A general approach and tool to evaluate the effectiveness of no-take marine reserves

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Abstract

Marine reserves are often implemented to preserve habitat and recover overfished stocks. To date, the evaluation of the reserves relies solely on biological data, ignoring socioeconomic and governance dimensions. In absence of a standardized methodology, existing data is analyzed in different ways, hindering the ability to compare results across communities. We developed a framework to evaluate the effectiveness of the reserves by matching 7 commonly stated management objectives to a set of 9 biophysical, 5 socioeconomic, and 14 governance indicators. This framework includes a standardized survey to collect governance and socioeconomic data. Biophysical indicators are evaluated with a Difference-in-Difference analysis, estimating the net effect of the reserve through time. Linear regression models are fitted to socioeconomic indicators through time, testing for the difference in trends before and after the implementation of the reserve. Governance indicators are analyzed based on literature, identifying common governance structures and their associated effectiveness. To make the framework accessible to fishers and decision makers, and allow replication of results, we developed an open source application. The results produced by the application contain a report for a general audience, and a technical report that can inform the renewal and decision-making process.

Introduction

Overfishing and unsustainable fishing practices are some of the major threats to the conservation of marine ecosystems around the world [1,2]. Marine Protected Areas (MPAs) are frequently proposed as fishery management and conservation tools to help fish stocks rebound [3,4] by limitting or restricting fishing effort and gears. No-take marine reserves (marine reserves hereinafter) are a particular type of MPAs, where all fishing effort and extractive activities are off-limits or highly limited. The International Union for the Conservation of

Nature [6] categorizes them as Ia (Strict Natural Reserves) or Ib (Wilderness Area). However, see [7] for a detailed regulation-based classification system.

MPAs have proven to increase biomass [4,8], enhance resilience of the bounded region [9], and preserve genetic diversity [10]. Compared to partially protected MPAs, marine reserves are known to have even higher levels of biomass, density, richness, and larger organisms [3]. Often, these effects are meassured as biological changes in the area through time and often lack a control site against which to compare [11]. This before-after comparison leaves aside other factors for which one must control [12], impeding us to talk about causation with complete certainty. While some studies have used control sites, their analyses do not estimate the net effect of the reserve, and often use a control-impact comparison approach [4,8,13,14]. A smaller fraction of studies use measurements of some biological atribute of a reserve and control sites before and after the implementation of the reserves, thus having a before-after-control-impact design [4,15,16], allowing them to use causal inference techniques to estimate the net effect of the reserve.

The diversity of approaches used to evaluate the effect of protected areas highlights the need to standardize approaches that enable us to truly evaluate the effect of protection. Though biophysical aspects are important to reserve success, the effectiveness of reserves also depends on the socioeconomic status and governance system of the local fishing community [17,18], dimensions largely ignored until recently. Currently, the only the IUCN framework [19,20] provides a comprehensive list of biophysical, socioeconomic, and governance indicators, and insight into how these indicators may be measured. However, it does not expand on how to analyze them, nor provide a user-friendly tool that enable replicability ans scalability of the analysis.

Open science and the development of tools have become ingreasingly popular to make science scalable and reproducible [21]. The Ocean Health Index [22,23], for example, has succesfully standardized a way to measure the health and benefits of the oceans. This has been succesfuly implemented at global scales, but also at country-level [24], and regional scales [25,26]. Open access tools are not limited to conservation, and have also been developed to evaluate fishery performance indicators [27], design territorial use rights for fisheries [28], or to improve decision making in the hydropower industry [29], among others.

The lack of a comprehensive framework -or the complexity of existing ones, which alienate non-experts- and user-friendly tools to evaluate the effectiveness of marine reserves calls for the development of a new framework and tool. Here, we present a framework to evaluate no-take marine reserves, which incorporates the biological, socioeconomic, and governance dimensions of these conservation areas. We provide a list of commonly stated management objectives, and match them to appropriate indicators that meassure the effectiveness of the management intervention. We include a simple approach to analyze these indicators, building on causal inference techniques [15], largely needed to truly understand the effect of management interventions [30]. At the same time, we introduce the Marine Reserve Evaluation App (MAREA), an open source web-based tool that automates the framework described in this paper. Case studies from three regions of Mexico are presented as proof of concept of the app.

Materials and methods

Here, we describe the proposed framework to evaluate the effectiveness of marine reserves (**Fig. 1**). We explain how management objectives were identified and matched to appropriate indicators that allow the evaluation of the reserves, and provide guidelines on data collection and formating. Alongside, methodologies to analyze these indicators are presented. Then, we describe the development of MAREA and provide guidance on how to use this user-friendly open access tool. Finally, we provide guidelines on how to interpret the results and output generated by MAREA.

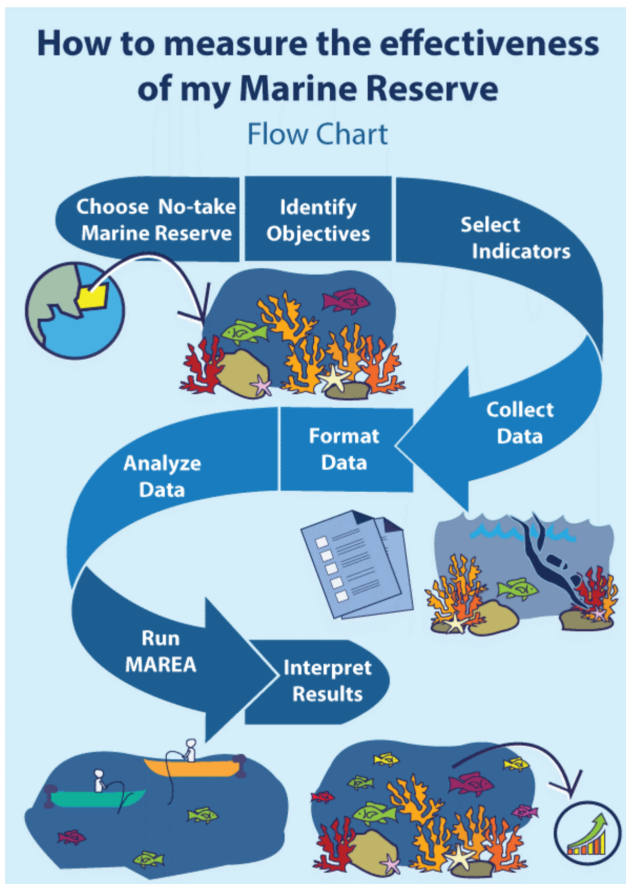

Figure 1: Workflow to evaluate the effectiveness of no-take marine reserves.

