Pros in procrastination?
Analyzing the consequences of delaying management in the Midriff Islands, Mexico

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The Bren School of Environmental Science & Management produces professionals with training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political and economic consequences that arise from scientific or technological decisions. 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:

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ABBREVIATIONS

FAO	Food and Agriculture Organization
GOC	Gulf of California
SSF	Small-scale fisheries
COBI	Comunidad y Biodiversidad
UNESCO	United Nations Educational, Scientific and Cultural Organization
EDF	Environmental Defense Fund
IUU	Illegal, unreported, and unregulated fishing
BAU	Business as usual
MPA	Marine protected areas
SCSMP	Strategic conservation and sustainable management plan
CONAPESCA	National Commission if Aquaculture and Fisheries
IUCN	International Union for the Conservation of Nature

CLIENT INTRODUCTION

Community and Biodiversity (COBI) is a Mexican civil society organization founded in 1999, focussed on marine ecosystems conservation. COBI addresses marine ecosystem conservation through enhancement of capacities for leaders and fisheries organizations, sustainable fisheries, marine reserves, and public policy. They are one of the Mexican Non-Governmental Organizations that are working on marine reserves with communities and with the support of the federal government. Marine reserves design, implementation, and monitoring have been important in Mexico as a tool to recover marine species, and restore biodiversity.

ABSTRACT

Overfishing is a problem that affects communities across the globe. The Food and Agriculture Organization (FAO) estimates that around 32% of all fish stocks are overexploited, which is concerning because three billion people rely on fish as a primary source of protein. This problem is particularly threatening to small-scale fisheries, which comprise of 90% of all fishing jobs. The Gulf of California is not immune to this problem, and has seen a precipitous decrease in the amount of fish caught in the past decade. Marine management actions can be used to help slow and reverse this trend, such as implementation marine reserves. Marine reserves are the strongest type of marine protected area that close off certain areas of the ocean to fishing. Overtime biomass inside the reserves will increase and eventually spill over into non-protected regions where fishers can benefit. In 2015 Comunidad y Biodiversidad (COBI) presented a reserve network design in the Midriff Islands, Mexico to the federal government to help protect small-scale fisheries and their ecosystems. To date, the reserve network has not yet been implemented. This Master's thesis project addresses the question: what are the consequences associated with delaying reserve network implementation? To address this question, we examined the consequences of delayed implementation on conservation, regional food security, and local livelihood. We found that marine reserves can provide conservation and social benefits under specific implementation year and size scenarios, as well as illegal fishing pressures.

EXECUTIVE SUMMARY

Global fish stocks are in decline due to unsustainable fishing, climate change, and a lack of appropriate marine management intervention, among other reasons (FAO, 2018). This is particularly concerning given that over three billion people rely on fish as a primary source of protein, and that healthy fisheries sustain livelihoods and economies across the globe, especially in developing countries. Small-scale fisheries, defined as a sub-sector of fisheries employing labour-intensive harvesting usually for direct consumption within communities, employ over 90% of global fishers and makes up to 50% of global catches (FAO, 2018). Unfortunately, global landings over the last 20 years are in a continuous decline (Pauly & Zeller, 2016). In an effort to maintain fisheries' benefits to conservation, livelihoods, and food security, governments and fisheries authorities have employed various marine management reform tools (Salas, 2007). This Master's thesis project considers marine reserves as a management tool for fisheries reform.

Marine reserves are areas of the ocean completely closed to fishing and other extraction activities. They are used to meet a myriad of objectives including conservation of biodiversity, recovery of depleted fish stocks, spillover of marine species to fishable areas, and insurance against environmental and management uncertainty, among other objectives (Allison et al., 2003; Gaines, 2010). Empirical observations suggest that marine reserves can harbor more biodiversity, higher abundance, and larger organisms (Allison et al., 2003; Roberts, 1995; Jennings et al., 1996; Castilla & Bustamante, 1989). For marine reserves to meet established objectives, they must be designed optimally and include considerations of proportion of the region of interest to be placed in the reserve network, the size of the network and spacing of individual reserves within the network, and location attributes of single reserves (Gaines, 2010).

In 2015 a reserve network for the Midriff Islands, a group of the largest islands in the Gulf of California (GoC), was proposed to the federal government. The islands host World Natural Heritage UNESCO sites, recognized as a biodiversity hotspot with conservation priority by the Mexican government (Álvarez-Romero et al., 2013; UNESCO, 2019). The objective of the reserve network is to provide conservation and fisheries benefits while simultaneously reducing opportunity cost to fishers and increasing yields and profits in the long term. The spatial planning process of the network design included the best available science and participation of key stakeholders including government authorities and small-scale fishers (Álvarez-Romero *et al.,* 2013; Álvarez-Romero *et al.,* 2017; Mancha, 2018). The proposed reserve network covers 5% (490 km^2) of the total project area and was designed to support coastal small-scale fisheries (those found in less than 200m in depth). The reserve network design was presented to the government in 2015, but it has yet to be implemented despite stakeholder support. Notably, this region has complex fisheries and socio-political structures (Giron-Nava et al., 2019).

Trade-offs associated with reserves are believed to have played a role in the network's delayed implementation, since the reserves imply constraining fishing exploitation rate relative to status quo, which results in short-term economic losses (Mangin et al., 2018; Finkbeiner & Basurto, 2015). Mexico ranks 16th in the world in total marine capture fisheries production with over 1.3 million metric tonnes landed in 2016 (FAO, 2018), however illegal, unreported and unregulated fishing in Mexico is estimated to be 40-60% of the reported landing values (Cisneros-Montemayor et al., 2013; EDF, 2012). The GoC alone accounts for up to 77% of Mexico's national landings (EDF, 2012), while small-scale fisheries in the region represent 35% of the total landings by volume, up to 68% of the total revenues, and employs up to 2,500 fishers (Giron-Nava et al., 2019). The trade-offs between conservation and livelihood led us to our main research question: what are the consequences of delaying the implementation of the reserve network in the Midriff Islands.

To answer this question we developed a bioeconomic model to quantify the consequences of delaying the implementation of the reserve network on conservation (fisheries biomass), livelihoods (profits from catch) and food security (fish catch or harvest). We assessed 12 small scale fisheries, which comprise over 90% of the total landing in the Midriff Islands and have an estimated value of $11 million (2015 estimate). First we assessed the status of the fisheries relative to maximum sustainable yield in 2015 via a catch-only stock assessment methods. We specifically examined the following scenarios and their interactions:

1) Business as usual (BAU) where the marine reserve network is never implemented;
3) Reserve network size covering 5%, 30%, and 50% of the project area;
2) Reserve network implemented in 2015, 2020, and 2030;
4) Ilegal, unreported and unregulated (IUU) fishing scenarios of 40% and 60%; and
5) For those scenarios with IUU fishing we also considered scenarios of perfect compliance where we removed the fishing effort associated with modeled illegal activity.

Results show that in 2015 all 12 fisheries were either overfished or overfished and continue to experience overfishing. The reserve network can provide benefits to conservation, food security, and livelihoods under specific implementation year and size scenarios, and when illegal fishing pressures are accounted for and/or addressed. Over 50 years (2015-2065) the proposed reserve network of 5% does not provide intended conservation, livelihoods and food security benefits. However, scenarios with larger reserve network sizes, IUU fishing and perfect compliance did provide additional benefits relative to BAU.

Delaying implementation of the reserve network results in more catch in the short term, but less biomass in the long run, highlighting the tradeoff between conservation and fisheries benefits. The optimal design to maximize benefits to conservation (138% increase) is a scenario with reserve network size of 50% at earliest implementation and accounting for 60% IUU (2015/50%/60%/0%). The scenario that maximizes benefits to livelihoods is a reserve size of 30% at earliest implementation and accounting for 60% IUU (2015/30%/60%/0%) where yearly catches exceed that of BAU in 2019 and pays off in 2022, 7 years after implementation. This scenario also maximizes benefits for food security with an increase in catch over 50 years of 71% relative to BAU. When management is delayed by 15 years (2030/30%/60%/0%), the percent change in biomass (+69%) and catch (+51%) decreases substantially relative to implementation in 2015. Benefits increase in scenarios with modelled IUU and where perfect compliance is assumed.

While the results of this study clearly suggest that implementation of a reserve network in the Midriff Islands would have conservation, food security and livelihood benefits, it is crucial to note that in all evaluated scenarios there is a window of time in which regional catch is below that of BAU due to the implementation. We recommend a portfolio of responses that can be used to alleviate this transition period. These include addressing enforcement and compliance, rights based management, alternative livelihoods and the use of technology. Ultimately, the success of the reserve network will depend on the social, political and environmental conditions.

INTRODUCTION

Fisheries around the world have experienced intense harvest for decades. Estimates by the United Nations Food and Agriculture Organization FAO (2018) suggest that 33% of global fish stocks are overexploited. Furthermore, approximately 50% of the reported catch belongs to the small-scale fisheries (SSF), and 90% of global fishing jobs are related to SSF (FAO, Small-Scale Fisheries 2015). With over three billion people relying on marine- based protein, overfishing poses significant threat to global food security. To address the growing problem of overfishing and impending seafood scarcity, governments and conservation organizations have developed a suite of marine management interventions, including size limits on the fish that can be harvested, gear restrictions, seasonal fishery closures, closing areas to fishing (marine zoning), limiting fishing permits, establishing fisheries quotas, and marine protected areas (MPAs), including the strongest type of MPAs- no-take marine reserves (Salas, 2007).

According to the International Union for the Conservation of Nature (IUCN), an MPA is, "any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment" (Kelleher, 1999). MPAs are varied in their nature and offer different levels of protection. No-take marine reserves are the highest form of protection, extractive activity is not allowed in these designated areas of the ocean. Marine reserves can meet a myriad of objectives, helping populations to recover from overfishing, rebound from other disturbances or pressures, among others (Roberts & Polunin, 1991; Allison *et al.*, 1998; McClanahan, 1999; McClanahan & Mangi, 2000; Gaines *et al.*, 2010). The ecological theory behind marine reserves is called the “spillover effect,” where over-exploited fish populations that become more abundant and attain a larger mean size within a protected area exhibit net movement across the boundary of a marine reserve (on the basis of fundamental physical principles of random movement) into fishable territory (Roberts & Polunin, 1991; Allison *et al.,* 1998; McClanahan & Mangi, 2000). Nevertheless, marine reserves present trade-offs for local communities that managers should consider during the design process. A major consideration is that closing an area for ecosystem protection reduces the size of fishing grounds leading to, at least in the near term, reduced catch and profits. Consequently, marine reserves often lack political support, since the implementation affects livelihoods in the short term (McClanahan 1999). Additionally, limited resources for implementation, monitoring, and enforcement may affect the performance of the reserves and delay their implementation.

However, delaying marine management interventions may result in increased costs in the long term. Mangin *et al.* (2018) modeled the cost of delaying fisheries management implementation in Mexico, specifically harvest policy, elimination of illegal fishing, and interpretation of rights-based fisheries management. Harvest policies included status quo, fishing at maximum sustainable yield (F_{MSY}), and economically optimal fishing mortality. A five-year delay in taking management actions results in a USD$51 million loss to average annual profit, while a 10-year delay results in a USD$96 million loss in minimum annual profit compared to that under prompt reform (Mangin *et al.*, 2018). Trade-offs associated with marine reserves are believed to have played a role in the network’s delayed implementation, since the reserves imply constraining fishing exploitation rate relative to status quo, which results in short-term economic losses (Mangin et al., 2018; Finkbeiner & Basurto, 2015).

Mexico ranks 16th in the world in total marine capture fisheries production with over 1.3 million metric tonnes landed in 2016 (FAO, 2018), however illegal, unreported and unregulated fishing in Mexico is estimated to be up to 40-60% of the reported landing values (Cisneros-Montemayor et al., 2013; EDF, 2012). The GoC alone accounts for up to 77% of Mexico's national landings (EDF, 2012), while small-scale fisheries in the region represent 35% of the total landings by volume, up to 68% of the total revenues (Giron-Nava et al., 2019). The Gulf of California (GoC) generates over 50,000 fishing jobs involving approximately 2,600 vessels, of which 2,500 are small scale boats up to 10.5 meters in length (Cisneros-Mata, 2010). The area is characterized by high levels of primary productivity, biological diversity, and fish biomass, thereby providing the local human population a large array of economically and culturally important ecosystem services, including fisheries. The provision of these services are at risk due to climate change but also well-documented policy failures, some leading to declines in stocks of fish caught in a large number of small-scale fisheries (Cinti A *et al.*, 2014). The trade-offs between conservation and livelihood led us to our main research question: what are the consequences of delaying the implementation of the reserve network in the Midriff Islands.

