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, recover overfished stocks, and secure livelihoods of coastal communities. As with any other management interventions, we need to better understand their effectiveness and impacts on coastal communities and the environment. To date, the evaluation of these reserves largely relies on analyzing ecological data, often ignoring socioeconomic and governance dimensions. Existing data are analyzed in different ways, hindering the ability to compare results across case studies. Moreover, analysis and evaluation of reserves is generally conducted by academic scientists, not the reserves managers and users, thereby hindering effective local management and rapid response to change. We present a framework and tool to evaluate the effectiveness of marine reserves by matching seven commonly stated management objectives to nine biological, five socioeconomic, and 14 governance indicators. We provide guidelines on how to properly collect data that can then be analyzed with standardized method. Biological indicators are evaluated with causal inference techniques, using a counterfactual approach, to assess the net effect of the reserve on each indicator. Linear regression models are fitted to socioeconomic indicators through time to test for differences before and after reserve implementation. Governance indicators are qualitatively analyzed using a framework developed through a literature review which identifies common governance structures and their associated effectiveness. To make the framework accessible to fishers and decision makers, and allow replication of results, we developed the open source, web-based Marine Reserve Evaluation App (MAREA). Together, this new framework and MAREA can further our understanding and support management of marine reserves.

Introduction

Overfishing and unsustainable fishing practices are two of the largest 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 and invertebrate stocks recover [3,4] by limiting or restricting fishing effort and gears. No-take marine reserves (marine reserves hereinafter) are a particular type of MPA, where all fishing effort and extractive activities are off-limits [6,7].

Empirical studies have shown that MPAs increase biomass [4,8], enhance resilience to climatic impacts [9,10], and preserve genetic diversity [11]. Compared to partially protected MPAs, marine reserves are known to have even higher levels of biomass, density, richness, and larger organisms [3,12]. These effects are often measured as biological changes in the area through time and lack a control site against which to compare [13]. This before-after comparison cannot account for other factors for which one must control [14] in order to attribute biological change to protection in the reserves. While some studies have used control sites, these analyses do not estimate the net effect of the reserve, and often use a control-impact comparison approach that does not address temporal variability [4,8,15–17]. A smaller fraction of studies have used a before-after-control-impact design comparing reserves to control sites before and after implementation [4,18,19], which allows the use of causal inference techniques that estimate the effect of the reserve.

As with any other policy intervention, it is important that we can measure its effect in order to adapt and learn [20,21]. The diversity of approaches currently used to evaluate the effect of marine reserves often does not answer the simple question: *What is the effect of a marine reserve on a given attribute?* This gap highlights the need to develop standardized approaches that enable us to evaluate the net effect of the intervention (*i.e.* causes of conservation outcomes; [20]). Furthermore, while biological aspects are important to reserve success, effectiveness also depends on the socioeconomic status and governance system of the local fishing communities [22,23], which are often ignored. By excluding these important dimensions, the evaluation provides only a partial picture of the impacts of the reserve. Currently, only the IUCN framework "How to evaluate your MPA" [24,25] provides a comprehensive list of biological, socioeconomic, and governance indicators, and insights into how these indicators may be measured, but does not provide guidelines on how to analyze them. Recent work by [26] integrates these three dimensions and suggests the use of causal inference techniques to provide a measure of the effect of implementing an MPA. However, these two novel approaches do not provide a user-friendly tool that enables replicability and scalability of the analysis, particularly when used by the fishers and decision makers themselves.

An increasingly popular way to make science reproducible, scalable and replicable is through Open Science and the development of open-access tools [27]. The Ocean Health Index [28,29], for example, has successfully standardized a way to measure the health and benefits of the oceans. This approach has been implemented at global scales, but also at country-level [30], and regional scales [31,32]. Open access tools are not limited to conservation, and have also been developed to evaluate fishery performance [33,34], design territorial use rights for fisheries (TURFs; [35]), and improve decision making in the hydropower industry [36], just to list a few.

The lack of a comprehensive framework and user-friendly tools to evaluate the effectiveness of marine reserves —or the complexity of existing ones, which alienate non–experts— calls for the development of a new framework and tool. The current work presents a framework to evaluate marine reserves, which incorporates the biological, socioeconomic, and governance dimensions of these areas. We first provide a list of commonly stated management objectives and match them to appropriate indicators that measure the effectiveness of the management intervention. We then include a simple approach to analyzing these indicators building on causal inference techniques [18], which help us understand the effect of management interventions [21,26]. We also introduce the Marine Reserve Evaluation App (MAREA), an open source web–based tool that automates the framework described in this paper and enables its broader use. Finally, we present a case study on the evaluation of a marine reserve established by the fishers of Isla Natividad (Mexico) in 2006, to demonstrate the potential of MAREA.

