPUE between zones, two-tailed *t*-tests were employed, using a significance level of 0.05, after data was tested for normality using the Shapiro–Wilk test and homogeneity of variances using graphical methods. Differences in population mean TL between zones per island were compared employing non-parametric pairwise Mann–Whitney *U* tests, as assumptions of normality could not be met after transformation. Comparisons of TL between islands were done using Kruskal-Wallis test (non-parametric ANOVA) and Bonferroni correction for multiple comparisons. Differences in size frequency distribution between individuals collected in take and NTZ were tested with Kolmogorov–Smirnov (K-S) tests. Data analyses were done using the R core software (version 2.15.1.), and vegan 2.4-0 [58] and ggplot2 version 2.1.0 packages [59].

3. Results

Between 2012 and 2014, a total of 48 survey dives were conducted, of which 17 were inside NTZs (Table 2). Of the 1055 lobsters sampled, 467 and 587 were female and male respectively, and one was undetermined. Overall lobster TL ranged from 14.2 to 41.2 cm, and mean size ranged between 23.1 and 30.0 cm among islands, inside and outside NTZs. Fernandina had the largest mean TL, ranging from 28 to 30 cm, and were significantly larger than those recorded at the other islands, inside and outside NTZs (Kruskal-Wallis, chi-squared = 24.04, P = < 0.00). Mean TL between zones across all islands did not differ significantly (Mann–Whitney test, $P > 0.05$). The majority of lobsters sampled fell in the size ranges of 23–25.9 cm, followed by 26–28.9 cm inside and outside no take zones (Fig. 2.). At all sites, very few juvenile lobsters (> 20 cm in size) and older larger adults (> 32 cm) were caught. Comparison of population size frequency distributions inside and outside NTZs at all islands were not significantly different (KS test, $P > 0.05$).

The relative abundance of lobsters per dive varied greatly inside NTZs 5–102 ind/h) and outside 2–112 ind/h). Floreana and Santa Cruz were the only islands with sample sizes big enough for statistical comparison between zones. While at Floreana the CPUE did not significantly differ (two sample *t*-test, t value = −1.40 p-value = 0.18) between zones, it did significantly differ at Santa Cruz (two sample *t*-test, t value = 3.963, p-value = 0.002), CPUE being higher inside the NTZs.

Table 3
Literature review of published studies assessing the response of lobster species in NTZs around the world. The *Age* column represents number of years each reserve had been protected at the time of the study.

Country	Reserve	Size (Km^2)	Age	Species	Positive response inside NTZ: Abundance (x greater)	Positive response inside NTZ: Total/carapace length (cm larger)	Study
Australia	Kingston Reefs	1.45	16	*Palinurus cygnus*	Yes (~34)	yes (0.84)	Babcock et al. 2007
Australia	Tasmanian NTZs			*Jasus edwardsii*			Barret et al. 2009
	Maria I reserve	15	3		yes (4.5)	yes (2.2)	
	Tinderbox	1.4	3		yes (2)		
	Governor Island Reserve	0.6	3		No	no	
	Ninepin point	7.3	3		No	no	
Italy	Sardinia	4	8	*P. elephas*	yes (7.5)	yes (1.7 − 2)	Follesa et al. 2008
New Zealand	Tawharanui Marine Park	3.5	22	*J. edwardsii*	yes (25)	–	Shears et al. 2006
New Zealand	Various NTZs			*J. edwardsii*			Pande et al. 2008
	Cape Rodney to Okakari Point	5.2	29		Yes	yes	
	Poor Knights Islands	24	4		No	yes	
	Kapiti Island	21.7	11		Yes	yes	
	Tuhua	10.6	4		No	yes	
	Te Whanganui A Hei	8.4	9		Yes	yes	
	Te Awaatu Channel	0.9	10		Yes	yes	
	Kokomohua	6.2	11		No	yes	
	Tonga Island	18.4	14		Yes	yes	
	Te Angiangi	4.5	8		Yes	yes	
	Pohatu	2.2	3		Yes	no	
Norway	Skagerrak Coast Marine Reserves	1 − 0.5	4	*Homarus gammarus*	yes (5)	yes (> 1)	Moland at al 2013
Spain	Columbretes Reserve	44	17	*P.elephas*	yes (5–20)	yes	Goñi et al. 2008
UK	Lundy Island NTZ	3.3	8	*H. gammarus*	yes (2.13)	yes (0.8)	Davies et al. 2014
UK	Lundy Island NTZ	3.3	5	*H. gammarus*	yes (5)	yes	Hoskin et al. 2011
USA	Western Sambo Ecological Reserve	30	4	*P. argus*	Yes	–	Cox and Hunt 2005

