Journal: https://besjournals.onlinelibrary.wiley.com/journal/2041210x

A Scalable and Normalized Reef Status Index for Assessing Fishing Pressure Reveals Conservation Gaps

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**Abstract**

1. Mitigating the overexploitation of marine habitats due to intensive fishing is crucial for ensuring the sustainability of coastal livelihoods globally. Although various conservation measures have been implemented to regulate or prohibit fishing activities, their efficacy varies.

2. To address this issue, we introduce the Normalized Reef Status Index (NRSI), a tool designed for rapid, standardized, and scalable assessments of fishing pressure on fish communities.

3. Given that human activities predictably "fish down" the food web, thereby disrupting trophic structures, the NRSI quantifies the extent to which these trophic pyramids are affected by fishing.

4. We applied the NRSI to 346 reefs in the Mexican Pacific to evaluate their status. Our findings indicate that only reefs within Fully Protected areas exhibit a trophic structure resembling a concave shape, which is indicative of low harvesting pressure. In contrast, most reefs scored below average, characterized by the absence or inconsistent presence of apex predators.

5. The depletion of marine resources poses a direct threat to coastal livelihoods and food security, but also jeopardizes the overall balance of marine ecosystems, upon which global ecological dynamics depend.

**Keywords:** Overfishing, Trophic pyramids, Marine Protected Areas, Ecosystem health, Human pressure, fishing management

**Introduction**

The overexploitation of marine habitats by fisheries poses a significant threat to both the livelihoods of coastal communities and the ecological balance of the oceans, with broader implications for ecosystem services (Jackson, 2001; Link & Watson, 2019; MacNeil et al., 2015; Srinivasan et al., 2010). To mitigate this overexploitation, various strategies such as fishery restrictions, management tools, and area-based protection measures—including marine reserves and fishing exclusion zones—have been implemented (Dinerstein et al., 2019; Grorud-Colvert et al., 2021; Sala & Giakoumi, 2017; Sala et al., 2021). However, the efficacy of these interventions varies considerably and thus, protection measures should be better contextualized to increase their efficiency and enhance conservation outputs (Edgar et al., 2014; Grorud-Colvert et al., 2021; McClanahan et al., 2006). Consequently, demand for tools that can provide standardized and replicable assessments of fishery conservation efforts is increasing (Rogers et al., 2022).

Fishing activities exert a predominant influence on fish community structures, necessitating effective monitoring methods. Visual census surveys have been widely accepted, non-destructive tool for this purpose (Rogers et al., 2022). These surveys yield direct ecological metrics such as fish richness, abundance, and biomass. However, it has become increasingly clear that relying solely on basic metrics like fish biomass is insufficient for comprehensively assessing reef status, given the multifaceted nature of ecological disruptions affecting fish communities (Ramírez-Ortiz et al., 2020). Therefore, a diverse array of indicators has been developed to depict reef conditions more accurately. These include multivariate indices (Aburto-Oropeza et al., 2015; Díaz-Pérez et al., 2016), functional diversity metrics (Streit & Bellwood, 2022), and the disaggregation of biomass into distinct trophic levels (Graham et al., 2017). The latter approach is particularly relevant in the context of the "fishing down" effect, wherein fisheries disproportionately target larger fish species, thereby altering the natural trophic structure of the reefs (Sala et al., 2004; Edwards et al., 2014; Graham et al., 2017).

The concept of "fishing down" refers to the human-induced preferential targeting of specific trophic levels, thereby disrupting the natural distribution of biomass across these levels by substituting lost species with alternative organisms within the trophic pyramid (Darimont et al., 2015; McClanahan & Muthiga, 2016; Pauly et al., 1998). This substitution phenomenon underscores the limitations of relying solely on overall biomass as an indicator of reef health (Ramírez-Ortiz et al., 2020). In scenarios where fishers do not selectively target higher trophic levels, a concave trophic distribution tends to emerge (Favoretto et al., 2020; Graham et al., 2017; Woodson et al., 2018). Such a distribution signifies a more direct energetic linkage between lower and upper trophic levels, representing a system of enhanced energy efficiency from an ecological perspective. Consequently, analysing the shape of the fish trophic pyramid serves as a valuable metric for assessing the status of reefs in relation to fishing pressure (Graham et al., 2017).

