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Juan Carlos Villaseñor-Derbez[1,*], **Eréndira Aceves-Bueno**[1,*], **Stuart Fulton**[2]

[1] *Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, USA*
[2] *Comunidad y Biodiversidad A.C., Guaymas, Mexico*

Correspondence*:
Juan Carlos Villaseñor-Derbez, Bren Hall, University of California, Santa Barbara, Santa Barbara, CA, 93106
jvillasenor@bren.ucsb.edu

ABSTRACT

Abstract here

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1 INTRODUCTION

Marine ecosystems around the world sustain significant impacts due to overfishing and unsustainable fishing practices (Halpern et al., 2008; Worm et al., 2006; Pauly et al., 2005). A common approach to manage the spatial distribution of fishing effort and recover stocks is through the implementation of marine reserves (*i.e.* areas where all fishing activities are off–limits; MRs) (Afflerbach et al., 2014; Krueck et al., 2017; Sala and Giakoumi, 2017).

Marine reserve science has largely focused on understanding the ecological effects of these areas, which include increased biomass, richness, and densities of organisms within the protected regions (Lester et al., 2009; Giakoumi et al., 2017; Sala and Giakoumi, 2017), climate change mitigation (Roberts et al., 2017), and protection from environmental variability (Micheli et al., 2012). However, there is considerably less literature focusing on the relationship between socioeconomic and governance structures and their relationship to ecological effectriveness (Halpern et al., 2013; López-Angarita et al., 2014; Mascia et al., 2017) or benefits to fisheries (Krueck et al., 2017); evaluations of marine reserves rarely provide a hollistic view of the social-ecological system (López-Angarita et al., 2014). Here, we combine causal inference techniques (De Palma et al., 2018) and the social-ecological systems framework (Ostrom, 2009) to provide a comprehensive ecological and socioeconomic evaluation of four community-based marine reserves in three coastal communities in Mexico.

Marine Reserves in Mexico have been commonly implemented as "core zones" within Biosphere Reserves (BRs) that are administered by the National Commision of Protected Areas (*Comisión Nacional de Áreas Marinas Protegidas*, CONANP). While CONANP has made efforts to have a participatory process, the implementation of these zones is still characterized by top–down approaches. This motivated Civil Society Organizations (CSOs) to work with coastal communities to implement community–based marine reserves (Uribe et al., 2010), which are usually established within a Territorial Use Rights for Fisheries (TURFs); thus making them TURF–reserves (Afflerbach et al., 2014). This bottom–up approach allows fishers to disign their own reserves, which increases compliance and self–enforcement (Gelcich and Donlan, 2015;

Espinosa-Romero et al., 2014; Beger et al., 2004). However, these reserves still lack legal recognition, making them vulnerable to poaching. In 2014, a new norm (NOM-049-SAG/PESC, 2014) allowed fishers to request the legal recognition of a community–based reserve under the name of “Fishing Refugia” (*Zona de Refugio Pesquero*, FR). This new norm thus combines bottom–up approaches to design marine reserves, along with a legal recognition of the management intervention. Since then, *39* FR have been implemented along the Pacific, Gulfof Caloifornia, and Mexican Caribbean coastlines, but no formal evaluation of their effectiveness has taken place.

While there are ecological factors defining the success of a MR (*i.e.* habitat representation, initial state of protection, connectivity to other protected areas), their effectivness also depends on the socioeconomic and governance settings under which they are implemented. Literature shows that many non-ecological characteristics can play an equally important role in the effectivenes of MRs. For example, age of a reserve (*i.e.* time since its implementation), size, and habitat contained were key to the effectiveness of MRs in Palau (Friedlander et al., 2017). In the Mediterranean, Di Franco et al. (2016) identify that surveilance and enfocrement, presence of a management plan, and involvement of fishers in management and decision–making along with promotion of sustainable fishing practices were the key fators that increased stock health and income to fishers. At a global level, Edgar et al. (2014) indicate that enforcement, age, size, and isolation were important factors determining effectiveness of the reserves.