Reserve objectives and indicators

Throughout this work, we will refer to the stated goals for which a reserve has been established as objectives. Given that this work was motivated by the need to provide a framework to evaluate mexican marine reserves, we focused on identifying objectives of Mexican marine reserves. However, we group these objectives into seven major categories, which can be applied to other conservation areas in the world. The list of objectives was gathered through a literature review from the reserves' stated objectives in official documents such as the Technical Justification Studies (*Estudios Tecnicos Justificativos*), agreements, decrees, and specific legislation [31]. Even though each reserve -or set of reserves- has its own goals, seven main categories of objectives were identified:

1. Avoid overexploitation
2. Conserve species under a special protection regime
3. Maintain biological process (reproduction, recruitment, growth, feeding)
4. Improve fishery production in nearby waters
5. Preserve biological diversity and the ecosystem
6. Recover overexploited species
7. Recover species of economic interest

Based on these seven objectives, we determined a set of indicators to evaluate the effectiveness. The list of indicators was built through a review of scientific literature, where we identified indicators that were used to measure similar objectives. A first filter eliminated indicators for which baseline data does not exist, or for which data aquisition was expensive or outside of the general scope. The initial list of indicators was reviewed at a workshop with participation of members from Mexican fishery management agencies and non-government organizations. Later, these were also presented to fishers from the Ensenada Fishing Cooperative (*S.C.P.P. Ensenada*), which provided input. Our final list of indicators includes, at least, those identified in review works such as [4] or [32].

Indicators are divided into three main types: biophysical, socioeconomic, and governance. Biophysical indicators (n = 7) focus on fish and invertebrate communities that are evaluated using underwater ecological surveys performed inside and outside the reserve (see Data section for specific sampling design and methodologies). Socioeconomic indicators (n = 3) reflect the performance of the fishery in terms of catches, income from catches and availability of alternative livelihoods. Governance indicators (n = 15) describe the governance structures under which the community operates. These indicators may be numeric (*e.g.* Fish biomass) or descriptive (*e.g.* Reasoning for reserve location). Our list includes indicators that respond to the implementation of the reserve (*i.e.* outcome variables) or that might further the understanding of its performance. In that sense, most biophysical and socioeconomic indicators are outcome variables, while governance indicators might explain poor reserve performance, for example. Whenever an indicator is said to also be applied to "Objective Species", it means that the indicator will be used for all species (*e.g.* Fish Biomass) and individual species that are either the conservation target of the reserve, or are of particular economic or ecological interest (*e.g.* Grouper Biomass). **Table 1** presents the proposed indicators. **Table 2** shows how objectives are matched with indicators.

Table 1: List of indicators to evaluate the effectiveness of no-take marine reserves, grouped by type. Type of data and units are provided.

Code	Indicator	Data type	Unit
Biophysical			
B1	Shannon diversity index	Continuous	
B2	Species richness	Discrete	Number of species / transect
B3	Density of mature organisms	Continuous	Percent points
B4	Density*	Continuous	Organisms/transect
B5	Natural Disturbance	Descriptive	
B6	Mean Trophic Level	Continuous	
B7	Biomass*	Continuous	kg/transect
Socioeconomic			
S1	Total landings*	Continuous	kg
S2	Income from total landings*	Continuous	$
S3	Alternative economic opportunities	Ordinal	
Governance			
G1	Access to the fishery	Categorical	
G2	Number of fishers	Discrete	
G3	Legal recognition of reserve	Binary	
G4	Reserve type	Descriptive	
G5	Illegal harvesting	Ordinal	
G6	Management plan	Binary	
G7	Reserve enforcement	Descriptive	
G8	Size of reserve	Discrete	
G9	Reasoning for reserve location	Descriptive	
G10	Membership to fisher organizations	Binary	
G11	Type of fisheries organizations	Categorical	
G12	Representation	Ordinal	
G13	Internal Regulation	Binary	
G14	Perceived Effectiveness	Categorical	
G15	Social Impact of Reserve	Categorical	

* The indicator is applied to objective species

Table 2: This table indicates which indicators must be used for each objective.

Objective	B1	B2	B3	B4	B4*	B5	B6	B7	B7*	S1	S1**	S2	S2*	S3	G1	G2	G3	G4	G5	G6	G7	G8	G9	G0	G1	G2	G3	G4	G5
Avoid overexploitation			x		x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Conserve species under a special protection			x		x	x			x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Maintain biological process				x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Improve fishery production in nearby waters			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Preserve biological diversity and the ecosystem			x		x	x			x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Recover overexploited species	x	x		x		x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Recover species of economic interest	x	x		x		x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Data and analyses

Biophysical data is collected via underwater ecological surveys as part of a reserve's monitoring program, often carried out by local fishers with guidance of non-government organizations, such as Comunidad y Biodiversidad or Niparajá. Local fishers,trained in scientific diving, perform SCUBA dives to record fish and invertebrate richness and abundances, as well as fish total length. This information is recorded along 30 m transects, with a sampling window of 2 m X 2 m. Between 10 and 24 transects are performed in each site at depths between 1 and 30 m. Ecological surveys are performed yearly in each reserve and its corresponding control site(s), before and after the implementation of the reserve. Control sites are areas where habitat is similar to that of the reserve, but with presence of fishing activity.

Having control sites for biophysical data allows us to use counterfactual approaches to evaluate the net effect of the reserve. The hypothesis that the indicators will respond the the implementation of the reserve is tested by analysing spatial and temporal changes in each numeric biophysical indicator (all but B5) using generalized linear models [15]. To account for variations in the environment and survey conditions, covariates that describe the environment and gathered during the underwater ecological surveys are included into a model with form:

$$I_{i,t,z} = \beta_0 + \sum_{t=2}^{T} \gamma_{i,t} Y_t + \beta_1 Z_{i,z} + \beta_2 P_{i,t,z} \times Z_{i,t,z} + \beta_3 T_{i,t,z} + \beta_4 V_{i,t,z} + \beta_5 D_{i,t,z} + \epsilon_{i,t,z} \tag{1}$$

In this model, i, t, and z are subindices for transect, time, and zone (control or reserve site), respectively. This model allows us to estimate the change in an indicator (I) based on the year (Y), tratment (Z), an interaction between a variable that indicates pre- or post-implementation (P) and treatment (Z), and covariates such as bottom temperature (T), visibility during the survey (V), and depth at which survey was performed (D). Here, years are modeled as factors, using the first year as the reference level. The treatment and post variables are modeled by dummy variables coded as Control = 0 and Reserve = 1; and Pre-implementation = 0 and Post-implementation = 1, respectively.

