A FRAMEWORK TO EVALUATE THE EFFECTIVENESS OF NO-TAKE MARINE RESERVES IN MEXICO

A Group Project submitted in partial satisfaction of the requirements for the degree of
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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Christopher Costello

Date

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Abstract

No-take reserves are often implemented to recover overfished stocks. In Mexico, the number of reserves has recently grown due to regulations that allow fishers to gain legal recognition of these areas. While the regulations include instructions for implementation, no guidelines are provided for monitoring or evaluating reserves. Comunidad y Biodiversidad (COBI) has been involved in the creation of no-take marine reserves distributed across Mexico. Current methods for reserve evaluation are not standardized and rely solely on biological data, excluding socioeconomic and governance dimensions. We developed a framework to evaluate the effectiveness of reserves by matching 7 commonly-stated management objectives to a set of 29 biophysical, socioeconomic, and governance indicators. 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 reserve implementation. Governance indicators are analyzed based on literature, identifying common governance structures and their associated effectiveness. To make the framework accessible to fishers and managers, we developed a guidebook that suggests methods of data collection and analysis, and an open-source web-based application that automates the analyses. Though designed for Mexican reserves, our framework can be applied to no-take marine reserves worldwide.

Executive summary

Overfishing and unsustainable fishing practices are major threats to the conservation of marine ecosystems around the world; this is particularly true for small-scale fisheries. Implementation of no-take zones (*i.e.* areas where the capture of one or more species is prohibited) is frequently proposed to help fish stocks rebound and to enhance nearby fishing areas. 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.

Comunidad y Biodiversidad (COBI) is an NGO which aims to promote marine conservation by facilitating the participation of fishermen in the design and management of community-based marine reserves in Mexico. COBI has been involved in the establishment of both government- and community-based marine reserves located in the Caribbean, Gulf of California, and the Pacific side of the Baja Peninsula.

Before creating the reserves, COBI visits the interested fishing community, records basic social and economic data, and performs underwater ecological surveys to provide baseline knowledge of the marine resources and their habitat. Fishers then design their reserves according to traditional knowledge, scientific data collected from underwater surveys, and accessibility of the area for monitoring. While reserves are implemented, COBI trains fishermen to collect biophysical data via underwater ecological surveys and oceanographic monitoring.

After many years of collaboration with fishermen, COBI has been involved in the creation of 29 community-based no-take marine reserves (21,106 hectares) distributed among 13 different communities in the Gulf of California, Pacific coast of Baja Peninsula, and the Caribbean. They also collaborated with government agencies to design and monitor 10 Marine Protected Areas (617,703 hectares) with no-take marine reserves (58,348 hectares) within their perimeters. These numbers represent a major advance in terms of marine conservation and community involvement, but the extent to which these reserves have met their objectives is unclear. Major differences in culture, natural resources, vulnerabilities, and governance structures between communities hinder the use of conventional frameworks for evaluating the effectiveness of marine reserves. As such, there is a strong need for an appropriate tool capable of measuring reserve effectiveness under these varying conditions.

Currently, only a few frameworks exist that provide indicators of effectiveness of MPAs (Pomeroy et al. 2005) and fisheries (Ostrom 2009; Basurto and Nenadovic 2012). However, these frameworks are general and not tailored to the local biophysical conditions, and socioeconomic and governance structures in Mexico. Adapting existing frameworks for Mexico was one of the motivations for COBI to work with a team of master's students from the Bren School. As the main deliverable of this project, COBI requested a framework that could be used by both managers and fishers in evaluating the effectiveness of the no-take reserves.

Our guidebook instructs users how to select appropriate biophysical, socioeconomic, and governance indicators, collect data for each indicator, format databases, and determine how well each reserve has met its stated objectives. We also developed a user-friendly application named

MAREA (Marine Reserve Evaluation Application) that automates the necessary analyses to evaluate the effectiveness of the marine no-take reserves, and provides the user with results that are simple to interpret. An explanation of the analyses performed by MAREA and examples of how to use the app are also provided in the guidebook. The final sections of the guidebook discuss how the user should interpret results and provides recommendations on how to improve reserve effectiveness.

Though our framework is designed for Mexican no-take marine reserves, we believe that the methodology of how to select indicators, collect data, and perform appropriate analyses can be applied to no-take marine reserves worldwide. The provided list of biophysical, socioeconomic, and governance indicators, and the real-world examples of how to evaluate reserve success based on these indicators, are applicable to small-scale fisheries across the globe. Furthermore, the guidebook is written in Spanish/English and is geared toward a non-academic audience to ensure that it is easily understandable and usable by both managers and fishers in Spanish- and English-speaking countries.