The objective of this work is twofold: i) Provide the first evaluation of community–based marine reserves in Mexico, and ii) provide a comprehensive evaluation of the social–ecological system to identify how sociocoenomic and governance characteristics relate to ecological effectiveness. With the purpose of providing a hollistic evaluation, we combine ecological, socioeconomic, and governance indicators. We use causal inference techniques to provide a measurement of the effect of the management intervention, and combine it with the social–ecological systems framework (Ostrom, 2009).

2 MATERIALS AND METHODS

2.1 Study area

We focus our evaluation in three coastal communities from the Pacific coast of Baja California (n = 1) and the Mesoamerican Reef System (n = 2; Fig 1). Isla Natividad (IN) lies west of the Baja California Peninsula (Fig 1B), where kelp forests (*Macrocystis pyrifera*) and rocky reefs are the predominant habitats. The island is home to a fishing cooperative (*Sociedad Cooperative de Producción Pesquera Buzos y Pescadores de la Baja California SCL*), that holds a TURF for spiny lobster (*Panulirus interruptus*). However, other resources like finfish (yellowtail jack, *Seriola lalandi*), sea cucumber (*Parastichopus parvimensis*), red sea urchin (*Mesocentrotus franciscanus*), snail (*Megastraea turbanica* y *M. undosa*), and abalone (*Haliotis spp*, until 2010) are also important sources of income. In 2006, the community decided to implement two community–based marine reserves within their fishing grounds, seeking to recover depleted stocks of invertebrate species (mainly lobster and abalone). Until today, these reserves are yet to be legally recognized as Fishing Refugia.

The other two communities are Maria Elena (ME; Fig 1C) and Punta Herrero (PH; Fig 1D) in the Yucatan Peninsula, where coral reefs and mangroves are the representative coastal ecosystems. ME is a fishing camp –visited intermitently during the fishing season– belonging to the Cozumel fishing cooperative. PH is home to the “José María Azcorra” fishing cooperative. The main source of income to both communities is the caribbean spinly lobster fishery (*Panulirus argus*), which is carried out within their respective TURFs. These communities also target finfish in the off season, mainly snappers (Lutjanidae) and groupers

(Serranidae). ME established eight marine reserves in 2012, and PH established four marine reserves in 2013. All these reserves are legally recognized as Fishing Refugia.