From 2010 to 2011, Comunidad y Biodiversidad (COBI), the National Commission of Natural Protected Areas, and Pronatura Noroeste developed a Strategic Conservation and Sustainable Management Plan (SCSMP) for the Midriff Islands region in the GoC. The program identified the main threats to the region as climate change and unsustainable fishing; to address these threats, 10 conservation targets were developed to be achieved through the implementation of a network of marine reserves (hereafter referred to as "reserve network"), also known as no-take marine reserves (Álvarez-Romero, 2013). COBI, various scientists, and local stakeholders designed the reserve network and presented it in 2015 to the federal government for implementation. The design considers opportunity costs for local communities, larval dispersal, and the effects of a warming ocean (three degrees celsius maximum increase in sea surface temperature). The process of the design included 32 government representatives, eight civil society organizations, four industrial fishery sector representatives, 132 representatives from coastal fishery sector and resulted in proposed recovery zones covering an area of 490 km^2 (representing 5% of the project area). Additionally, the process was supported by the local communities (Álvarez-Romero *et al.,* 2013; Álvarez-Romero *et al.,* 2017; Mancha, 2018). The federal government has yet, to date, implement the reserve network presented in 2015.

This research aims to quantify the consequences of delaying the implementation of the reserve network on conservation (fisheries biomass), livelihoods (profits from catch) and food security (fish catch or harvest). Specifically, this project focuses on the implementation of the above-mentioned reserve network that has yet to be implemented since its completion in 2015.

METHODS

Overview

A bioeconomic model was developed to quantify the consequences of delaying the implementation of a reserve network. Through taxonomic aggregation 12 taxa of invertebrates and fish caught in small-scale fisheries were selected to be analyzed (hereafter called “fisheries”). Due to the data-limited nature of the fisheries, a catch-only stock assessment method was used to inform fisheries reference points including biomass (B), fishing exploitation rate (F), intrinsic growth rate (r) and carrying capacity (K). These reference points were then used to model bioeconomic population dynamics after 2015 estimating fisheries value changes at various scenarios. We analyzed the effect of no reserve network implementation (BAU), reserve network implemented at different years after 2015 (implementation year), different percentage of the project area included in the reserve network (reserve network size), illegal, unreported, and unregulated fishing (IUU) and perfect compliance in IUU scenarios (perfect compliance). Additionally, all interactions of implementation year, reserve network size, IUU and perfect compliance were explored, a total of 48 scenarios. 2015 was chosen as the start year since this is when the proposed reserve network was presented to the Mexican federal government for implementation. Supplementary information contains detailed descriptions of methods. Additional information on methods are included in the supplementary information.

Study site

The Midriff Islands region, commonly referred to as the Galapagos of the northern hemisphere, includes 45 islands, including two of the largest islands in Mexico, Tiburon and Isla Angel de la Guarda. Up to 70 species are harvested by small scale fishers. The region is characterized by rocky reef temperate ecosystem and is home to a diverse range of marine species. The planning area for the reserve network was limited to coastal habitat, less than 200 meters in depth covering 11,100 km^2, specifically targeting critical habitat of small scale fisheries. The proposed marine reserve network represents 5% of the planning area (Figure 1).

Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors, Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

Figure 1: Map of the Midriff Island Region and the proposed reserve network (red).

Taxonomic aggregation of fisheries

National fisheries landing records collected from 2005-2015 by National Commission of Aquaculture and Fisheries (CONAPESCA) were used in this analysis. The database includes more than 7.2 million entries of total weight landed by fishers in Mexico. Fisheries were selected from this database after filtering by state (Sonora and Baja California), fleet (small scale fisheries), landing sites within the project area, identified taxa of interest and availability of five years or more of landings data. Filtration led to 12 fisheries, where biological parameters were based on species driving catch; identified for each fishery based on the dominant species landed in the aggregation and expert knowledge (Table 1). These 12 fisheries represent over 90% of total landings in the project area and were valued at $11M USD in 2015.

With data-limited fisheries with poor reporting, performing stock status assessments based on taxonomic groups instead of species is a feasible alternative. This type of aggregation has been done in the region before (Rodriguez-Dominguez *et al.,* 2014), and in other monitoring processes around the world (Toral-Granda *et al.*, 2008).

Table 1: List of 12 fisheries analyzed, species driving catch and their common names in English and Spanish

Fishery	Species driving catch	Common name in English	Common name in Spanish

Invertebrates			
Atrina	*Atrina tuberculosa*	Clam	Callo de hacha
Callinectes	*Callinectes bellicosus*	Crab	Jaiba café
Octopus	*Octopus bimaculatus*	Octopus	Pulpo lunarejo
Panulirus	*Panulirus inflatus*	Lobster	Langosta azul
Fish			
Cephalopholis	*Cephalopholis cruentata*	Graysby	Cabrilla
Dasyatis	*Dasyatis dipterura*	Diamond Stingray	Mantarraya
Epinephelus	*Epinephelus acanthistius*	Rooster Hind	Baqueta
Lutjanus	*Lutjanus argentiventris*	Yellow snapper	Pargo amarillo
Micropogonias	*Cynoscion othonopterus*	Gulf weakfish	Curvina golfina
Mugil	*Mugil curema*	White mullet	Lebrancha
Scomberomorus	*Scomberomorus maculatus*	Atlantic Spanish mackerel	Sierra
Squatina	*Squatina californica*	Pacific angel shark	Angelito

Estimating fisheries reference points from catch-only data

Formal stock assessments have not been conducted for the 12 fisheries. To estimate stock status, our analysis utilized a catch-only, data-limited stock assessment method (Froese et al., 2017) through an R package called datalimited2 (Free, 2018) to estimate fisheries reference points. Fisheries reference points are benchmarks used to compare the current status of the stock to its desirable or not desirable state, here presented relative to maximum sustainable yield (MSY).

Froese et al. (2017) utilizes a Bayesian state-space implementation of the Schaefer production model with emphasis on informative priors. Monte-Carlo simulations are used by the algorithm to determine viable r-k pairs, that is, those pairs that are compatible with corresponding calculated biomass trajectories from observed catch series. The method utilizes a series of annual catch data and a qualitative estimate of resilience. Resilience estimates are used to define intrinsic growth rate (r) priors. Resilience for fisheries was estimated based on (i) the dominant species driving catch in the aggregation from the CONAPESCA database and (ii) for those with no species-specific data, expert knowledge on local fisheries was used to identify species driving catch.

Carrying capacity (K) priors were defined based on the following assumptions: K is larger than the largest catch in the series, maximum sustainable catch is expressed as a fraction of the available biomass based on productivity (r), and fraction of maximum catch and K is larger in substantially depleted stocks (Free, 2018). Priors for r were adopted from Thorson et al. (2017), who uses multivariate model to predict life history traits for fish globally using FishBase data and is used to derive predictions for r. Priors for the start and end of the time series were adopted from Giron-Nava et al. (2019).

Bioeconomic model

A bioeconomic model was developed to forecast fisheries status under several reserve network scenarios to assess the consequences of delaying intervention using biological, fishery and economic parameters (Table 2). The model is comprised of a biological component that allows the projection of population growth that is linked to an economic component that estimates profits as a result.

Table 2: Parameters used in the bioeconomic model, their description and method of estimation.

Symbol	Type	Parameter description	Method
B	**Biological**	**Biomass**	**datalimited2**
K	**Biological**	**Carrying capacity**	**datalimited2**
r	**Biological**	**Intrinsic growth rate**	**datalimited2**
F	**Fishery**	**Fishing exploitation rate**	**datalimited2**
I	**Fishery**	**Immigration**	**estimated**
m	**Biological**	**Migration rate**	**estimated**
p	**Economic**	**Ex-vessel price of fish***	**COBI 2018**
c	**Economic**	**Cost of fishing**	**estimated**
λ	**Fishery**	**Entry/exit rate of the fishery**	**estimated**

*Data source provided were in Mexican Pesos, conversion used: $1 USD = 20 Mexican Pesos.

Biological model

Fisheries reference points resulting from the catch-only algorithm were used as input into a dynamic Schaefer surplus production model (Equation 1). The project area was represented by a matrix of 11,236 patches, each representing approximately 1km^2 of project area. For the 5% reserve network size the matrix maintained the area-perimeter ratio of the proposed reserve network, for 30% and 50% scenarios the reserve network was added at random using a sample() function in R. The model tracks biomass, catches, and fishing exploitation rate inside and outside the marine reserve in every patch at every time step.

Equation 1: $$B_{ij,t+1} = B_{ij,t} + B_{ij,t}\, r \quad (1 - (B_{ij,t}/K_{ij}) - F_{ij,t}\, B_{ij,t} + I_{ij,t} - mB_{ij,t}$$

The matrix model (patch$_{ij}$, row *i*, column *j*) represent the project area where fishing exploitation rate (F) is $F_{ij,t}$> 0 if a patch is outside the reserve network, and is 0 if inside. Biomass ($B_{ij,t}$) is the biomass of fish in each patch in time period t; in t=1 $B_{ij,1} = B_1/total\ patches$. Logistic growth in each patch is represented by parameters r and K, where $K_{ij} = K \quad /total\ patches$. Immigration (I) is modeled using Von Neumann neighborhood movement (Das, 2011) and parameterized migration rate (m) for each fishery based on home range estimates.

Economic model

Profits to be made are a function of B_t and F_t, as adopted from Costello et al. 2016 (Equation 2):

Equation 2: $$\pi_t = pH_t - cF_t^{\beta}$$

Where p is the ex vessel price of fish, $H_t = F_t B_t$is harvest, c is a cost parameter, F is the fishing exploitation rate, and β is a salar cost parameter that determines how linear cost are. The model assumes β=1 which results in a linear relationship between units of effort added to the fishery and cost associated. Cost was estimated assuming open-access equilibrium occurs at B/B_{MSY} = 0.3 (Costello et al., 2016), such that the profits associated with fishing are 0 at this threshold and fishers have no incentive to keep fishing.

Net present profit (NPP) over all projected years was calculated using Equation 3:

Equation 3: $$NPP = \sum_{t=0}^{T} \frac{\pi_P - \pi_{SQ}}{(1+\sigma)^t}$$

Where $\pi_P$are profits made in the reserve scenario and π_{SQ} is profits at status quo or business as usual, σ represents the discount rate, here assumed to be 10% (Coppola et al., 2014) as this is used by the federal government to evaluate public projects.

Bioeconomic Dynamics

Fishing exploitation rate in open access was recalculated at every time step (Equation 4) in each patch based on the assumption that entry/exit into the fishery is proportional to profits (π_t) that could be made relative to maximum profit at MSY (π_{MSY}).

Equation 4: $$f_{ij,t+1} = f_{ij,t} + \lambda \frac{\pi_{ij,t}}{\pi_{ij,MSY}}$$

$\lambda$is an entry/exit constant, here assumed to be 0.1 (Costello et al., 2016) and $\pi_{ij,MSY} = \pi_{MSY}/total\ patches$.

Regional Illegal, Unregulated and Unreported (IUU) fishing

Illegal, unreported and unregulated (IUU) in Mexico is estimated to be up to 40-60% of the reported landing values (Cisneros-Montemayor et al., 2013; EDF, 2012). To account for IUU, landing estimates in metric tons (MT) were inflated by 40 and 60% as a sensitivity analysis. These landings were then run as unique scenarios in the data-limited stock assessment model and the resulting fisheries reference points were then used in the bioeconomic model. It was assumed that underreporting stays constant through time.

Scenarios

The bioeconomic model was used to assess a business as usual scenario and scenarios with fully factorial combination (Figure 1) of reserve implementation year of 2015, 2020, and 2030, different total areas protected from fishing (reserve network size) of 5%, 30% and 50%, and different levels of IUU (IUU fishing) of 40% and 60% . Additionally we modelled perfect compliance for scenarios with IUU. This was done by removing the level of IUU from fishing effort, for example in IUU 40% scenario we removed 40% of fishing exploitation rate. The initial fishery status was a result of the catch-only stock assessment algorithm and described the status of the fishery in 2015 only. The business as usual scenario (BAU) presents status quo where fisheries remain open access and there is no reserve network implementation.

Scenarios will be referenced using the following naming convention: implementation year/ reserve network size/ IUU fishing / perfect compliance using their numerical values, for example 2015/ 20% /40% /40%.

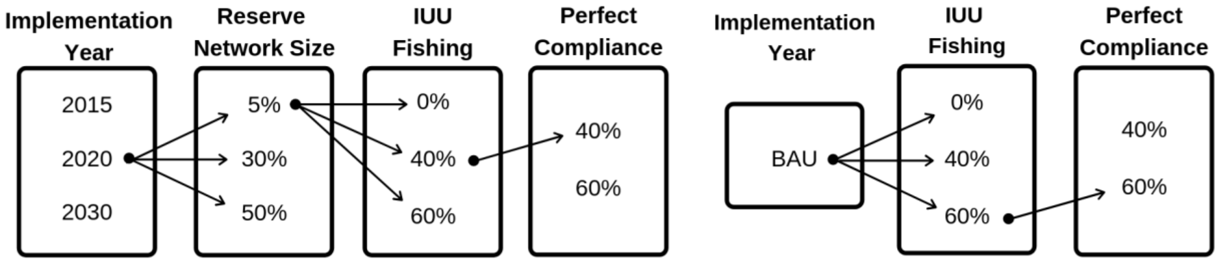

Figure 1: Flowchart of one scenario pathway. The model was run under every combination of implementation date, reserve size, levels of IUU, and perfect compliance for a total of 48 scenarios. Each scenario was run for all 12 fisheries individually and then aggregated. In the scenarios with implementation date BAU, no reserve size was used.