Socioeconomic data is collected by the fishers or fishery management agencies, which record landings, income, and sometimes prices for each species. In order to control for inflation and changes in buying power, income is adjusted with the countries consumer price index:

$$I_t = RI \times \frac{CPI_t}{CPI_T} \tag{2}$$

Where I_t represents the adjusted income for year t as the product between the reported income for year t and the ratio between the consumer price index (CPI) in that year to the present year's (T) CPI. Since no control sites are available, numeric socioeconomic indicators (G1 and G2) are evaluated with a simplified version of *eq. 1*:

$$I_t = \beta_0 + \beta_1 P_t + \epsilon_t \tag{3}$$

While this model does not allow assertion of a causal relation, we can still measure changes in mean landings and income before and after the implementation of the reserve and provide valuable input.

Governance data, however, is not readily available nor systematically gathered by the community or any other organizations. In this case, we created a survey specifically designed to collect information needed for the proposed indicators (B5, S3, and G1-G15). The survey is included as supplementary material (**Appendix 1**). To analyze governance information, we performed a literature review of common governance structures and ther relation to effectiveness in managing fisheries or marine reserves. These approach has prooven to succesfuly allow the evaluation of governance structures [33]. Governance information is not analyzed in a quantitative way, but is presented along with the biophysical and socioeconomic indicators to provide managers and users with a full description of the reserve.

Marine Reserve Evaluation App (MAREA)

MAREA was developed in R Studio [34] using the shiny framework [35]. This provides the tools to build interactive web applications, hosted on an open server. MAREA can be accessed at turfeffect.shinyapps.io/marea. While the original version was developed in spanish (aimed mainly at Latinamerican countries), all its content can be translated by a translation tool availabe within the environment.

MAREA is designed into a 6-step process. The first part provides an introduction to the app, and provides the user with an overview of the process. Then, the user must select management objectives, and MAREA will automatically select appropriate indicators, based on **Table 2**. Then, the user can load the data, using standard *.csv formatting; sample datasets are provided in the environment. Once data have been loaded, MAREA identifies all reserves in the data, and lets the user select the reserve to be evaluated. At this point, the user can also specify the year of implementation of the reserve, as well as select objective species that are of particular management interest. Before presenting the results MAREA provides the user with a section to confirm that all the decisions taken before are correct. Finally, the user is taken to the results, which are represented in two ways.

The first result is a color-coded scorecard, intended to provide a general overview of the effectiveness of the reserve to a general public. The scorecard provides a global score for the reserve, a general score for each category of indicators, and an individual score for each selected indicator. The global and category scores are determined by the percentage of positive indicators, overall and for each category. For numeric biophysical indicators (all but B5), the color is defined by the sign of the interaction term coefficient (β_2) in *eq. 1.* For socioeconomic indicators, colors are assigned based on the direction of the slope (β_1). Red, yellow or green are used for $\beta_i < 0$, $\beta_i = 0$, and $\beta_i > 0$ respectively. The intensity of the color is defined by the significance of coefficient, testing the null hypothesis of no change ($i.e.$ $H_0 : \beta_i = 0$) with Student t-test. Cutoff values are $p < 0.05$ and $p < 0.1$. Thus, even in a case where $\beta_i > 0$ if the coefficient is not significant ($i.e.$ $p > 0.1$) the indicator will be assigned a yellow color. A legend (**Fig. 2**) is provided in the app to aid in the interpretation of these results. Governance indicators, however, are evaluated binomially and can be either red or green. The color is defined based on what literature shows to be a positive (green) or negative (red) value for each indicator. However, due to the nature of some governance indicators, which require the user to provide a narrative, only indicators XXX are presented in the scorecard.

Figure 2: Legend used to interpret the scorecard produced by MAREA. Colors indicate direction of change, and color intensity is given by the statistical significance.

The second output from MAREA is a technical report, intended to communicate information and statystical results in a rigurous way. This report also includes a scorecard as a summary of the results, but provides more information for each indicator. For all numeric indicators, the technical report includes graphs of the value of the indicator, for the reserve and control sites through time. It also provides a regression table [36] that summarizes the value of all coefficients in the regression and their respective standard errors. The summary table also provides information on model fit (R^2) and significance of the regression.

The scorecard is produced with functions from the Shinydashboard package [37]. The technical report is produced by a parameterized Rmarkdown document [38] processed by the knitr package [39]. Another feature of MAREA is that the user can choose to share the data. Once the technical report is downloaded, information on the reserve, its management objectives, and all uploaded data is saved into a central repository. These data can be accessed at any time by any person interested in aquiring them.

Case study

We apply the proposed framework and tool to evaluate the effectiveness of one no-take marine reserves from Isla Natividad, in Baja California Sur, Mexico. Isla Natividad is located 8 Km off the Pacific Coast of the Baja Peninsula (**Fig. 3**). Fishers in Isla Natividad operate under a fishing cooperative (S.C.P.P. Buzos y Pescadores de la Baja California), which promotes co-management of marine resources [40,41]. Additionaly, fishers have Territorial Use Rights for Fisheries (TURFs), that provide them with exclusive rights to exploit the marine resources for which they hold permits.