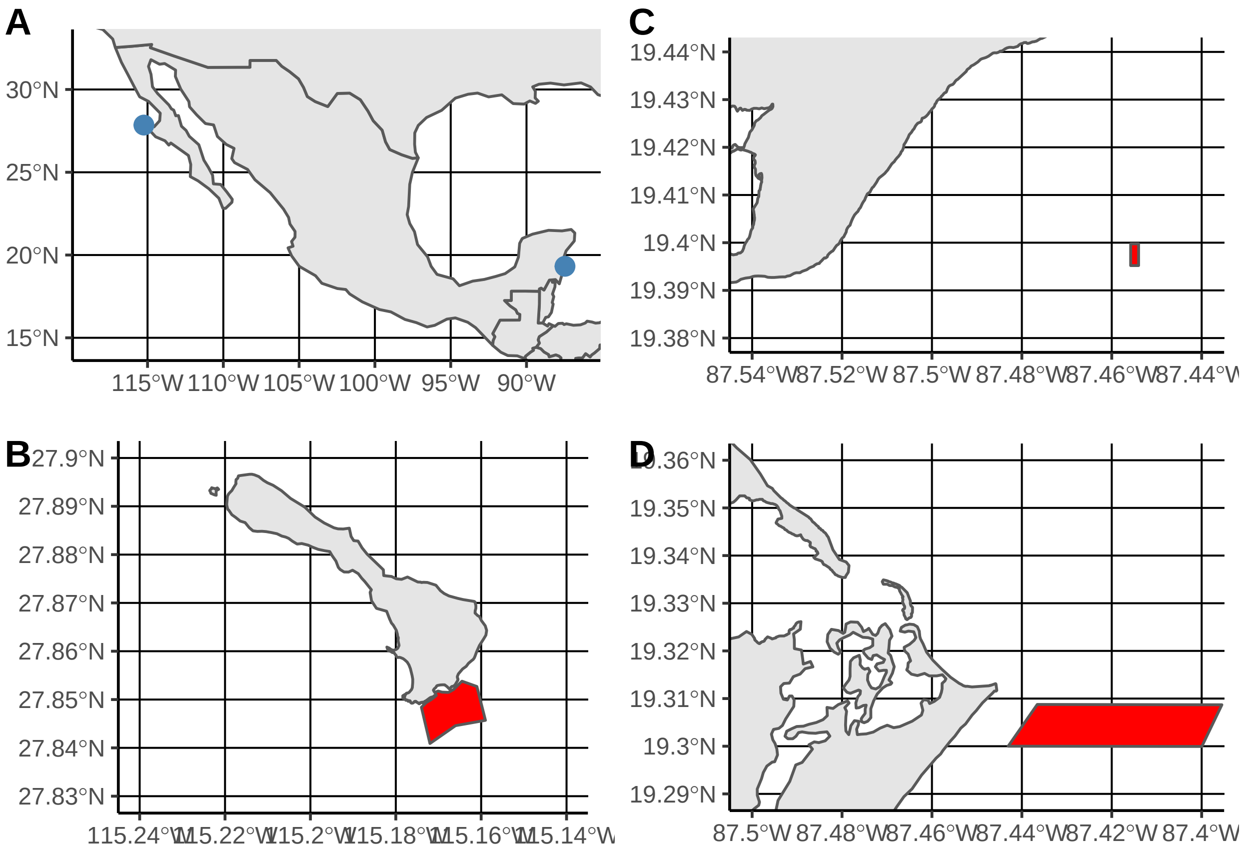

Figure 1. Location of the three coastal communities studied (A). Isla Natividad (B) is located off the Baja California Peninsula, Maria Elena (C) and Punta Herrero (D) are located in the yucatan Peninsula.

2.2 Data collection

To perform the evaluation of these reserves we use thre sources of information. Ecological data come from the annual ecological monitorings of reserve and control areas, carried out by members from each community and personnel from the Mexican CSO "Comunidad y Biodiversidad" (COBI). These monitorings record richness and abundances of fish and invertebrate species in the reservs and control sites. For fish census, size structures are also collected to derive biomass. We define control sites as regions with habitat characteristics similar to the corresponding reserves, and that presumably had the same probability of being selected as reserves during the design phase. From all the reserves in these three communities, we use the ones that have data for reserve and control sites before and after the implementation of the reserve. This provides us with a Before–After–Control–Impact (*i.e.* BACI) design that allows us to capture and control for temporal and spatial dynamics (De Palma et al., 2018; Ferraro and Pattanayak, 2006). BACI designs and causal inference techniques have proven effective to evaluate marine reserves, as they allow us to causaly attribute observed changes to the intervention (Moland et al., 2013; Villaseñor-Derbez et al., 2018). All reserves were surveyed annualy from at least one year before implementation until 2016. Table 1 shows a summary of the number of reserves, year of implementation, and number of transects for each reserve.

Table 1. Summary of commuity–based marine reserves by community. Imp = Year of implementation, Start = Year of first sampling, number of fish transects in control (Cf) and reserve (Rf) sites, and number of invertebrate transects in Control (Ci) and Reserve (Ri) sites.

Community	Reserve - Control	Imp	Start	Cf	Rf	Ci	Ri
Isla Natividad	La Plana / Las Cuevas - La Dulce / Babencho	2006	2006	405	242	415	245
Maria Elena	Cabezo - Cabezo (Control)	2012	2012	44	45	27	21
Punta Herrero	El Faro - El Faro (Control)	2013	2013	39	40	24	32
Punta Herrero	Manchon - Manchon (Control)	2013	2012	43	45	27	42

Socioeconomic data come from landing receipts reported to the National Commission for Aquaculture and Fisheries (*Comisión Nacional de Acuacultura y Pesca*; CONAPESCA). Data contain monthly lobster landings (Kg) and value (MXP) from 2000 to 2014. This information was aggregated by year, and economic values were adjusted by the Consumer Price Index (OECD, 2017) via Eq 1.

$$I_t = RI_t \times \frac{CPI_t}{CPI_T} \tag{1}$$

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 in that year (CPI_t) to the most recent year's consumer price index (CPI_T).