RESULTS

While the initial status of the 12 fisheries are poor, projecting into the future with implementation of reserve networks at 5% does not improve their health, regardless of the year implemented. However, scenarios with larger reserve network sizes, IUU fishing and perfect compliance did provide additional benefits to biomass, catch, and profits relative to BAU. Holding all other variables constant, delaying implementation of the reserve network results in more catch in the short term, but less biomass in the long run. Examining different sizes of reserve networks we found that a reserve of size 30% optimizes biomass, catch, and profits. In IUU scenarios projected benefits of any reserve network regardless of size are proportionally larger, and eliminating IUU fishing in the future further increases the benefits of reserve network implementation.

1. Fisheries status under different reserve network implementation years.

Our results from the catch-only stock assessment indicate that in 2015 all 12 fisheries are overfished and recovering (F/F_{MSY} and $B/B_{MSY} < 1$) or are overfished and continue to experience overfishing ($F/F_{MSY} > 1$ and $B/B_{MSY} < 1$) (Figure 2). These initial fisheries status baselines served as comparison for projecting how fisheries health changes over time in the different scenarios. Additionally, there is no appreciable change in all 12 fisheries' health by 2065 in BAU (BAU/5%/0%/0%) (Figure 2). When modeling fisheries health over the same time frame of 50 years in different implementation year scenarios (2015/5%/0%/0%, 2020/5%/0%/0%, and 2030/5%/0%/0%), the fisheries still remain overfished and continue to experience overfishing.

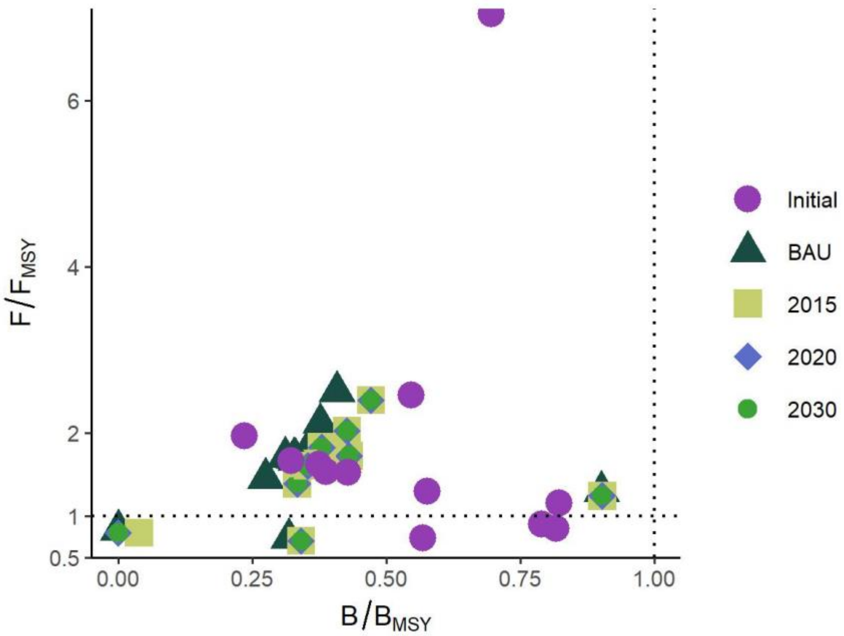

Figure 2: Kobe plot with fishery status in 2065 for reserve network implementation year scenarios representing 5% of project area (all/ 5%/ 0%/ 0%). Each point represents a fishery and the color represents each scenario of reserve network implementation year. The "Initial" scenario is the status of each fishery in 2015, other points are fishery status at year 2065. Fisheries in the quadrant F/F_{MSY} and $B/B_{MSY} < 1$ are overfished and recovering, those in $F/F_{MSY} > 1$ and $B/B_{MSY} < 1$ are overfished and continue to experience overfishing.

2. Impacts on biomass, catch and profits with delay of a 5% reserve network

The analysis below includes the results from implementation of a 5% marine reserve network in BAU, 2015, 2020, and 2030 over a 50 year time frame from 2015-2065. It does not include IUU fishing, and therefore nor does it include perfect compliance. Implementation of a 5% marine reserve network does not provide catch and profit benefits unless IUU is accounted for and perfect compliance occurs.

2.1 Illegal, Unregulated, and Unreported fishing at 0%

In the 2015/5%/0%/0% scenario, aggregate biomass increases 49,000 MT (6.8%), aggregate catch decreases 11,000 MT (-4.3%), and aggregate profits decrease by $2 million USD2018 (-0.04%), relative to BAU (Table 3). In this scenario the catch estimates do not exceed catch estimates for BAU over 50 years (2015-2065), and thus the catch lost from reserve network implementation is never recovered (Table 3). In the 2030/5%/0%/0% scenario, from 2015-2065 aggregate biomass increases 34,000 MT (4.7%), aggregate catch decreases 7,000 MT (-2.9%), and aggregate profits decrease by $1 million USD2018 (-0.02%), relative to BAU (Table 3). Similarly to the 2015 scenario, the catch estimate in the 2030 implementation year scenario never exceeds BAU and catch lost from implementation in never recovered (Table 3).

While aggregated biomass is larger in 2065 with the earliest reserve implementation date (2015), aggregated catch and profits are lowest in this scenario. Vice versa, no implementation of a reserve network leads to the lowest aggregated biomass by 2065, but highest aggregated catch and profits (Table 3). While the 2015,2020&2030/5%/0%/0% scenarios results in an increase in biomass, higher catch relative to BAU was not observed over the 50 year projection; thus this investment never reaches a pay-off point (Figure 3).

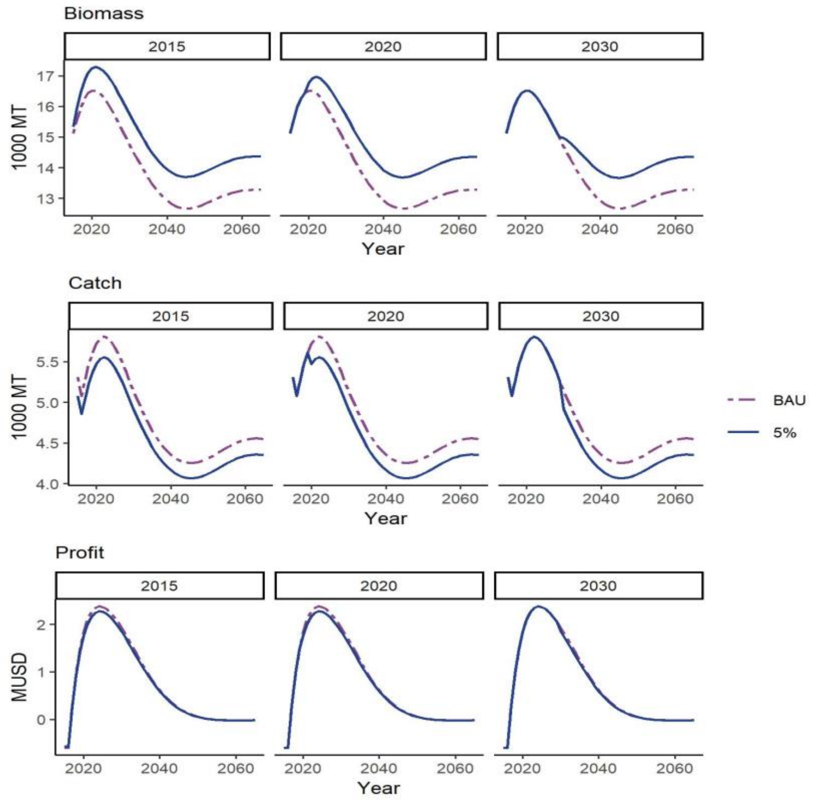

Figure 3: Biomass, catch and profit at various implementation years for a 5% reserve network (all/5%/0%/0%). Biomass and catch are in 1000 MT and profit is in millions of US 2018 dollars discounted at 10%. 2015, 2030 and 2030 labels indicate implementation years.

Table 3: Aggregated biomass, catch and profits for all scenarios relative to BAU. Year cross refers to the year in which catch in the scenario was equal to or exceeded BAU. Loss is 1000s MT of catch lost as a result of implementation of the reserve network and payoff year refers to the year in which this loss was completely compensated for in the reserve network scenario. NA's represent those scenarios where catch does not pay off relative to BAU. Profits are in million USD in 2018 dollars discounted 10%.

				Absolute difference relative to BAU			**Percent change relative to BAU**					
Implementation year	**Reserve size**	**IUU fishing**	**Perfect compliance**	**Biomass (1000MT)**	**Catch (1000MT)**	**Profit (MUSD)**	**Biomass (%)**	**Catch (%)**	**Profit (%)**	**Year cross**	**Loss (1000MT)**	**Payoff year**
BAU	BAU	0%	0%	0	0	$0.00	0	0	0	NA	NA	NA
BAU	BAU	40%	0%	0	0	$0.00	0	0	0	NA	NA	NA
BAU	BAU	60%	0%	0	0	$0.00	0	0	0	NA	NA	NA
2015	5%	0%	0%	49	-11	-$1.72	7	-4	-0.04	NA	NA	NA
2015	30%	0%	0%	659	170	$23.29	92	70	1	2019	-3	2023

2015	50%	0%	0%	977	58	$7.42	137	24	0	2022	-2	2032
2015	5%	40%	40%	275	12	$65.51	27	3	1	2020	-1	2025
2015	5%	40%	0%	69	-15	-$2.76	7	-4	0	NA	NA	NA
2015	30%	40%	40%	1112	249	$68.13	110	71	1	2021	-5	2026
2015	50%	40%	40%	1544	87	$32.87	153	25	1	2024	-2	2035
2015	30%	40%	0%	946	252	$31.22	94	72	0	2020	-3	2023
2015	50%	40%	0%	1402	89	$7.19	139	26	0	2023	0	2032
2015	5%	60%	60%	508	30	$103.34	45	8	2	2021	-1	2026
2015	5%	60%	0%	78	-17	-$2.51	7	-4	0	NA	NA	NA
2015	30%	60%	60%	1400	265	$93.31	123	68	2	2022	-4	2028
2015	50%	60%	60%	1857	88	$52.25	164	23	1	2025	-2	2037
2015	30%	60%	0%	1058	278	$39.52	93	71	1	2019	0	2022
2015	50%	60%	0%	1568	97	$15.09	138	25	0.26	2022	0	2031
2020	5%	0%	0%	43	-9	-$1.66	6	-4	-0.04	NA	NA	NA
2020	30%	0%	0%	600	156	$11.61	84	64	0	2024	-1	2027
2020	50%	0%	0%	884	55	-$1.25	124	22	0	2026	-1	2034
2020	5%	40%	40%	271	13	$66.22	27	4	1	2020	-2	2025
2020	30%	40%	40%	1069	246	$64.83	106	70	1	2023	-3	2027
2020	50%	40%	40%	1474	93	$34.63	146	27	1	2026	-1	2034
2020	5%	40%	0%	62	-13	-$2.50	6	-4	0	NA	NA	NA
2020	30%	40%	0%	863	233	$16.34	86	67	0	2024	-2	2027
2020	50%	40%	0%	1272	86	-$2.79	126	25	0	2026	-1	2034
2020	5%	60%	60%	505	31	$104.08	44	8	2	2021	-2	2026
2020	30%	60%	60%	1367	265	$92.93	120	68	2	2023	-1	2028
2020	50%	60%	60%	1804	95	$56.41	159	24	1	2026	-3	2036
2020	5%	60%	0%	69	-15	-$2.47	6	-4	0	NA	NA	NA
2020	30%	60%	0%	963	255	$20.24	85	65	0	2024	-3	2027
2020	50%	60%	0%	1418	92	$0.41	125	23	0	2026	-2	2034
2030	5%	0%	0%	34	-7	-$0.70	5	-3	-0.02	NA	NA	NA
2030	30%	0%	0%	492	125	$4.52	69	51	0	2034	0	2036
2030	50%	0%	0%	711	48	-$0.80	99	20	0	2036	-1	2041

2030	5%	40%	40%	258	18	$69.52	26	5	1	2020	-2	2024
2030	30%	40%	40%	937	224	$72.83	93	64	1	2020	-2	2024
2030	50%	40%	40%	1261	107	$61.05	125	31	1	2020	-2	2024
2030	5%	40%	0%	48	-10	-$0.96	5	-3	0	NA	NA	NA
2030	30%	40%	0%	708	190	$7.11	70	54	0	2034	-1	2036
2030	50%	40%	0%	1022	77	-$0.46	101	22	0	2035	0	2040
2030	5%	60%	60%	493	37	$108.04	43	9	2	2020	-1	2025
2030	30%	60%	60%	1247	258	$107.97	110	66	2	2020	-1	2025
2030	50%	60%	60%	1608	125	$92.35	142	32	2	2020	-1	2025
2030	5%	60%	0%	53	-11	-$1.05	5	-3	0	NA	NA	NA
2030	30%	60%	0%	789	205	$7.83	69	52	0	2034	-1	2036
2030	50%	60%	0%	1138	80	-$0.43	100	20	0	2035	-3	2041

2.2 Accounting for 60% IUU fishing and simulating perfect compliance

In the IUU 60% scenarios the magnitude of biomass, catch, and profits increasing proportionally for all metrics, compared to the IUU 0% (Figure 4). While the magnitude is larger, the trend in differences with implementation year scenarios remains the same. At earliest implementation year, when IUU fishing is accounted for (2015/5%/60%/0), aggregated biomass is 7% greater and catch 4% less compared to BAU (Table 3). At the latest implementation year and accounting for IUU (2030/5%/60%/0), aggregated biomass is 5% greater and catch 3% less compared to BAU (Table 3). Neither the catch in 2015/5%/60%/0% or 2030/5%/60%/0% scenarios exceed the catch in BAU, so catch lost from implementation is never recovered. However, if IUU is addressed and perfect compliance occurs 2015/5%/60%/60% sees an increase of 123% for biomass and a 68% increase in catch compared to BAU, with catch exceeding BAU in 2022 and catch lost from reserve network implementation recovered in 2028. If IUU is addressed and perfect compliance occurs 2030/5%/60%/60% sees an increase of 110% for biomass and a 66% increase in catch compared to BAU, with catch exceeding BAU in 2020 and catch lost from reserve network implementation recovered in 2025 (Table 3; Figure 5).