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 brief guidelines on data collection. Alongside, methodologies to analyze these indicators are presented. Then, we describe the development of MAREA and explain how this user-friendly open access tool can be used by anyone. Finally, we provide guidelines on how to interpret and use the results and output generated by MAREA.

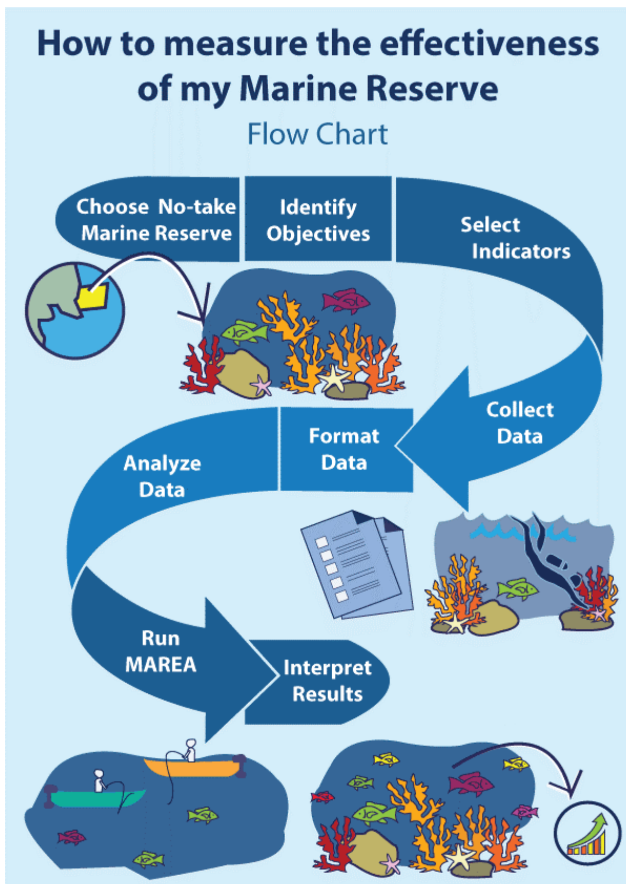

Figure 1: Workflow to evaluate the effectiveness of marine reserves.

Marine Reserve objectives and indicators

Throughout this study, we will refer to the stated goals for which a marine reserve was designed as objectives. This work was motivated by the need to provide a framework to evaluate Mexican marine reserves. Thus, our focus was on identifying common objectives of marine reserves in Mexico. However, we group these objectives into seven major categories, which can be applied to marine reserves worldwide. The list of objectives was developed through a literature review, which compiled stated objectives in and legislation [37,38] and official documents such as the Technical Justification Studies (*Estudios Tecnicos Justificativos*), agreements, and decrees associated to these areas. Even though each reserve 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 associated indicators to evaluate reserve effectiveness. The list of indicators was compiled through a review of scientific literature in which we identified indicators that were used to measure similar objectives. A first filter eliminated indicators for which baseline data do not typically exist in Mexico. The preliminary 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*), in Baja California, who provided input. Our final list of indicators includes those identified in review works such as [4] or [39].

Indicators are divided into three main categories: biological, socioeconomic, and governance (Table 1). Biological indicators (n = 7) focus on fish and invertebrate communities that are evaluated using underwater ecological surveys performed inside and outside the reserve (see Data and Analysis 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 (*e.g.*, access rights to the fishery, number of fishers, legal recognition of the reserve). 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 biological and socioeconomic indicators are outcome variables. On the other hand, governance indicators are viewed as possible explanatory variables of reserve performance. Whenever an indicator is applied to "Target species", it means that the indicator can be used for all species (*e.g.* Fish Biomass) and/or for 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, and 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

In many coastal marine reserves of Mexico, biological data are collected via underwater ecological surveys as part of a reserve's monitoring program, often carried out by local fishers with guidance from Civil Society Organizations (CSOs). Scientific divers record fish and invertebrate richness and abundances, as well as fish total length along belt transects. Ecological surveys are performed yearly in each reserve and corresponding control site(s), before and after the implementation of the reserve, allowing us to have a before-after-control-impact (*i.e.* BACI) sampling design. Control sites are areas where habitat is similar to that of the reserve, but with presence of fishing activity. While transect dimensions (i.e. length and width) and sampling methods might vary from study to study, the general idea remains the same: richness, abundances, and sizes of organisms are recorded in a study-specific standardizes way. For this reason, MAREA does not assume specific transect dimensions, and pertinent indicators are calculated per transect (Table 1).