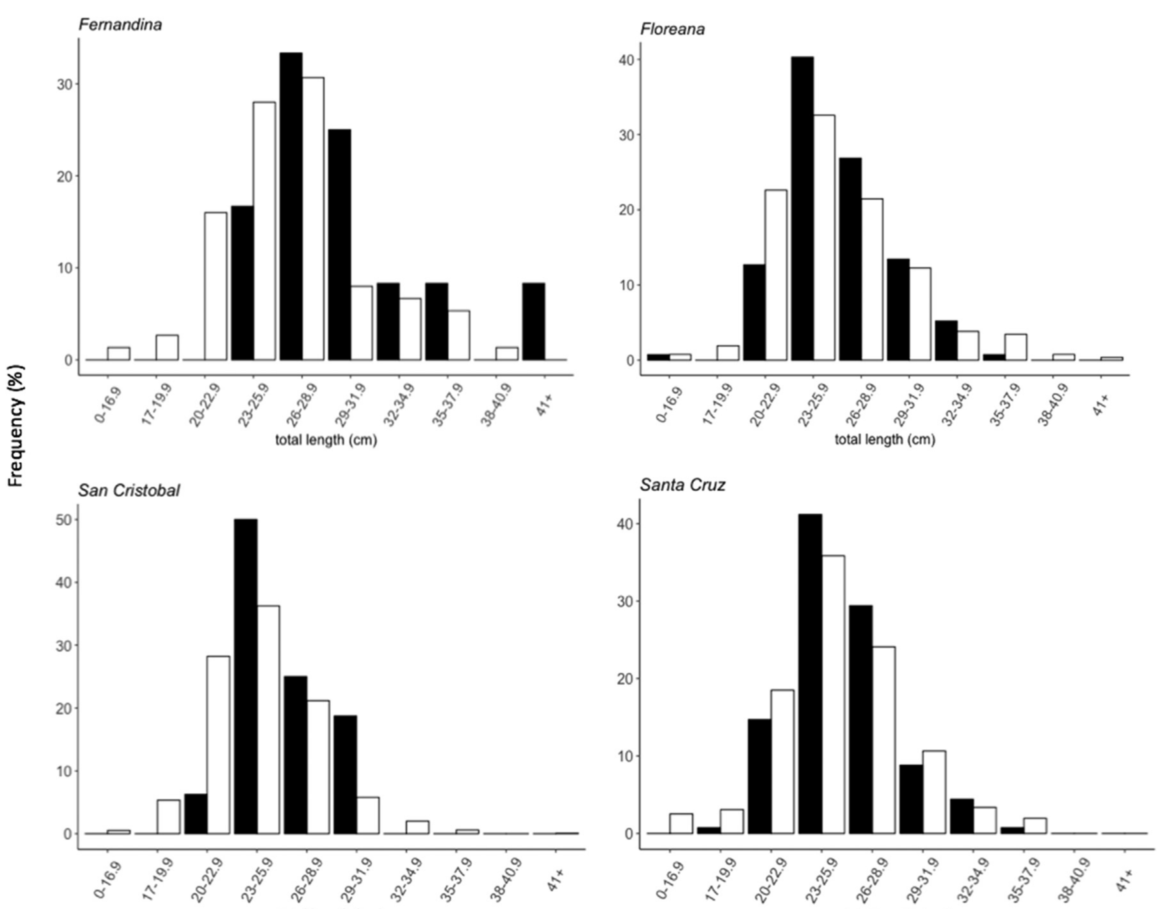

Fig. 3. Histograms of size frequency distribution of NTZs (black) and open to fishing zones (white) for *P. penicillatus* surveyed at four islands sampled in the Galapagos Marine Reserve during 2012–2014.

