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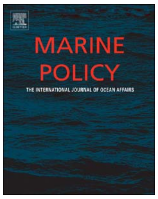

The cost of management delay: The case for reforming Mexican fisheries sooner rather than later

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ABSTRACT

Management reform has the potential to rebuild fisheries and increase long-term harvest and profitability. But timing is critical: delaying reform implementation significantly reduces the potential socio-economic and biological benefits of improved management. This study models the costs of delaying reform in terms of annual biomass, harvest, and profit for 28 Mexican fisheries, parameterized using novel, fishery-specific data. Three types of reforms are examined: 1) harvest policy, 2) elimination of illegal fishing, and 3) implementation of rights-based fisheries management. The harvest policies examined in this analysis are status quo (no reform), F_{MSY}, and economically optimal fishing mortality. The results show that prompt management reforms lead to improved annual aggregate biomass, harvest, and profit over time. However, delaying reform results in substantial costs. Just a 5-year delay of the implementation of comprehensive reform leads to a 51 million USD loss to average annual profits. Without reform, stock status can continue to decline, and the recovery of harvests and profits are further delayed. Over a given time-horizon, delayed reforms can dramatically reduce the number of healthy stocks. The results demonstrate that delayed reform can significantly diminish potential benefits that could be secured through improved management; this highlights the importance of prompt timing considerations during policy reform.

1. Introduction

Overfishing has driven the decline of many fish stocks across the globe, threatening sustainable harvests and profits of both industrial and small-scale commercial fishing sectors, as well as food and job security in regions that depend on fishing for the local provision of protein and employment. Inadequate fishery institutions, illegal fishing (which undermines sound rules and regulations), and the misalignment of incentives due to a lack of secure rights are major challenges that have precluded sustainable management [1–3]. Approximately 63% of global stocks are currently below management targets, and many stocks still require management reform in order to ensure their sustainable and profitable productivity into the future [4–6]. Several studies demonstrate the potential long-term benefits of management reform in terms of stable harvests, increased profits, and healthy stocks [6–9]. Murawski [10] found that of 24 depleted fisheries, all but one showed signs of biomass recovery following reduction in fishing mortality. Similar biomass recovery has been seen following reforms in the United States' Gulf of Mexico red snapper fishery, while the value of the fishery – as reflected in quota prices – has also increased [11,12]. Most studies show that if overfishing is occurring, long-term benefits can be achieved through appropriate reductions in fishing mortality [6,7]. This simple, yet proven concept also implies that delaying reforms will result in economic and ecological costs, because the stock will be driven down even further, requiring more time and resources to recover. This *cost of delay* has received almost no attention in the literature and is the principal focus of this paper.

Delays in fisheries reform can occur for numerous reasons. For overfished fisheries, improved management implies constraining harvest relative to the status quo. This usually entails short-term harvest and economic losses. While this may explain why top-down reforms are often resisted by the fishing sector, it also implies that there may be

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significant implementation delays [13,14]. Where the reforms involve rights-based management, fishermen may resist if the initial allocation of rights is perceived as disadvantageous [15]. Other factors that can lead to delayed reform include long periods of implementation (e.g. when stakeholders resist reforms or have competing interests), uncertainty in scientific advice, and lack of capacity and resources to implement reforms [14,16].

Previous research and case studies suggest that management reform delays can undermine both biological and fishery benefits. Shertzer & Prager [14] found that longer delays in management reform required larger harvest reductions for longer periods of time. Delayed reform has also been shown to affect biomass indicators – studies report that reform delays increase the risk of stock collapse [14,17,18]. Indeed, delayed management (at least 5 years) in the southeast Australian orange roughy fishery is believed to have contributed to the further decline of these stocks. By the time the recommended catch limits were adopted, several stocks had already collapsed [17,19]. Timely reform is, on the other hand, expected to help prevent stock collapse and require less drastic harvest reductions at the onset of reform compared to severe reductions that may be needed as stock conditions continue to decline during delays [14]. Further, prompt management reform has been shown to result in faster recovery, greater annual harvest rates, and more years for which harvest exceeds status quo harvest [14]. These findings are especially relevant in the case of stocks that are not yet depleted but are subject to unsustainable fishing pressure. In their review of 154 global fish populations, Pinsky & Byler [18] found that fishery collapses were best explained by the magnitude of overfishing, and that long-term depletion was best explained by the duration of overfishing. Therefore, the prompt curbing of overfishing regardless of depletion level can simultaneously prevent long-term depletion, require more modest harvest reductions, and lead to the more rapid realization of biological and economic benefits.