Background and Significance

Marine Reserves

Overfishing and unsustainable fishing practices are some of the major threats to the conservation of marine ecosystems around the world (Pauly et al. 2005; Halpern et al. 2008). No-take marine reserves (marine reserves, hereinafter) are areas where the capture of one or more species is prohibited (IUCN-Ia Reserve types; IUCN 2017). These are frequently proposed to help fish stocks rebound or enhance nearby fishing areas (Lester and Halpern 2008; Lester et al. 2009). While marine reserves have proven to increase biomass (Lester et al. 2009; Aburto-Oropeza et al. 2011), enhance resilience within the reserve's borders (Micheli et al. 2012), and preserve genetic diversity (Munguía-Vega et al. 2015), it is not uncommon to find sites with poor management. Though biophysical aspects are important to reserve success, their effectiveness also depends on the socioeconomic status and governance system of the local fishing community (Basurto et al. 2013), dimensions largely ignored until recently.

Marine reserves in Mexico

No-take marine reserves have been traditionally established as core zones within "Biosphere Reserves" (BR). These areas are managed by the National Commission of Natural Protected Areas (CONANP). Until today, 39 BRs in Mexico protect some portion of the marine environment. However, only 25 of these include (small) core zones where fishing is off-limits. While CONANP has made efforts to include users and stakeholders in the creation of these reserves, the process is still characterized by a top-down approach, which can lead to a lack of compliance from users. The agency's insufficient funding and personnel limit monitoring and enforcement of the reserves, thus hindering reserve performance.

As a way to provide a bottom-up alternative to the implementation of marine reserves, Non-Government Organizations (NGOs) worked tightly with fishing communities to establish community-based marine reserves (Uribe et al. 2010). These are commonly established within the premises of "concessions," a form of territorial use rights for fisheries (TURF). By allowing fishers design their own reserves, a larger portion of the community agrees with the defined boundaries, and thus, respect them (Gelcich and Donlan 2015; Espinosa-Romero et al. 2014; Beger et al. 2004). Additionally, fishers are allowed to implement the reserves for a fixed period of time (typically 5 years), after which the area can be reopened to fishing. This gives fishers a sense of confidence that, if needed, they will still have access to the area to fish[1]. The reserves are directly enforced and monitored by the users who often use small skiffs as patrol

[1] So far, only one community has decided to reopen their reserves. All others have decided to continue their conservation efforts.

boats or spot illegal activity from land. Nevertheless, these reserves lack legal recognition; thus, infractors cannot be held accountable for their lack of compliance.

However, a 2014 regulation (NOM-049-SAG/PESC 2014) allowed fishers to request the establishment of marine reserves under the name of Fishing Refuges (FRs). Management of FRs combines a top-down and bottom-up approach d by granting legal recognition to reserves proposed by communities. Upon revision by the Fishery Management Agency (CONAPESCA) and the Fisheries Research Institute (INAPESCA), the fishing refuges are established for the period of time requested by fishers[2]. Monitoring and enforcement of these reserves is typically done by the fishing community[2], often with help from local NGOs. Until this regulatory change, reserves established by fishers had no legal support, and were only recognized by themselves. As of today, 35 Fishing Refuges have been established in the Pacific, Gulf of California, and Caribbean coasts of Mexico.

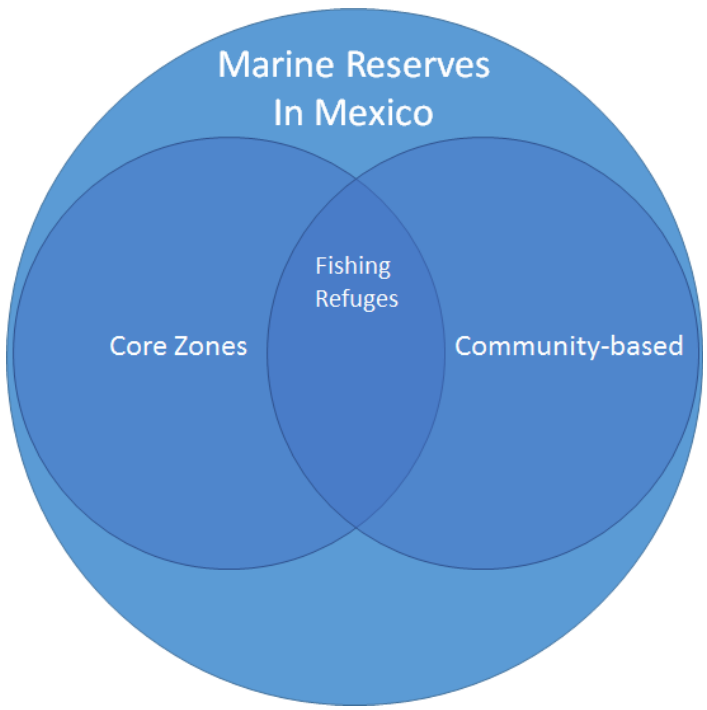

Figure 1- Venn diagram of marine reserves in Mexico. Core zones inside Biosphere Reserves, community-based reserves, and Fishing Refuges are types of no-take marine reserves in Mexico. Fishing Refuges are depicted as the intersection between the bottom-up approaches from community-based reserves and the top-down approach of providing legal support for core zones inside Biosphere Reserves.