Having control sites for biological data allows us to use causal inference techniques [18,20] to evaluate the net effect of the reserve. The hypothesis that the indicators will respond to implementation of the reserve is tested by analyzing spatial and temporal changes in each numeric biological indicator (all but B5) using generalized linear models [18]. To account for variations in the environment and survey conditions, covariates that are gathered during the underwater ecological surveys are included into a model with form:

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

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), a dummy variable that indicates treatment (Z; *i.e.* control or reserve), an interaction between a dummy variable that indicates pre– or post–implementation (P) and treatment (Z), and covariates such as bottom temperature (T; in °C), horizontal visibility during the survey (V; in m), and depth at which survey was performed (D; in m). ϵ represents the error term associated to the equation. Here, years are modeled as factors, using the first year as the reference level. By modelling years as factors, we avoid imposing a linear structure in the way an indicator changes through time (*i.e.* the change in biomass between 2006 and 2007 does not have to be the same as the change between 2015 and 2016). The treatment and implementation variables, modeled as dummy variables, are coded as Control = 0 and Reserve = 1; and Pre-implementation = 0 and Post-implementation = 1, respectively.

Socioeconomic data are often collected by fishers, fishery management agencies or OSCs by recording landings, income, and sometimes prices for each species. To control for inflation and changes in buying power, income is adjusted with the country's consumer price index [40]:

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

Where I_t represents the adjusted income for year t as the product between the reported income for that year and the ratio between the consumer price index (CPI) in that year to the most recent year's (T) CPI. Since no control sites are typically available for this data type, 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 establishing 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. For both models (eq. 1 and eq. 3), coefficients are estimated via ordinary least squares, and heteroskedastic-robust standard errors are calculated.

Governance data are not readily available nor systematically collected by the community or other organizations. Therefore, 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 develop a framework based on a literature review of common governance structures and their relation to effectiveness in managing fisheries or marine reserves (Appendix 2). This approach has been proven to successfully evaluate governance structures [41]. Governance information is not quantitatively analyzed, but it is presented along with the biological and socioeconomic indicators to provide managers and users with a more complete description of the reserve.

ME QUEDÉ AQUí

Marine Reserve Evaluation App (MAREA)

MAREA was developed in R Studio [42] using the shiny framework [43], which 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 at Mexico and other Latinamerican countries), all its content can be translated by a translation widget availabe within the environment.

MAREA is designed into a 6-step process, divided in tabs. The first tab provides an introduction to the app and an overview of the evaluation process. Then, the user selects management objectives, which MAREA automatically matches to appropriate indicators, based on **Table 2**. The user can then load the data, using standard *.csv files; sample datasets are provided within MAREA. 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, and indicate 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 until then are correct. Finally, the user is taken to the results tab, where results can be viewed at a glance or downloaded as a technical report.

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 indicator. The global and category-level 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 and 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 a Students 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 within the scorecard to aid in the interpretation of these results. Governance indicators, however, are represented by red or green. The color is defined based on what literature shows to be a positive (green) or negative (red) factor for a reserve. However, due to the nature of some governance indicators, which require the user to provide a narrative, only some indicators are presented in the scorecard (although all are included in the techniical report).

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 more formal and technical 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 report includes a graph of the value of the indicator, for the reserve and control sites, through time. It also provides a regression table that summarizes the value of all coefficients in the regression and their respective robust 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 [44]. The technical report is produced by a parameterized Rmarkdown document [45] processed by the knitr package [46]. 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 marine reserve from Isla Natividad, in Baja California Sur, Mexico. Isla Natividad is located 8 Km off the Pacific Coast of the Baja Peninsula (**Fig. 3**), where fishers operate under a fishing cooperative (S.C.P.P. Buzos y Pescadores de la Baja California) that promotes co-management of marine resources [47,48]. Additionaly, fishers have Territorial Use Rights for Fisheries (TURFs) that provide them with exclusive access rights to exploit the marine resources in a given perimeter.