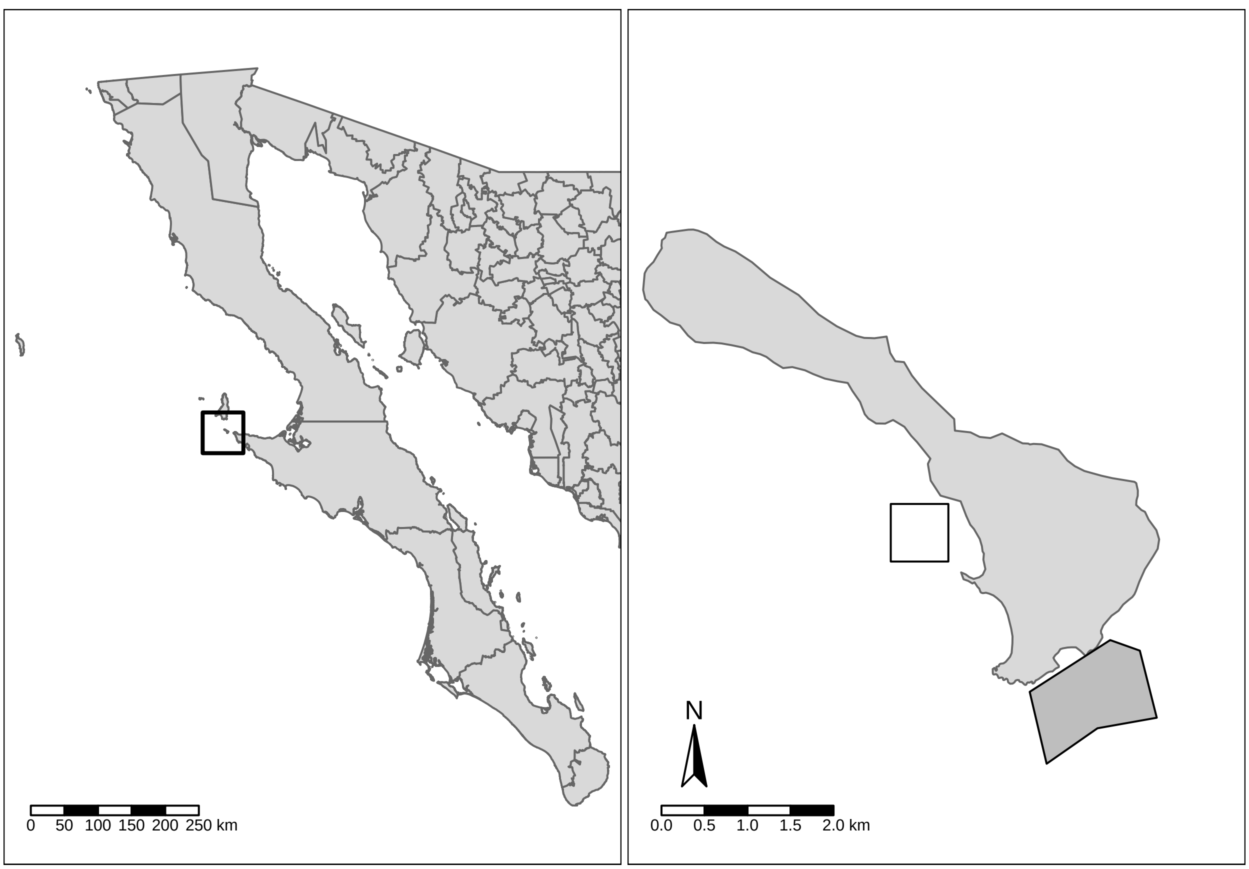

Figure 3: General location of Isla Natividad (left) and map of the island (right). The marine reserve polygon is indicated in gray, and the approximate location of the control site is shown with no fill.

In 2006, the community implemented two marine reserves within their TURF. These reserves have prooven to be effective in enhancing resilience to climate variations [9] and preserving genetic diversity of highly valuable commercial species, like abalone [10]. These ecological benefits have been translated into economical benefits, enhancing population persistance and supporting abalone fisheries [42]. For the purpose of this evaluation, we will focus on the "La Plana / Las Cuevas" Marine reserve, located in the southern end of the Island (**Fig. 3**) and its corresponding control site "La Dulce / Babencho".

The reserve was implemented to recover species of economic interest -which have been overexplotied in the last years- in order to enhance fishery production in nearby waters. Fishers were also interested in preserving biological diversity and the ecosystem. Thus, objectives objectives 4-7 were selected. Using **Table 2** to match these objectives with appropriate management indicators, we selected all biophysical, socioeconomic, and governance indicators.

Biophysical data was gathered by fishers from the community. The reserves have been monitored following a standardized ReefCheck protocol [43] to collct data on fish and invertebrate communities inside and outside the reserves between 2016 and 2017. A total of 242 and 245 transects were performed in the reserve site for fish and invertebrate surveys, respectively. Similar sampling effort was applied to the control site, with 221 fish and 222 invertebrate transects. Between 12 and 27 transects were performed in each site every year.

Socioeconomic data was obtained from the National Comission for Fisheries and Acuaculture (Comisión Nacional de Pesca y Acuacultura; CONAPESCA). The data contains species-level (9 spp) information on monthly landings and income from 2000 to 2014. Data on landings and income was aggeregated by year, and the yearly Consumer Price Index was included. From the 9 species available, we selected as objective species those that contribute the most (88.27%) to historical income: lobster (*Panulirus interruptus*; 71.76%), red sea urchin (*Strongylocentrotus franciscanus*; 9.33%), snail (*Megastraea undosa*; 3.93%), and sea cucumber (*Parastichopus parvimensis*; 3.23%). Abalone species (*Haliotis fulgens*; 4.52 and *Haliotis* *corrugata*; 6.16) were excluded because the cooperative decided to implement an informal closure on the species to allow its populations to recover. Eliminating all fishing preasure on these species means that control sites receive (for this species) the same treatment.

For govenance data, we constructed the database based on our knowledge of the area, as well as prototype interviews performed to liders of the fishing cooperative.

Results and Discussion

The results shown here intend to highlight the relevance and utility of the framework and tool, which automate the analysis and make it replicable. First, we present the scorecard generated by MAREA to provide an overview of the state of the reserve. Then, we provide (mdoified for style) a set of figures generated by MAREA, showing time-series for biophysical and socioeconomic indicators as well as tables containing the magnitude and significance of the β_2 and β_1 coefficients. A table with the governance indicators is also provided and discussed.

The scorecard (**Fig. 4**)shows that, overall, the reserve has a good performance achieving a general score of 63.6% of positive indicators. All category-level scores were also high, with values of 66.7%, 60%, and 75% positive indicators for Biophysical, Socioeconomic and Governance, respectively.

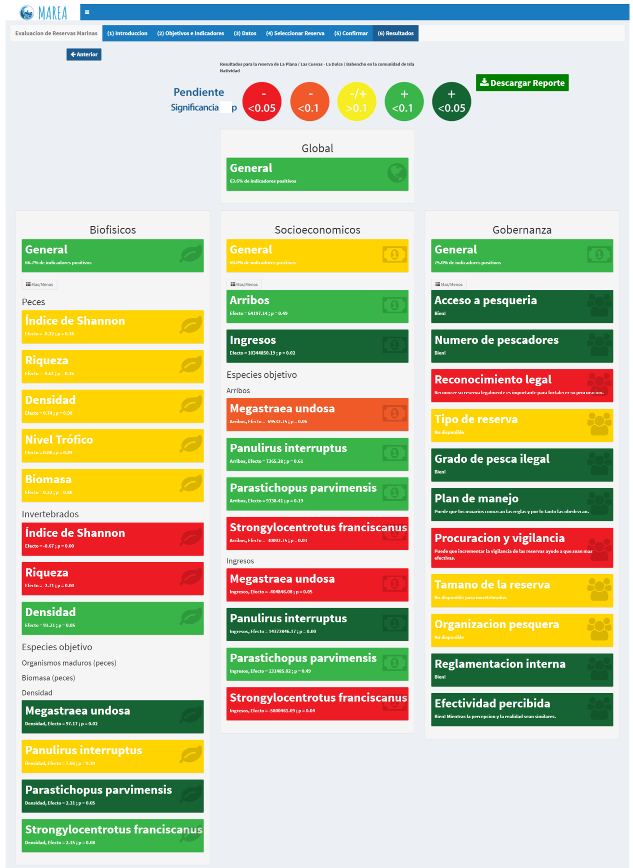

Figure 4: Scorecard for the "La Plana / Las Cuevas" marine reserve in Isla Natividad, Mexico. This scorecard was produced by MAREA.)