[2] As exceptions, "Zona de Refugio Pesquero Golfo de Ulloa" and "Zona de Refugio Pesquero Akumal", created by CONAPESCA as closure zones to reduce bycatch of sea turtles.

Independent of the mechanism used to implement the reserve, they can be categorized by their degree of protection as **total** or **partial**, or by their timespan as **permanent** or **temporary**:

- Total reserves are completely no-take and all extractive activities are off-limits.
- Partial reserves allow the extraction of specific species or use of specific fishing gears.
- Permanent reserves are put in place forever and extraction is only allowed if it is a partial reserve.
- Temporary reserves are put in place for a fixed period of time and then re-opened to allow fishing.

Thus, a total permanent reserve will prohibit extraction forever, while a temporary partial reserve will prohibit extraction of some particular resources for a fixed period of time. It is worth mentioning that core zones within BRs are always total permanent reserves.

While new Mexican legislation has allowed for important advances in marine conservation, the extent to which these reserves have been successful remains unknown. While some of the existing reserves have been evaluated, they are often treated as common MPAs, disregarding their no-take aspect. Thus, there is a need for a standardized framework to evaluate the effectiveness of no-take marine reserves in Mexico.

Comunidad y Biodiversidad and Marine Conservation in Mexico

Comunidad y Biodiversidad (COBI) is an NGO that promotes marine conservation through community involvement. After many years of collaboration with fishers, COBI has been involved in the creation of 29 community-based no-take marine reserves distributed among 13 different communities in the Gulf of California, Pacific coast of Baja Peninsula, and the Caribbean. They also collaborate with government agencies to design and monitor core zones within Biosphere Reserves. While these efforts represent a major advance in terms of marine conservation and community involvement, the extent to which these reserves have met their objectives remains unclear due to the absence of a framework to evaluate them. There are major differences in culture, natural resources, vulnerabilities, and governance structures between communities. This hinders the use of conventional frameworks that evaluate the effectiveness of marine reserves, and calls for the development of an appropriate tool capable of properly measuring the effectiveness of Mexican no-take marine reserves. Providing a tool to assess of the performance of these reserves will not only provide COBI with information to inform decision-making, but will also empower fishers with the necessary information to manage their own reserves.

Significance

Currently, only a few frameworks exist that provide indicators of effectiveness for MPAs (Pomeroy et al. 2005) and fisheries (Ostrom 2009; Basurto and Nenadovic 2012). The IUCN framework provides a comprehensive list of biophysical, socioeconomic, and governance indicators, and how these indicators might be measured. However, these frameworks are general and not tailored to no-take reserves nor the local biophysical conditions, and socioeconomic and governance structures in Mexico. Furthermore, these frameworks do not describe how to use these indicators or provide a tool for evaluating them.

The lack of a comprehensive framework --or the complexity of existing ones, which alienate non-experts-- calls for the development of a new framework. This was one of the motivations for COBI to work with a team of master's students from the Bren School. As the main deliverable of this project, COBI requested a framework that could be used by both managers and fishers in evaluating the status of the no-take reserves.

We developed a framework to evaluate no-take marine reserves. While motivated by the need to evaluate Fishing Refuges, this framework was designed to encompass all forms of no-take marine reserves (*i.e.* Fishing Refuges, core zones of Biosphere Reserves, and community-based marine reserves). Our framework incorporates biological, socioeconomic, and governance dimensions, and provides a list of common objectives, their corresponding indicators, and standardized methodologies to analyze the data, while our web-based application is a user-friendly tool that allows users to automate the analyses and easily interpret results.

Project Objectives

The main objective of the project was to build a framework that enables fishers and managers to evaluate the effectiveness of no-take marine reserves in Mexico. Particular objectives were then divided into:

1. Identify the objectives of existing marine reserves in Mexico.
2. Determine a set of biophysical, socioeconomic, and governance indicators that measure the performance of the reserve and achievement of reserve objectives.
3. Develop a standardized and replicable set of analyses to evaluate the indicators.
4. Build a web-based application to automate the proposed analyses.
5. Develop an English/Spanish guidebook to aid fishers and managers in implementing the framework.

Methods

Reserve objectives

Objectives are the stated goals for which a reserve has been established. The list of objectives was gathered through a literature review from the reserves' stated objectives in official documents such as the Estudios Tecnicos Justificativos (ETJ), agreements, decrees, and specific legislation (NOM 049). Even though each reserve -or set of reserves- has its own goals, it was possible to identify seven main categories of objectives:

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

Selection of Indicators

Based on these seven objectives, we determined a set of indicators to evaluate the effectiveness of no-take marine reserves in Mexico. The list of indicators was built through a review of scientific literature, where we identified indicators that were used to measure similar objectives. The indicators were also presented at a workshop, where members of fishery management agencies (INAPESCA, CONAPESCA) and NGOs (COBI, Niparajá, The Nature Conservancy), provided input. The list of indicators was also evaluated by our Faculty Advisor, Client, and External Advisors. Our final list of indicators is tailored to the objectives of no-take reserves in Mexico and only includes indicators can be measured by existing data or data that can be easily be obtained by our client.

