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research paper

Targeted education reduces marine protected area boundary encroachments: a case study from the Florida Keys

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ABSTRACT.—Compliance with marine protected area (MPA) regulations is considered a primary determinant of MPA success, though few studies have directly quantified this. The Florida Keys (USA) contain several types of MPAs that are managed by multiple state and federal agencies. The present study evaluated the use of lobster traps, relative to control areas, in two types of MPAs that protect coral reef habitat and prohibit lobster trap fishing: MPAs with marked boundaries vs MPAs with unmarked boundaries. The number of traps, trap owners, and trap location coordinates were recorded in replicate MPAs before and after an educational outreach effort to promote better recognition of trap fishing regulations in MPAs. The mean density of traps (number of traps km^{-2}) was greatest in unmarked MPAs during both pre- [40.5 (SE 7.1) traps] and posteducation [23.9 (SE 4.5) traps] surveys; however, the reduction in trap density was not significant. Traps observed in unmarked MPAs were typically distributed throughout each area. In contrast, the density of traps in marked MPAs pre- [5.4 (SE 1.47) traps] and posteducation [1.3 (SE 0.6) traps] was significantly different, and traps were mostly concentrated near MPA boundaries. The density of trap owners posteducation was reduced in both marked and unmarked MPAs; however, the reduction was only significant in marked MPAs [2.1 (SE 0.5) to 0.6 (SE 0.3)]. The results of the this research highlight the critical roles of communication and fisher behavior in the management of MPA compliance and performance.

The use of marine protected areas (MPAs) as a conservation and fisheries management tool has gained traction on a global level (Boersma and Parrish 1999, Agardy et al. 2003). MPAs are designated for a broad range of objectives, with their main purpose being to limit or exclude human activity to reduce or prevent overexploitation of marine resources (Agardy et al. 2011). With the development of MPAs continuing to rise, so are the expectations that this management tool will accrue numerous benefits for biodiversity, fisheries, and habitats. However, these benefits may not come to fruition if consideration is not given to the full spectrum of social, economic, and ecological factors that can influence MPA effectiveness (Edgar et al. 2014, Halpern 2014).

Compliance, or the ability of people to conform to rules (Hauck 2008), is considered a primary determinant of MPA success and the lack thereof is often cited as one of the main causes of MPA failure (Sutinen et al. 1990, Campbell et al. 2012, Read et al. 2015). Drivers of compliance include a broad range of ecological and socioeconomic conditions that divide stakeholders into groups that comply with or violate regulations (Sutinen et al. 1990, Pollnac et al. 2010). For example, abundance and value of target species, moral and social norms, knowledge of boundaries and applicable regulations, perceived legitimacy of rules and enforcement, and severity of penalties are all considered drivers of compliance (Kuperan and Sutinen 1998, Nielsen and Mathiesen 2003, Hauck 2008, Bergseth et al. 2015). The pervasiveness of noncompliance with MPA regulations threatens to undermine the environmental protection and potential benefits of MPAs (Jameson et al. 2002, Byers and Noonburg 2007, Read et al. 2015).

The critical role of compliance has increasingly received attention by ecosystem managers striving to understand the performance of their MPAs. Nevertheless, direct observation and quantification of compliance levels in MPAs are lacking in the scientific literature (Bergseth et al. 2015). The present study is the first to directly quantify the level and spatial patterns of compliance with MPAs that prohibit spiny lobster, *Panulirus argus* (Latreille, 1804), trap fishing by commercial spiny lobster fishers in the Florida Keys, USA. The objectives of the study were to: (1) quantify the number of lobster traps and trap owners fishing within MPAs where lobster trap fishing is prohibited and different methods of boundary identification are used; (2) examine the spatial distribution of compliance with respect to MPA boundaries; and (3) evaluate whether a targeted educational outreach effort improved compliance with MPAs prohibiting lobster trap fishing.

Methods

Site Description.—The Florida Keys are a 354-km-long island chain off the southern tip of Florida (USA) that extend from Key Biscayne to the Dry Tortugas and are encompassed by the Florida Keys National Marine Sanctuary (FKNMS). Approximately 8 km seaward of the island chain in the Atlantic Ocean lies a series of coral reefs known as the Florida Reef Tract. This easily accessible coral reef is one of the most heavily exploited ecosystems in the world, having a long history of commercial and recreational fishing (Ault et al. 2005a,b). Degradation of these coral reefs has led to the development of several MPAs that are used in conjunction with other management tools, thus resulting in an intensely government-regulated environment.

