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A framework to assess the health of rocky reefs linking geomorphology, community assemblage, and fish biomass

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ABSTRACT

The recovery of historic community assemblages on reefs is a primary objective for the management of marine ecosystems. Working under the overall hypothesis that, as fishing pressure increases, the abundance in upper trophic levels decreases followed by intermediate levels, we develop an index that characterizes the comparative health of rocky reefs. Using underwater visual transects to sample rocky reefs in the Gulf of California, Mexico, we sampled 147 reefs across 1200 km to test this reef health index (*IRH*). Five-indicators described 88% of the variation among the reefs along this fishing-intensity gradient: the biomass of piscivores and carnivores were positively associated with reef health; while the relative abundances of zooplanktivores, sea stars, and sea urchins, were negatively correlated with degraded reefs health. The average size of commercial macro-invertebrates and the absolute fish biomass increased significantly with increasing values of the *IRH*. Higher total fish biomass was found on reefs with complex geomorphology compared to reefs with simple geomorphology ($r^2 = 0.14$, $F = 44.05$, $P < 0.0001$) and the trophic biomass pyramid also changed, which supports the evidence of the inversion of biomass pyramids along the gradient of reefs' health. Our findings introduce a novel approach to classify the health of rocky reefs under different fishing regimes and therefore resultant community structures. Additionally, our *IRH* provides insight regarding the potential gains in total fish biomass that may result from the conservation and protection of reefs with more complex geomorphology.

1. Introduction

Humans have impacted ecosystems to such an extent that few places on Earth have escaped anthropogenic influence. Just considering marine ecosystems alone, most oceans are trawled and fished repeatedly (Halpern et al., 2008), new areas are impacted through ever-expanding fisheries (Zeller and Pauly, 2005), marine species abundance is being driven to unprecedented low levels through overfishing (Worm et al., 2006), and community assemblages are altered in diverse ways (Tegner and Dayton, 2000; Turner et al., 1999). The recovery of historic community assemblages on reefs is a primary objective for the management of marine ecosystems worldwide; both for the health of marine resources, and for the heightened economic benefits and food security of coastal communities that depend on them (Beaumont et al., 2008; Cinner et al., 2012; Newton et al., 2007).

To date, most studies of reef community recovery have focused on the monitoring of reef fish biomass and abundance of associated invertebrate populations as a proxy of the health of the reef systems. These studies have used the effect of no-take marine reserves (NTMRs) or gradients in fishing pressure (Lotze et al., 2011)

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to attempt to understand changes in fish biomass after the implementation of such reserves or along gradients of exploitation pressure (Browman, 2011; Hawkins et al., 2006; McClanahan et al., 2007; Roberts, 1995; Russ et al., 2005; Wantiez and Thollot, 1997). These studies or natural experiments demonstrate an ecological succession to the recovery of species richness: the quick, initial return of herbivorous fishes followed more slowly by the rebuilding of carnivores and piscivores. Additionally, they have shown that macro-invertebrates such as sea urchins decline concomitantly and, in many cases, calcareous algae increase to become a dominant group in the benthos. Other studies have use paired comparisons to demonstrate differences in community and food-web structures between NTMR (or areas of low fishing pressure) and open-access areas by analyzing the re-establishment of predatory interactions within the communities (Edgar et al., 2011; Edgar and Stuart-Smith, 2009; Floeter et al., 2006; Guidetti et al., 2008; Halpern, 2003; Lester and Halpern, 2008; Lester et al., 2009; McClanahan, 2011; Micheli et al., 2004; Mumby et al., 2006; Pollnac et al., 2010; Tyler et al., 2011). Some studies have correlated gradients of fishing pressure or human population size to fish biomass (Dulvy et al., 2004; Friedlander and DeMartini, 2002; Pinca et al., 2011; Sandin et al., 2008). These reveal that with a move towards healthier systems there are concurrent, significant increases in secondary productivity and ecosystem stability, and generally elevated rates of population recruitment and resilience. Finally, a last group of studies correlate gradients in fish biomass with reef community attributes, such as algal cover or sea urchin densities, using degree of fishing pressure as an explanatory variable (McClanahan et al., 2011; Mora et al., 2011; Newman et al., 2006) and show that thresholds in the community assemblage can be seen along a gradient of fish biomass in ways that can inform fisheries management (Honey et al., 2010).