Mexico is an ideal country in which to examine the impacts of delayed reform due to the importance of its fishing sector, the availability of data, and the potential for management reform to address issues in a number of its fisheries. Mexico is one of the principal fishing countries in the world, ranking number 16 in terms of total production and has recently emerged as an important global exporter [20]. Over 200,000 fishers rely on fisheries resources for their livelihoods, and over 2 million people rely (directly or indirectly) on these resources [20,21]. However, the potential ecological, economic, and social benefits from many of Mexico's fisheries are largely unfulfilled due to unsustainable harvest rates and illegal fishing pressure, which have led to low fish populations and reduced profits. Mexico's long coastline (> 11,000 km), along with inconsistent administrative practices and limited enforcement in the fishing sector, enable illegal fishing [22,23]. The effect of illegal fishing is believed to be substantial. A recent study estimated that between 1950 and 2010 actual harvests were nearly double reported harvests [22,24]. Similarly, a survey of Mexican fishery experts consistently found that unreported and illegal fishing represents 40–60% of reported landings [25]. In addition, management strategies that emphasize harvest volume rather than value have led to minimal profitability in the fishing sector. Currently, added value for fisheries products in Mexico is 80% less than the global average. While the global average for added value is USD $3 for every USD $1 extracted from fishing, Mexico only generates an additional USD $0.60 [26]. The prevalence of illegal fishing and lack of added value products suggest that both sustainability and profitability could benefit from eliminating illegal fishing as well as from implementing rights-based fisheries management (RBFM) approaches. This study addresses both issues.

This study builds on the previous literature in a number of ways. First, this study focuses on 28 important fisheries in Mexico in terms of volume and value [Table A1] to analyze the impacts of delayed management in an important fishing nation. Together, landings from these 28 fisheries represent about 60% of Mexico's total annual catch. Second, instead of modeling hypothetical fish stocks, a bioeconomic model adapted from a recent modeling approach [6] is parameterized with data from these 28 Mexican fisheries, which represent a range of life-histories, current stock conditions, and current fishing pressures. Third, in addition to examining the costs of delayed reform in terms of harvest and stock status, this study examines the economic effect of delayed reform, focusing on profits to the fishing sector. Finally, the performance of three different kinds of management reforms under prompt and delayed reform are examined: 1) implementation of a new harvest control policy, 2) elimination of illegal fishing, and 3) adoption of a version of rights-based fishery management (RBFM). Emphasis is placed on results for stocks that are both currently overexploited and projected to reach overexploited status under a business-as-usual (BAU) scenario. Following Costello et al. [6] stocks for which $B/B_{MSY} < 0.8$ are considered overexploited.

While the recovery potential of any given fish stock depends on inherent factors such as its current biological condition and growth rate, management reforms will clearly play a role in recovery timing and value. This study focuses on two distinct factors: (1) the type of management reform, and (2) the timing of management implementation. Using the model and methods described below, the following questions are explored:

- What is the likely future for Mexico's 28 fisheries under business as usual (BAU)?
- What are the annual implications of management reform on biomass, harvest, and profit compared to BAU?
- What factors are responsible for benefits in biomass, harvest, and profit?
- What is the cost of delaying management reform, measured by harvest, biomass, and profits?
- How do reform delays affect the timing of fishery recovery?

2. Materials and methods

2.1. Approach

Future catch, profit, and biomass trajectories are modeled for each of the 28 individual Mexican fisheries using a discrete-time Pella-Tomlinson surplus production model, following the Costello et al. [6] approach, making three important modifications. First, all input parameters are calculated using fishery-specific data as opposed to global aggregates. Second, the model is modified to include illegal fishing, which is also parameterized with fishery-specific data. This novel approach allows for the examination of the effects of eliminating illegal fishing in each fishery. Finally, the model is modified to vary the year of reform implementation in order to test the effect of implementation delays. Within this expanded structure, the model is individually parameterized to each of the 28 Mexican fisheries.

For each fishery, trajectories are estimated over a 20-year time horizon. Each management scenario assumes that the same reform is applied across all 28 fisheries; for example, a scenario in which RBFM is implemented, models the reform for all 28 fisheries. Each individual reform is evaluated separately, as well as all of the different combinations of possible reforms. Resulting indicators reflect only legal harvests and profits. Reform implementation can occur as early as year 2, and as late as year 20. The full range of possibilities is examined, which allows for an assessment of how the length of delay affects each fishery indicator.