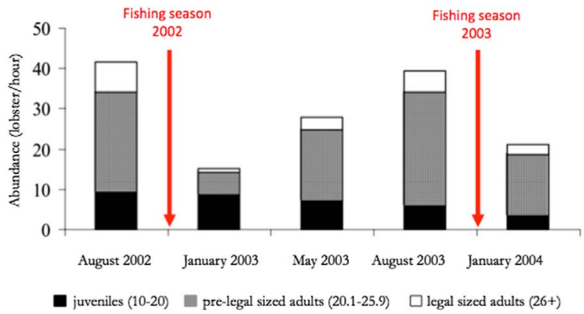

Fig. 4. CPUE (ind. hour^{-1}) of *P. penicillatus* in the site El Edén, Santa Cruz, 2002–2004, adapted from Hearn 2004.

4. Discussion

Overall this study shows that *P. penicillatus* populations inside NTZs are not responding after more than 11 years of protection. Numerous studies conducted around the world have demonstrated that lobsters respond favorably and rapidly to protection from fishing through NTZs, showing increases in abundance, average size and biomass (Table 3). Nevertheless, results of this study indicate that this has not been the case for *P. penicillatus* populations in the five NTZs in the GMR. Overall, no significant differences were found for the comparisons of TL, population size structure and CPUE of red spiny lobsters inside versus outside the NTZs, with the exception of CPUE values being higher inside the NTZ at Santa Cruz. This lack of difference is indicative of *P. penicillatus* populations not responding to the protection they received for over 11 years within the assessed NTZ.

Mean TL among *P. penicillatus* populations in both zones ranged between 25.0–26.0 cm, with the exception of Fernandina where means ranged 28.3–30.1 cm. No significant difference was found between zones at five islands. It was expected to find mean TL to be larger in most NTZs, as lack of fishing meant population mean sizes could have recovered to what they used to be (~ 28–31 cm [40,56]) over the last 11 years. Similar studies comparing mean lobsters sizes between zones found mean sized to be significantly larger inside NTZs following 4–29 years old (Table 3) [9,15,60,61]. Furthermore, many studies have found higher abundances of larger size classes in protected areas, principally those above the legal catch size [62,63], which again was not the case in the GMR based on this study (Fig. 3). Mean TL at Fernandina (28.7 cm) was significantly larger in comparison to the other three islands. Hearn [53] also found a similarly higher mean TL at Fernandina. This size difference among islands may be the product of the waters of western side of the Archipelago being more productive and thus supporting larger growth rates [64], and Fernandina being a further distance from the nearest port [65]. Nonetheless, no size differences were found between zones.

The lack of a positive response of *P. penicillatus* populations to the NTZs in the GMR could be a consequence of several factors. NTZs in the GMR easily meet two of Edgar et al's. [5] five NEOLI variables (No-take, Enforced, Old, Large, and Isolated); being no-take and > 10 years old. The features that remain unclear are whether the lack of response of *P. penicillatus* populations is a result of lobsters leaving the NTZ (system is not isolated), the NTZs are not big enough, or if there is lack of compliance.

All sampling sites took place along, coastal rocky reef slopes and walls, ideal lobster habitat, often broken up by sandy patches. However, no habitat maps have been created for the GMR coastlines to determine extent of continuous habitats within sampled sites. Given that *P. penicillatus* have small home ranges, and are not known to migrate far (< 5 km) [52], it is likely that only those residing near the boundary cross between zones. Furthermore, studies conducted in other parts of the world on lobsters (Table 3) demonstrate that positive responses can be found in NTZs that are not isolated. This suggests that habitat isolation is unlikely the reason no response was detected among lobster population inside the NTZ. However, cross boundary movements of P. *penicillatus* should be studied in the GMR's NTZ network, as it could provide information about net loss of lobsters as well as spillover patterns [66].