In 2006, the community implemented two marine reserves within their TURF [49]. The reserves from Isla Natividad have prooven to be effective in enhancing resilience to climate variations [9] and preserving genetic diversity of highly valuable commercial species, like abalone [11]. These ecological benefits have been translated into economical benefits, enhancing population persistance and supporting abalone fisheries [50]. For the purpose of this evaluation, we will

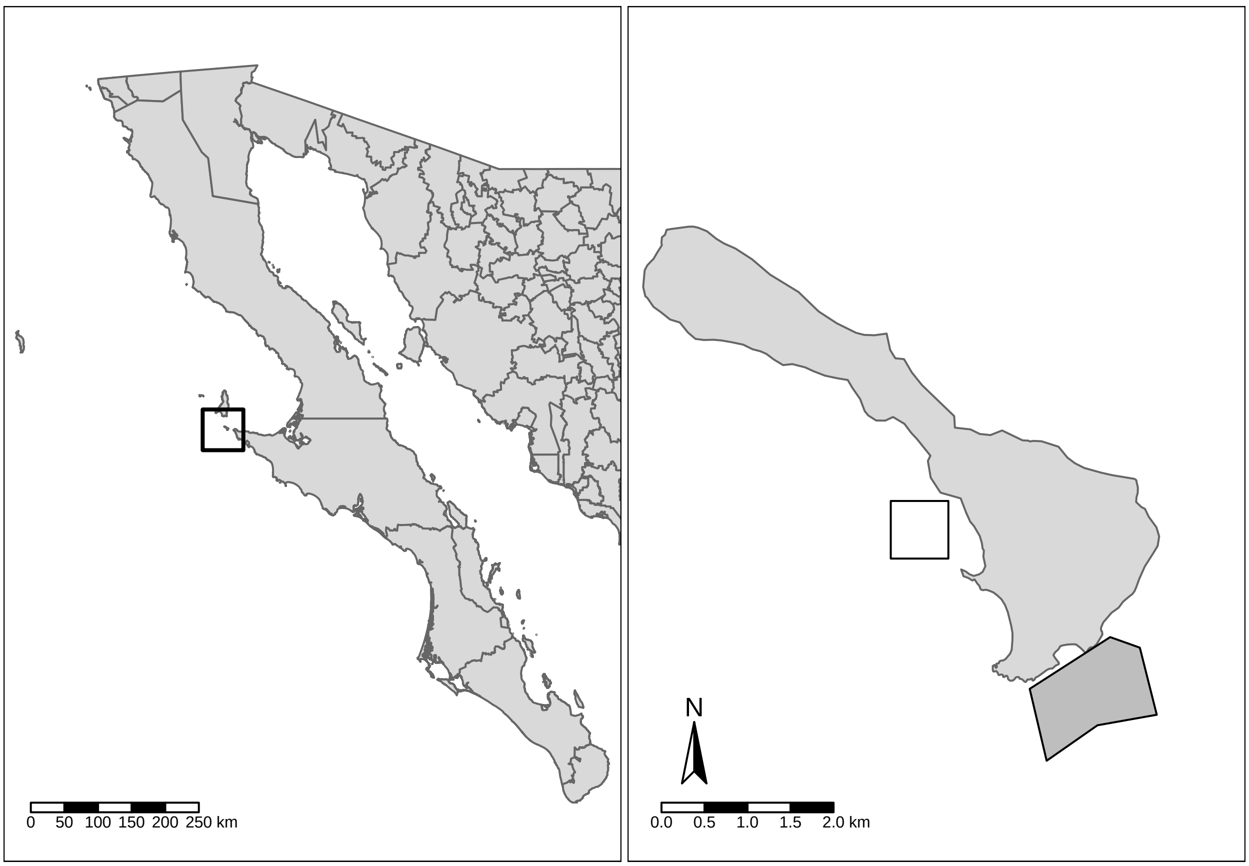

Figure 3: General location of Isla Natividad (left) and map of the island (right). The marine reserve polygon is indicated in gray, and the approximate location of the control site is shown with no fill.

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 were overexplotied- 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 [51] 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.