The waters surrounding the Florida Keys contain a mosaic of MPAs, managed by multiple levels of state and federal government. The MPAs evaluated in the present study include the John Pennekamp Coral Reef State Park's Lobster Exclusion Zones, Florida Keys National Marine Sanctuary's Sanctuary Preservation Areas, and the National Marine Fisheries Service's Spiny Lobster Closed Areas (Fig. 1). These MPAs share two characteristics important for the purpose of this study: (1) they protect coral reef habitat, and (2) they prohibit the use of lobster traps within their boundaries.

John Pennekamp Coral Reef State Park is located in Key Largo, one of the northernmost islands of the Florida Keys island chain. Within the marine boundaries of the park, adjacent to land, are the Pennekamp Lobster Exclusion Zones (PLEZ), established to protect coral formation areas from the impacts of both recreational and

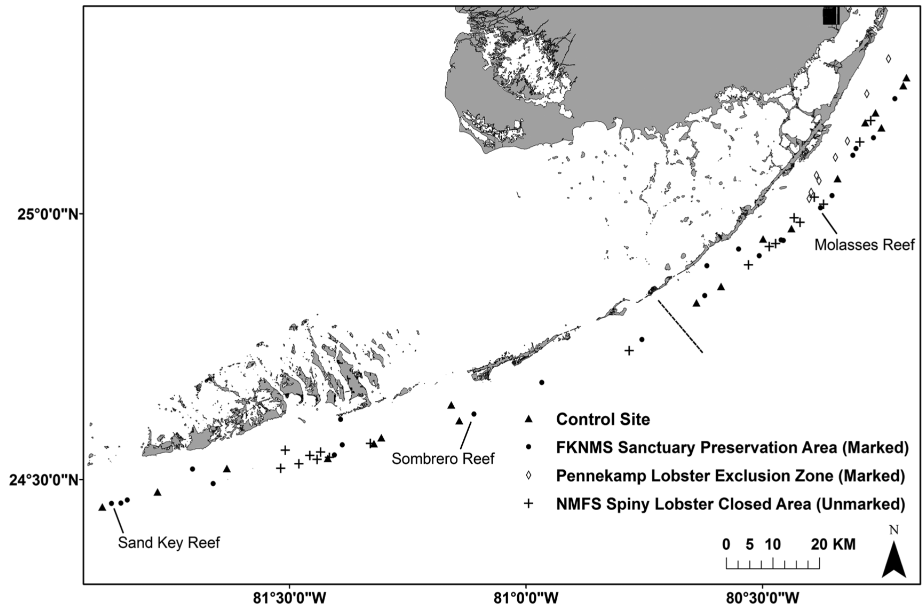

Figure 1. Map showing the locations of the areas evaluated for fisher compliance in the Florida Keys, USA. The areas evaluated included control sites that were open to lobster trap fishing (black triangle, *n* = 18), Florida Keys National Marine Sanctuary's Sanctuary Preservation Areas (black circle, *n* = 18), National Marine Fisheries Service Spiny Lobster Closed Areas (black cross, *n* = 18), and Pennekamp Lobster Exclusion Zones (white diamond, *n* = 8). The dashed line indicates the division of the study area into the Upper Keys and Middle/Lower Keys regions.

commercial lobster fishing. The PLEZs were originally established in 1993 and are managed by the Florida Division of Recreation and Parks. The original sizes and location of boundaries have since been modified and today there are eight PLEZs encompassing a total area of approximately 12 km^2. The boundaries of the PLEZs have been physically marked on the water with spar buoys since 2001, but the boundary information is not available on navigation charts.

The FKNMS' Sanctuary Preservation Areas (SPA) were established in 1997 to protect coral reef habitat and reduce conflicts between resource users (National Oceanic and Atmospheric Administration 2007). The SPAs are managed by the federal government through the National Oceanic and Atmospheric Administration's Office of National Marine Sanctuaries. There are 18 SPAs that encompass a total area of approximately 17 km^2. The boundaries of the SPAs are physically marked on the water with buoys at each corner and their boundary information is available on navigation charts.