2.2. Model description

2.2.1. General equations

This analysis uses a deterministic discrete Pella-Tomlinson (PT) model [27], a generalized version of the logistic growth model. The PT model is given as follows:

Table 1
Summary of the five management scenarios examined. Each scenario has three components: harvest control policy, illegal fishing (present or eliminated), and RBFM (implemented or not implemented).

Scenario name	Scenario description	Harvest policy	Illegal fishing	RBFM
BAU	BAU	SQ	Present	Not implemented
Scenario 1	No Illegal Fishing	SQ	Eliminated	Not implemented
Scenario 2	Maximize Yield & No Illegal Fishing	$\mathrm{F_{MSY}}$	Eliminated	Not implemented
Scenario 3	Maximize Profits & RBFM	Economically optimal	Present	Implemented
Scenario 4	Maximize Profits, No Illegal Fishing, & RBFM	Economically optimal	Eliminated	Implemented

$$B_{t+1} = B_t + \frac{\phi+1}{\phi} g B_t \left(1 - \left(\frac{B_t}{K}\right)^{\phi}\right) - H_{L,t} - H_{I,t} \tag{1}$$

where B_t is the biomass in time step t, ϕ is a shape parameter, g is the population growth rate, K is the carrying capacity of the population, $H_{L,t}$ is the harvest of the legal fishing fleet, and $H_{L,t}$ is the harvest of the illegal fishing fleet. Profits for the legal fishing fleet are tracked using the following economic model:

$$\pi_{L,t} = pH_{L,t} - c(gf_{L,t})^{\beta} \tag{2}$$

where $\pi_{L,t}$ is the legal fishing profit in time step t, p is the ex-vessel price, $f_{L,t}$ is the ratio of legal fishing mortality rate $F_{L,t}$ to F_{MSY} (where, for the Pella-Tomlinson model, $F_{MSY}=g$), c is a variable cost parameter, and β governs the shape of the cost per unit effort.

2.2.2. *Management scenarios*

A range of alternative management scenarios are modeled for each fishery. These scenarios each have a combination of the following three factors: 1) a harvest policy, which can be status quo (SQ), $\mathrm{F_{MSY}}$, or economically optimal, 2) the presence or elimination of illegal fishing, and 3) the presence or absence of RBFM (scenarios defined in Table 1).

The portion of the fishery that is intervened upon depends on the stated scenario. All of the fisheries have two fleets – one responsible for legal domestic fishing mortality and one responsible for illegal fishing mortality. Due to the international nature of the yellowfin tuna fishery, a third fleet that represents international fishing pressure is included for the analysis of that fishery, which is not affected by management reforms in this analysis. The harvest control rule and RBFM reforms directly affect only the legal domestic fishing mortality. The illegal fishing reform directly affects only illegal fishing mortality. None of the reforms affect the international fishing mortality in the yellowfin tuna fishery. The portion of the fishery affected by an intervention, which depends on the management scenario, is hereafter referred to as the intervention fleet.

2.2.2.1. Harvest policy. The harvest policy determines how fishing mortality will evolve over time for the intervention fleet, and for any given scenario is one of the following: 1) SQ, 2) F_{MSY}, and 3) the economically optimal fishing mortality, which is based on a dynamic optimization model. The dynamic optimization takes into account the initial cost and price parameters (RBFM not present) as well as the initial division of fishing mortality among the domestic legal, domestic illegal, and the international fleets, to determine the economically optimal fishing mortality rate for any given level of biomass. The economically optimal fishing mortality is the harvest control rule that ensures the greatest economic benefits for the legal domestic fishers under the current conditions.

Under the SQ harvest policy, the legal domestic fishing mortality conservatively remains constant at its initial level over the time horizon. The equation determining the legal fishing mortality under SQ for each time step is given as follows:

$$f_{L,t,SQ} = f_{L,0} \tag{3}$$

The F_{MSY} harvest policy ensures that total fishing mortality is equal to F_{MSY}, accounting for illegal fishing and international fishing mortalities if present. The equation determining the legal fishing mortality under the F_{MSY} reform for each time step is given as follows:

$$f_{L,t,FMSY} = 1 - f_{I,t} - f_{INT,t} \tag{4}$$

where $f_{I,t}$ is the ratio of illegal fishing mortality rate $F_{I,t}$ to $F_{MSY,}$ and $f_{INT,t}$ is the ratio of international fishing mortality rate $F_{INT,t}$ to F_{MSY}.