Within the biophysical indicators, the greatest effect of the reserve was observed for snail and cucumber densities, with values of $\beta_3 = 97.17$ ($p < 0.05$) and $\beta_3 = 2.31$ ($p < 0.05$), respectively. Urchin and lobster densities also increased by $\beta_3 = 2.15$ and $\beta_3 = 7.66$ respectively. However, changes in urchin densities were only significant at $p < 0.1$, and not significant for lobster ($p > 0.1$). Shannon's diversity index ($\beta_3 = -0.67$) and richness $\beta_3 = -2.71$ showed a significant decrease ($p < 0.05$). Fish indicators showed no significant change ($p > 0.1$), with negative trends for Shannon's diversity index and fish species richness and positive trends for density, biomass, and mean trophic level. Changes through time for these indicators are presented in **Figure 5**, and a summary of β_3 coefficients is provided in **Table 3**.

In the case of socioeconomic indicators, total landings were on average 64.20 tones higher

($p > 0.1$) after the implementation of the reserves. Total income was \$10,344.85 ($p < 0.05$) thousands of Mexican Pesos (MXP) higher after the implementation of the reserves. On avergae, lobster and cucumber landings and increased, while urchin and snail landings and income decreased. **Figure 6** presents the changes in this indicators through time, and **Table 4** summarizes this information.

All invertebrates show increased densities within the reserve, as compared to the control site, providing evidence that the reserve is effectively protecting these species. While we are not able to infer causality from the socioeconomic analysis, we are able to identify important trends. For example, snail and urchin density hve significantly increased within the reserve, but their landings and income have decreased. The opposite is observed for lobster and cucumber, which have shown increases in densities, landing, and income. While further information on market behaviour of each species is needed, these results provide insights into the state of the reserve, as well as the associated fisheries.

In terms of governance, it is evident that the community is strongly organized, which is a cause of their success. The first point of success is the existance of a fishing cooeprative that is also affiliated to federation. These polycentric governance structures allow different levels of organization that foster communication and cooperation; federations also provide bargain power with governments [33,44]. Fishers also have good management instruments. Access to the fishing resources they exploit is managed through permits and fishing quotas. Along with a stable number of fishers participating in extractive activities, these limit the total fishing effort effort applied. Additionally, their TURF promotes a sense of stewardship of their resources and incentivizes correct resource management [40,44]. Together, these structures enabled a participative, bottom-up process during the reserve design phase; Opinions of all fishing members -and often non-fishers, but community members- were included. Participation of community members in reserve survailance and yearly monitoring indicate commitment and interest, and allow informal communication of results to un-involved community members.

While the reserve has not been legaly recognized (as of this moment), the community has started the process to have the reserve be recognized as a fishery replenishment zone (*Zona de Refugio Pesquer*) under the corresponding Mexican norms [31]. Furthermore, the reserve is partially isolated from poaching activity and fishers have internal regulations pertaining the reserves. The low level of illegal fishing by members of the community and outsiders both inside and outside the reserve represents another indication of effectiveness. A summary of governance indicators is provided in **Table 5**.

Table 3: Summary of average treatment effect of the La Plana / Las Cuevas marine reserve on biophysical indicators. Asterisks indicate significance level, with (*) indicating *p* < 0.1 and (**) *p* < 0.05.

Indicator	Estimate (SD)	t-score
Shannon fish	-0.22 (0.16)	-1.40
Richness fish	-0.61 (0.43)	-1.41
Density fish	0.74 (6.15)	0.12
Trophic fish	0.00 (0.01)	0.14
Biomass fish	0.22 (1.47)	0.15
Shannon invert	-0.67 (0.22)**	-3.05
Richness invert	-2.71 (0.81)**	-3.35
Density invert	91.21 (47.11)*	1.94
Lobster	7.66 (8.93)	0.86
Urchin	2.15 (1.23)*	1.74
Snail	97.17 (42.90)**	2.27
Cucumber	2.31 (1.17)**	1.98

Table 4: Summary of average treatment effect of the La Plana / Las Cuevas marine reserve on socioeconomic indicators. Asterisks indicate significance level, with (*) indicating *p* < 0.1 and (**) *p* < 0.05.

Indicator	Estimate (SD)	t-score
Landings	64.20 (90.07)	0.71
Income	10344.85 (3982.20)**	2.60
Lobster landings	7.37 (13.95)	0.53
Urchin landings	-30.00 (9.49)**	-3.16
Snail landings	-69.53 (33.82)*	-2.06
Cucumber landings	9.34 (6.72)	1.39
Lobster income	14372.85 (3634.64)**	3.95
Urchin income	-5800.46 (1867.50)**	-3.11
Snail income	-404.85 (187.07)**	-2.16
Cucumber income	131.49 (185.66)	0.71