Indicators are divided into three main types: biophysical, socioeconomic, and governance. Biophysical indicators focus on fish and invertebrate communities that are evaluated using underwater ecological survey data and natural disturbances that may impact these communities. Socioeconomic indicators reflect the performance of the fishery in terms of catches, income from catches and availability of alternative livelihoods. Governance indicators describe the governance structures under which the community operates.

These indicators may be numeric or descriptive. Numeric indicators will respond to the effect of the reserve, while the descriptive indicators may hinder or benefit reserve effectiveness. Most biophysical and socioeconomic indicators are numeric. Natural disturbance, alternative economic opportunities and the governance indicators are descriptive. The following is a list of the three types of indicators:

Biophysical Indicators:

1. Biomass
2. Density
3. Density of mature organisms
4. Mean trophic level
5. Natural disturbance
6. Richness
7. Shannon diversity index

Socioeconomic Indicators:

1. Alternative economic opportunities
2. Income from landings
3. Landings

Governance Indicators:

1. Access to the fishery
2. Illegal harvesting
3. Internal regulation
4. Legal recognition of the reserve
5. Management plan
6. Membership to fisher organizations
7. Number of fishers
8. Perceived effectiveness
9. Reasoning for reserve location
10. Representation
11. Reserve enforcement
12. Reserve type
13. Size of the reserve
14. Social impact of reserve
15. Type of fishers organizations

The final list of indicators, with detailed descriptions, can be found in section 3 of our guidebook. This section provides a describes how descriptive indicators and the reserve itself are expected to affect the numeric biophysical and socioeconomic indicators.

Data Description

Obtaining high-quality data is one of the most important steps in evaluating the effectiveness of reserves. The analysis, results and subsequent suggestions for how to improve management are based on this information. In the guidebook, we described the data needed to perform the analysis of each indicator, as well as, how to collect and format the data.

Biophysical data

The data collected in the underwater ecological surveys includes observed fish and invertebrate richness and abundances, as well as total length for fish. This information is obtained via 30m-long belt transects with a sampling window of 2 m X 2 m. Transect monitoring is performed yearly in each reserve, and its corresponding control site(s). Between 10 and 24 transects are performed in each site at depths between 1 and 30 m.

Information such as species-specific allometric growth parameters, trophic levels, and size at maturity (LT_{50}) was found in the literature (Marks and Klomp 2003), or via web databases (*e.g.* FishBase; (Froese and Pauly 2016).

Socioeconomic data

The data for this section includes regional landings (recorded by a government agency or at the community-level) and information on average annual price per kilo for each species.

Governance data

After selecting the indicators, the group checked for available governance data that matched the indicators. Though some of the data was available in the literature, there were gaps that needed to be addressed. We sought to fill these gaps through the creation of a survey, which focuses on the perceptions of fishers.

As part of the framework, our group designed a survey to obtain missing data by interviewing community leaders and fishers. The first draft of the survey was tested over the summer in different fishing communities in Mexico. With the feedback we received from fishers and interviewers, we revised the questions. We used a survey from the Natural History Society Niparajá CA that had been tested and successfully applied to fishers as a reference for wording the questions.

The second draft of the survey was tested during a field trip to the community of El Rosario. After this second trial, we determined that the survey was considered too long to be answered by the average fisher. Therefore, we divided the survey into 2 parts: one to be answered only by community leaders, and the other to be answered by everyone else. This reduced the interview time, enabling interviewers to perform more surveys and get better answers from fishers who had only so much time and patience to answer questions. We also noticed that fishers had difficulty understanding the wording of some questions. We reworded these questions and created the final version of the survey, which can be found on the appendix A of the guidebook.

Access Database File

In order to help users record and organize data from surveys, the group created a Microsoft Access database file. The file has a user-friendly interface for inputting data. Once data is inputted, the file organizes the data into an Excel spreadsheet that has the required format for analysis using MAREA. How to use and extract the data from the file is explained in the section 5.4 of the guidebook.

Data analysis

The description of the analyses here is intended for an academic audience. Our guidebook breaks down these analyses in a simple way so fishers and managers can learn about what goes into our analysis, how it is performed, and interpret results.

It is also important to note that some indicators may take time to change. For example, biomass may not change within two years of reserve implementation, because recruitment of a particular species may take longer than two years. Our client is currently working on a project to determine how many years it takes before an effect is observed after reserve implementation. This will help set expectations for how long a manager may have to wait for indicators to change. In the meantime, we encourage reserve managers to analyze their reserve annually to determine when/if a change occurs.

Numeric Indicators

Biophysical Analysis

We are interested in determining the net effect of the reserve. To do this, we need to track changes in our indicators through time and across the reserve and control area. In ecology, this is known as a "Before-After-Control-Impact" analysis, also referred to as BACI (Smith et al. 1993). In econometrics, this is often called "Difference in Difference," or DiD. This methodology allows us to make causal inferences of the effect of the reserve (Burgess et al. 2016), while estimating the magnitude of the effect. For this analysis, we use data before and after the reserve was established for both control and reserve sites. Our guidebook describes what the control site must possess (*i.e*. similar environmental characteristics but still has fishing pressure).