The National Marine Fisheries Service's (NMFS) Spiny Lobster Closed Areas (SLCA) were developed in response to a biological opinion regarding the spiny lobster fishery that concluded that spiny lobster trap fishing was a risk to staghorn, *Acropora cervicornis* (Lamarck, 1816), and elkhorn, *Acropora palmata* (Lamarck, 1816), corals (National Marine Fisheries Service 2009). Both coral species are listed as threatened under the Endangered Species Act (ESA), which required NMFS to protect these species by expanding or creating new closed areas (Gulf of Mexico and South Atlantic Fishery Management Councils 2012). To meet the ESA requirements, 60 new closed areas were established in the Atlantic federal waters of the Florida Keys in 2012. They encompass a total area of approximately 15 km^2 and prohibit lobster trap fishing within their boundaries. The SLCAs were the most recently established type of MPA evaluated in the present study. They are not physically marked on the water and their boundary information is not available on navigation charts.

Sampling Design.—A stratified sampling approach was used to quantify fisher compliance with closed areas that prohibit lobster trap fishing. The sampling effort was stratified by region (Upper Keys and Middle/Lower Keys) and MPA type (SPA, SLCA, PLEZ). We sampled all SPAs in both regions (n = 9 per region), all PLEZs (n = 8), which are located only in the Upper Keys, and a randomly selected subsample of the 60 SLCAs from both regions (n = 9 per region).

Nine control sites open to lobster trap fishing that contained coral reef and hardbottom habitat were established in each region. The median size of all existing MPAs was used to select the size of control sites (0.26 km^2). The locations of control sites containing coral reef and hardbottom habitat were randomly selected in ArcGIS v10.1 using the FWC-FWRI Unified Florida Reef Map Layer v1.2, Class Lv0. Excluding nearshore hardbottom habitats, all coral reef and hardbottom habitat on the Atlantic side of the Florida Keys was selected and site locations were randomly generated within this layer. All control sites were ground-truthed prior to establishment to verify the presence of this habitat.

Data Collection.—Surveys for determining the number of traps and fishers fishing in control areas and MPAs were conducted during September 2014 and 2015, which is typically considered part of the height of the lobster season in terms of fishing effort and landings (Florida Fish and Wildlife Conservation Commission 2017). By September, all traps likely to be used during the fishing season would have been deployed, and prior to and during our surveys no winds capable of causing trap movement (*see* Lewis et al. 2009) had occurred. The purpose of the 2014 survey was to obtain baseline data on the number of traps and trap owners, whereas the purpose of the 2015 survey was to evaluate whether compliance had improved following an educational effort. Hereafter, these surveys will be referred to as preeducation (2014) or posteducation (2015). All surveys were conducted by boat and encompassed the entire MPA or control area. The number of traps and their associated trap owners identified by the fishing license number were recorded within MPAs and controls. Fisher identification was facilitated by Florida's trap-marking regulations, which require that commercial trap fishers mark each trap with a buoy that includes their fishing license number (Florida Administrative Code 68B-24). Trap location coordinates were also recorded in MPAs, but not in controls. The same methodologies were used in both years of the survey.

Educational Outreach Effort.—During the preeducation surveys, an educational outreach effort was conducted to inform fishers about the MPAs and that they prohibited lobster trap fishing. If a trap was found within the boundaries of an MPA, fishers received a courtesy notice written in English and Spanish informing them that they were fishing in an area where lobster traps were prohibited. Fishers were also provided the link to a website offering more information about the MPAs. Courtesy notices were specific to each MPA type. The courtesy notice was attached to the trap rope with a cable tie, directly above the trap buoy. This placement prevented the courtesy notice from being caught in trap haulers and allowed fishers to continue fishing their traps as normal. Coordination with the Gulf of Mexico Fishery Management Council (GMFMC) also resulted in all commercial lobster trap fishers being mailed a copy of the GMFMC's booklet, *A Guide to Closed Areas for Commercial Spiny Lobster Trap Fishing* (Gulf of Mexico Fishery Management Council 2014). This guide provided only information on the NMFS Spiny Lobster Closed Areas.

Data Analysis.—Data analyses focused on the relationship between fisher compliance and the type of MPA boundary marking (marked or unmarked). To assess differences in the number of traps and number of fishers observed within MPAs compared to controls (open fishing areas), data were analyzed by fitting generalized linear mixed models (GLMM) assuming a Poisson distribution with a log-link function using the lme4 package in the statistical software R v3.3.2 (Bates et al. 2015). Fixed effects considered during model fitting included the type of boundary marking used, also referred to as boundary type (marked, unmarked, or control), the type of survey conducted (pre- or posteducation), and the interaction between these two factors. MPA name was included as a random effect to account for repeated observations from the same MPAs between the pre- and posteducation surveys. To account for variation in trap and fisher counts due to differences in MPA size (0.05–4.68 km^2), the area of each MPA was log transformed and incorporated into the model as an offset; hence, the response variable being modeled was a rate (counts km^{-2}) instead of a raw (integer) count. For both trap and fisher count models, the full models (all terms and interactions) were considered against the null models (intercept-only). Least squares means post hoc pairwise comparison tests were conducted to determine which specific pairs of the categorical predictor variables exhibited significant differences. Pairwise comparisons were conducted using the lsmeans package in R v3.3.2 (Lenth 2016).