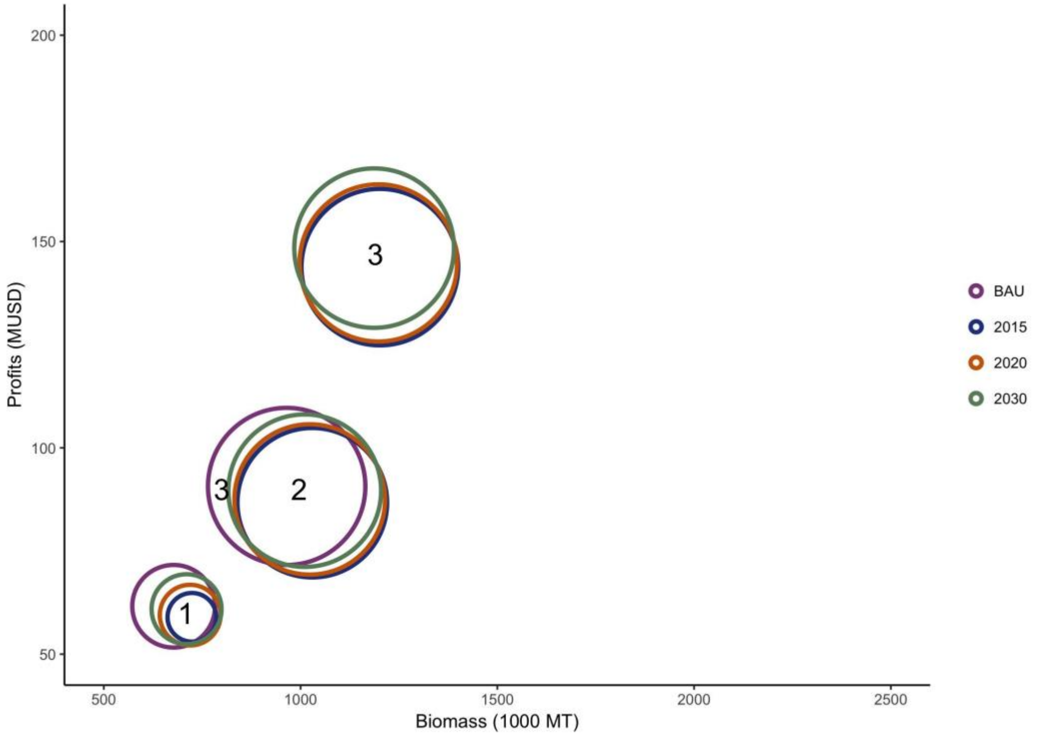

Figure 4: Aggregate biomass, catch, and profit in 2065 for 5% reserve network scenarios. Implementation years are presented in different colors and the size of the circle is representative of aggregate catch from 2015 - 2065. The numbers represent: (1) IUU 0%, (2) IUU 40%, and (3) IUU 40% with perfect compliance. For example, 2015/5%/0%/0%= Unadjusted catch data, 2015/5%/40%/0%= Accounting for IUU, and 2015/5%/40%/40% = Perfect Compliance.

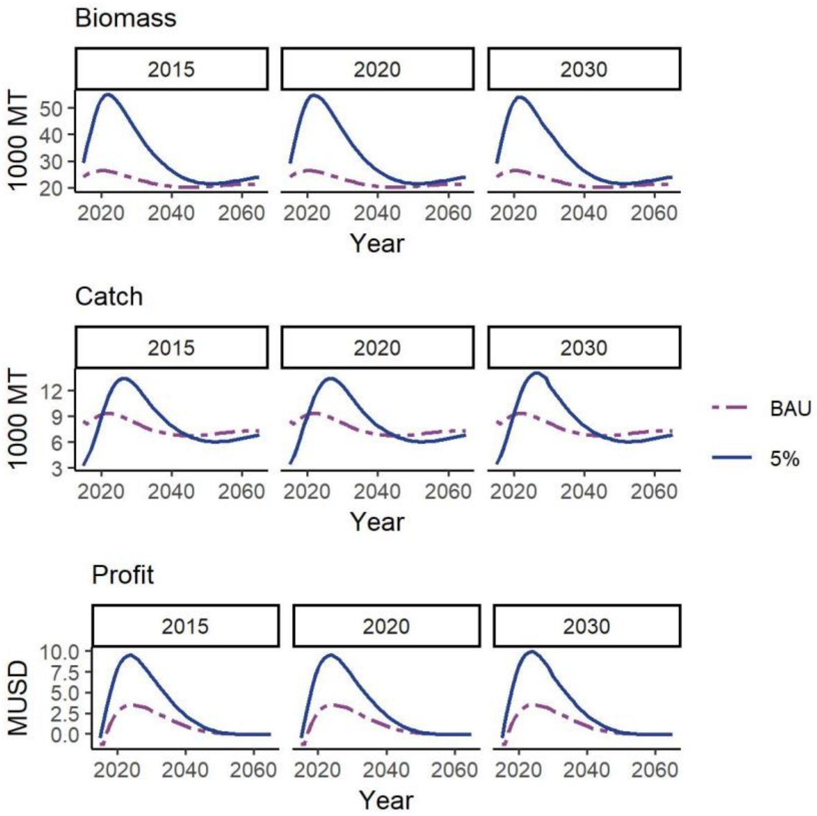

Figure 5: Biomass, catch and profit at various implementation years for a 5% reserve network (all/5%/60%/60%). Biomass and catch are in 1000 MT and profit is in millions of US 2018 dollars. 2015, 2030 and 2030 labels indicate implementation years.

3. Impacts on biomass, catch, and profits with delayed implementation of a 30% and 50% reserve network

Aggregated biomass, catch, and profits results suggest that a 30% marine reserve size is the optimal size for biomass, catch and profit benefits. These benefits are increased when accounting for IUU and simulating perfect compliance.

3.1 Illegal, Unregulated, and Unreported fishing at 0%

Biomass increases as the reserve network sizes increase, with the largest biomass estimates resulting from a reserve network that covers 50% of the project area (134% relative to BAU 2015/50%/0%/0%), and the smallest biomass resulting from BAU (Table 3; Figure 6). Catch is highest with the implementation of a reserve network that encompasses 30% of the region and earliest implementation (70% greater relative to BAU 2015/30%/0%/0%), and lowest with a reserve network that encompasses 50% of the region and delayed implementation (20% increase relative to BAU 2030/50%/0%/0%). In the 2015/30%/0%/0% scenario yearly observed catch exceeds BAU in 2019 and loses due to implementation are paid off in 2023 (Table 3). The 2030/50%/0%/0% scenario early observed catch exceeds BAU in 2036 and loses due to implementation are paid off in 2041.

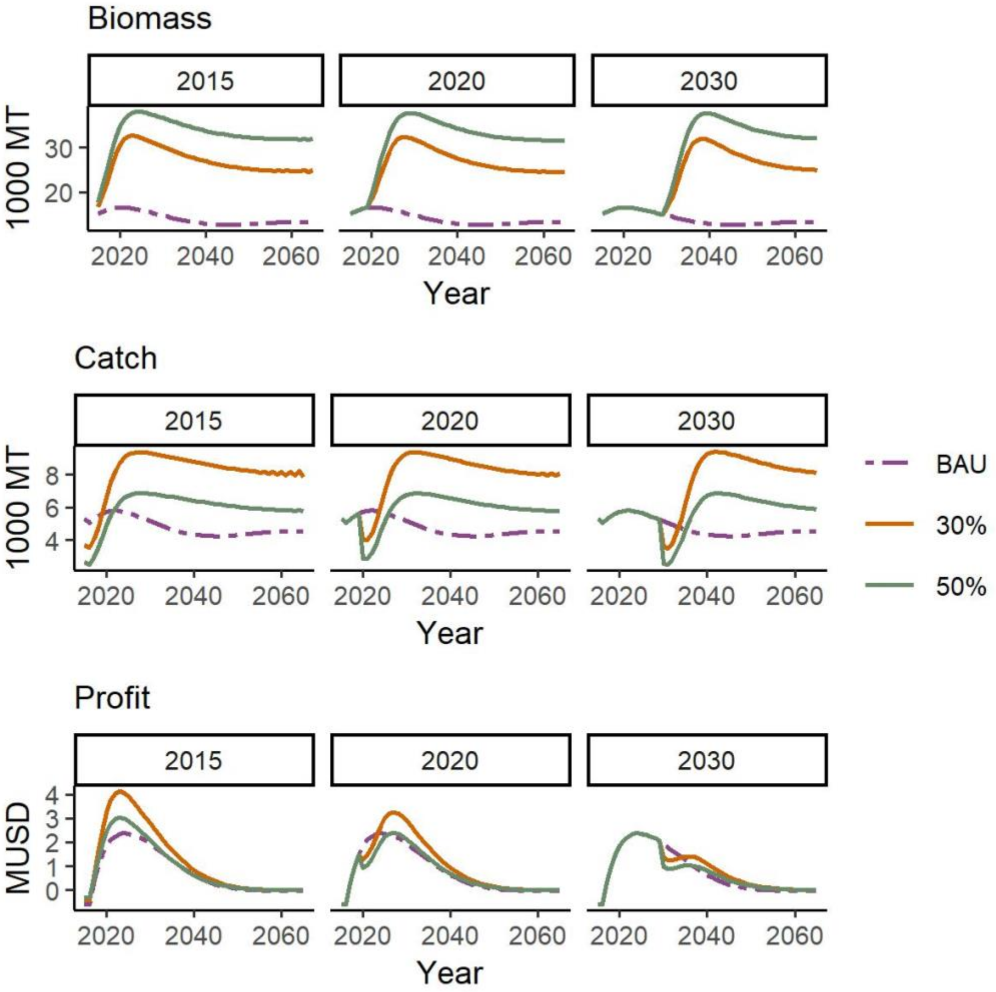

Figure 6: Biomass, catch and profit at various implementation years (all/30%&50%/0%/0%). Biomass and catch are in 1000 MT and profit is in millions of US 2018 dollars. 2015, 2030 and 2030 labels indicate implementation years.

3.2 Accounting for IUU and simulating perfect compliance

Similar to the 5% reserve network scenario, IUU scenarios with 30% & 50% reserve size see a similar proportional increase (Figure 7), benefits are larger with increased reserve size and IUU fishing scenario (Figure 9,10). 2015/50%/60%/0% yields the highest biomass 138% increase relative to BAU but yields one of the lowest catch and profit benefits of 25% and >1% increase relative to BAU. However, losses in catch associated with the reserve implementation payoff in 2041. 2015/30%/60%0% yields a 93% increase in biomass, a 71% increase in catch and a 1% increase in profits relative to BAU. This scenario also represents the earliest reserve payoff in 2022.