The model evaluates the change of an indicator though time, and controls for the differences between the reserve and control sites. To estimate this difference, we include an interaction term between Zone (reserve - control) and Post (before - after). The model has the form:

$$I_{i,t} = \beta_0 + \Sigma_{t=2}^{T} \gamma_{i,t} Year_t + \beta_2 Zone_i + \beta_3 Zone_i \times Post_{i,t} + \beta_4 T + \beta_5 V + \beta_6 D + \epsilon_{i,t}$$

Where:

- i and t subindices indicate transect and time, respectively
- I = indicator value
- $Year$ = dummy variable for year, where the first year is coded as the reference level
- $Zone$ = dummy variable for zone, where control is coded as the reference level
- $Post$ = dummy for before/after implementation where before is coded as the reference level
- T = bottom water temperature (°C)
- V = vertical visibility (m) in the transect
- D = transect depth (m), and
- ϵ is the error term associated with the regression.

This model follows the parallel trend assumption, which states that, in the absence of a treatment, both sites would follow the same trend. The difference observed in this trend is β_3, our difference in difference (DiD) estimate. This coefficient represents the mean effect of the reserve through time.

Temperature, visibility, and depth are included as covariates that allow us to account for environmental differences between sites. They increase the precision of our estimate, because these variables affect the abundance and richness, as well as the ability of research divers to accurately count fish[3]. Coefficients are estimated with an Ordinary Least Squares regression. We calculated cluster- and heteroskedastic-robust standard errors to account for clustering (due to the spatial component) and differences in variance in the data. These standard errors inform us about how certain we are about the DiD estimate.

Because the reserve and control sites are not right next to each other, we do not expect that the reserve would affect the control site directly. However, if the reserve is very effective and there is a lot of spillover, you would expect to see an effect in the control site. Nevertheless, if there is still fishing pressure in those control sites, you would see that the trend in the reserve would still be greater than in the control site.

Socioeconomic Analysis

Unlike the biophysical indicators, we do not have a control to compare against for socioeconomic indicators. Therefore, we cannot use a BACI or DiD approach and are unable to assume that changes in these indicators are purely explained by the reserve. However, we can still extract some useful information about the relationship between the socioeconomic indicators and the implementation of the reserves. The linear regression models used compare mean income and landings before and after the implementation of the reserve. MAREA adjusts income from landings for inflation using Mexico's Consumer Price Index (CPI) available at the Organization for Economic Co-operation and Development (OECD) website.

The model has the following structure:

$$I_t = \beta_0 + \beta_1 Y_t + \varepsilon_t$$

Where:

- β_x = represent the coefficients for each variable
- *I* = The indicator being measured (landings or income from landings)
- *Y*= A dummy variable for years as before or after the implementation of the reserve
- Subindex *t* represent time steps
- ϵ is the error term associated with the regression.

Descriptive indicators

We discussed several methods for evaluating descriptive indicators (natural disturbance, alternative likelihood and governance indicators). Because most of these indicators (e.g. type of fishing organization) are not randomly assigned, causally linking them to reserve effectiveness is not possible. Instead, we approach this by: i) Including short narratives of the descriptive indicators in the technical report generated by MAREA, and ii) Whenever the value of a particular indicator

[3] Lower visibilities, for example, might limit the number of fish a diver sees. In contrast, more visibility might cause divers to include fish outside the 2 X 2 m sampling window, resulting in higher richness or abundances.

is associated with detrimental impacts on the fishery, we provide users with a warning message and an explanation based on examples extracted from scientific literature. For example, if Governance indicator # 1 "*Type of access to the fishery*" has a value of "*Open Access,*" we explain that "*Literature suggests that Open Access leads to depletion of fish stocks, and causes overall profits to be null.*" By including this descriptive information in the report, we bring all the information together, facilitating decision making processes.

Creation of MAREA with a Shiny App

The purpose of MAREA is to automate the analyses of our framework, ensuring replicability and ease of application. The app produces a color-coded scorecard that helps users interpret results at a glance, and generates a technical report that includes graphs of each indicator through time, along with regression tables containing the coefficients of the fitted models. The app is free and all the user needs is internet access and the link to the webpage.

MAREA has been tested by our advisors, client and peers for correct functioning and formatting, and to check if it accomplished the desired data analysis. The Shiny app can be found at the following link: https://turfeffect.shinyapps.io/marea/. The guidebook provides a detailed explanation of how to use the Shiny app and interpret results.

MAREA was developed as a Shiny App, using the Shiny 1.0.0 package (Chang et al. 2017). This provides a framework to join R, CSS, JavaScript, and HTML into a single product. R code provides the functionality (the processes), CSS controls the appearance, JavaScript connects the interface to R, and HTML provides a wrapper around all this.