Governance data were collected at the community–level, using key informants to collect the necesary information on X, Y, and Z. Algo mas de Ere.

2.3 Data analysis

Following a framework that relates reserve objectives to performance indicators (Villaseñor-Derbez et al., 2018), we use five biological, two socioeconomic, and five governance indicators to evaluate these marine reserves Table 2.

Table 2. List of indicators used to evaluate the effectiveness of marine reserves, grouped by category.

Category	Indicador
Biological	Abundance
	Richness
	Shannon's diversity index
	Biomass
	Abundance of target species (lobsters)
Socioeconomic	Income from target species
	Landings from target species
Governance	Type of access to the fishery
	Perceived degree of illegal fishing
	Reserve surveilance anf enforcement
	Type of fishing organization
	Age of the reserve

Biological indicators are analyzed with a difference–in–differences analysis (Eq 2), which allows us to estimate the effect that the reserve has on the biological indicators by comparing trends across time and treatments (Moland et al., 2013; Villaseñor-Derbez et al., 2018). The analysis is performed with generalized linear models of the form:

$$I_i = \alpha_i + \gamma_{it} Year_t + \beta Zone_i + \lambda_{it} Year_t \times Zone_i + \sigma_j Spp_j + \epsilon \tag{2}$$

Where year–fixed effects are represented by $\gamma_{it} Year_t$, and $\beta Zone_i$ captures the difference between reserve ($Zone = 1$) and control ($Zone = 0$) sites. The interaction term $\lambda_{it} Year_t \times Zone_i$ represents represent the mean change in the indicator inside the reserve, for year t, with respect to the first year of evaluation in the control site (See Table 1). When evaluating biomass and abundances, we include species–fixed effects (σ_j). For abundances and richness (*i.e.* count data) the model is estimated with a quasipoisson error distribution.

Socioeconomic indicators are evaluated with a similar approach (Eq 3), where landings and income before and after the implementation of the reserve are compared:

$$I_i = \beta_0 + \beta_1 Post \tag{3}$$

This approach does not allow for a causal attribution of the observed changes to the reserve, but still allows us to draw important information that can inform our conclusions. For both approaches, model coefficients are estimated via ordinary least–squares and heteroskedastic–robust standard errors (Zeileis, 2004).

2.3.1 Governance

Texto de ere y los SES

3 RESULTS

Our methodological approach with biological indicators allows us to make a causal link between the implementation of marine reserves and the observed trends by accounting for temporal and spatial dynamics (De Palma et al., 2018). The effect of the reserve is captured by the λ_t coefficient, and represents the difference observed between the control site before the implementation of the reserve and the reserve site at time t after controling for other time and space variations (*i.e.* γ_t and β respectively). Here we present the effect that marine reserves had on each of the biological indicators for each coastal community, along with the trends in socioeconomic indicators of lobster catches and revenues. We also provide an overview of the state of the socioeconomic and governance settings of each community, and discuss how these dimensions might be intertwined with each other.

3.1 Biological

Effect sizes for biological indicators are shown in Figure 2, and Figure 3 shows the summarized biological effects by community. Isla Natividad shows inconsistent effects across data sources (*i.e.* fish vs. invertebrates). For example, the reserve had a small effect on fish abundances (Fig 2A), where only year 2010 showed significat effect sizes in fish abundances ($p < 0.05$) and all other years oscillated above and under zero ($p > 0.05$). However, invertebrate abundances (Fig 2B) presented a positive trend relative to the control site before implementation ($p < 0.05$) for all but 1 year (2008). Maria Elena and Punta Herrero showed no significant increase in fish and invertebrate abundances ($p < 0.05$), except for invertebrates in Punta Herrero for 2014 –right after the implementation of the reserves– which showed a significant increase (*i.e.* $\lambda_{2014} = 2.5$, $p < 0.05$). Full tables with model coefficients are presented in the supplementary materials (**S1 Table**, **S2 Table**, **S3 Table**).