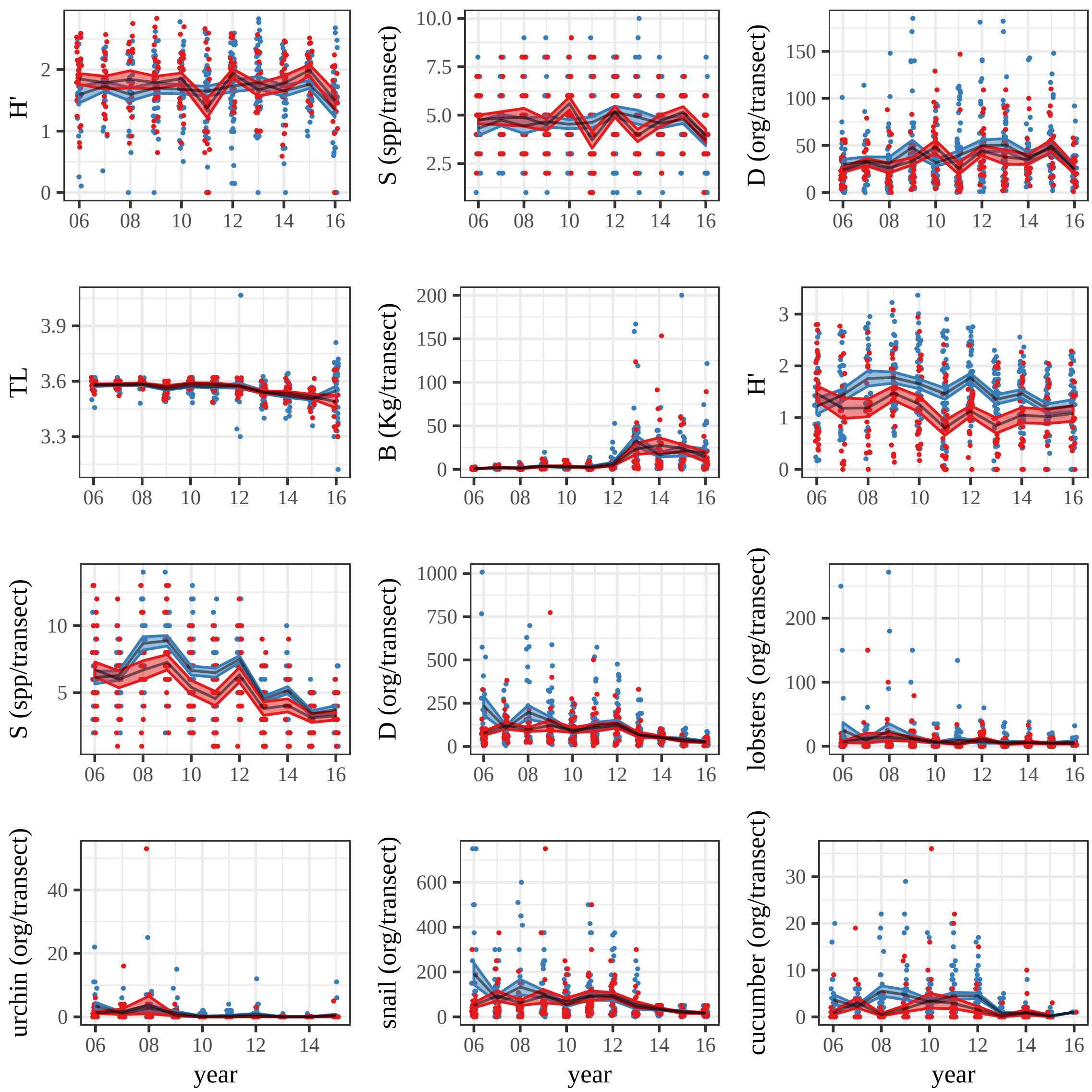

Figure 5: Plots for values of each biophysical indicator (y-axis) through time (x-axis). Red and blue correspond to the reserve and control sites, respectively. Black lines indicate yearly mean values, and ribbons indicate +/- 1 standard error. Dots are horizontally jittered to aid visualization.

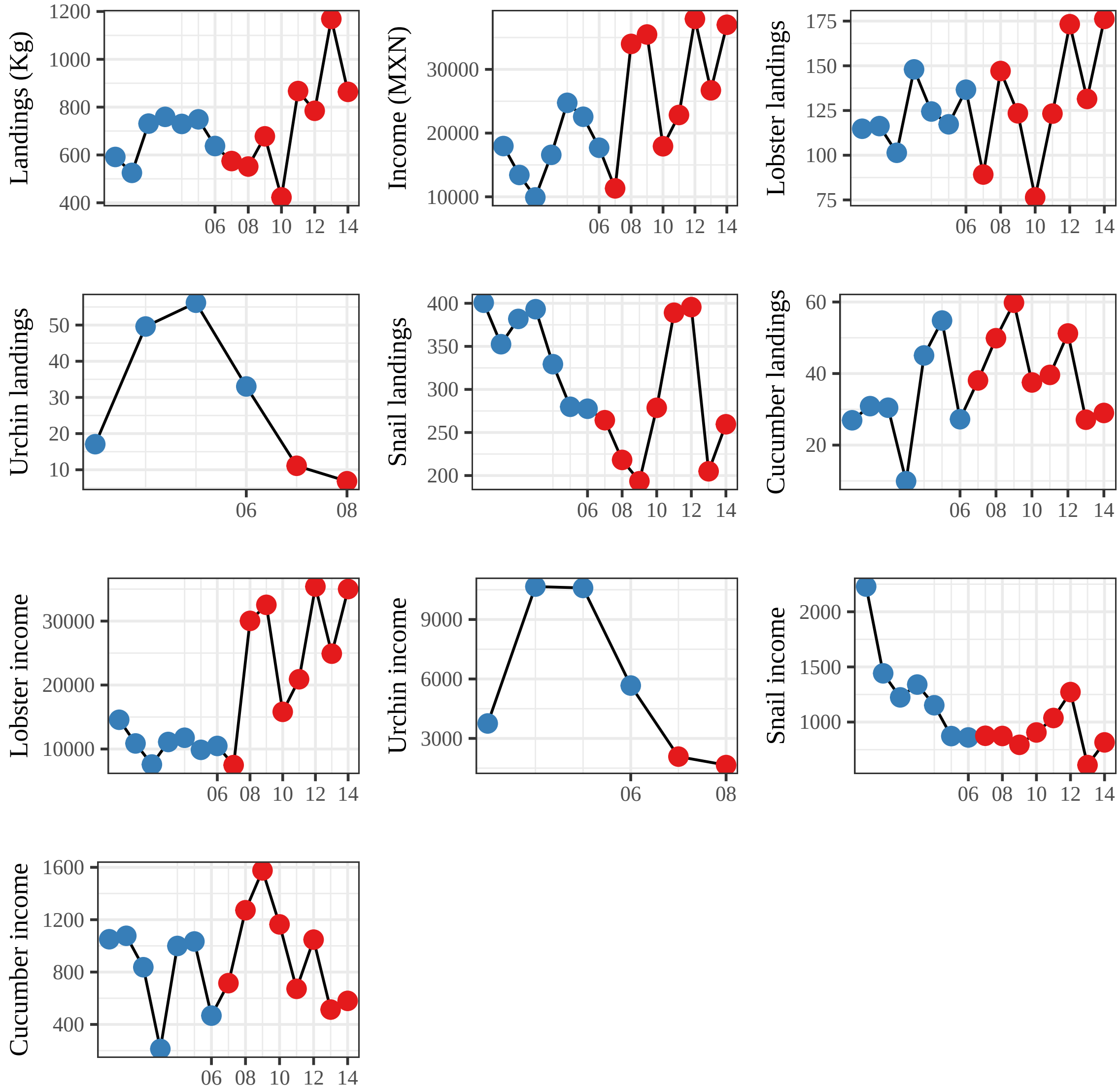

Figure 6: Plots for values of each socioeconomic indicator (y-axis) through time (x-axis). Red and blue correspond to before and after the implementation of the reserve, respectively.

Table 5: Summary of governance indicators.