To determine the legal fishing mortality for any given biomass under the economically optimal scenario ($f_{L,t,ECONOPT}$), the following term is dynamically optimized for each possible biomass level to maximize the discounted future stream of profits. This determines a policy function where $f_{L,t,ECONOPT}$ is a function of B_t.

$$\max_{f_1, f_2, \dots} \sum_{t=1}^{\infty} \frac{\pi(B_t, f_t)}{(1+\delta)^t} \tag{5}$$

where δ is the discount rate.

2.2.2.2. Illegal fishing. This study also models whether or not illegal fishing is eliminated in each fishery. When illegal fishing is eliminated, $f_{I,t} = 0$. When illegal fishing is not eliminated, it is assumed that the initial illegal fishing mortality stays constant over time, thus $f_{I,t} = f_{I,0}$. This value is different for each fishery and is derived in the initial parameterization (see Section 2.3). Importantly, this still allows illegal harvest to change as the underlying biomass changes, though the fraction of the stock harvested by the illegal sector remains constant over time.

2.2.2.3. Rights-based fisheries management. The third management reform component is the possible implementation of RBFM. This option is examined because it has been shown to decrease fishing costs and increase product prices through improved quality, strategic market timing, and other value-added activities [28]. When RBFM is implemented, it is assumed that ex-vessel prices go up by some factor and that variable fishing costs go down by some factor. When RBFM is not implemented, it is assumed that prices and costs remain at their original levels. Prices and costs under RBFM are described as follows:

$$p_{RBFM} = p_{NORBFM}\gamma_p \tag{6}$$

$$c_{RBFM} = c_{NORBFM}\gamma_c \tag{7}$$

where p_{RBFM} is the price under RBFM, $p_{NO\ RBFM}$ is the price without RBFM, γ_p is the RBFM price scalar (typically > 1), c_{RBFM} is the variable fishing cost parameter under RBFM, $c_{NO\ RBFM}$ is the variable fishing cost parameter without RBFM, and γ_c is the RBFM variable fishing cost scalar (typically < 1). The parameters $\mathrm{\gamma_c}$ and $\mathrm{\gamma_p}$ are discussed in Section 2.3.

2.2.3. *Reform delays*

To examine the effects of delayed reform, the time at which reform begins is varied, and it is assumed that the BAU scenario persists up until the first year of reform. In all cases, a 20-year forward-looking time horizon is simulated. The year in which reform implementation occurs varies over the range from 2 to 20 years, assuming year 1 represents current conditions. Reform beginning in year 2 of the simulation is therefore considered to have no delay, while reform beginning in any subsequent year is considered delayed. When management is applied in year t, it is applied to all 28 fisheries and continues for the duration of the simulation. For example, reform starting in year 7 is considered a 5-year delay. In this case, the BAU scenario is applied for years 1 through 6 of the simulation, and the reformed management scenario is applied in years 7–20. Therefore, the length of reform delay varies from 0 to 18 years.

2.2.4. Model parameterization

For all species, it is assumed that $\phi = 0.188$ [29]. Given the intrinsic growth rate of the species r, the parameter g is calculated as follows:

$$g = \frac{r\phi}{\phi + 1} \tag{8}$$

Maximum sustainable yield (MSY) is calculated based on the maximum reported catch [metric tons] for each species using the following equation [30]:

$$\text{MSY} = 1.78(10^{-0.8644+1.0976\log_{10}(\text{maxium reported catch})}) \tag{9}$$

Using this value of MSY and the dynamics of the Pella-Tomlinson model, carrying capacity is calculated as follows:

$$K = \frac{\text{MSY}(\phi + 1)^{\frac{1}{\phi}}}{g} \tag{10}$$

Using this value of K, B_{MSY}, the level of biomass that allows for MSY, is:

$$B_{MSY} = \frac{K}{(\phi + 1)^{\frac{1}{\phi}}} \tag{11}$$

Finally, the variable fishing cost for each species can be backed out using the following equation:

$$c = \frac{\text{frac} * \text{p}(f_{L,0} + f_{I,0})\frac{B_0}{B_{MSY}}\text{MSY}}{(g(f_{L,0} + f_{I,0}))^{\beta}} \tag{12}$$

where *frac* is estimated as current total costs divided by revenues.