Trap location coordinates inside MPAs were used to calculate trap distance from MPA boundaries using the Near tool in ESRI ArcGIS v10.1. A generalized linear model (GLM) assuming a gamma distribution and an identity link function was used to examine differences in the distance of traps from the MPA boundary in relation to the area of the MPA. The main effects considered included the ratio of MPA perimeter to area (P/A ratio), type of boundary marking (marked, unmarked, or control), and the interaction between these two effects. Similar to the trap and fisher count models, the full model was considered against the null model. Lastly, trap distance from boundary distributions in marked and unmarked MPAs were also assessed for differences using a two-sample Kolmogorov-Smirnov (K-S) test.

Results

Traps in MPAs.—Lobster traps were observed in all three types of MPAs. The mean density of traps (number of traps km^{-2}) observed was greatest in the unmarked MPAs during both the pre- and posteducation surveys (Fig. 2). The percentage of MPAs with traps observed inside the boundaries decreased between the pre- and posteducation surveys; from 61.5% to 26.9% and 94.4% to 72.2% in marked and unmarked MPAs, respectively. In contrast, traps were observed in 94.4% of the control areas during both surveys. The total number of traps observed in MPAs decreased

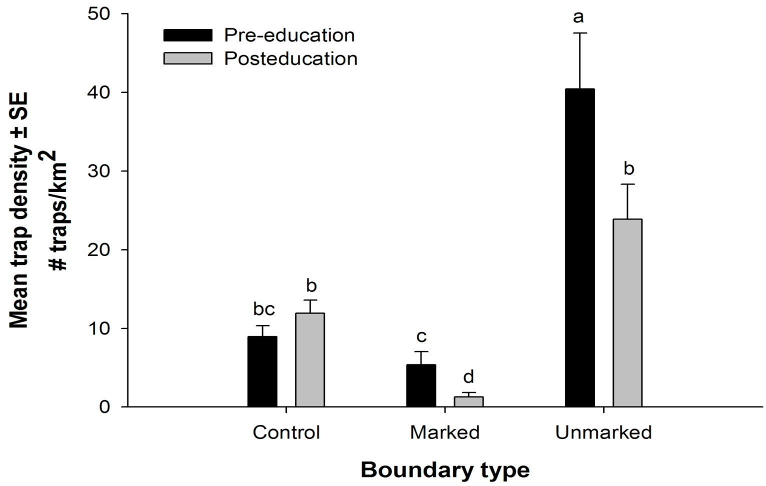

Figure 2. Mean density of spiny lobster, *Panulirus argus,* traps (SE) in terms of number of traps km^{-2} observed in each type of area evaluated for lobster trap fishing compliance preeducation (black bars) and posteducation (gray bars). Control areas (n = 18) were open to lobster trap fishing. Marked (n = 26) and unmarked (n = 18) marine protected areas refers to the presence or absence of physically marked boundaries. Bars with different letters are significantly different.

from 285 traps during the preeducation survey to 159 traps posteducation. This was equivalent to a 44.2% reduction in the number of traps following the educational outreach effort.

Results of the GLMM indicated that the density of traps observed in MPAs varied significantly based on boundary type, type of survey, and the interaction between these two parameters (Table 1). During the preeducation survey, significantly more traps were observed in control areas open to fishing and in unmarked MPAs than in marked MPAs. Significantly more traps were also observed in unmarked MPAs than controls. Posteducation, there were still significantly more traps in unmarked MPAs than marked MPAs. The density of traps observed in marked MPAs was significantly

Table 1. Results of the generalized linear mixed model evaluating the relationship of the density of lobster traps (traps km^{-2}) observed in marine protected areas (MPAs) to the fixed effects of boundary type (marked, unmarked, control) and survey type (pre- or posteducation), and the random effect of MPA name. An asterisk indicates statistically significant P-values at the $\alpha = 0.05$ level.