The app is composed of two main parts, the UI (User Interface) and the server. The UI contains all the visual elements, like buttons, dialog boxes, graphs and other elements with which the user interacts. The server contains the functionality of the app, and controls the processes ran by it. For example, the UI contains a button to "Download a Report." When the user clicks this button, the server triggers the process of creating a report and makes it available through a download menu. After development, the app is deployed into a server where R is installed. The app is then accessed as if it was a web page.

After MAREA performs the analyses, a scorecard will be displayed. This will show a Global score box that indicates the overall score for the reserve, an overall score box for each of the three types of indicators (biophysical, socioeconomic, governance), and one score box for each selected indicator. The color of general boxes will be assigned based on the percentage of positive indicators, using 20% intervals.

When the user selects objectives on the Shiny app, it automatically selects the appropriate indicators for the selected objectives. Thus, the overall score does not include indicators that are not needed to measure the selected objectives. Nevertheless, the user can unselect indicators that they do not think are a good measure or select additional indicators for that objective. This will allow users from different communities (or governments) to choose to focus on indicators that are most important to their community. However, the selected indicators will still have equal weights to avoid providing an incentive for the user to change the weight to get a better reserve score. In addition, we focused on the percent of indicators that are positive so that the user can decide how much they care about which indicators are positive or negative. For each indicator box, the color will be assigned based on the DiD estimate. A yellow color will indicate that no change was observed, while green and red colors indicate positive and negative changes, respectively. Thanks to the way in which MAREA performs the analysis, we can not only obtain a positive or negative value of our DiD estimate, but also a p-value associated with it. We incorporate this into the color scheme by having two shades of green and red (See legend below).

For descriptive indicators, color is based on whether the value of the indicator deviates from what scientific research has described as being beneficial to reserve effectiveness. Green is assigned if the indicator is in line with what is considered to be beneficial, and red for what is detrimental to reserve effectiveness.

Figure 2- Legend to interpret the box colors on the scorecard generated by MAREA. Values represent the p-value associated with the DiD estimate for biophysical indicators and slope estimate for socioeconomic indicators. + and - indicate if the estimate was positive or negative, respectively.

After viewing the scorecard, the user can then click a button to generate a report of results. The detailed results report generated by MAREA contains the color-coded scorecard, time series plots for the reserve and control area, and tables containing the model residual standard error, F statistic and R^2 value, as well as, model coefficients and their associated p-values for each indicator.

Recommendations for the Improvement of Reserves:

If any of the biophysical or socioeconomic indicators were yellow, orange, or red on the scorecard, the user will want to know possible reasons for why the reserve has not been effective and how to make improvements. Looking at the descriptive indicators may provide the user with valuable insight. For example, if illegal fishing has increased, the community may want to increase enforcement of the reserve and/or seek legal recognition of the reserve. Table 8 in Appendix E of the guidebook describes which types of descriptive indicators are expected to have a beneficial, detrimental or no impact on reserve effectiveness based on the literature. Changing these indicators to the type expected to be most beneficial may help increase reserve effectiveness. Note: There is no proven causal relationship between a type of descriptive indicator and reserve effectiveness. Following these recommendations of improvement may not lead to increased effectiveness as these improvements are based on literature and each place may have different attributes.

Results

Due to the nature of our project, where rather than asking us to evaluate the reserves, we were asked to build a framework that could be used to evaluate the reserves at any point in time, our results include the tables where objectives are matched with indicators, along with a summary of the main deliverables (guidebook and app).

Selection of indicators

The tables below are used for selecting indicators based on the seven commonly-stated objectives of existing reserves in Mexico we identified. These are the indicators we chose to incorporate into our framework, based on stated objectives, data availability and literature review.

The reserve objectives are located on the left-hand side of the biophysical table (Table 3.2) and socioeconomic table (Table 3.3). A dot in the row of the selected objective means that biophysical or socioeconomic indicator should be selected in order to measure the effectiveness of the reserve. For governance indicators, the user would select all the indicators listed in section 3.1.3 of the guidebook to evaluate the reserve.

Table 1- Table matching the biophysical indicators with stated objectives of reserves currently established in Mexico.

Objectives	Biophysical								
	Biomass	Biomass of objective species	Density	Density of mature organisms	Density of objective species	Natural Disturbance	Richness	Shannon Diversity Index	Trophic Level
Avoid overexploitation	*	*	*	*	*	*			*
Conserve species under a special protection regimen		*		*	*	*			
Contribute to maintain biological process (reproduction, recruitment, growth, feeding)	*		*	*		*	*	*	*
Improve fishery production in nearby waters	*	*	*	*	*	*			
Preserve biological diversity and the ecosystem	*		*	*		*	*	*	*
Recover overexploited species		*		*	*	*			
Recover species of economic interest		*		*	*	*			

Table 2- Table matching the socioeconomic indicators with stated objectives of reserves currently established in Mexico.