While the number of fish species oscillated above and bellow zero through time for all reserves, none of these changes were statistically significant ($p > 0.05$) indicating that the reserves had no effect on fish species richness (Fig 2C). For invertebrate species in Isla Natividad, all effect sizes were negative, but only significant for 2008, 2009, 2011, and 2014 ($p < 0.05$; Fig 2D). For Maria Elena and Punta Herrero, the data do not show significant changes in invertebrate species richness ($p > 0.05$).

Effect sizes for Shannon's diversity index for fish (Fig 2E) in Isla Natividad oscillated between $\lambda_{2011} = -0.45$ and $\lambda_{2010} = -0.005$, but were not significantly different from null hypotheses of no change (*i.e.* $\lambda_t = 0$; $p > 0.05$). For invertebrates in that same community (Fig 2F), Shannon's diversity index showed a significant decrease between 2008 and 2014, with largest decrease observed for 2011 ($\lambda_{2011} = -0.91$; $p < 0.05$). In the case of Maria Elena and Punta Herrero, Shannon's diversity index for fish showed increases in the order of $\lambda_t = 1$. For Maria Elena and Punta Herrero, these effects were only statistically significant for 2014, and 2014 and 2015 ($p < 0.05$).

Biomass was only evaluated for fish data (Fig 2G). In Isla Natividad, fish biomass presented a steady but small increase ($p > 0.05$), and exhibited an increased variability in biomass between 2013 and 2016. Maria Elena and Punta Herrero also showed small, non-statistically significant increases in fish biomass ($p > 0.05$). The last biological indicator is abundance of target species, *Panulirus interruptus* and *P. argus*, for the Pacific and Caribbean, respectively (Fig 2H). Isla Natividad presented small constantly-positive effects but were not significantly different from the reference point of control site before the implementation of the reserve ($p > 0.05$. Maria Elena showed significant increases in lobster densities in the order of $\lambda_t = 10$ ($p < 0.05$). Finally, punta herrero presented alternating negative and positive effects, but these were not different from the baseline case ($p > 0.05$).