Parameter	Estimate	Variance	SE	z-value	P
Fixed effects					
Intercept	1.99		0.31	6.51	<0.001*
Boundary type (marked)	−1.20		0.41	−2.89	0.004*
Boundary type (unmarked)	1.34		0.41	3.26	0.001*
Survey type (posteducation)	0.29		0.20	1.41	0.159
Boundary type (marked):posteducation	−1.73		0.31	−5.59	<0.001*
Boundary type (unmarked):posteducation	−0.61		0.23	−2.62	0.009*
Random effect					
Intercept (MPA name)		1.19			

Table 2. Least squares means (LS means) pairwise post-hoc comparisons for significant predictors of the density of traps (traps km^{-2}) observed in control areas, and marked and unmarked marine protected areas (MPAs) between pre- and posteducation surveys. Pairwise estimates were back-transformed from log scale and are displayed in the response scale as the ratio of least squares means. P-values were Tukey adjusted. Only contrasts that were significant at the level of $\alpha = 0.05$ are displayed.

Contrast	LS means ratio	SE	Z-ratio	P
Preeducation				
Control, marked	3.31	1.37	2.89	0.040
Control, unmarked	0.26	0.11	−3.26	0.010
Marked, unmarked	0.08	0.03	−6.48	<0.001
Posteducation				
Control, marked	18.61	8.28	6.57	<0.001
Marked, unmarked	0.26	0.11	−8.41	<0.001
Between surveys (pre-, post-)				
Control, marked	13.96	6.30	5.83	0.001
Marked, control	0.23	0.09	−3.65	0.004
Marked, marked	4.22	0.98	6.21	<0.001
Marked, unmarked	0.11	0.04	−5.62	<0.001
Unmarked, marked	53.41	23.08	9.21	<0.001

reduced posteducation, but not in unmarked MPAs (Table 2). There also was no significant difference in the density of traps observed between control areas pre- and posteducation, nor was there a significant difference between control areas and unmarked areas posteducation.

Visual examination of trap locations inside the boundaries of MPAs indicated that traps were distributed differently in marked and unmarked MPAs (Fig. 3). A two-sample K-S test confirmed that the distributions were significantly different (D = 0.22, P < 0.0001). Traps were observed to be distributed throughout the entire area

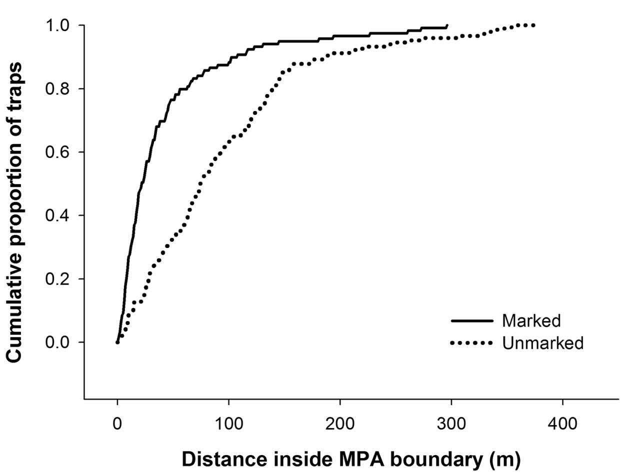

Figure 3. Cumulative proportion of traps observed as a function of the distance inside the boundaries of marine protected areas that prohibit lobster trap fishing in the Florida Keys, USA. Marked (solid line) and unmarked (dotted line) marine protected areas refers to the presence or absence physically marked boundaries. Trap distributions were significantly different between marked and unmarked marine protected areas (two-sample K-S test: D = 0.22, P < 0.0001).