Objectives	Socio-economical				
	Alternative economic opportunities	Income by landings	Income by landings of objective species	Landings	Landings of objective species
Avoid overexploitation	*	*	*	*	*
Conserve species under a special protection regimen	*	*		*	
Contribute to maintain biological process (reproduction, recruitment, growth, feeding)	*				
Improve fishery production in nearby waters	*	*	*	*	*
Preserve biological diversity and the ecosystem	*				
Recover overexploited species	*		*		*
Recover species of economic interest	*	*	*	*	*

Table 3- Analysis of descriptive indicators based on literature. Options highlighted in red are expected to be detrimental to reserve effectiveness. Options in green are expected to be beneficial.

Type of indicator	Indicator	Options	Brief Explanation
Biophysical	Natural Disturbance	Yes	Natural disturbance may decrease biophysical indicators, and therefore, socioeconomic indicators (*i.e.* landings and income from landings).
		No	With no large natural disturbances, biophysical and socioeconomic indicators are more likely to stay the same and be less variable.
Socioeconomic	Alternative economic opportunities	Yes	Less illegal fishing is likely to occur if other sources of income are available to make up for the possible loss of income from landings from the closure of fishing grounds.
		No	With no alternative economic opportunities, illegal fishing may increase due to the possible loss of income from landings from the closure of fishing grounds.
Governance	Fishery access	TURF	TURF incentives fishers to manage their resources.

		Permits	Reduces effort.
		Quotas for the whole fishery	Reduces effort.
		Individual Quotas	Reduces effort.
		Open Access	The fishery is unrestricted. This can lead to long-term, negative impacts on the marine environment and organisms that live there.
	Number of fishers	Lower	If effort, as measured by the number of fishers, decreases, the density and abundance of fished species will increase.
		Same	If effort stays the same, the density and abundance of fished species will stay the same.
		Higher	If effort increases, the density and abundance of fished species will decrease.
	Legal recognition of reserve	Yes	There will be a higher threat of punishment (as only the Mexican government can punish illegal fishers who are not part of the local fishing community), which de-incentivizes illegal fishing.
		No	There will be a low threat of punishment as the local fishing community cannot punish illegal fishers.
	Reserve type	Temporary	The reserve has not been in place long enough to protect species. It may be reopened for fishing in between renewal.
		Permanent.	The reserve has been in place long enough to protect species.
		Partial	Fishing disturbance will still occur. Illegal fishing is more difficult to spot.
		Total	No fishing disturbance. Illegal fishing is easy to spot.
		Inside TURF	Fishers are more likely to profit from the benefit of the reserve, which encourages them to protect their resources.
		Outside TURF	People outside of the local fishing community also benefit from the reserve. The de-incentivizes the local community from bearing the economic costs of protection themselves.

	Illegal harvesting	Lower	Biophysical indicators (*e.g.* biomass, density), and therefore, socioeconomic indicators (*i.e.* landings and income from landings), will increase due to decreased fishing pressure and disturbance.
		Same	Illegal fishing decreases biophysical indicators (*e.g.* biomass, density), and therefore, socioeconomic indicators (*i.e.* landings and income from landings).
		Higher	Increased illegal fishing decreases biophysical indicators (*e.g.* biomass, density), and therefore, socioeconomic indicators (*i.e.* landings and income from landings).
	Management plan	Yes	There is a better chance that members will be aware of the rules and limits of the reserve. Therefore, it is more more likely that rules will be obeyed.
		No	Members will not be aware of the rules and limits of the reserve. Therefore, it is more less likely that rules will be obeyed.
	Reserve enforcement	Patrol boats	Reserves are small. Therefore, patrol boats are effective.
		Sighting from land	Reserves in Mexico are small and close to shore. Therefore, sighting from land is effective.
		VMS	Reserves in Mexico are small. VMS resolution is too large to determine whether someone is inside or outside the reserve.
		Government	Government participation can strengthen enforcement as it has the authority to punish reserve violators.
		Community	Engaging fishers with the monitoring of their reserves incentivizes them to protect their resources.
	Size of reserve	Smaller than home range	May not be large enough to protect the objective species.
		Same as home range	Protects the objective species and enough surveillance can be applied.
		Bigger than the home range	May be difficult to provide enough surveillance.
	Reasoning for reserve location	Scientific knowledge	The location is based on peer-reviewed research of the requirements of species that live there.

		Community knowledge	Provides a better understanding of local conditions.
		Without prior knowledge	The reserve will not have a significant positive impact on protected species as it may be placed in areas that are not important to the species.
	Membership to fisher organizations	Yes	Provides a sense of ownership of resources and cooperation with the other members.
		No	Not belonging to a group might reduce the capacity of cooperation and participation.
	Type of fisher organizations	Cooperative	Provides a platform for communication and cooperation. Cooperatives promote a sense of ownership and responsibility to manage resources.
		Federation or confederation	Provides a platform for communication and cooperation. Federations and confederations promote a sense of ownership and responsibility to manage resources.
		Association	Provides a platform for communication and cooperation. However, associations do not promote a sense of ownership and responsibility to manage resources.
		Union	Provides a platform for communication and cooperation. However, unions do not promote a sense of ownership and responsibility to manage resources.
	Representation	Bottom-up	Community members are empowered to develop their own rules, but may not have enough authority to make them effective in practice.
		Top-down	When upper management *(i.e.* government, NGOs and researchers) is involved in designing management plans, the plan may not represent the needs of the community and might be hard to enforce
		Combination of bottom-up and top-down	With the support from upper management entities, the enforcement of local rules can be achieved
	Internal Regulation	Yes	An organization’s internal set of rules are often more strict than formally recognized regulations and tailored to meet reserve objectives.
		No	Formally recognized regulations are often not strict enough to meet reserve objectives.