The NTZs assessed in this study are smaller (16–48 km^2) than the ideal size (> 100 km^2) suggested by Edgar et al. [5] (see Table 1). However, previous studies of lobster populations in NTZs that ranged from 0.5 to 21.7 km^2 in size found positive responses, (Table 3) demonstrating that well managed NTZs can be effective in supporting the recovery of lobsters. In a meta-analysis of 13 New Zealand marine reserves that ranged in size from < 1–24.5 km^2 in area, the authors found that the top three reserves in which lobsters responded the most to protection were not the largest but the oldest, as these ranked 7th, 10th, and 9th in size, and 4th, 1st, 3rd in age [12]. The authors concluded that the size of a reserve was not a significant predictor variable in explaining the variability in lobster response ratio, whilst a reserve's age was, as older reserves showed greater lobster response ratios, especially after nine years and more [12]. This suggests that the size of NTZs in the GMR is not the most likely driver behind the lack of a positive response.

On the other hand, the lack of enforcement and compliance in NTZs has been a longstanding feature troubling the management of the GMR [67,68]. Hearn [53] surveyed lobster abundances at various sites before and after the fishing season, reporting > 60% decline in *P. penicillatus* abundances in a NTZ between 2002 and 2004 after the fishing season (Fig. 4). Such a post-fishing season decline is indicative that poaching was taking place inside the NTZ. Moreover, Hearn conducted a mark-and-recapture assessment from which he reported that lobsters marked in the Eden NTZ were landed on fishing docs and were said to have been caught at sites ~10 – 20 km away from the NTZ [69]. This implies that these lobsters migrated long distances, which is unlikely given the species' small home ranges [52], or that fishers were not complying with NTZ.

Lack of clear demarcation of the zone's boundaries were used as an excuse by infringing fishers caught at the time [36]. However, after physical demarcation was completed in 2006, illegal fishing activities inside NTZs continued, often witnessed by marine researchers in the field in the GMR (Authors pers. obs.). Another issue that weakened compliance in GMR was the local fishing cooperatives never fully institutionalised the sanctioning of members who infringed the regulation of the GMR's zoning scheme [36]. NTZ's potential to support the recovery of exploited species depends largely on the strength of the fishing regulations in place and compliance [18]. Thus, the lack of response inside NTZs in the GMR may be attributed to the lack of compliance due to weak surveillance and enforcement, and lack of buy-in by the local fishing sector.

Surveillance and compliance within the GMR is the responsibility of the DPNG, in coordination with the Ecuadorian Navy, the latter being the authority responsible for arresting offenders [70]. In 2006, a vessel monitoring systems (VMS) was implemented in the GMR [37]. For a while this led to improvements in surveillance and sanctioning capacity and reduction in illegal tuna and shark fishing [36,71]. However, according to a recent analysis [72], the DPNG's surveillance and compliance system has considerably weakened over the last decade due to the financial instability of public institutions, and poorly defined legal procedures for law enforcement and systematised standard procedures in place. Major challenges include: limited manpower for patrolling, absence of a systematic plan for patrolling the reserve, lack of defined course of action and judicial procedures to address infractions, dearth of functioning patrol vessels due to a lack of adequate boat maintenance systems, lack of skilled personal and training programs to address maintenance issues, and general lack of continuous updating and training of staff [72].

Nevertheless, the GMR is one of the first MPAs to implement an automatic identification system (AIS) to track vessels less than 20 m long, such as those used by lobster fishers [72]. Once fully operational, this system could significantly increase compliance, given that it provides real time vessel coordinates, thereby helping to improve detection of infractions while reducing operation cost and number of park rangers needed for surveillance activities [70]. The full benefits of the AIS will, however, only be felt if a comprehensive legal framework is in place, in which infringements detected will lead to penalties that provide a sufficient deterrent. Additionally, it needs to ensure users will properly deploy and maintain transponders and penalize those who do not.

An unexplored explanation for the lack of response is the possibility that *P. penicillatus* population recovery was underestimated, due to populations being healthier in fishing zones than in NTZs prior to the zoning of 2001. This could only be tested with lobster population datasets before and after NTZ establishment, which do not exist. However, coastal baseline surveys of benthic communities were conducted across the archipelago between 2000 and 2001 [34]. These surveys showed that lobster densities were not significantly different among sites that were designated as NTZ and those where fishing remained allowed. Due to methodical differences, it was not possible to compare abundance data with those of this initial survey, but their study indicates spiny lobsters were present in similar densities in both zones [34].