In this study, we introduce the Normalized Reef Status Index (NRSI), which was designed to be rapid, scalable, and standardized in assessing marine rocky reef status. The NRSI is constructed to facilitate comparisons across spatial and temporal scales, as well as to account for varying levels of protection and management practices affecting reefs. The novelty of the index is the capability of summarizing the trophic composition within the reefs in such a way that can easily be integrated into further and more holistic assessments (e.g. Seguin et al., 2023). Indices such as the NRSI serve as critical instruments for informing governmental bodies and stakeholders about the status of reefs, thereby providing a basis to hold them accountable for any inaction.

**Materials and Methods**

*Reef fish surveys*

Fish data have been systematically collected since 1998 across 346 reefs using SCUBA-assisted underwater visual belt transect surveys, following standardized methodologies (Aburto-Oropeza et al., 2015; Favoretto et al., 2017, 2020; Ulate et al., 2016, 2018) (Fig. 1). Prior to conducting the surveys, each diver underwent specialized training in in situ species identification as well as size and distance estimation techniques. At each survey site, two-person diving teams executed 50-meter transects: one observer focused on recording fish data, while the other documented epibenthic macroinvertebrates (hereafter referred to as "invertebrates"). Within each site, a total of eight transects were conducted—four at a depth of 20 meters and four at a depth of 5 meters. During each transect, divers counted and estimated the sizes of all fish within a five-meter-wide belt, covering a total area of 250 m2, across two passes. Different behavioral groups, namely mobile and territorial species, were surveyed in separate passes to ensure accurate counts. All invertebrates were enumerated and identified along 30-meter transects within a one-meter-wide belt, covering an area of 30 m2.

Fish total lengths were estimated to the nearest centimeter and subsequently converted to body weights. The biomass of individual fish was calculated using the allometric length-weight conversion formula W = aTLb where parameters a and b are species-specific constants, TL is the total length in cm, and W is weight in grams. Length-weight fitting parameters were sourced from FishBase (Froese & Pauly, 2000). Biomass estimates by species were then derived by multiplying individual weights with numerical densities, with the results converted to tons per hectare.

*Management level assessment*

Each reef location was spatially intersected with the official Marine Protected Area (MPA) shapefile provided by the National Commission of Natural Protected Areas in Mexico (CONANP, 2020). All relevant management plans were meticulously reviewed to ascertain the specific management regulations implemented within each area. Subsequently, these management levels were categorized into four distinct groups, as delineated by the MPA guide (Grorud-Colvert et al., 2021). It is important to note that fishing refuges were treated as a separate category. Unlike MPAs, fishing refuges are designed to exclude fishing activities but serve objectives and purposes that differ from those of traditional marine protected areas. These fishing refuges were established in the Gulf of California in 2012 and have been consistently monitored using the same standardized methodologies applied to the other reef locations (Mascareñas-Osorio et al., 2015).

*Normalized Reef Status Index*

The first step in the analysis involves calculating the relative fish biomass across different trophic levels. Specifically, the biomass of fish belonging to Apex Trophic Levels (ATL), which are situated at both the bottom (2-2.5) and top (4-4.5) of the trophic pyramid (as depicted in Fig. 2), is summed separately from that of the Central Trophic Levels (CTL, encompassing 2.5-3, 3-3.5, and 3.5-4). Subsequently, the ratio between the ATL and CTL relative biomass is computed to represent the tendency toward a concave trophic pyramid. The final step in the index calculation involves normalization, which constrains the index value within an interval range of -1 to 1. The formula for the Normalized Reef Status Index (NRSI) is as follows:

(1)

The NRSI lower bound of -1 denotes a 'very poor' status, indicative of ecosystems that are significantly degraded or under substantial stress. Conversely, the upper bound of 1 corresponds to a 'very good' category, reflecting ecosystems that are in a relatively pristine or undisturbed state. The continuous scale of the NRSI can be discretized into categorical levels by designating breaks: Very poor = '[-1,-0.75]', Poor = '[-0.75,-0.25]', Fair = '[-0.25, 0.25]', Good = '[0.25,0.75]', Very good = '[0.75,1]'. However, creating categorical levels can be somewhat arbitrary and while it is powerful in communicating overall status, the use of continuous NRSI index is advised for a more nuanced interpretation.