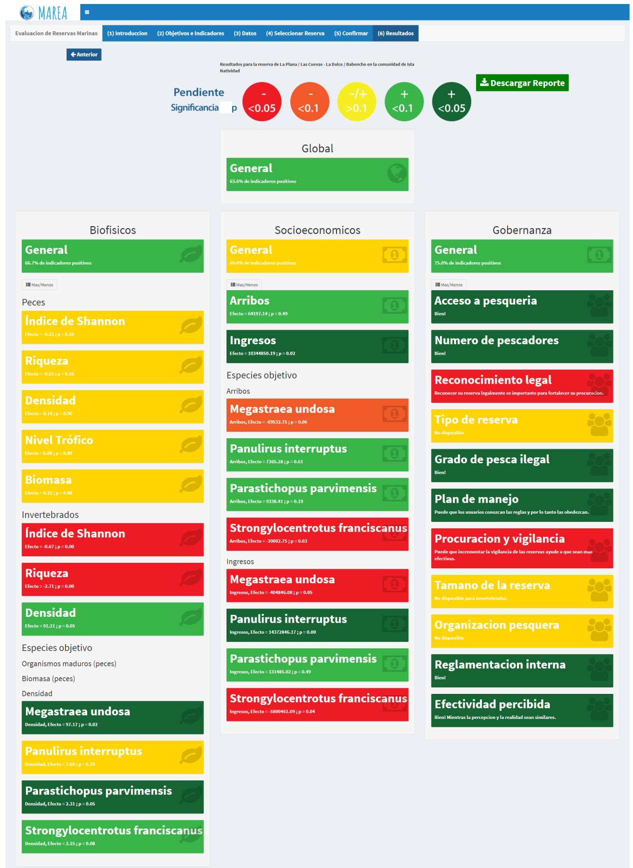

Figure 4: Scorecard produced by MAREA for the "La Plana / Las Cuevas" marine reserve in Isla Natividad, Mexico.

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.

The results identified by our framework and MAREA are consistent to those previously published [9,50]. 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 have 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 [41,52]. 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 [47,52]. 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 [37]. 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