2.2.5. Assumptions and caveats

The Pella-Tomlinson model used does not capture effects relating to age structure, nor does it allow for analysis of certain specific management interventions such as a minimum size limit or other management policies that affect different age classes. Rather, the model allows for the exploration of how a range of hypothetical management scenarios might affect the fishery. From the perspective of the fishery manager, perfect information in setting these policies is assumed. From the perspective of the fleet being intervened upon, perfect compliance with the policies is assumed. Additionally, the model is not spatially explicit, so this study does not directly model how spatial management would affect the fishery. The model also excludes external forcing or random effects in the environment or market. Finally, a single-species model is used and thus this study does not account for trophic interactions between species. While all of these assumptions are surely relevant for real-world tactical fishery policy design, the intent for this study is to provide general guidance on the likely costs of delays in management reforms.

2.2.6. Reform scenarios

A given scenario consists of a harvest control rule (SQ, F_{MSY}, or economically optimal), a degree of illegal fishing (present or absent), and an RBFM situation (present or absent). Altogether, this yields a set of 12 possible scenarios to consider. This study focuses on the following five scenarios that capture the most relevant and interesting combinations of interventions [Table 1]:

- *Business-as-usual (BAU)*: This scenario consists of the SQ harvest policy, constant illegal fishing pressure equal to current conditions, and absence of RBFM. It represents a scenario in which management reform does not occur.
- *Scenario 1 (No Illegal Fishing):* This scenario consists of the SQ harvest policy, elimination of illegal fishing, and absence of RBFM. It represents a reform that effectively targets illegal fishing, but does not intervene in the legal sector.
- *Scenario 2 (Maximize Yield & No Illegal Fishing):* This scenario consists of the F_{MSY} harvest policy, elimination of illegal fishing, and absence of RBFM.
- *Scenario 3 (Maximize Profits & RBFM):* This scenario consists the economically optimal harvest policy, constant illegal fishing pressure equal to current conditions, and implementation of RBFM.
- *Scenario 4 (Maximize Profits, No Illegal Fishing, & RBFM)*: This scenario consists of the economically optimal harvest policy, complete elimination of illegal fishing, and implementation of RBFM. This represents a benchmark scenario in which all three possible reforms occur.

Table 2
Description of parameters used in the model.

Parameter	Type of parameter	Description	Method
ϕ	Biological	Shape parameter	Estimated
g	Biological	Growth parameter	Estimated
K	Biological	Carrying capacity	Estimated
B_0	Biological	Initial biomass	Fishery-level data
$f_{L,0}$	Fishery	Initial legal fishing mortality	Fishery-level data
$f_{I,0}$	Fishery	Initial illegal fishing mortality	Fishery-level data
λ	Fishery	Open access coefficient	Estimated
β	Economic	Cost parameter	Estimated
$p_{NO\ RBFM}$	Economic	Price	Fishery-level data
$c_{NO\ RBFM}$	Economic	Cost parameter	Fishery-level data
γ_P	Economic	RBFM price scalar	Fishery-level data
γ_C	Economic	RBFM cost scalar	Fishery-level data

2.3. Data

While some of the parameters used in the model are calculated (see Section 2.2.4), many are based on novel fishery-level data collected for this analysis [Table 2]. Input data for 28 Mexican marine stocks from different climatic regions and ecological environments included fisheries status, life-history parameters, and economic and management variables (details are described in Cisneros-Mata [31], see Table A2 for fishery specific parameters). Price of landings and catch came from official reports [32–35]. Landings were in some cases estimated from data aggregated for multiple species. All parameter values and their derivations are given in Cisneros-Mata [31]; here, explanations are provided for specific cases. For example, for blacktip sharks along the Mexican Pacific coast, total catch was assumed to come from 300 small scale boats, each with a mean CPUE of 3105 kg/year in 2011 [34,36,37]; maximum catch was in this case estimated as double the sum of that year. For skipjack, maximum catch was considered to be 10%, 10%, and 5% of total catch series in 2010 in Baja California, Baja California Sur, and Sonora respectively [34]. Biomass relative to biomass at MSY (B_t/B_{MSY}) and intrinsic rate of population growth (r) mostly came from published reports for the stocks considered or otherwise from similar species.

The relative increase in price of landed fish and relative decrease in cost of fishing after the implementation of RBFM were determined using the current values and an open-access parameter, which describes how easy it is to enter a fishery. For fisheries in which current unit price is high and access is easily obtained (e.g., enforcement is not present), prices do not increase much. However, fisheries that are closed access