All of the aforementioned studies illustrate differences in reef community assemblages and the fish biomass along a gradient of anthropogenic/fishing pressure, but due to the enormous variation in type and quality of the observations in many of these studies, direct comparison is difficult and predictive capacity for non-surveyed areas is limited (Hughes et al., 2010). For instance, a meta-analysis must account for (1) distinctions between the absolute and relative effects of a NTMR, (2) inconsistencies in protection level among NTMRs, and (3) the different ecological characteristics of NTMR and control sites (e.g., substrate rugosity, depth, current regime, etc.) (Halpern, 2003). Furthermore, most methodologies do not account for differences in fishing practices across study reefs. The common lack of baseline data in many of the studies also complicates the extrapolation of results (Sandin et al., 2008).

Here we present a general framework to describe and compare changes in the community assemblages of macro-invertebrates and fishes on rocky reefs that occur along a gradient of fishing pressure, and develop an index that characterizes the level of health of these rocky reefs, which can be compared across the gradient to understand the stages of reef community assemblages. In order to develop an approach that could be applied to rocky reefs outside our study area, we emphasized a priori five critical design considerations: (1) sampling scale must be large enough to capture biogeographic variation; (2) within different regions inside our sampling study area, reefs in protected/low fishing pressure areas that have low or zero extractive activities must exist to ensure a reliable baseline for "unimpacted"/"healthy"; (3) all reefs sampled must share similar rocky habitat characteristics in order to avoid habitat-related differences in reef community species (Sala et al., 2002); (4) two levels of geomorphologic reef structure – complex and simple – can be recognized; and (5) fishing practices are similar and typical of artisanal fishing along the region (Aburto-Oropeza et al., 2008; Sala et al., 2004).

Working under the overall hypothesis that, as fishing pressure increases, the biomass in upper trophic levels decreases followed by intermediate levels, whilst herbivores increases in relative abundance, we focused on answering five primary research questions: (1) How does the reef community as a whole vary as a function of increasing fishing pressure?; (2) what species are good indicators of reef conservation status?; (3) of these potential indicator species, what is the minimum number that can be used to assess reef health?; (4) how do these species agree with other indicators used in the literature?; and (5) how do changes of these indicators explain the absolute and relative changes of different components of these assemblages?

2. Material and methods

2.1. Reefs studied

In order to account for biogeographic patterns in species richness, we distributed the sampling effort across approximately 1200 km of latitude (10.62 degrees from the southernmost reef to the northernmost reef), covering seven regions of reefs along the Gulf of California from the southern Islas Marías archipelago to the Midriff Islands in the north (Fig. 1). The importance of properly setting historical baselines, which are defined as the condition of a given area or ecosystem prior to or in the initial stage of a human stressor (i.e. fishing pressure), is recognized as fundamental in research concerning reef community health (Edgar et al., 2004). The lack of a historical baseline makes it difficult to assess the health of a particular reef and, in many cases, compromises many of the models that test community change and reef health (Edgar et al., 2009; Jennings and Blanchard, 2004). We sampled reefs in "protected/low fishing pressure" marine areas in the region, in order to set them as baselines for this study:

Cabo Pulmo National Park is a high biodiversity area and has a large cover of coral populations settled on long basaltic dykes that run parallel to the coast. The Mexican government declared the area a Marine National Park in 1995, covering 71 km^2 of coastal and offshore reefs. After the designation, people from Cabo Pulmo town self-organized and acted collectively to pass a resolution that prohibits all commercial extractive activities throughout the park. Fish biomass inside the park has increased significantly in all trophic levels at annual rates varying between 12 and 25% and total biomass has increased by 3.49 t ha^{-1} in one decade (Aburto-Oropeza et al., 2011).

Islas Marías Archipelago is a group of four volcanic islands approximately 150 km northwest of Nayarit, Mexico. The archipelago was officially declared a biosphere reserve in 2000, however, a federal penal colony established on the largest island (Maria Madre) has been functioning since 1905 and serving as a *de facto* reserve. The island complex has therefore been consistently patrolled by the Mexican Navy, limiting access to vessels unrelated to the operation of the facility to 15 nautical miles offshore. Although precise catch data is not available, the surrounding waters of the islands are lightly exposed to anthropogenic pressures from hook and line fishing by the prison inmates. Nevertheless, this fishing pressure on nearshore reefs is considered low by comparison to the rest of the Gulf of California (Erisman et al., 2011).

With the exception of reefs in Cabo Pulmo and Islas Marias regions, all the other surveyed reefs allow fishing activities and thus were placed in one of two categories: (1) MPAs, reefs that are inside one of the other five Marine Protected Areas in the region but are under unregulated fishing pressure or those lacking enforcement (Rife et al., 2012); and (2) open access, reefs that do not have any protection and receive consistent fishing pressure throughout the year.