To capture temporal variations in the Normalized Reef Status Index (NRSI), we employed a locally estimated scatterplot smoothing (LOESS) curve. Additionally, a linear model was fitted to the NRSI values over time for each individual reef. To assess the impact of different management levels on NRSI, a separate linear model was estimated using maximum likelihood (ML) methods. Standardized parameters were derived by fitting the model to a standardized version of the dataset. Statistical significance was evaluated through the computation of 95% Confidence Intervals (CIs) and p-values, which were obtained using a Wald t-distribution approximation.

**Results**

Of the 346 reefs surveyed 133 reefs are Not Protected, 135 are Lightly Protected, 15 are fishing refuge, and 63 are Fully Protected. The effect of Lightly Protected areas on the NRSI is statistically significant and negative (beta = -0.05, 95% CI [-0.10, -6.41e-03], t(1409) = -2.22, *p* = 0.026; Std. beta = -0.13, 95% CI [-0.25, -0.02]). The effect of Fishing Refuge is statistically non-significant and positive (beta = 9.14e-03, 95% CI [-0.09, 0.11], t(1409) = 0.19, *p* = 0.853; Std. beta = 0.02, 95% CI [-0.21, 0.25]). The effect of Fully Protected areas is statistically significant and positive (beta = 0.38, 95% CI [0.32, 0.43], t(1409) = 12.91, *p* < 0.001; Std. beta = 0.91, 95% CI [0.77, 1.04]). Over time, only sites form Fully Protected areas showed an average NRSI trend above zero (Fig. 4). Within each protection level, 83% of the sites within Fully Protected areas showed an increase in their NRSI value (i.e., a positive slope obtained by fitting a linear model), as did 70% of the reefs within Fishing Refuges, 55% within Lightly Protected, and 56% within Not Protected. However, none of these slopes were significant (*p* > 0.05).

**Discussion**

The Normalized Reef Status Index (NRSI) offers a rapid, standardized, and scalable methodology for assessing the fishing pressure exerted on fish communities. The index is predicated on the well-documented phenomenon of "fishing down," wherein humans disproportionately target larger fish, thereby disrupting natural trophic structures (Pauly et al., 1998; Sala et al., 2004). Consequently, the NRSI is sensitive to the removal of apex predators and the ensuing cascading effects on reef ecosystems (Graham et al., 2017; Pauly et al., 1998; Sala et al., 2004).

Marine protected areas in the Gulf of California have largely underperformed, failing to mitigate the ongoing overexploitation that has persisted for several decades (Rife et al., 2013a; Sala et al., 2004; Ulate et al., 2018). The urgency for implementing more robust and effective conservation measures is accentuated by these failures. This problem is not isolated to the Gulf of California but is indicative of a global trend, as mounting evidence points to the necessity for more dynamic and adaptive forms of protection to mitigate ocean overexploitation (Sala et al., 2018). The notable exception is Cabo Pulmo National Park, which currently boasts the highest NRSI alongside the remote Revillagigedo Archipelago (Aburto-Oropeza et al., 2011) within the Fully Protected category (Fig. 4). Our findings corroborate that areas prohibiting fishing activities outperform Lightly Protected marine reserves that permit fishing within their boundaries (Fig. 3,4). Fishing refuges, established circa 2009, have also shown no significant impact and, due to the absence of older baseline data for direct comparison, their effectiveness remains inconclusive. However, no significant recovery has been observed over a seven-year period (Fig. 4), and fishing refuges exhibit no discernible differences in NRSI compared to Open Areas (Fig. 3).