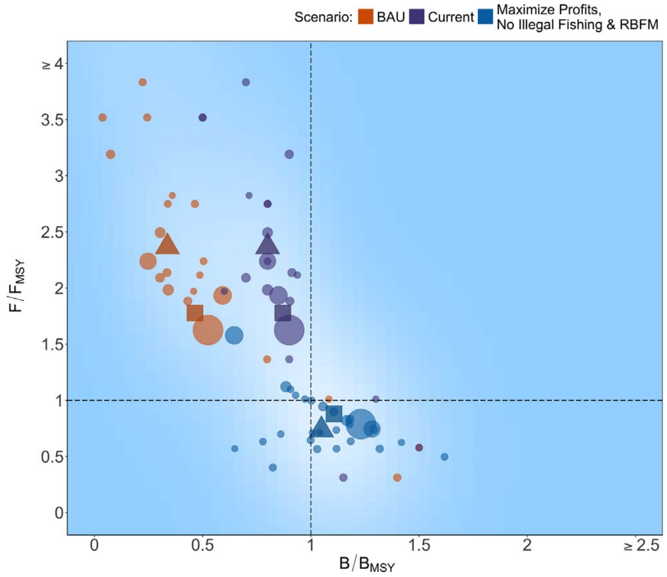

Fig. 1. Kobe plot showing current and future status under BAU and Scenario 4 (Maximize Profits, No Illegal Fishing, & Rights Based Management) in year 20 for all 28 fisheries. Dot size correlates to MSY, and background shading correlates to the density of fisheries with similar B/B_{MSY} and F/F_{MSY} values. Triangles represent the median status of fisheries (Current: $B/B_{MSY} = 0.8$, $F/F_{MSY} = 2.37$; BAU: $B/B_{MSY} = 0.34$, $F/F_{MSY} = 2.37$; Scenario 4: $B/B_{MSY} = 1.05$, $F/F_{MSY} = 0.74$). Squares represent the MSY-weighted average status of fisheries (Current: $B/B_{MSY} = 0.87$, $F/F_{MSY} = 1.77$; BAU: $B/B_{MSY} = 0.47$, $F/F_{MSY} = 1.78$; Scenario 4: $B/B_{MSY} = 1.11$, $F/ F_{MSY} = 0.88$).

experience comparatively higher price increases [31]. Illegal fishing rates refer to unreported catches and were obtained through a census of Mexican fisheries experts [22].

3. Results

3.1. BAU and comprehensive reform projections

Under the *BAU* scenario, the percentage of fisheries with a healthy biomass level (which is defined here as $B/B_{MSY} \geq 0.8$) drops from 57% (16 of 28 fisheries) in year 1 to just 11% (3 fisheries) by year 20 [Fig. 1]. This drop occurs quickly – by year 5, only 14% (4 fisheries) are at a healthy level [Fig. 2]. In contrast, if the most comprehensive set of reforms (*Maximize Profits, No Illegal Fishing, & RBFM*) is implemented immediately, 89% (25 fisheries) of fisheries have a projected healthy biomass by year 20 (Figs. 1 and 2). Under BAU, annual aggregated biomass, harvest, and profit all decrease compared to year one indicators. By year 20, BAU results in 38% less biomass in the water, 47% lower harvests, and a 97% decrease in profits compared to the current status in year 1 [Fig. 3]. This striking baseline suggests that BAU has simultaneously poor economic, ecological, and food security outcomes.

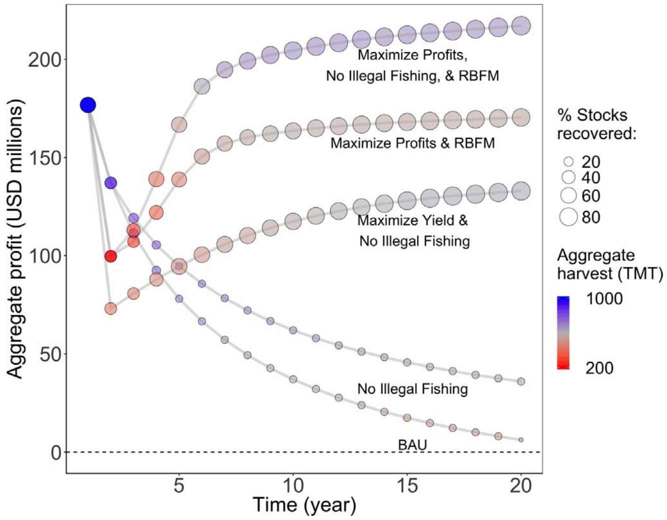

Fig. 2. Profit trajectories for the five management scenarios over time. The size of the bubble represents the percentage of stocks with a biomass level $\geq 0.8\ B_{MSY}$ over time. The color represents the aggregate harvest in each time step.