Indicator	Description
Access to the fishery	Permits, Territorial Use Rights for Fisheries, Quotas
Number of fishers	Stable
Legal recognition of reserve	Not recognized, but the community has started the process to declare it as a Fishery Replenishment Zone (Zona de Refugio Pesquero) under the @nom049sagpesc_2014-V6
Reserve type	
Illegal harvesting	Due to its relative isolations, neither the reserve or TURF suffer from significant illegal harvesting
Management plan	The reserve does not have a management plan, but written rules exist within the cooperative
Reserve enforcement	Fishers have two land stations equiped with radars and patrol boats 24/7 to patrol the reserves.
Size of reserve	The reserve is big enough to protect the targeted sesile or not highly mobile invertebrates (lobster, urchin, snail, cucumber, and abalone)
Reasoning for reserve location	The reserves were put in place in zones that, according to local knowledge, were once very productive. Habitat heterogeneity and ease of monitoring, surveilance and enforcement were also considered.
Membership to fisher organizations	The fishers are part of fisher roganizations.
Type of fisheries organizations	The fishers are part of a cooperative (S.C.P.P. Buzos y Pescadores de la Baja California) and are afiliated to a federation (FEDECOOP).
Representation	Reserves were designed by fishers in a bottom-up approach, incorporating expertise from academics and NGO members. This was a highly inclusive and participatory process.
Internal Regulation	Fishers have stringent internal regulations to control fishing effort throughouth their TURF, assigning different fishing zones and gears to different teams. Rules pertaining the marine reseves also exist.
Perceived Effectiveness	The fishers have a positive perception about the effectiveness of their reserve, often stating that they have seen significant economic benefits.
Social Impact of Reserve	The reserves have had a significant positive social impact. Fishers are proud to be an world-class case of success in marine conservation, allowing them to have increased social capital.

Conclusions

One of the greatest challenges in management measuring the extent to which objectives have been met. The present framework provides a simple and straightforward way to align management objectives with performance indicators. We aknowledge that these 25 indicators might not fully describe a particular reserve. However, we believe that these provide a starting point to perform the evaluation, and urge decision-makers, managers, and users to include other indicators (*e.g.* larval dispersal or connectivity) that are relevant to their reserve.

The proposed methodologies, specially the way in which biophysical indicators are evaluated, provide valuable information for managers. The analysis isolates the net effect of the reserve, providing a propper measure of reserve effectiveness. We agree there is room for improvement in the way in which socioeconomic and governance data are analized. However, we believe that providing a unifying platform where all can be analyzed and comprehensively presented represents a valuable step towards effective management.

The main value of MAREA is that it provides a free, simple, and replicable way to perform rigurous analysis. The tool can easily be used by fishers, NGO members, and managers in government agencies, providing transparency of the analysis and results. The way in which results are presented allow this information to be interpreted by a wider audience. The scorecard is easily understandable by experts and non-experts, and can be used as an effective tool for communicating the results of yearly evaluations. On the other side, the technical report can serve as a tool for managers and scientists to rapidly communicate information at a more technical level.

While the first release of MAREAis now available, it will continue to be developed and maintained. This will incorporate new features, and enhance current ones, aiming to improve user experience and expand the scope of the analysis. Yet, we believe that this first release represents a major step towards effective management of marine reserves.

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References

1. Pauly D, Watson R, Alder J. Global trends in world fisheries: Impacts on marine ecosystems and food security. Philos Trans R Soc Lond, B, Biol Sci. 2005;360: 5–12. doi:10.1098/rstb.2004.1574

2. Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, et al. A global map of human impact on marine ecosystems. Science. 2008;319: 948–952. doi:10.1126/science.1149345

3. Lester S, Halpern B. Biological responses in marine no-take reserves versus partially protected areas. Mar Ecol Prog Ser. 2008;367: 49–56. doi:10.3354/meps07599

4. Lester S, Halpern B, Grorud-Colvert K, Lubchenco J, Ruttenberg B, Gaines S, et al. Biological effects within no-take marine reserves: A global synthesis. Mar Ecol Prog Ser. 2009;384: 33–46. doi:10.3354/meps08029

5. Sala E, Costello C, De Bourbon Parme J, Fiorese M, Heal G, Kelleher K, et al. Fish banks: An economic model to scale marine conservation. Marine Policy. 2016;73: 154–161. doi:10.1016/j.marpol.2016.07.032

6. IUCN. Protected areas categories [Internet]. International Union for Conservation of Nature. 2017. Available: https://www.iucn.org/theme/protected-areas/about/protected-areas-categories

7. Horta e Costa B, Claudet J, Franco G, Erzini K, Caro A, Gonçalves EJ. A regulation-based classification system for marine protected areas (mpas). Marine Policy. 2016;72: 192–198. doi:10.1016/j.marpol.2016.06.021

8. Aburto-Oropeza O, Erisman B, Galland GR, Mascareñas-Osorio I, Sala E, Ezcurra E. Large recovery of fish biomass in a no-take marine reserve. PLoS ONE. 2011;6: e23601.

doi:10.1371/journal.pone.0023601

9. Micheli F, Saenz-Arroyo A, Greenley A, Vazquez L, Espinoza Montes JA, Rossetto M, et al. Evidence that marine reserves enhance resilience to climatic impacts. PLoS ONE. 2012;7: e40832. doi:10.1371/journal.pone.0040832

10. Munguía-Vega A, Sáenz-Arroyo A, Greenley AP, Espinoza-Montes JA, Palumbi SR, Rossetto M, et al. Marine reserves help preserve genetic diversity after impacts derived from climate variability: Lessons from the pink abalone in baja california. Global Ecology and Conservation. 2015;4: 264–276. doi:10.1016/j.gecco.2015.07.005

11. Betti F, Bavestrello G, Bo M, Asnaghi V, Chiantore M, Bava S, et al. Over 10 years of variation in mediterranean reef benthic communities. Marine Ecology. 2017;38: e12439. doi:10.1111/maec.12439

12. Davies TK, Mees CC, Milner-Gulland EJ. Use of a counterfactual approach to evaluate the effect of area closures on fishing location in a tropical tuna fishery. PLoS ONE. 2017;12: e0174758. doi:10.1371/journal.pone.0174758

13. Guidetti P, Baiata P, Ballesteros E, Di Franco A, Hereu B, Macpherson E, et al. Large-scale assessment of mediterranean marine protected areas effects on fish assemblages. PLoS ONE. 2014;9: e91841. doi:10.1371/journal.pone.0091841

14. Friedlander AM, Golbuu Y, Ballesteros E, Caselle JE, Gouezo M, Olsudong D, et al. Size, age, and habitat determine effectiveness of palau's marine protected areas. PLoS ONE. 2017;12: e0174787. doi:10.1371/journal.pone.0174787

15. Moland E, Olsen EM, Knutsen H, Garrigou P, Espeland SH, Kleiven AR, et al. Lobster and cod benefit from small-scale northern marine protected areas: Inference from an empirical before-after control-impact study. Proc Biol Sci. 2013;280: 20122679. doi:10.1098/rspb.2012.2679