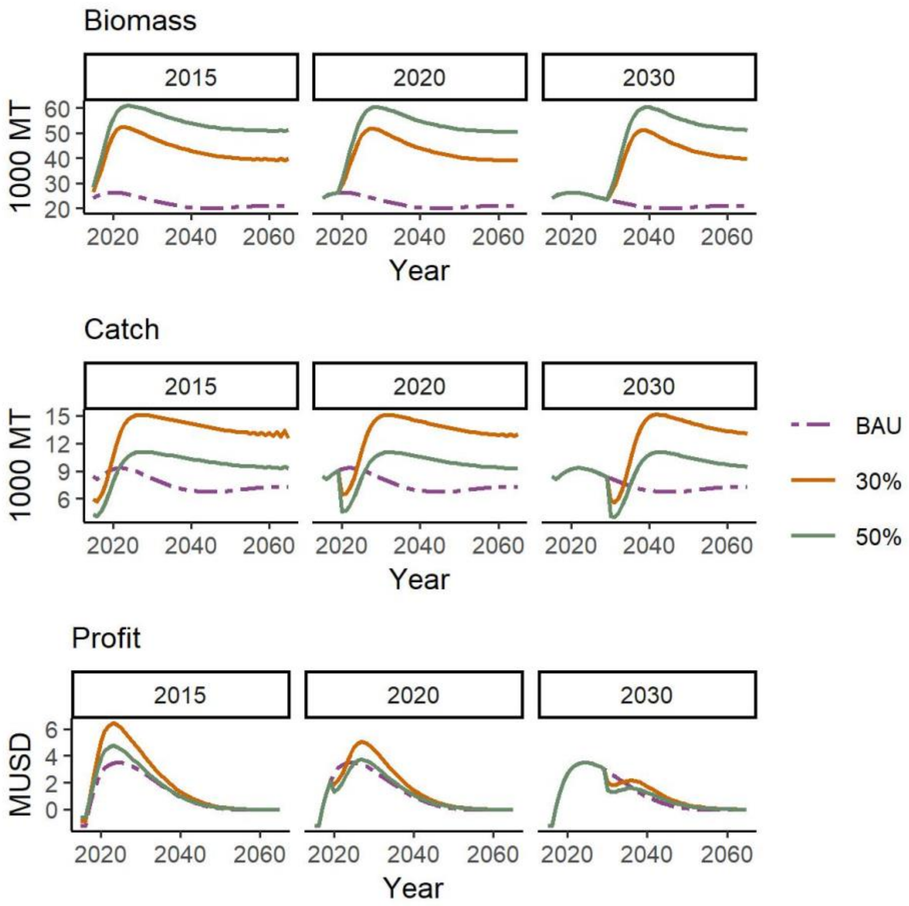

Figure 7: Biomass, catch and profit at various implementation years (all/30%&50%/60%/0%). Biomass and catch are in 1000 MT and profit is in millions of US 2018 dollars. 2015, 2030 and 2030 labels indicate implementation years.

These benefits are further increased in IUU scenarios when perfect compliance is simulated (Figure 8, 9, 10). 2015/50%/60%/60% yields the highest increased aggregated biomass of 1857 thousand MT (164%) relative to BAU , and 2030/30%/40%/40% yields the lowest biomass of 937 thousand MT (93%) relative to BAU. 2015/30%/60%/60% yields the highest catch benefit of 265 thousand MT (123%) increase relative to BAU and 2015/50%/40%/40% yields the lowest catch of 87 thousand MT (25%) increase relative to BAU.

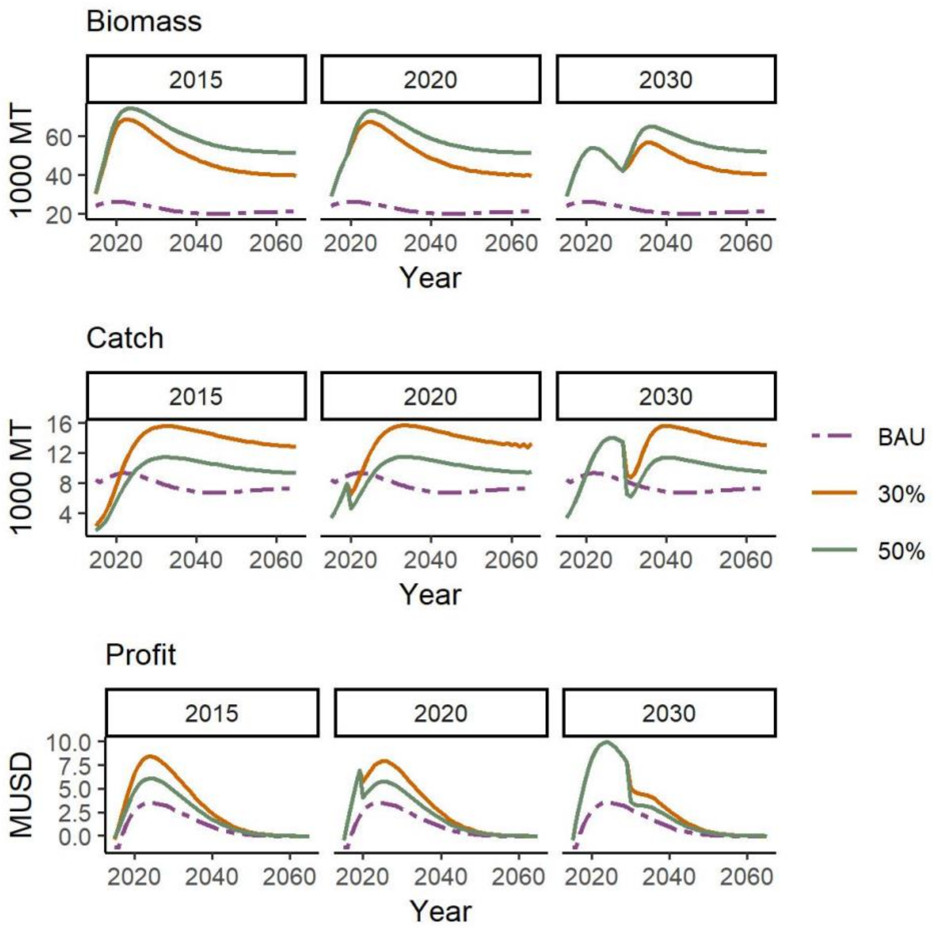

Figure 8: Biomass, catch and profit at various implementation years (all/30%&50%/60%/60%). Biomass and catch are in 1000 MT and profit is in millions of US 2018 dollars. 2015, 2030 and 2030 labels indicate implementation years.

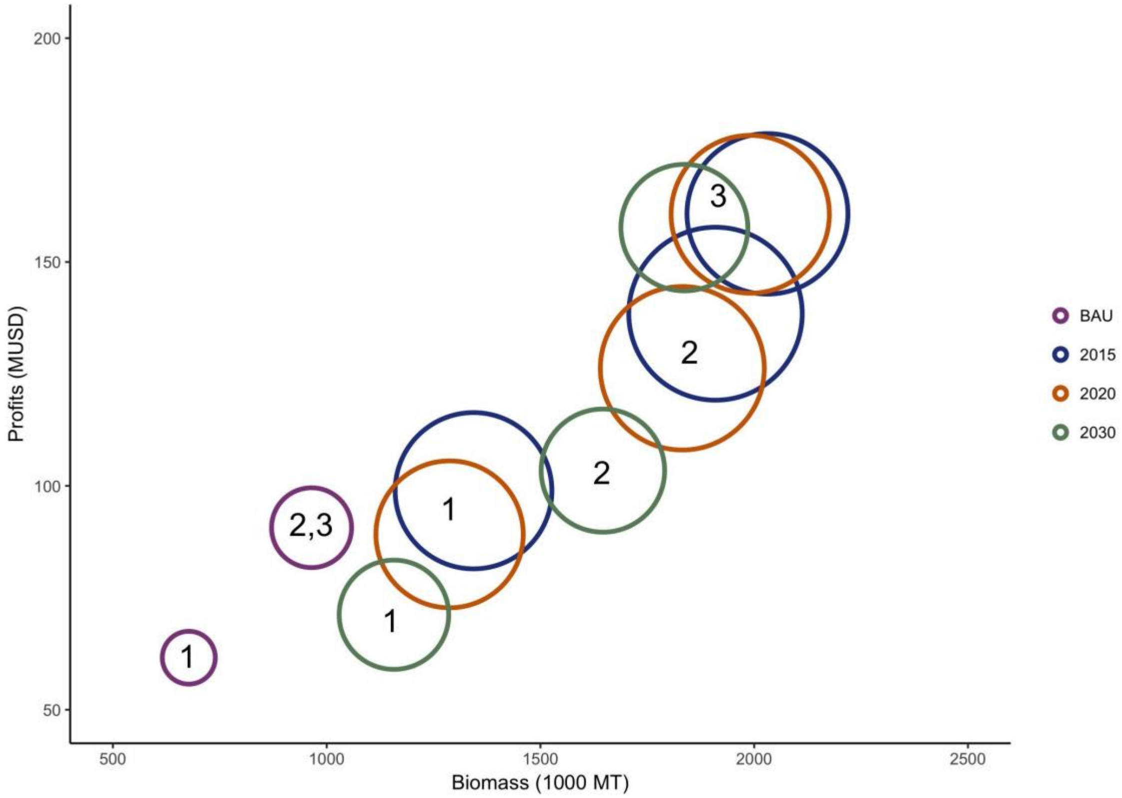

Figure 9: Aggregate biomass, catch, and profit in 2065 for reserve network size of 30%. Implementation scenarios are presented in different colors and the size of the circle is representative of aggregate catch from 2015- 2065. The numbers represent (1) IUU 0%, (2) IUU 40%, and (3) IUU 40% and perfect compliance. For example 2015/30/0/0= Unadjusted Catch Data, 2015/30/40/0= Accounting for IUU, and 2015/30/40/40 = Perfect Compliance.

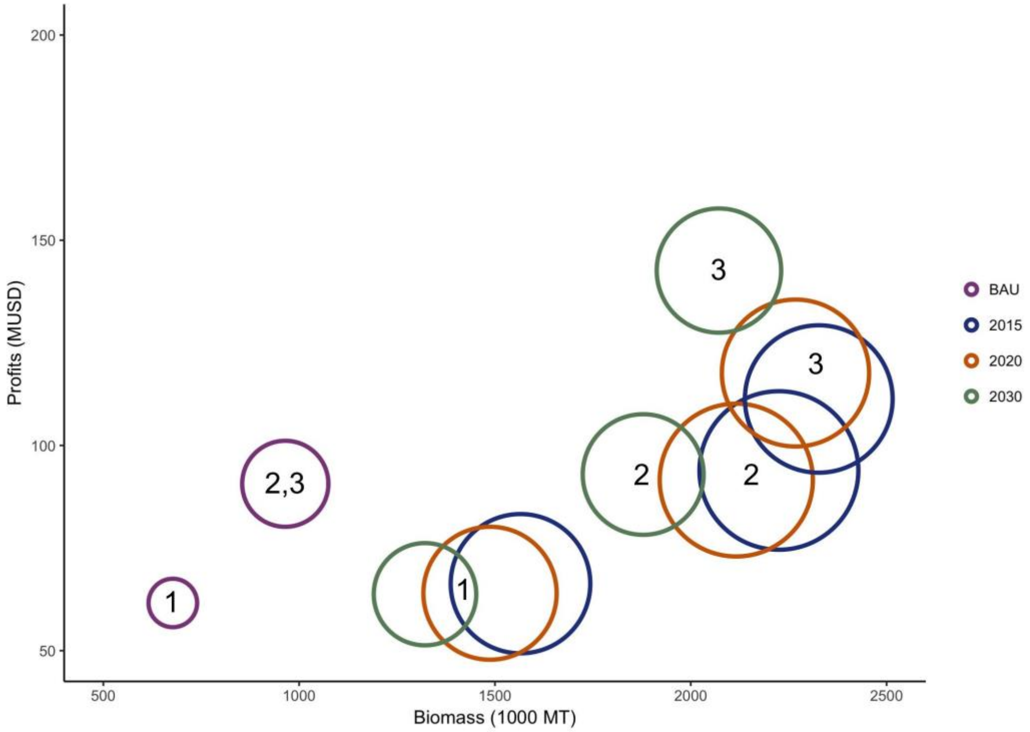

Figure 10: Aggregate biomass, catch and profit in 2065 for reserve network size of 50%. Implementation scenarios are presented in different colors and the size of the circle is representative of aggregate catch from 2015- 2065. The numbers represent (1) unadjusted catch data, (2) accounting for IUU, and (3) perfect enforcement. For example 2015/50/0/0= Unadjusted Catch Data, 2015/50/40/0= Accounting for IUU, and 2015/50/40/40 = Perfect Compliance.

DISCUSSION AND CONCLUSIONS

We found that the reserve network can provide benefits to conservation, food security, and livelihoods under specific implementation year and size scenarios, and when illegal fishing pressures are accounted for and/or addressed. Based on findings by Gaines et al. (2010) and Krueck et al. (2017), it was hypothesized that non-delayed implementation of a reserve network in 2015 coupled with protecting 30% of the region of interest would result in optimal benefits to both conservation and livelihoods. Indeed, our results suggest that strongly protecting 30% of fished habitats can help rebuild depleted fisheries (i.e. all fisheries are closer to $F/F_{msy} = 1$, and $B/B_{msy} =$ when 30% of the region is protected), achieving biodiversity conservation goals as well as increases in long-term fisheries productivity to support regional food security.

Furthermore, our results suggest that the *opportunity cost* to local communities of implementing the reserve network was minimized in the scenario where a 30% reserve network was implemented in 2015 and catch was inflated by 60% to account for IUU fishing (2015/30%/60%/0%). In this scenario, the implementation of a reserve network leads to catch estimates that exceed that of BAU by 2019, and the catch lost from reserve network implementation is recovered by 2022 with a net gain in biomass of 1058 thousand MT relative to BAU after 50 years. In this scenario the percent change in biomass and catch are maximized relative to BAU, +92% and +70% respectively, when management is not delayed. When management is delayed by 15 years (2030/30%/60%/0%), the percent change in biomass (+69%) and catch (+51%) decreases substantially relative to implementation in 2015.