3.2. Reform scenarios – Immediate implementation in year 2

In contrast to BAU, implementing Scenario 4 (*Maximize Profits, No Illegal Fishing, & RBFM*) in year 2 causes most fisheries to achieve a sustainable biomass level, as well as higher annual profits and harvests. This scenario immediately begins the rebuilding process for fisheries. In year 2, only 32% of fisheries (9 fisheries) have a biomass $\geq 0.8\ B/B_{MSY}$. By year 5, 57% of fisheries are projected to be recovered, and by the end of the 20-year time horizon 89% of fisheries are projected to be recovered [Fig. 2].

When implemented immediately, all four alternatives to *BAU* eventually surpass annual aggregate biomass, harvest, and profit indicators under *BAU* [Fig. 3]. Annual biomass experiences immediate increases when any of the four reform scenarios are implemented, while all scenarios except the *No Illegal Fishing* scenario produce annual harvests and profits that initially experience declines relative to *BAU* before they recover. Annual harvest under *BAU* is surpassed in year 7, 11, and 13 under the most comprehensive reform, the *Maximize Yield & No Illegal Fishing*, and the *Maximize Profits & RBFM* scenarios, respectively. Annual profit under *BAU* is surpassed in year 3, 5, and 4 under those scenarios, respectively [Fig. 3].

The most comprehensive reform results in the highest annual aggregated profit and harvest in year 20 compared to the other four management scenarios [Fig. 3]. However, *Maximize Yield & No Illegal Fishing*, which focuses on maximizing legal yields rather than profits, results in the largest aggregated biomass at the end of the time horizon. The *No Illegal Fishing* scenario performs substantially worse than the other alternatives to *BAU* in terms of aggregate biomass and profit in year 20. The *Maximize Profits & RBFM* scenario performs the worst in terms of aggregate harvest in year 20.

3.3. Cost of delayed reform

The main objective of this paper is to determine the economic and ecological costs of delayed management reform for fisheries that are overexploited and/or subject to overfishing. To determine the implications of delayed management reform, costs in terms of forfeited long-term biomass, harvest, and profit are examined focusing on Scenario 4. Costs are reported as losses to potential annual biomass, harvest, and profit indicators averaged across all 28 fisheries. This study finds that these costs are significant and continue to increase as the delay in implementation increases. The short-term implications for harvest and profit are also examined.

The minimum annual harvest, or the lowest annual harvest experienced over the 20-year time horizon, decreases as the delay in implementation of reforms increases; in other words, longer delays lead to annual harvest lows not experienced with swift reform [Table 3]. Long-term harvest is also negatively affected by delays. The average annual harvest decreases as the delay increases. For example, an 8-year delay results in about a 45,000 MT loss to average annual harvest [Fig. 4].

The results reveal similar trends in economic indicators. The minimum annual profit, as with harvest, decreases as the delay