The evidence strongly advocates for the strengthening of conservation measures across the rocky reefs of the Mexican Pacific. Areas that completely prohibit fishing activities, particularly if they are either remote or well-designed, have demonstrated significant potential for fish community recovery (Aburto-Oropeza et al., 2011; Edgar et al., 2014; Rife et al., 2013b; Ulate et al., 2018). The NRSI serves as an accessible, scalable tool for assessing reef conditions that reflect trophic structure across both time and space. Its continuous application represents an asset for enhancing marine conservation efforts.

If an assessment of a marine habitat objective centers on fishery pressure, relying solely on biomass as an indicator is insufficient. Targeting specific trophic levels can induce cascading effects that may paradoxically result in increased biomass measurements over time. For instance, Lightly Protected areas in the Gulf of California have experienced biomass increases in recent years; however, this does not necessarily signify an improvement in reef functionality (Ramírez-Ortiz et al., 2020; Rife, et al., 2013b).

While no single metric can comprehensively capture all facets of a reef's ecological status, the NRSI can be integrated with other indicators, by being rapid, scalable, and standardized in assessing marine rocky reef status. The NRSI facilitate normalized comparisons across spatial and temporal scales, levels of protection and management practices affecting reefs. The NRSI can incorporate the trophic composition within the reefs in such a way that can easily be integrated into further and more holistic assessments (e.g. Seguin et al., 2023). The NRSI should serve as an informative tool for stakeholders and marine protected area managers, aiding in the adaptation of management practices or the strengthening of protection measures.

**Acknowledgments**

We wish to thank the research teams that have monitored the Gulf of California’s rocky reefs over the past two decades providing important data, particularly, Ismael Mascareñas-Osorio, Benigno Guerrero-Martinez, and José Cota-Nieto, from the Centro para la Biodiversidad Marina y la Conservación, A.C. We acknowledge the students who have also participated in these monitoring campaigns. Monitoring has been made possible through the support of many groups and individuals, special thanks to the International Community Foundation, the David and Lucile Packard Foundation, and National Geographic Pristine Seas.

**Author Contributions:** Fabio Favoretto and Octavio Aburto-Oropeza conceptualized and planned the experiment; Fabio Favoretto and Eduardo León-Solórzano analyzed the data; Fabio Favoretto, Catalina López-Sagástegui, and Eduardo León-Solórzano drafted the manuscript, Catalina López-Sagástegui, Eduardo León-Solórzano, and Octavio Aburto-Oropeza reviewed the manuscript.

**Competing Interest Statement:** We have no conflict of interest to disclose.

**Classification:** Biological sciences, Ecology

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**Figures and Tables**

**A map of a large area

Description automatically generated**

**Figure 1.** Reefs sites part of the study coloured according to their level of protection (Grorud-Colvert et al., 2021).

A picture containing icon

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**Figure 2.** This study uses a conceptual diagram of the trophic pyramid framework (Graham et al., 2017; Woodson et al., 2018) behind the Normalized Reef Status Index (NRSI).

Chart

Description automatically generated

**Figure 3.** Distribution of the Normalized Reef Status Index (NRSI) values for each reef groped by four current management levels [according to (Grorud-Colvert et al., 2021)]. The black vertical line represents a fair intermediate value for the index, and the dashed red vertical line represents the median distribution of all NRSI values for each group. Negative values mean a poor reef status, whereas positive values mean a high reef status (i.e., with large predators and trophic pyramids with a tendency to be concave).

Graphical user interface, chart, application

Description automatically generated

**Figure 4.** Temporal variation of each of the reefs surveyed grouped four current management levels [according to (Grorud-Colvert et al., 2021)]. Each dot is a reef, colored according to the Normalized Reef Status Index (NRSI) value and categorized into five qualitative categories. The horizontal dashed line represents a fair value of the reef as a reference. All the points above have a positive status, whereas all points below have a negative one. The black line is a locally estimated scatterplot smoothing (LOESS) curve that represents the average tendency of the NRSI for each management level.