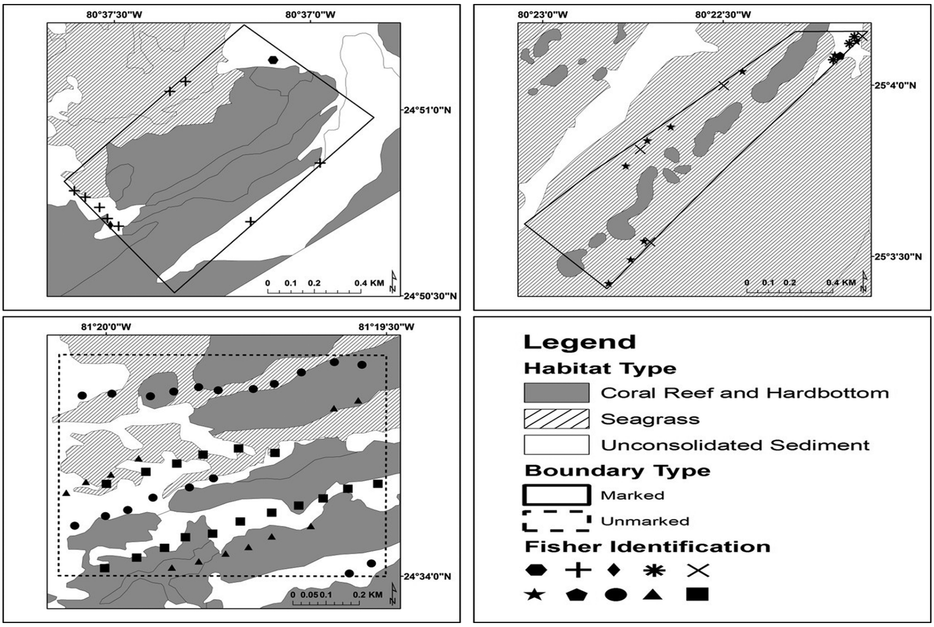

Figure 4. Locations of lobster traps observed inside the boundaries of marked (solid black line) and unmarked (dashed black line) marine protected areas that prohibit lobster trap fishing in the Florida Keys, USA. Map legend symbols correspond to individual fishers that were identified by the fishing license number indicated on each trap buoy.

of unmarked MPAs. In contrast, traps were concentrated near the boundaries of the marked MPAs, with the majority of traps (approximately 76%) observed within 50 m of the boundary. Traps were also observed in relatively straight lines regardless of the boundary type, typical of trap fishing methods used in the Florida Keys (Fig. 4). The GLM indicated that for a trap observed within an MPA, the distance to its boundary varied significantly with the P/A ratio and the type of boundary marking as shown by the significant interaction term of the model (Table 3).

Trap Fishers in MPAs.—The mean density of fishers (number of fishers km^{-2}) was greater in controls and unmarked MPAs than in marked MPAs (Fig. 5). Thirty-two fishers had traps fishing in MPAs during the preeducation surveys. Twenty fishers had traps fishing in MPAs during the posteducation surveys. Thirteen of the twenty fishers were observed during the preeducation surveys, while the remaining seven were new fishers who were not observed during the previous surveys. Traps from these seven fishers were observed only within the unmarked MPAs. The density of

Table 3. Results of the generalized linear model evaluating the relationship between the distance of lobster traps observed inside marine protected areas (MPAs) and the main effects of Perimeter to Area ratios (P/A ratio) of MPAs and boundary type (marked, unmarked, or control). An asterisk indicates statistically significant *P*-values at the α = 0.05 level.

Parameter	Estimate	SE	*t*-value	*P*
Intercept	−0.007	0.01	−1.04	0.300
P/A ratio	0.006	1.60	3.95	<0.001*
Boundary type (unmarked)	0.007	0.01	0.90	0.370
P/A ratio:Boundary type (unmarked)	−0.004	1.66	2.69	0.010*

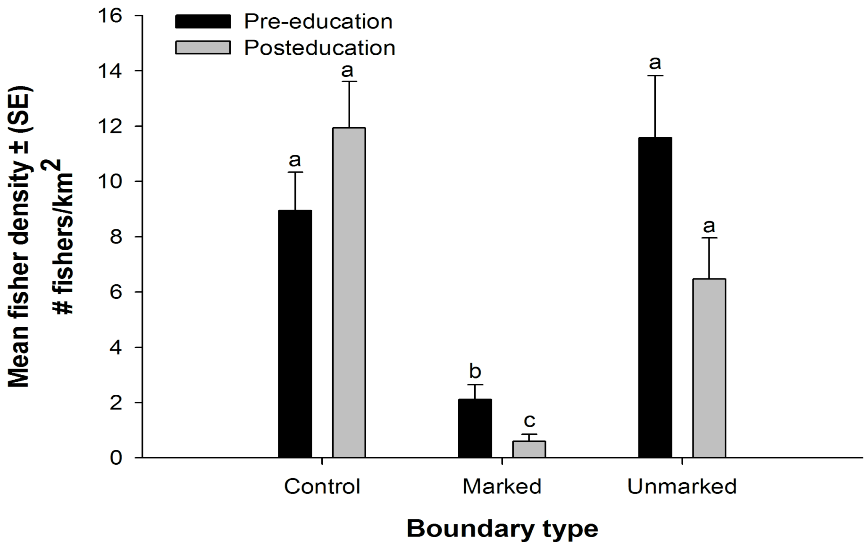

Figure 5. Mean density of fishers (trap owners) (SE) in terms of number of fishers km^{-2} observed in each type of area evaluated for lobster trap fishing compliance preeducation (black bars) and posteducation (gray bars). Control areas (n = 18) were open to lobster trap fishing. Marked (n = 26) and unmarked (n = 18) marine protected areas refers to the presence or absence of physically marked boundaries. Bars with different letters are significantly different.

fishers with traps in both marked and unmarked MPAs declined in posteducation surveys, and increased in the controls.