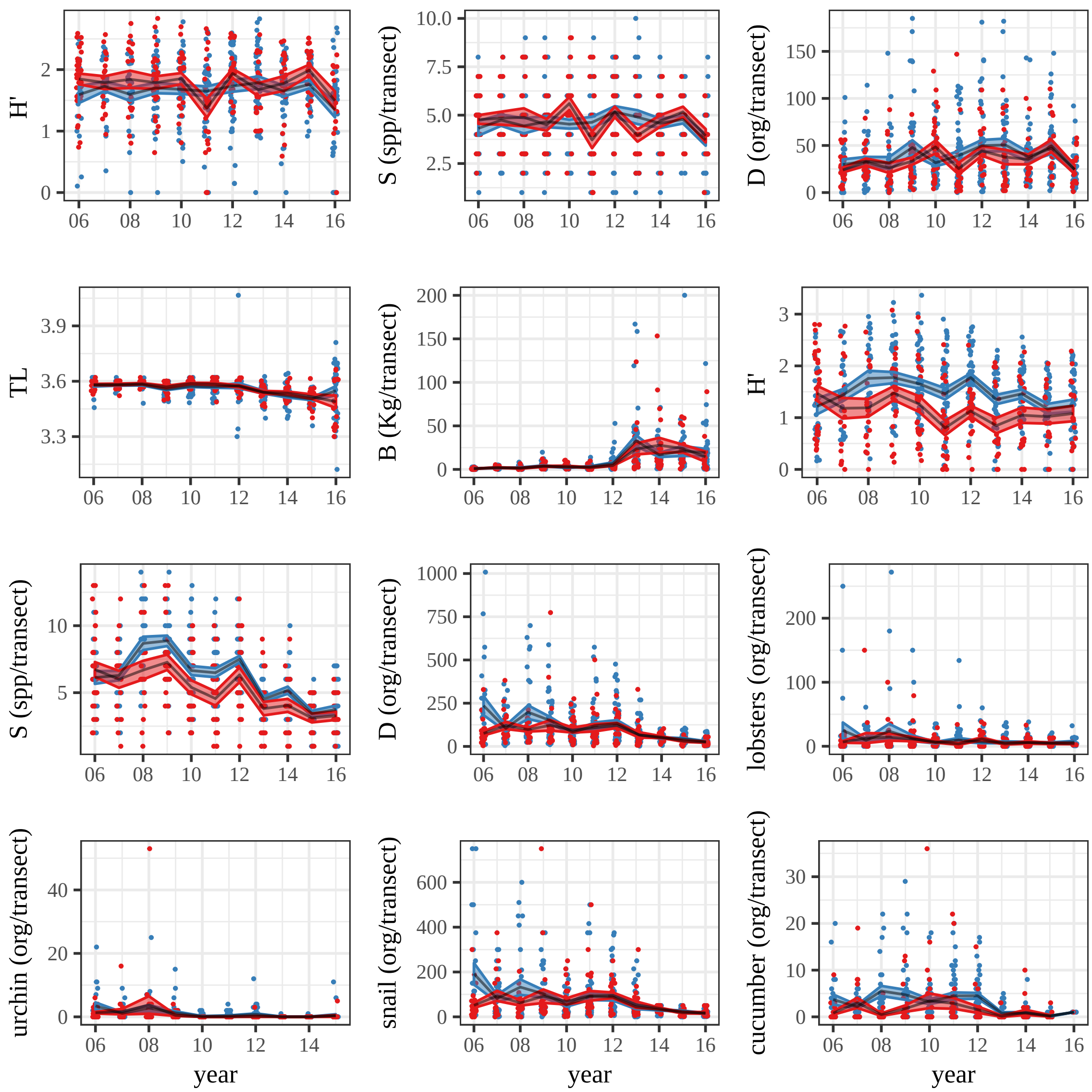

Figure 5: Plots for values of each biophysical indicator (y-axis) through time (x-axis). Red and blue correspond to the reserve and control sites, respectively. Black lines indicate yearly mean values, and ribbons indicate +/- 1 standard error. Dots are horizontally jittered to aid visualization.