The *greatest return on investment* for conservation benefits occurs in the scenario where a 50% reserve network was implemented in 2015, with IUU fishing of 60% in a state of the world with perfect compliance (2015/50%/60%/60%). In this scenario, catch with the implementation of a reserve network exceeds that of BAU by 2025 and the catch lost from reserve network implementation is recovered by 2037 with a net gain in biomass of 1857 MT relative to BAU after 50 years. These results illustrate that a reserve network larger than 30% prolongs the transition period when catch is less than that of BAU, a non-optimal situation in regards to food security and livelihood.

This study employs a novel use of a protected area matrix patch model to predict changes in regional biomass, catch and profits based on a comprehensive reserve network design. The structure of the bioeconomic model facilitates ranking of scenarios to assess the optimal combination of implementation year, reserve network size, and IUU fishing reform that minimizes opportunity cost and maximizes return on investment. However, because the model assumes no age structure in the biomass projections it does not take larval dispersal explicitly into account. This is important to note because the reserve network was designed to enhance larval dispersal connectivity in the region (Álvarez-Romero et al., 2017). Additionally, the model is not spatially explicit in that it does not capture the likely distribution of species of interest; rather, in alignment with Armstrong (2007), it assumes homogeneous distribution of biomass throughout the region. Finally, the results of the IUU fishing sensitivity analysis suggests that the trends observed in the model output remain the same as the level of IUU fishing is changed (i.e. biomass increases with reserve network implementation while catch and profits temporarily decrease), while the magnitude of the trends change proportionally with catch inflation. With knowledge of IUU activity on the ground, not accounting for IUU fishing results in cost estimates that are lower than reality, making this part of the analysis optimistic.

While the results of this study clearly suggest that implementation of a reserve network in the Midriff Islands would have conservation, food security and livelihood benefits, it is crucial to note that in all evaluated scenarios there is a window of time in which regional catch is below that of BAU due to the implementation. This period of time will likely be challenging for local communities where small-scale fishing is a common form of employment, as is the case in the Midriff Islands. Considering that Mexico's population growth rate is 1.6%, managers and communities need to be creative in the ways the face the needs of a growing population in a world with finite resources (World Bank, 2017). Solving the dilemma between short-term and long term goals will improve the effectiveness of the reserve network and its benefits. We suggest a portfolio of responses to help alleviate this inevitably challenging transition period. Ultimately, the expert knowledge of local policy makers should be called upon to proactively address this transitional period.

Enforcement and compliance Model outputs suggest that completely eliminating IUU fishing minimizes the opportunity cost of reserve network implementation, that is, there is perfect enforcement and compliance of reserve network. Between 1950-2010, actual harvests in the GoC were estimated to be 40-60% of reported harvests (Cisneros-Montemayor et al., 2013; EDF 2012). Increase of fish densities in reserves can foster an increase in illegal activity, however research has shown that initial investment in enforcement efforts can provide the greatest return on maintaining benefits of reserves (Beyers & Noonburg, 2007). Additionally, modifying current fines and penalties to be proportional to the economic value of seized products has also been recommended in the region; fines in Mexico are below those of other countries and often a negligible amount when compared to the value of species (EDF, 2912).

Rights based management: Other management tools when paired with a reserve network can increase its benefits. Well organized rights-based systems have been documented to alter economic incentives for fishers, such that they no longer compete for catches since competitive fishing no longer occurs and thus is a promising solution for fisheries reform (Beddington, Agnew & Clark, 2007; Costello, Gaines & Lynham, 2008). In particular, coupling reserves with territorial user rights fisheries (TURFS), allocation of rights to exclusive harvest within a given geographic area, can enhance the efficiency by increasing fishery profit and abundance (Costello & Kaffine, 2010). Other rights based tools include cooperatives and individual transferable quotas (ITQ). In addition to conservation and economic benefits, these management tools can result in increased coordination and cooperation among stakeholders and building of social capital.

Alternative livelihoods Alternative livelihoods can be employed to overcome the initial consequences of reserve network implementation. In particular, we suggest that subsidies can be used to fund initial programs. Subsidies have been documented to undermine the sustainability of fisheries because they lead to bioeconomic equilibriums with high levels of fishing and low stock size (Beddington, Agnew & Clark, 2007). Regional estimates of subsidies range from \$15,000-\$85,000 from 2011 to 2016, representing non-negligible annual seed funding for this program (See SI for further information on subsidies). Reallocating small-scale, capacity-enhancing subsidies (e.g. fuel subsidies), which currently provide perverse incentives for fishers to overfish, towards programs that increase compliance with the reserve network can deter fisheries from undesirable bioeconomic equilibriums. Such programs can support fishers displaced from the small-scale industry due to the reserve network implementation.

Technology Technological advancements and innovation can be used at various stages of fisheries management including initial policy assessment, monitoring, fishing activity, processing product, and development/adoption of policy measures (). Tools include monitoring, control and surveillance, vessel monitoring system, automatic identification system, electronic logbooks among others. The use of technology can also have implications for access to seafood markets and increasing the value of products.

In conclusion, this study suggests that an optimally designed reserve network can effectively slow or reverse the trend of declining fish stocks. We note that the implementation of the reserve network will have a short-term opportunity cost for local communities that should be proactively addressed by local policy makers before implementation to lessen the burden of management on fishers.

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SUPPLEMENTARY INFORMATION

Data filtration

This analysis utilized the federal fisheries landing database from the National Commission for Fisheries and Aquaculture (CONAPESCA). The database includes more than 7.2 million entries of total weight landed by fishers' in Mexico from 2005-2015. Landings in the database were reported by state for both small-scale and industrial fisheries. For the purpose of this study, only landings from small-scale fisheries from Baja California and Sonora were analyzed. While this is the federal database there have been identified errors in reporting and recording including species identification. With advice from our client we decided to aggregate by genera as there is more confidence in the data at this taxonomic level. To filter fisheries landing records from the Midriffs Island region, we selected 29 landing sites within the region using the "Atlas de localidades pesqueras de México," (Ramirez, 2019) ("Atlas"). Landing sites identified were verified with expert knowledge.

Taxonomic aggregation of fisheries

We identified genera of interest that were included in the design of the marine reserve network; all fisheries are reef based and considered small-scale. Due to inaccurate recording of species names at the landing sites, we aggregated landing records by genus level to reduce error and uncertainty. After the data filtration process, the aggregated genus analysis includes landings estimates for 12 genera over a 10-year time period (2005-2015). However, not all fisheries have 15 complete years of landings data. All analysis was completed using RStudio Version 1.1.456.

Species driving catch

Fisheries reference values were estimated through a data-limited stock assessment model developed by Froese et al., 2017. The assessment utilizes a qualitative metric of species resilience, given that our fisheries were aggregated at the genus level species driving catch was defined as the species within the aggregation with the highest landing or as indicated by expert knowledge. The resilience value for each representative species was used to determine the fisheries reference points (r,vK, MSY, F, etc.) and, therefore, stock status of each fishery (SI Table 1). Collectively, the 12 fisheries account for more than 94% of the total landings in the Midriff Island region. Resilience estimates informed the selection of fisheries reference prior ranges for intrinsic growth rate (r) used in the catch only stock assessment method (SI Table 2).

SI Table 1: Resilience and regional catch percentage for each fishery driving species

Fishery	**Species driving catch**	**Resilience**	**Regional catch (%)**
Invertebrates			
Atrina	*Atrina tuberculosa*	Low*	8.15%
Callinectes	*Callinectes bellicosus*	High*	24.19%
Octopus	*Octopus bimaculatus*	Medium*	10.54%
Panulirus	*Panulirus inflatus*	Low*	0.29%
Cephalopholis	*Cephalopholis cruentata*	Medium	2.26%
Fish			

Dasyatis	*Dasyatis dipterura*	Low	2.17%
Epinephelus	*Epinephelus acanthistius*	Very Low	1.77%
Lutjanus	*Lutjanus argentiventris*	Low	0.67%
Micropogonias	*Cynoscion othonopterus*	Medium	1.68%
Mugil	*Mugil curema*	Medium	4.12%
Scomberomorus	*Scomberomorus maculatus*	Medium	37.05%
Sphoeroides	*Sphoeroides annulatus*	Medium	0.40%
Squatina	Squatina californica	Very Low	1.17%

* Resilience values obtained by expert knowledge

Resilience is an estimate of how an organism will rebound to disturbance events, such as fishing pressure (Fishbase, 2019). This parameter is important when estimating fisheries reference points, and therefore it was incorporated into the data-limited stock assessment model.

SI Table 2: Fisheries reference prior ranges for intrinsic growth rate (r) based on resilience estimate

Resilience	**Prior r ranges**
High	0.6 – 1.5
Medium	0.2 - 0.8
Low	0.05 - 0.5
Very low	0.015 -0.1

Estimating fisheries reference points from catch-only data

Since our fisheries data consisted only of catch, this analysis used an R software package called "datalimited2" to estimate fisheries reference points (Free, 2017). The reference points estimated relate to standard fisheries reference points. Datalimited2 uses catch-only stock assessment models (cMSY and a Bayesian surplus production) developed by Froese et al., 2017. Literature shows cMSY is one of the best catch-only stock assessment models; when evaluated against 128 real stocks, where estimates of biomass were available from full stock assessments, the Bayesian surplus production model estimates of r, k and MSY were used as benchmarks for the respective CMSY estimates and were not significantly different in 76% of the stocks (Froese et al., 2017).

Maximum sustainable yield (MSY), fishing mortality rate, biomass at MSY and fishing mortality at MSY were calculated based on equations 1, 2, 3, 4, respectively (Martell & Froese, 2013).

Equation 1 $MSY = 0.025rk$

Equation 2 $F= catch/biomass$

Equation 3 $B_{MSY} = k/2$

Equation 4 $F_{MSY} = r/2$

The output of the data-limited stock assessment model (cMSY) provides an average estimate as well as hi-low bounds for each fisheries reference point. To date, this analysis has only utilized the average estimates. Future work will assess how sensitive the model results are to changing the estimate of a single parameter. Additionally, future work will incorporate expert knowledge into the datalimited2 code and use reference point priors to constrain cMSY and produce more accurate fisheries reference points.

Bioeconomic Model

The initial stock status of the fisheries in 2015 relative to MSY was assessed through a Kobe plot to compare fishery status in a normalized space using the reference points resulting from the catch-only stock assessment (SI Table 3, SI Figure 1).

With the baseline stock status established we developed a bioeconomic model to forecast changes in fisheries status under several marine reserve implementation year and size scenarios to assess the consequences of procrastination. The model is comprised of a biological component that estimates the projection of population growth, and an economic component that estimates profits as a result of catch (fishing exploitation rate).

Input parameters are listed in SI Table 3, intrinsic growth rate (r), carrying capacity (K), fishing exploitation rate (F), Biomass (B), maximum sustainable yield (MSY), biomass capable of producing MSY (B_{msy}), F compatible with MSY (F_{msy}) were estimated through the catch-only stock assessment; profit at MSY (profit.msy), fishing exploitation rate compatible with open-access equilibrium ($\underline{f}$) and cost of fishing (c) were calculated using equations 7, 8, and 9 below, respectively; ex-vessel prices (p) for each fishery were provided by COBI from market surveys.