The GLMM indicated that the density of fishers with traps in these areas varied significantly based on the type of boundary marking and survey type as shown by the significant interaction term (Table 4). Pre- and posteducation, control areas, and unmarked MPAs had significantly more fishers fishing traps in them than marked MPAs. There was not a significant difference in the density of fishers observed among or between control areas and unmarked MPAs, both preeducation and posteducation. The density of fishers with traps in marked and unmarked MPAs declined posteducation; however, the decline was only significant in marked MPAs (Table 5).

Table 4. Results of the generalized linear mixed model evaluating the relationship of the density of fishers (fishers km^{-2}) observed in marine protected areas (MPAs) to the fixed effects of boundary type (marked, unmarked, or control) and survey type (pre- or posteducation), and the random effect of MPA name. An asterisk indicates statistically significant P-values at the α = 0.05 level.

Parameter	Estimate	Variance	SE	z-value	P
Fixed effects					
Intercept	2.04		0.24	8.67	<0.001
Boundary type (marked)	−1.74		0.33	−5.26	<0.001*
Boundary type (unmarked)	−0.06		0.34	−0.17	0.870
Survey type (posteducation)	0.29		0.20	1.41	0.160
Boundary type (marked):posteducation	−1.60		0.41	−3.89	<0.001*
Boundary type (unmarked):posteducation	−0.52		0.32	−1.64	0.100
Random effect					
Intercept (MPA name)		0.53			

Table 5. Least squares means (LS means) pairwise post-hoc comparisons for significant predictors of the density of fishers (fishers km^{-2}) whose traps were observed in control areas, and marked and unmarked marine protected areas between the pre- and posteducation surveys. Pairwise estimates were back-transformed from log scale and are displayed in the response scale as the ratio of least squares means. *P*-values were Tukey adjusted. Only contrasts that were significant at the level of $\alpha = 0.05$ are displayed.

Contrast	LS means ratio	SE	*Z*-ratio	*P*
Preeducation				
Control, marked	2.67	0.74	3.60	0.004
Marked, unmarked	0.40	0.11	−3.31	0.010
Posteducation				
Control, marked	13.30	5.03	6.84	<0.001
Marked, unmarked	0.13	0.05	−5.05	<0.001
Between surveys (pre-, post-)				
Control, marked	9.98	3.85	5.96	<0.001
Marked, control	0.28	0.74	−4.83	<0.001
Marked, marked	3.70	1.32	3.67	0.003
Unmarked, marked	9.37	3.65	5.75	<0.001

Discussion

Though the literature regarding the evaluation of MPAs is ever expanding, the majority of publications have focused on biological indicators or theoretical examinations of drivers of success rather than directly quantifying compliance (Bergseth et al. 2015). The present study is the first to directly quantify the level and spatial patterns of fisher compliance in MPAs that prohibit lobster trap fishing in the Florida Keys.

As expected, the density of traps in the unmarked MPAs was greater than that in the marked MPAs. The striking difference in the density of traps between the unmarked MPAs and the open fishing areas that served as controls was, however, unexpected. Though significantly more traps were observed in unmarked MPAs, there was not a significant difference in the density of fishers observed fishing in the controls and unmarked MPAs. In addition, there was not a significant difference in the density of traps between controls and unmarked MPAs posteducation. These observations suggest that fishers do indeed use the control areas and perhaps moved some traps from unmarked MPAs to controls posteducation; however, they may not perceive them to be as productive lobster fishing grounds as the unmarked MPAs. The controls suggest that effort in the fishery as a whole did not change between surveys, and that the reduction in the density of fishers and density of traps observed fishing in the MPAs was likely related to the educational outreach effort.