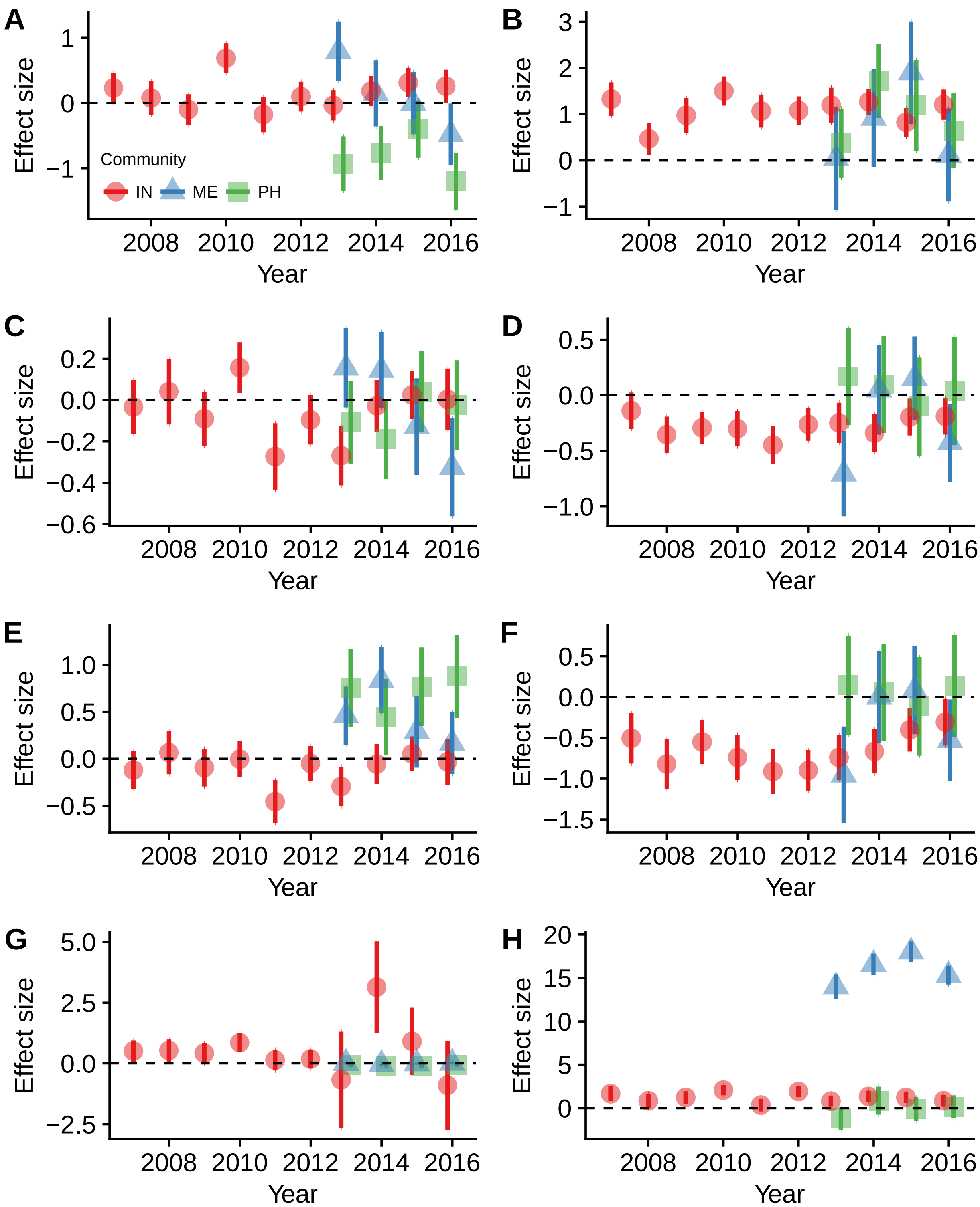

Figure 2. Effect sizes for marine reserves from Isla Natividad (IN; red cirlcles), Maria Elena (ME; blue triangles), and Punta Herrero (PH; green squares) for community-levell indicators. Plots are ordered by survey type (left: fish; right: invertebrates) and indicators: Abundance (A, B), Richness (C, D), Shannon's diversity index (E, F),fish biomass (G), and lobster (*Panulirus spp*) abundances (H). Points are jittered hotizontally to avoid overplotting. Points indicate the effect size, and errorbars are heteroskedastic-robust standard errors.