SI Table 3: Input parameters for the bioeconomic model for each fishery

Fishery	**r**	**k**	**f**	**b**	**m**	**msy**	**bmsy**	**fmsy**	**p**	$\underline{f}$	**c**	**profit.msy**
Invertebrates												
Atrina	0.282	15,693	0.151	2,526	0.02	1,107	7847	0.091	\$23,750	1.7	\$87	\$18
Callinectes	0.500	6,396	0.439	1,815	0.46	1,905	3198	0.596	\$1,750	1.7	\$1.7	\$2.3
Octopus	0.664	3,918	0.430	1,128	0.11	650	1959	0.332	\$5,500	1.7	\$3.2	\$2.5
Panulirus	0.282	288	0.127	114	0.06	20	144	0.141	\$10,000	1.7	\$0.4	\$0.1
Fish												
Cephalopholis	0.453	1,513	0.555	414	0.09	171	756	0.227	\$1,250	1.7	\$0.3	\$0.1
Dasyatis	0.610	937	0.259	382	0.26	143	468	0.305	\$1,250	1.7	\$0.2	\$0.1
Epinephelus	0.447	773	1.574	269	0.25	86	387	0.224	\$2,500	1.7	\$0.3	\$0.2
Lutjanus	0.378	955	0.228	178	0.12	90	477	0.141	\$2,375	1.7	\$0.5	\$0.2
Micropogonias	0.566	1,028	0.326	423	0.7	145	514	0.283	\$750	1.7	\$0.1	\$0.1
Mugil	0.579	3,403	0.344	659	0.53	493	1701	0.224	\$750	1.7	\$0.5	\$0.3
Scomberomorus	0.566	29,056	0.367	6,346	0.7	4,108	14528	0.242	\$1,125	1.7	\$5.7	\$3.2
Squatina	0.062	4,187	0.029	492	0.7	65	2093	0.015	\$1,250	1.7	\$1.7	\$0.1

Biological model

The project area was rasterized and converted to a matrix comprised of 11,236 patches each representing 1km^2. For the 5% reserve size scenarios the matrix maintains the area to perimeter ratio of the proposed marine reserve network, such that 489 patches are considered reserves, with total perimeter of 988 km. For other scenarios marine reserves were cumulatively added using a sample() function in R. The dynamic Schaefer surplus production model is described by:

$$B_{ij,t+1} = B_{ij,t} + B_{ij,t}\, r \quad (1 - (B_{ij,t}/K_{ij}) - F_{ij,t}\, B_{ij,t} + I_{ij,t} - mB_{ij,t} \tag{1}$$

Where i, j represent the patch in column i and row j of the matrix, fishing exploitation rate (F) is $F_{ij,t} > 0$ if a patch is outside the marine reserve network, and is 0 if inside. Biomass ($B_{ij,t}$) is the biomass of fish in each patch in time period t; in t=1 $B_{ij,1} = B_1/\mathit{total\ patches}$. Logistic growth in each patch is represented by parameters r and K, where $K_{ij} = K \quad /\mathit{total\ patches}$. Immigration (I) is modeled using Von Neumann neighborhood movement (Das, 2011), this includes four-directional movement north, south, east and west of each patch.

$$I_{ij,t} = 0.25mB_{i+1j,t} + 0.25mB_{i-1j,t} + 0.25mB_{ij+1,t} + 0.25mB_{ij-1,t} \tag{2}$$

Movement rate (m) was parameterized based on length of patch (each patch 1km) and home range (HR) of the fisheries:

$$m = \frac{2\left(\frac{HR}{2}L\right) + 2\left(\frac{HR}{2}(L-HR)\right)}{L^2} \tag{3}$$

Home ranges of the 12 target fisheries were estimated from the literature (SI Table 4). When a distinct home range estimate was not available, expert knowledge about life history characteristics was utilized. With home range estimations from literature reviews, percent of biomass moving in and out of patches was calculated using equation 3. This equation focuses on the biomass movement along the edges of the patch, where the home range distance allows the biomass to move out of the patch. The biomass in these areas can either move further into the patch or out of it. Equation 3 estimates with the percentage of biomass that leaves the patch, which was applied to the total biomass in that patch, which was then used in equation 2 to track movement of biomass into neighboring patches. This parameterization calculation does not include age structure and assumes habitat and biomass homogeneity within each patch.

SI Table 4: Home range and movement parameter for each fishery

Fishery	Scientific name Species driving catch	Home range (m^2)	Movement parameter (m)	Source
Invertebrates				
Atrina	*Atrina tuberculosa*	100	0.02	Escamilla-Montes, R (2017)
Callinectes	*Callinectes bellicosus*	70,000	0.46	Cisneros-Mata, M.A. et al (2019)
Octopus	*Octopus bimaculatus*	3250.9	0.11	Hofmeister, JKK. (2015)
Panulirus	*Panulirus inflatus*	1000	0.06	Per. comm. Lenihan, 2019
Fish				
Cephalopholis	*Cephalopholis cruentata*	2000	0.09	Popple, J.D and Hunte, W. (2005)
Dasyatis	*Dasyatis dipterura*	20000	0.26	Tilley, A et al (2013)
Epinephelus	*Epinephelus acanthistius*	1800	0.25	Per.comm, Lenihan, 2019
Lutjanus	*Lutjanus argentiventris*	4000	0.12	Nanam, A. and Yamada, Y. (2008)

Micropogonias	*Cynoscion othonopterus*	10,000,000	0.7	Gherard, K.E (2013)
Mugil	*Mugil curema*	101,118.07	0.53	Idyll, C.P. and Sutton, J.W (1952)
Scomberomorus	*Scomberomorus maculatus*	10,000,000	0.7	Godcharles, M. F., & Murphy, M. D. (1986)
Squatina	*Squatina californica*	314,159.27	0.7	Inland Fisheries Ireland (IFI)

Economic model

Profits are a function of B_t and F_t, as adopted from Costello et al., 2016:

$$\pi_t = pH_t - cF_t^{\beta} \tag{4}$$

Where p is the ex-vessel price of fish, $H_t = B_t F_t$ is harvest, c is a cost of fishing parameter, F is the fishing exploitation rate, and β is a scalar cost parameter that determines how linear cost are. Here we assume β=1 which results in a linear relationship between units of effort added to the fishery and cost associated. For our patch model, re-writing this equation results in:

$$\pi_{ij,t} = pf_{ij,t}b_{ij,t}MSY_{ij} - c_{ij}(F_{ij,t}) \tag{5}$$

$$\pi_t = \sum_{i=1}^{i} \quad \sum_{j=1}^{j} \quad pf_t b_t MSY - c(F_t)^{\beta} \tag{6}$$

Where $f_t = F_t/F_{msy}$, $b_t = B_t/B_{msy}$, $\pi_{ij,t}$ is the legal fishing profit to be made in each patch in time t, p is the ex vessel price of fisheries, c is the cost associated with fishing $c_{ij} = c/total\ patches$, and $MSY_{ij} = MSY/total\ patches$. Total profits in each year (π_t) is calculated as the sum of profits in each patch in time t.

Profits at MSY are calculated assuming equilibrium is at 0.3 $B_t/B_{msy}(\underline{b})$ where profits= 0 (Costello et al., 2016).

$$\pi_{MSY} = pMSY - cF_{msy} \tag{7}$$

To calculate c we first assess the fishing mortality estimated at bioeconomic equilibrium which occurs:

$$\underline{f} = \left(\frac{\phi+1}{\phi}\right)\left(1 - \frac{b}{\phi+1}\right) \tag{8}$$

Where ϕ is a shape parameter in the Pella-Tomlinson model; Schafer model results when ϕ = 1, which was used here. The cost associated with fishing is then calculated as:

$$c = p\underline{f}\underline{b}MSY/\underline{f}F_{msy} \tag{9}$$

Net present profit (NPP) over all projected years was calculated as:

$$NPP = \sum_{t=0}^{T} \frac{\pi_P - \pi_{SQ}}{(1-\sigma)^t} \tag{10}$$

Where π_P represents profits made in the marine reserve network scenario and π_{SQ} represents profits at status quo or business as usual, σ represents the discount rate, here assumed to be 10% (Coppola et al., 2014) as this is used by the federal government to evaluate public projects.

Bioeconomic Dynamics

Fishing exploitation rate in open access was recalculated at every time step in each patch based on the assumption that entry/exit is proportional to the profits (π_t) that could be made relative to maximum profit at MSY (π_{MSY}).

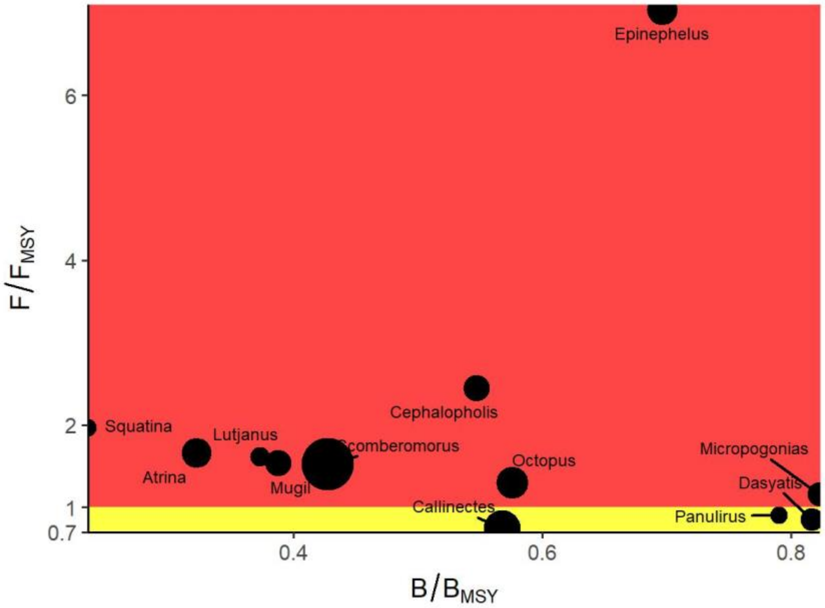
$$f_{ij,t+1} = f_{ij,t} + \lambda \frac{\pi_{ij,t}}{\pi_{ij,MSY}} \tag{11}$$

λ is an entry/exit constant, here assumed to be 0.1 (Costello et al., 2016) and $\pi_{ij,MSY} = \pi_{MSY}/total\ patches$.

Additional results

Initial status of fisheries

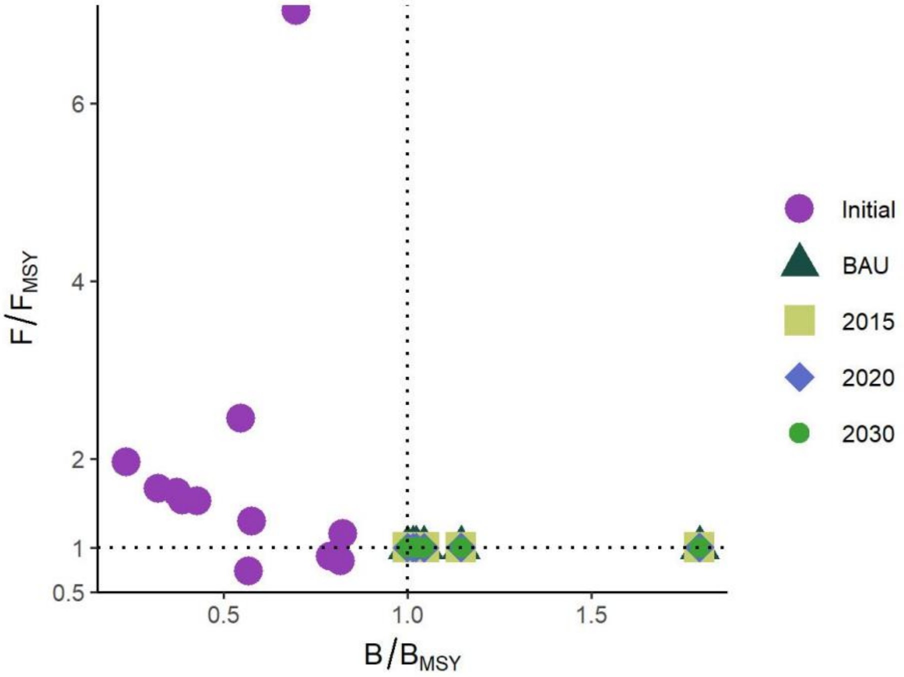
Outputs from the catch-only stock assessment suggest that the initial status of every fishery is either overfished or experiencing overfishing (SI Figure 1). Three fisheries are overfished and recovering and nine fisheries are overfished and continue to experience overfishing. The initial status of a fishery is relevant to whether or not a reserve network could provide benefits. For example, a fishery in good health is less likely to see increased benefits as its already in good health while a fishery that is overexploited will likely see benefits from relieved fishing pressure.



SI Figure 1: Kobe plot with fishery status of each fishery in 2015. Quadrants show the status of the fisheries. Species in the red quadrant ($F/F_{MSY} > 1$ and $B/B_{MSY} < 1$) are overfished and continue to experience overfishing, species in the yellow quadrant (F/F_{MSY} and $B/B_{MSY} < 1$) are overfished and recovering.

Fishing mortality at maximum sustainable yield (Fmsy)

Under a scenario where fishing mortality is set to fishing mortality at maximum sustainable yield, all the fisheries move towards the $F/F_{MSY} = 1$ and $B/B_{MSY} >= 1$; in other words, the fisheries are being maximally sustainably fished, under all management implementation scenarios (SI Figure 2). This trend occurs since fishing mortality at F_{MSY} is optimal and will allow the biomass in each fishery to build. That is, if the fisheries are managed at MSY their overall health is significantly improved when compared to the initial status in 2015.



SI Figure 2: Kobe plot with fishery Status in 2065 when fishing effort is F_{MSY} (all/5%/0%/0%) Each point represents a fishery and the color represents each scenario of reserve network implementation year. The “Initial” scenario is the status of each fishery in 2015, other points are fishery status at year 2065. Fisheries in the quadrant F/F_{MSY} and $B/B_{MSY} < 1$ are overfished and recovering, $F/F_{MSY} > 1$ and $B/B_{MSY} < 1$ are overfished and continue to experience overfishing, F/F_{MSY} and $B/B_{MSY} > 1$ are experiencing overfishing and those with F/F_{MSY} and $B/B_{MSY} < 1$ are in good health.