The reduction in the density of fishers observed fishing traps in MPAs posteducation was an important indicator of the effectiveness of the educational outreach effort. Though the density of fishers with traps in both marked and unmarked MPAs declined, the difference was only significant in the marked MPAs. Immediately following the placement of the courtesy notices, numerous phone calls were received from fishers expressing the concern that the courtesy notices were actually a law enforcement effort; thus, it was difficult to determine whether the motivation for removing traps from MPAs was a result of increased awareness through education, fear of law enforcement action, or perhaps some combination of the two (Alder 1996). Fishers are likely to continue fishing areas where they have fished in the past (Holland and Sutinen 2000), which might help to explain why some continued to fish in MPAs, especially the unmarked MPAs where the perceived risk of law enforcement action may be less. The seven new fishers with traps in unmarked MPAs did receive the mailing, but not the courtesy notices on their traps. The courtesy notices had to be physically removed from the traps by fishers, increasing the chances that they would read the information, whereas the mailing may or may not have been received or read by fishers. There are two important implications related to the observance of these seven new fishers with traps in the unmarked MPAs: (1) the targeted educational outreach effort of placing a courtesy notice on the trap buoy was more effective than just the mailing of *A Guide to Closed Areas for Commercial Spiny Lobster Trap Fishing* alone, and (2) continued education may be required to ensure that commercial lobster trap fishers are aware of the location of MPAs.

The spatial distribution of traps within MPA boundaries indicated the presence of an edge or boundary effect, which was particularly noticeable in marked MPAs. The significant interaction between the P/A ratio and type of boundary marking type suggests that not only the shape of the MPA, but also the presence of boundary markers influenced how far traps were fished inside MPA boundaries. Fishing within MPAs is most likely to occur near the boundary for numerous reasons, including the ease of access and exit, and accidental straying into the MPA (Kritzer 2004). This infringement can significantly affect the resources and habitats an MPA was designed to protect, and result in ecological changes along the boundaries, especially in small MPAs (Kritzer 2004, Dearden and Topelko 2006). The concentration of traps near marked MPA boundaries suggests that fishers may be using the “fishing-the-line” strategy, in which there are real or perceived benefits of spillover of fishery species and increased yield per catch (Kellner et al. 2007, Horta e Costa et al. 2013). The spatial distribution of traps inside unmarked MPAs was markedly different, with traps distributed throughout. This difference in the spatial distribution of traps is another indication that fishers were either not aware of the MPA regulations or were indifferent to them.

The drivers of compliance were not explicitly evaluated in our study, but they are worth considering in the context of marked and unmarked MPAs. The absence of physical boundary markers and boundary information on navigation charts were the two most obvious reasons for the lack of compliance in unmarked MPAs; however, it is unknown whether the noncompliance was a result of a lack of awareness or social factors. The lack of compliance in marked MPAs is likely related to the “fishing-the-line” strategy, given that the majority of traps were observed near the boundaries. Drivers of compliance, such as fisher’s perception of the fishery managers and regulations, fear of law enforcement, as well as moral and social norms, likely played a role in the level of compliance observed in our study.

The results of the present study have several MPA policy implications related to the role of compliance and MPA performance. Social factors are considered to be the main drivers of MPA success (Mascia 2003). For example, fishers’ behavior, fishing strategies common in the area, and numerous other social factors should be thoroughly evaluated and incorporated into a MPA’s design, and changes in these social factors should be included as measures of a MPA’s success. The spatial distribution of fishing effort plays a critical role in MPA effectiveness (Murawski et al. 2005). For instance, the concentration of traps near marked MPA boundaries imparts the need to consider buffer zones that incorporate into MPA design "fishing-the-line" strategies and potential non-compliance so that possible impacts to the intended protected resources are made less likely. Though compliance was greater in the marked MPAs, marking MPA boundaries provides its own challenges. Trade-offs associated with marking an MPA's boundaries—including cost and maintenance, the ability to enforce regulations, the concentration of fishing effort outside of MPAs, and possibly creation of navigational hazards—should be considered before marking MPA boundaries. The inclusion of boundary information related to fishery management closures on nautical charts is also a challenge as nautical chart manufacturers are resistant to incorporating information that is relevant to only a few hundred people. The results of our study also highlight the importance of developing clear MPA regulations that are widely accessible and the use of targeted outreach for communicating to fishers the regulations and changes in them. Future research into MPAs should further evaluate the coupled human–natural resource interactions that influence MPA performance, as a combination of multiple factors (e.g., MPA design, compliance, law enforcement, fisher behavior, etc.) rather than individual factors will ultimately determine MPA success (Edgar et al. 2014, Halpern 2014). Such research will assist policymakers in developing successful MPAs that produce the benefits sought from policy objectives.

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