It is important to highlight that this study's findings relied on a restricted dataset. Given that evaluating the effectiveness of the provisional NTZs was a secondary objective of the Lobster Population Monitoring Program, consistent sampling efforts within and across sites in NTZs were perhaps not prioritized. Only 5 southern sites out of the 78 NTZs established in the GMR where surveyed (Fig. 1). Lack of spatial and temporal replicates, meant data from the three years (2012–2014) had to be pooled to increase sample sizes, to enable comparative testing between zones per island. Short-comings of this study thus were the inability to evaluate annual trends and to statistically compare differences in relative abundance (CPUE) between zones for all islands. Additionally, large CPUE variability, combined with few replicates, means that the results need to be interpreted with caution. For instance, we found that mean CPUE in the Santa Cruz NTZ was twice as high as the adjacent fishing zones, potentially indicative of positive response. Nevertheless, given how extraordinarily high the mean CPUE was (> 70 lobsters/h.), it is possibly a misleading figure, apart from the small sample size (n = 5 dives), each site was often sampled by numerous fisherman, thus lobster fishing experiences could have varied, introducing bias or inconsistencies. Additionally, as *P. penicillatus* is a gregarious species, it is feasible for a fisherman to catch an unusually high number of lobsters if he encounters a large group, especially if he knows where to find them.

For future lobster population monitoring campaigns, which also seek to assess the response to protection, i.e. the effectiveness of no-take zones, it is strongly recommended that the number of sampling sites increase inside NTZs with enough replicates to ensure the acquisition of representative datasets. The same sites should also be consistently sampled yearly to enable detection of inter-annual trends. Ideally, dive sites should be selected randomly, number and length of dives standardized and all surveying fisherman be of equal experience. Alternatively, to this last suggestion, the fisherman's years of experience in lobster catching should be recorded to include as an explanatory variable. Similar methodologies were employed by Cox and Hunt [73] to evaluate a NTZ in Florida. They standardized all dives to 60 min, and dives were undertaken by a core group of 4 surveyors to reduce inconsistency.

The proposed re-zoning scheme for the GMR is a crucial opportunity for its stakeholders to set specific conservation and fisheries management goals for the proposed NTZs, with verifiable management objectives and targeted monitoring and evaluation programs. Furthermore, efforts should go towards establishing a baseline database of the new proposed NTZs that will enable the evaluation to be based on a before–after control-impact (BACI) program. Given that many of the new larger proposed NTZs are overlaying most of the original NTZ sampling sites for lobster monitoring, advantage should be taken of these historical datasets, and thus it is strongly suggested these sites remain as key sampling sites as part of future *P. penicillatus* monitoring programs.

5. Conclusions

Establishing rigorous monitoring programs to assess the effectiveness of the NTZs is critical, not just for the effective management of marine resources, but also to inform community members, which in turn can help to gain their acceptance of the MPA and its zoning. While the data of the Lobster Population Monitoring Program was restrictive for rigorous statistical analysis, this study indicates *P. penicillatus* populations are not positively responding despite being protected in the assessed NTZs since 2001. If rapidly growing and reproducing species such as *P. penicillatus* are not responding to NTZ protection, other species with slower growth and breeding rates are likely not benefiting either. There is a strong need to ensure compliance across the network of NTZs in the GMR. This will greatly depend on investing and improving current surveillance framework and instituting clearly defined legal procedures for law enforcement. The soon to be approved proposed re-zoning scheme of NTZ in the GMR, is a window of opportunity to ensure that NTZs serve their purpose of supporting the recovery of commercially exploited and endangered species.

Acknowledgements

We thank the Fishing Cooperatives and Galapagos National Park's rangers for all their support in undertaking the field work needed to collect the data for the Lobster Population Monitoring Programme. Financial support was provided by the Helmsley Charitable Trust. Suggestions made by Michael Tanner were very useful for improving this paper and the map's zoning layer made by Nicolas Moity. This publication is contribution number 2187 of the Charles Darwin Foundation for the Galapagos Islands.

Competing interests

The authors declare that they have no competing interests.

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