Changing fisheries status and trends under IUU scenarios

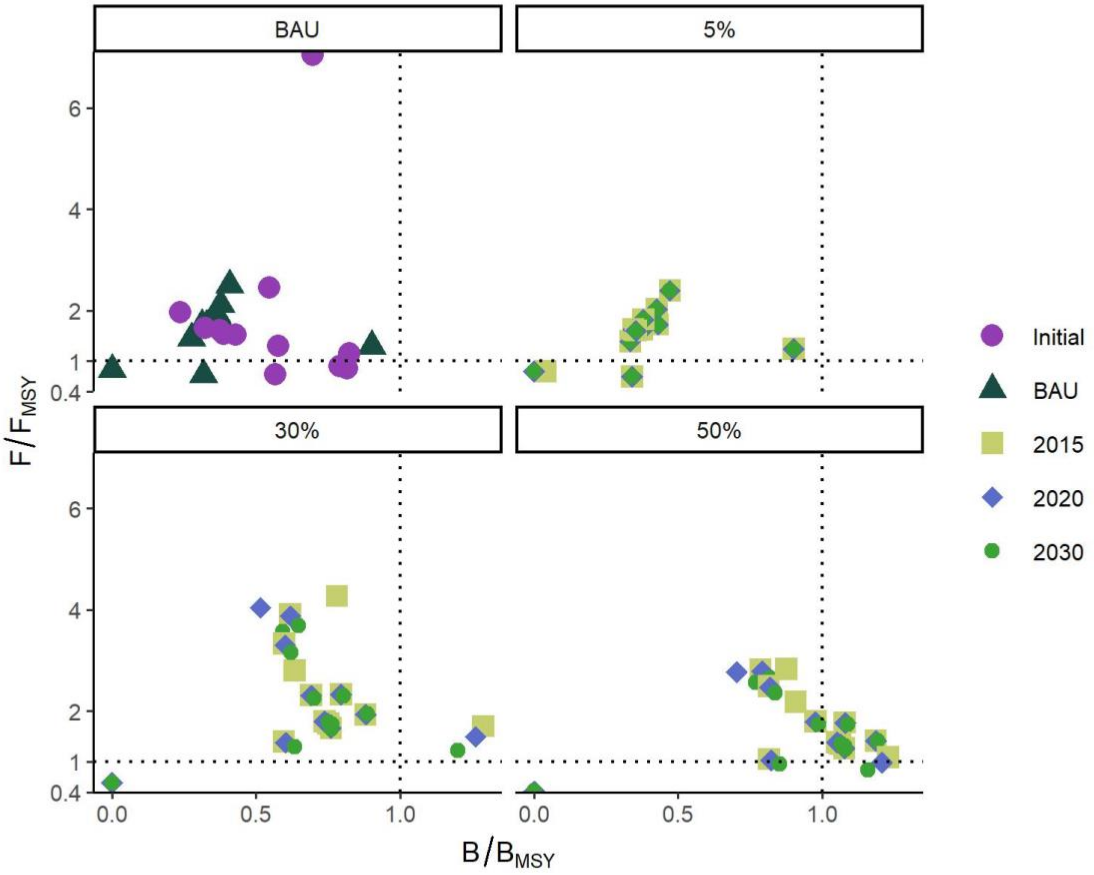
Illegal, unreported and unregulated (IUU) in Mexico, is estimated between 40-60% of the reported landing values (Cisneros-Montemayor et al., 2013; EDF, 2012). Therefore, we conducted a sensitivity analysis to estimate the effects of IUU with an increase of 40% and 60%, of the reported landing values. These inflated IUU scenarios were ran as individual stock assessments generating specific fishery reference values.

Scenarios

The bioeconomic model was used to assess a business as usual scenario and scenarios with fully factorial combination (Figure 1) of reserve implementation year of 2015, 2020, and 2030, reserve network size of 5%, 30% and 50%, IUU fishing of 0%, 40% and 60% and for those scenarios with IUU perfect compliance was modeled. This was done by removing the level of IUU from fishing effort. For example in IUU 40% scenario we removed 40% of fishing exploitation rate. The initial fishery status was a result of the catch-only stock assessment algorithm and described the status of the fishery in 2015 only. The business as usual scenario (BAU) presents status quo where fisheries remain open access and there is no reserve network implementation.

Changing reserve network sizes

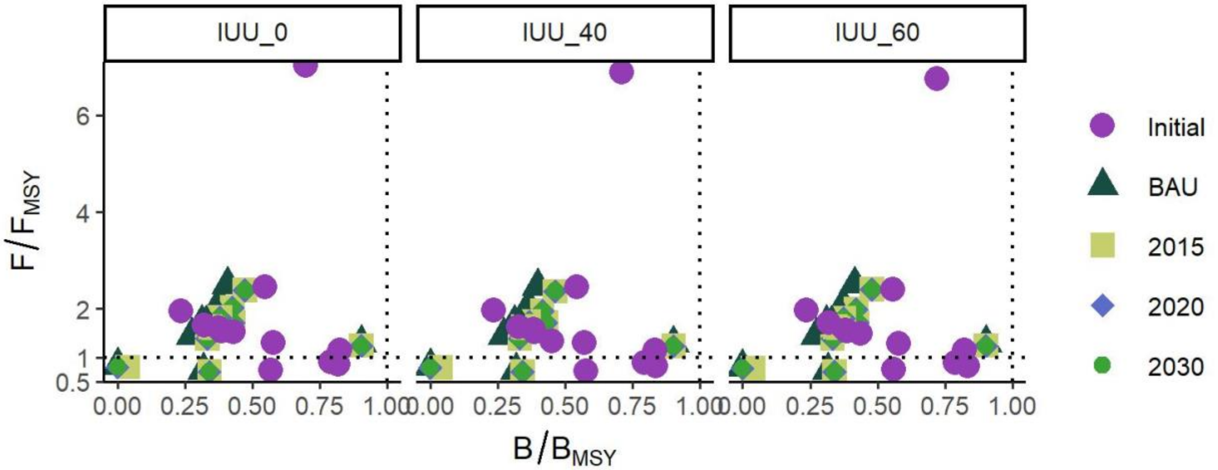
In order to assess the effects of increasing the current marine reserve network size, we varied marine reserve network size from 5% to 30% and 50% increase. Status of the fisheries are shown by each of the scenarios assessed (SI Figure 4). A larger reserve network results in improved fishery status relative to BAU and other reserve size scenarios.



SI Figure 3. Kobe plots of fishery status in 2065 with reserve network size scenarios (all/ all / 0%/ 0%). Each point represents a fishery and the color represents each scenario of reserve network implementation year. The “Initial” scenario is the status of each fishery in 2015, other points are fishery status at year 2065. Fisheries with F/F_{MSY} and $B/B_{MSY} < 1$ are overfished and recovering, $F/F_{MSY} > 1$ and $B/B_{MSY} < 1$ are overfished and continue to experience overfishing, F/FMSY > 1 and B/BMSY <1 are experiencing overgishing, and F/FMSY <1 and B/BMSY > 1 are in good health. BAU represents no reserve network implemented, other plots represent the size of the reserve network modeled.

Regional Illegal, Unregulated and Unreported (IUU) fishing

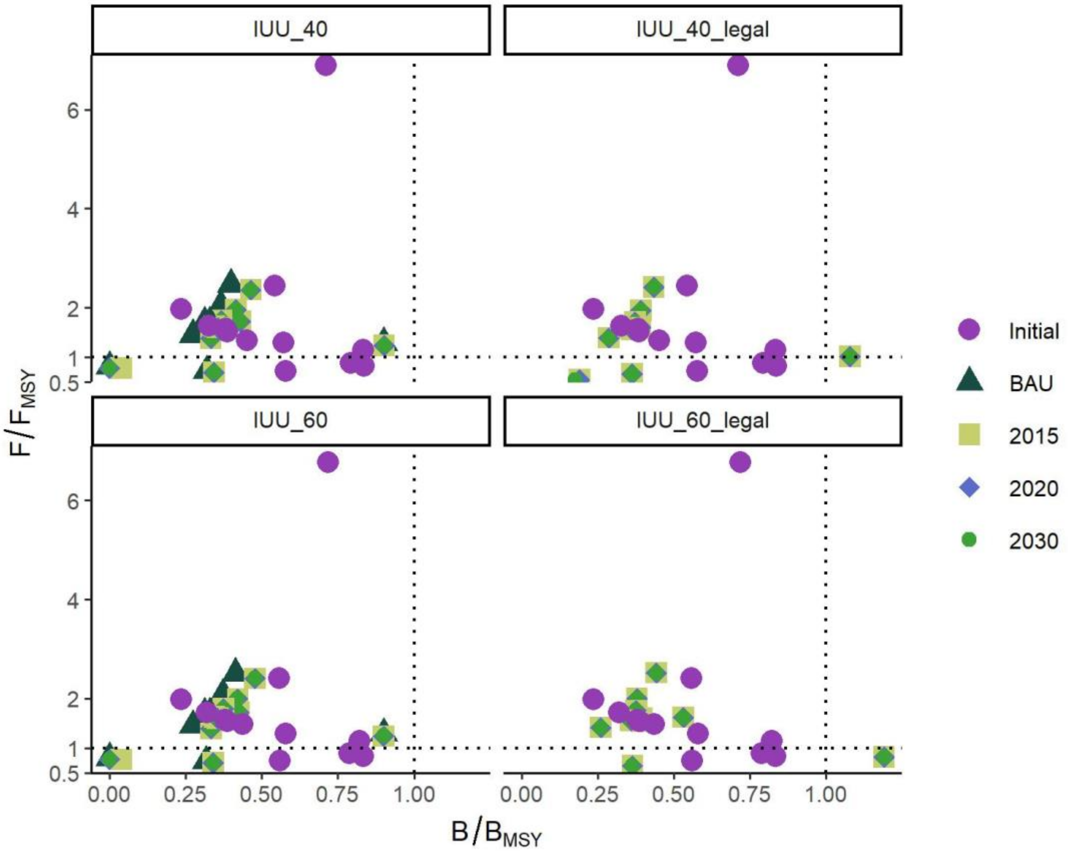
The results of the IUU fishing sensitivity analysis suggests that the trends observed in the reported catch scenario remain the same (i.e. biomass increases with reserve network implementation while catch and profits decreases), while the magnitude of the trends change as presented in results. These results were expected given that IUU inflation had no effect on B/B_{MSY} nor F/F_{MSY}, but had a linear effect on MSY (i.e. if catch is inflated by 20%, MSY increased by 20%). F_{msy} is a function of the intrinsic growth rate (“r”), which is specific to the species and not influenced by catch ($F_{msy} = r/2$). B_{msy} is related to carrying capacity (“k”), which is estimated from catch ($B_{msy} = k/2$). However, a systematic increase in k from catch inflation cancels out for B/B_{msy}, because biomass estimates are being increased by the same amount as B_{msy}. These findings were similar to those of Costello et al., 2016. Because costs of fishing are dependent on MSY, not accounting for IUU fishing results in cost estimates that are lower than reality, making this part of the analysis very important.



SI Figure 4: Kobe plots with fishery status in 2065 with IUU scenarios (all/5%/all/0%). Each point represents a fishery and the color represents each scenario of reserve network implementation. The “Initial” scenario is the status of each fishery in 2015, other points are fishery status at year 2065. Fisheries in the quadrant F/F_{MSY} and $B/B_{MSY} < 1$ are overfished and recovering, those in $F/F_{MSY} > 1$ and $B/B_{MSY} < 1$ are overfished and continue to experience overfishing.

Simulating perfect compliance in IUU fishing scenarios

Results from simulating perfect enforcement for IUU scenarios of 40% and 60% revealed an increase in fishery status over time (SI Figure 5) this effect became more evident when coupled with larger reserve sizes as depicted in (SI Figure 3). This suggests that addressing IUU fishing in the region can result in improved fisheries over 50 years.



SI Figure 5: Kobe plots with fishery status in 2065 with IUU scenarios and perfect enforcement (all/5%/all/all). Each point represents a fishery and the color represents each scenario of reserve network implementation. The "Initial" scenario is the status of each fishery in 2015, other points are fishery status at year 2065. Fisheries in the quadrant F/F_{MSY} and $B/B_{MSY} < 1$ are overfished and recovering, those in $F/F_{MSY} > 1$ and $B/B_{MSY} < 1$ are overfished and continue to experience overfishing. IUU_40_legal and IUU_60_legal represent scenarios with perfect compliance for each IUU scenario respectively.

Subsidies

In Mexico, CONAPESCA has subsidy programs to help and support fishers, such as fuel subsidies to small-scale fisheries. The federal government is annually subsidizing small-scale fisheries gasoline by approximately $3 million (Dominguez-Sánchez et al., 2019). However, in the Midriffs Islands, subsidies have been decreasing from 2011 to 2016. For example, in 2011 the region received an estimate of $85,431 dollars while in 2016 it received an estimate of $15,554 dollars of fuel subsidies for small-scale fisheries. Subsidy theory suggests that offsetting the costs of fishing creates perverse incentives for fishers to overfish (Sumaila et al., 2009). While this was not explicitly included in our models, we acknowledge that this could have impacts on fishing behavior and, therefore, the Midriff Islands' stocks.