16. Soykan CU, Lewison RL. Using community-level metrics to monitor the effects of marine

protected areas on biodiversity. Conserv Biol. 2015;29: 775–783. doi:10.1111/cobi.12445

17. Basurto X, Gelcich S, Ostrom E. The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. Global Environmental Change. 2013;23: 1366–1380. doi:10.1016/j.gloenvcha.2013.08.001

18. Basurto X, Nenadovic M. A systematic approach to studying fisheries governance. Glob Policy. 2012;3: 222–230. doi:10.1111/j.1758-5899.2011.00094.x

19. Pomeroy RS, Watson LM, Parks JE, Cid GA. How is your mpa doing? A methodology for evaluating the management effectiveness of marine protected areas. Ocean Coast Manag. 2005;48: 485–502. doi:10.1016/j.ocecoaman.2005.05.004

20. Pomeroy RS, Parks JE, Watson LM. How is your mpa doing ? A guidebook of natural and social indicators for evaluating marine protected areas management effectiveness [Internet]. IUCN; 2004. doi:10.2305/IUCN.CH.2004.PAPS.1.en

21. Lowndes JSS, Best BD, Scarborough C, Afflerbach JC, Frazier MR, O'Hara CC, et al. Our path to better science in less time using open data science tools. Nat ecol evol. 2017;1: 0160. doi:10.1038/s41559-017-0160

22. Halpern BS, Longo C, Hardy D, McLeod KL, Samhouri JF, Katona SK, et al. An index to assess the health and benefits of the global ocean. Nature. 2012;488: 615–620. doi:10.1038/nature11397

23. Halpern BS, Frazier M, Afflerbach J, O'Hara C, Katona S, Stewart Lowndes JS, et al. Drivers and implications of change in global ocean health over the past five years. PLoS ONE. 2017;12: e0178267. doi:10.1371/journal.pone.0178267

24. Selig ER, Frazier M, O'Leary JK, Jupiter SD, Halpern BS, Longo C, et al. Measuring indicators of ocean health for an island nation: The ocean health index for fiji. Ecosystem

Services. 2015;16: 403–412. doi:10.1016/j.ecoser.2014.11.007

25. Halpern BS, Longo C, Scarborough C, Hardy D, Best BD, Doney SC, et al. Assessing the health of the u.S. west coast with a regional-scale application of the ocean health index. PLoS ONE. 2014;9: e98995. doi:10.1371/journal.pone.0098995

26. Elfes CT, Longo C, Halpern BS, Hardy D, Scarborough C, Best BD, et al. A regional-scale ocean health index for brazil. PLoS ONE. 2014;9: e92589. doi:10.1371/journal.pone.0092589

27. Anderson JL, Anderson CM, Chu J, Meredith J, Asche F, Sylvia G, et al. The fishery performance indicators: A management tool for triple bottom line outcomes. PLoS ONE. 2015;10: e0122809. doi:10.1371/journal.pone.0122809

28. Oyanedel R, Macy Humberstone J, Shattenkirk K, Rodriguez Van-Dyck S, Joye Moyer K, Poon S, et al. A decision support tool for designing turf-reserves. BMS. 2017;93: 155–172. doi:10.5343/bms.2015.1095

29. Vilela T, Reid J. Improving hydropower choices via an online and open access tool. PLoS ONE. 2017;12: e0179393. doi:10.1371/journal.pone.0179393

30. Burgess MG, Clemence M, McDermott GR, Costello C, Gaines SD. Five rules for pragmatic blue growth. Marine Policy. 2016; doi:10.1016/j.marpol.2016.12.005

31. NOM-049-SAG/PESC. NORMA oficial mexicana nom-049-sag/pesc-2014, que determina el procedimiento para establecer zonas de refugio para los recursos pesqueros en aguas de jurisdicción federal de los estados unidos mexicanos. DOF. 2014;

32. Woodcock P, O'Leary BC, Kaiser MJ, Pullin AS. Your evidence or mine? Systematic evaluation of reviews of marine protected area effectiveness. Fish Fish. 2017;18: 668–681. doi:10.1111/faf.12196

33. Espinosa-Romero MJ, Rodriguez LF, Weaver AH, Villanueva-Aznar C, Torre J. The changing role of ngos in mexican small-scale fisheries: From environmental conservation to

multi-scale governance. Marine Policy. 2014;50: 290–299. doi:10.1016/j.marpol.2014.07.005

34. R Core Team. R: A language and environment for statistical computing [Internet]. Vienna, Austria: R Foundation for Statistical Computing; 2017. Available: https://www.R-project.org/

35. Chang W, Cheng J, Allaire J, Xie Y, McPherson J. Shiny: Web application framework for r [Internet]. 2017. Available: https://CRAN.R-project.org/package=shiny

36. Hlavac M. Stargazer: Well-formatted regression and summary statistics tables [Internet]. Cambridge, USA: Harvard University; 2015. Available: http://CRAN.R-project.org/package=stargazer

37. Chang W, Borges Ribeiro B. Shinydashboard: Create dashboards with 'shiny' [Internet]. 2017. Available: https://CRAN.R-project.org/package=shinydashboard

38. Allaire J, Cheng J, Xie Y, McPherson J, Chang W, Allen J, et al. Rmarkdown: Dynamic documents for r [Internet]. 2017. Available: https://CRAN.R-project.org/package=rmarkdown

39. Xie Y. Knitr: A general-purpose package for dynamic report generation in r [Internet]. 2017. Available: http://yihui.name/knitr/

40. McCay B. Territorial use rights in fisheries of the northern pacific coast of mexico. BMS. 2017;93: 69–81. doi:10.5343/bms.2015.1091

41. McCay BJ, Micheli F, Ponce-Díaz G, Murray G, Shester G, Ramirez-Sanchez S, et al. Cooperatives, concessions, and co-management on the pacific coast of mexico. Marine Policy. 2014;44: 49–59. doi:10.1016/j.marpol.2013.08.001

42. Rossetto M, Micheli F, Saenz-Arroyo A, Montes JAE, De Leo GA, Rochet M-J. No-take marine reserves can enhance population persistence and support the fishery of abalone. Can

J Fish Aquat Sci. 2015;72: 1503–1517. doi:10.1139/cjfas-2013-0623

43. Suman CS, Saenz-Arroyo A, Dawson C, Luna MC. Manual de instruccion de reef check california: Guia de instruccion para el monitoreo del bosque de sargazo en la peninsula de baja california. Pacific Palisades, CA, USA: Reef Check Foundation; 2010.

44. Finkbeiner EM, Basurto X. Re-defining co-management to facilitate small-scale fisheries reform: An illustration from northwest mexico. Marine Policy. 2015;51: 433–441. doi:10.1016/j.marpol.2014.10.010