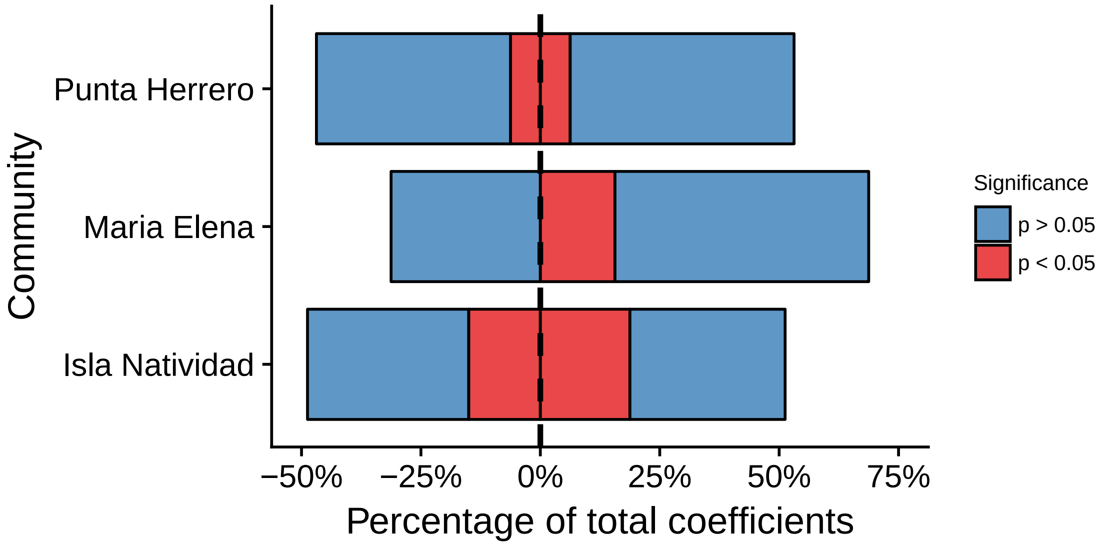

Figure 3. Summarized effects of the marne reserves by direction (positive - negative) and significance.

3.2 Socioeconomic

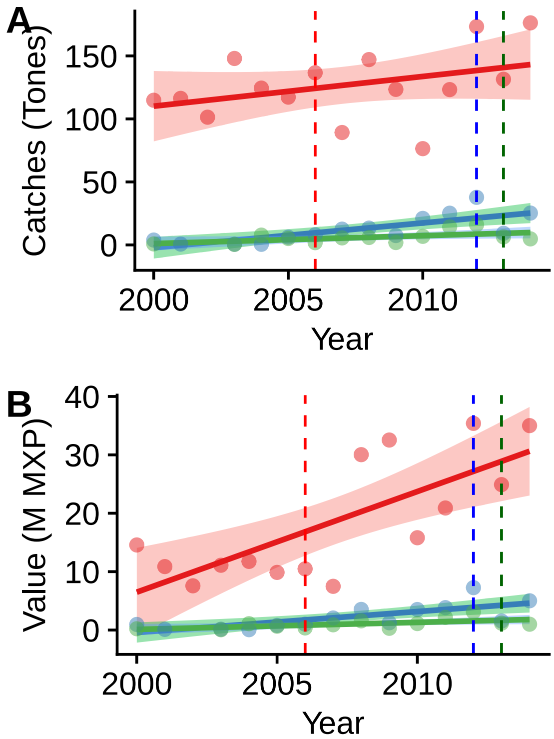

Figure 4. Time series of lobster catches (A) and revenues (B) in at Isla Natividad (IN; red circles), Maria Elena (ME; blue triangles), and Punta Herrero (PH; green squares).

3.3 Governance

4 DISCUSSION

The biological effects of the reserve contrast the existing literature. Why no effect on bio? IN hypoxia. ME and PH, age? Perhaps is the use of causal inference methods?

Isla natividad no funciona por hipoxya

Maria Elena funciona “bien”

Punta Herrero no funciona por poaching.

Aun con las mejores caracteristicas sociales, noe s posible vencer al ambiente (IN). Para el Caribe, parece ser que buena vigilancia y poca pesca ilegal son determinantes para obtener buenos resultados. Preguntarle a Stuart si ME solamente se pesca durante lanosta, y todo el ano es reserva.

IN captures more dynamics. Reflects hypoxia events. Citar paper Giron

Differences between fish and inverts sheds a lights on direct and indirect effects (Paper que recomendo Fio).

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

JC and EA analyzed and interpreted data, discussed the results and wrote the manuscrip. SF and JT edited the manuscript and discussed the results.

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SUPPLEMENTAL DATA

Supplementary Material should be uploaded separately on submission, if there are Supplementary Figures, please include the caption in the same file as the figure. LaTeX Supplementary Material templates can be found in the Frontiers LaTeX folder

S1 Figure

Timeseries of indicators for IN

S2 Figure

Timeseries of indicators for ME

S3 Figure

Timeseries of indicators for PH

S1 Table

Coefficient estimates for Isla Natividad

S2 Table

Coefficient estimates for Maria Elena

S3 Table

Coefficient estimates for Punta Herrero

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FIGURE CAPTIONS