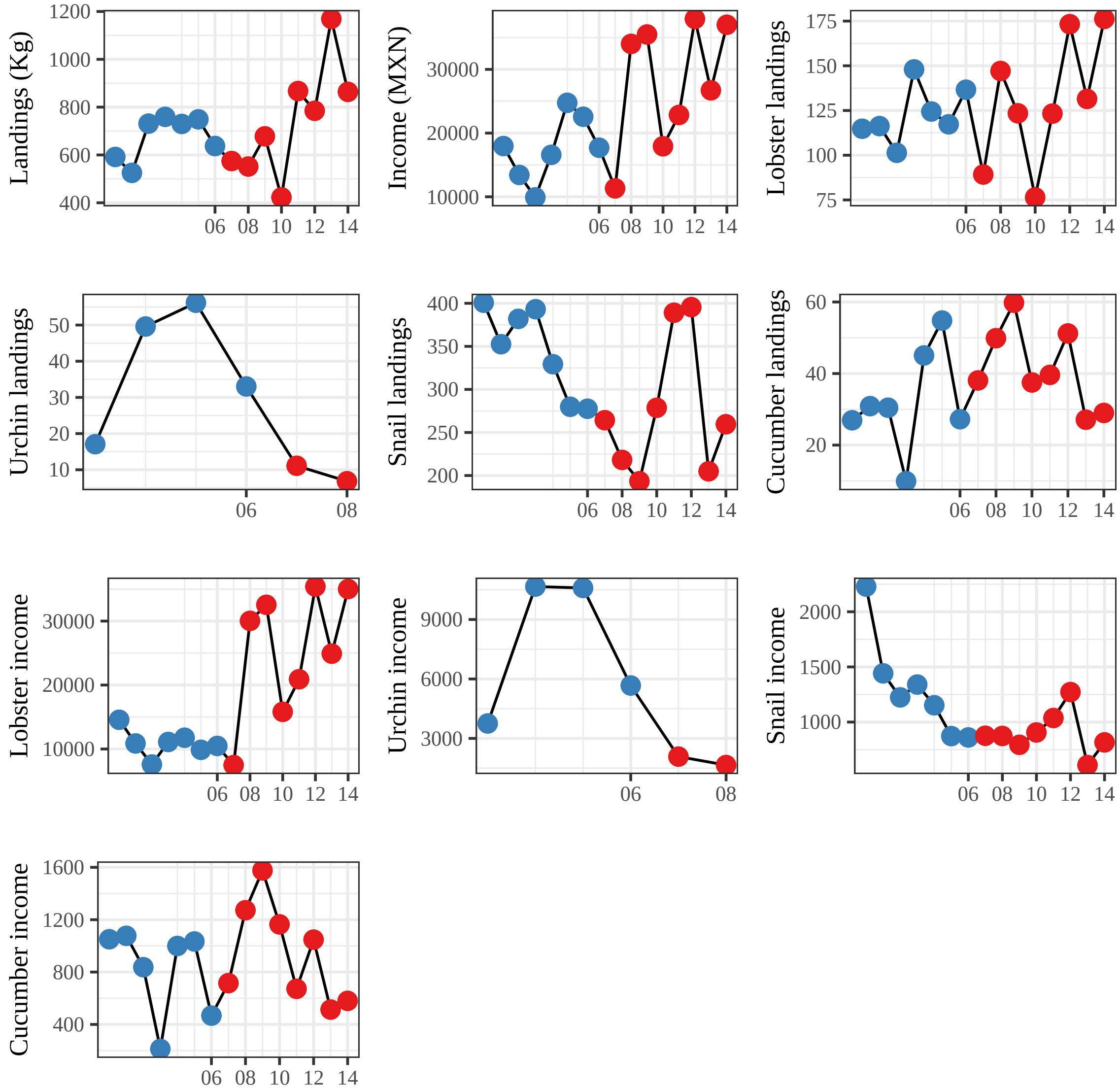

Figure 6: Plots for values of each socioeconomic indicator (y-axis) through time (x-axis). Red and blue correspond to before and after the implementation of the reserve, respectively.

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 acknowledge there is room for improvement in the way in which socioeconomic and governance data are analized. Despire this, we believe that providing a unifying platform where all can be analyzed and comprehensively presented represents a valuable step towards evidence-based effective management.

Furthermore, MAREA's value 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. Roberts CM, O'Leary BC, McCauley DJ, Cury PM, Duarte CM, Lubchenco J, et al. Marine reserves can mitigate and promote adaptation to climate change. Proc Natl Acad Sci U S A. 2017;114: 6167–6175. doi:10.1073/pnas.1701262114

11. 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

12. Edgar GJ, Stuart-Smith RD, Willis TJ, Kininmonth S, Baker SC, Banks S, et al. Global conservation outcomes depend on marine protected areas with five key features. Nature. 2014;506: 216–220. doi:10.1038/nature13022

13. 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

14. 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

15. 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

16. 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

17. Rodriguez AG, Fanning LM. Assessing marine protected areas effectiveness: A case study with the tobago cays marine park. OJMS. 2017;07: 379–408. doi:10.4236/ojms.2017.73027

18. 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

19. 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

20. Ferraro PJ, Pattanayak SK. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. PLoS Biol. 2006;4: e105. doi:10.1371/journal.pbio.0040105

21. 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

22. 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

23. 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

24. 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

25. 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

26. Mascia MB, Fox HE, Glew L, Ahmadia GN, Agrawal A, Barnes M, et al. A novel framework for analyzing conservation impacts: Evaluation, theory, and marine protected areas. Ann N Y Acad Sci. 2017;1399: 93–115. doi:10.1111/nyas.13428

27. 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

28. 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

29. 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

30. 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

31. 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

32. 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

33. 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

34. Dowling N, Wilson J, Rudd M, Babcock E, Caillaux M, Cope J, et al. FishPath: A decision support system for assessing and managing data- and capacity- limited fisheries. In: Quinn II T, Armstrong J, Baker M, Heifetz J, Witherell D, editors. Assessing and managing data-limited fish stocks. Alaska Sea Grant, University of Alaska Fairbansk; 2016. doi:10.4027/amdlfs.2016.03

35. 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

36. 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

37. 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;

38. LGEEPA. Ley general del equilibrio ecológico y la protección al ambiente. DOF. 2017; Available: http://www.diputados.gob.mx/LeyesBiblio/pdf/148/_240117.pdf

39. 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

40. OECD. Prices - inflation (cpi) - oecd data [Internet]. 2017. Available: https://data.oecd.org/price/inflation-cpi.htm

41. 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

42. 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/

43. 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

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

45. 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

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

47. 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

48. 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

49. Afflerbach JC, Lester SE, Dougherty DT, Poon SE. A global survey of -reserves, territorial use rights for fisheries coupled with marine reserves. Global Ecology and Conservation. 2014;2: 97–106. doi:10.1016/j.gecco.2014.08.001

50. 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

51. 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.

52. 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