	Perceived Effectiveness	Yes	If members of the fisheries organizations perceive that the reserves help them meet stated objectives, then they will be more likely to comply with the rules of the no-take area. This is because they believe that the reserve is enabling them to receive more benefits (*e.g.* more fish and larger, more valuable fish) than if the area was not protected.
		No	If members do not believe they are receiving benefits, they are less likely to comply with reserve rules.
	Social Impact of Reserve	Positive	If community members believe that the reserve has had a positive effect on their local community (in terms of local economy, governance and management), they are likely to be more supportive of the reserve and comply with its rules.
		Same	If community members believe that the reserve has not had an effect on their local community (in terms of local economy, governance and management), they are less likely to be supportive of the reserve and comply with its rules.
		Negative	If community members believe that the reserve has had a negative effect on their local community (in terms of local economy, governance and management), they are unlikely to be supportive of the reserve and comply with its rules.

Guidebook

We successfully created a guidebook that walk users through implementing a framework to determine the effectiveness of no-take marine reserves. The guidebook instructs users how to select biophysical, socioeconomic, and governance indicators to measure effectiveness based on reserve objectives. It then discusses how to collect data in the field for each indicator and how to format databases to facilitate data analysis. An explanation of the necessary analyses along with examples of how to perform each analysis is provided. The final sections discuss how users should interpret the results of each analysis and provide recommendations for improvement based on these results.

Shiny App

MAREA can be used to automate the analyses in our framework. Because it was not within the scope of our project to perform the analyses ourselves, we do not have results to report on the effectiveness of no-take marine reserves in Mexico. However, our client suggested that we include example analyses in the guidebook to demonstrate how our framework could be applied. These examples are located in section 9 of the guidebook.

Discussion and Conclusion

Although there is room for improvement of the framework (*e.g.* incorporation of more indicators), the framework was designed to best fit the need of our client. Therefore, we used existing reserve objectives and data that COBI has or could realistically obtain (from their own underwater monitoring, government agencies, or conducting the proposed survey) to inform which indicators we selected for the framework. In doing so, we successfully created a framework specific to evaluating the effectiveness of no-take marine reserves in Mexico as requested by our client.

The indicators we selected are the ones we considered to be the most valuable in determining the effectiveness of no-take marine reserves in Mexico. However, there can be other elements (*e.g.* habitat quality, catch per unit effort, change in community knowledge of environmental sustainability) that could be added to widen the scope of the analysis.

We used information from the literature to establish what governance practices we expect may decrease or increase reserve effectiveness. These are general trends that might not hold true for Mexico, or another location. For example, it is unknown whether there is a causal relationship between a given reserve type and increased effectiveness of the reserve. Consequently, incorporating a recommendation, particularly a governance recommendation (*e.g.* changing the type of reserve), does not guarantee that the reserve will meet its stated objectives.

Furthermore, multiple factors may be responsible for the decreased effectiveness of a reserve, not just a single factor. This hinders the ability of managers and fishers to determine which of these factors, if any, has a disproportional large impact on reserve effectiveness, and therefore, is more cost-effective to address.

Additionally, using survey data may pose a constraint on the analysis and how our client can interpret results. Surveys capture the characteristics of the communities and allows us to collect data about what people think, feel, and know about reserves. However, surveys are prone to local biases that arise when the wording of questions causes people to interpret questions differently than what is intended. To minimize this issue, we tested the survey on fishers and community leaders and reworded to ensure that the questions are understood. Thus, we believe our client can capture useful information from the survey.

QCA would help the user determine if there is a causal relationship between a governance indicator and a biophysical and socioeconomic outcome. It also helps identify which combinations of indicators lead to greater reserve effectiveness. However, this methodology requires the creation of a table containing all the possible combinations of indicators and measured outcomes. Besides the lack of governance data and the impossibility of getting this data within the time constraint for this project, the analysis of governance data was not within the scope of the project, which is solely the creation of the framework.

This framework will be used by COBI and fishers to analyze the effectiveness of the no-take marine reserves they have helped implement and improve management of these reserves. INAPESCA (Mexican government fisheries agency) is interested in potentially implementing our framework as the go-to way of analyzing all no-take marine reserves in Mexico.

Though our framework is designed for Mexican no-take marine reserves, we believe that the methodology of how to select indicators, collect data, and perform appropriate analyses can be applied to no-take marine reserves worldwide. The provided list of biophysical, socioeconomic, and governance indicators, and the real-world examples of how to evaluate reserve success based on these indicators, are applicable to small-scale fisheries across the globe.

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