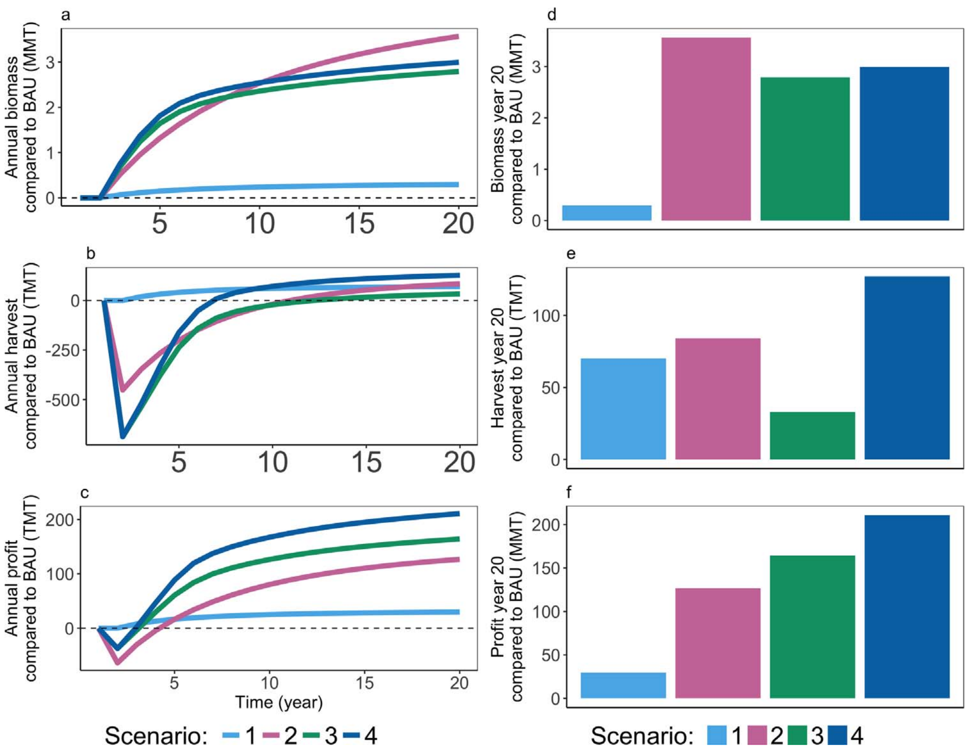

Fig. 3. Annual absolute increases in aggregated biomass, harvest, and profit compared to BAU over time. Plots on the left, from top to bottom, represent the annual increase in aggregate biomass, harvest, and profit compared to BAU over time, while the plots on the right show increases for year 20 only. All management reforms were implemented in year 2.

Table 3
Minimum annual harvest and profit indicators for varying implementation years for Scenario 4 (*Maximize Profits, No Illegal Fishing, & Rights Based Management*).

Implementation year	Length of delay (Years)	Minimum annual harvest (TMT)	Minimum annual profit (USD Million)
2	0	192.9	99.7
4	2	128.7	79.4
6	4	100.5	69.1
8	6	81.7	61.9
10	8	69.3	56.9
12	10	60.7	53.7
14	12	53.7	51.6
16	14	47.8	50.0
18	16	42.9	48.9

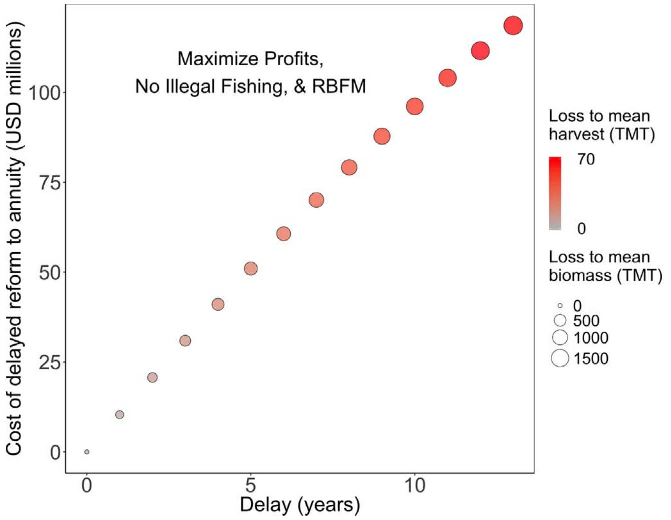

Fig. 4. Cost of delayed reform on aggregate annuity, average mean harvest, and average mean biomass for the most comprehensive reform scenario, Scenario 4 (*Maximize Profits, No Illegal Fishing, & Rights Based Management)*. Longer delays lead to greater costs in profits, biomass, and harvest.

increases and can lead to significant declines in annual profits compared to that under prompt reform. An 8-year delay in implementing Scenario 4 leads to a minimum annual profit of about 57 million USD, while the lowest annual profit without a delay is nearly 100 million USD (75% higher) [Table 3]. The average annual profit similarly decreases as the delay increases. A 5-year delay results in a 51 million USD loss to average annual profit, while a 10-year delay results in a 96 million USD loss [Fig. 4].

Intuitively, delayed reform also affects the timing of fishery recovery. As expected, as the delay in reform increases, the number of fisheries that reach a healthy status by the end of the time horizon decreases. In order to maintain or increase the current (year 1) percentage of fisheries with a stock size ≥ 0.8 B_{MSY}, Scenarios 2, 3, and 4 must be implemented by year 7, 8, and 11, respectively. Scenario 4 (*Maximize Profits, No Illegal Fishing, & Rights Based Management*) performs almost as well as a complete closure in all 28 fisheries. The length of time needed for a fishery to recover also tends to increase as the delay increases. To examine these results, the average number of years necessary for a fishery to reach a healthy stock size for each delay is analyzed for Scenario 4 [Fig. 5]. A delay of 5 years more than doubles the mean time needed for recovery from 6 years to 14. An 18-year delay (the longest examined here) results in only 3 fisheries with a biomass ≥ 0.8 B_{MSY} at the end of the 20-year time horizon. With this extreme delay, fisheries will require 30 years, on average, to recover, or 5 times as many years compared to reform without delay. Two fisheries do not recover regardless of when reform is implemented. Only the 26 fisheries that eventually recover were include in this particular analysis. In order

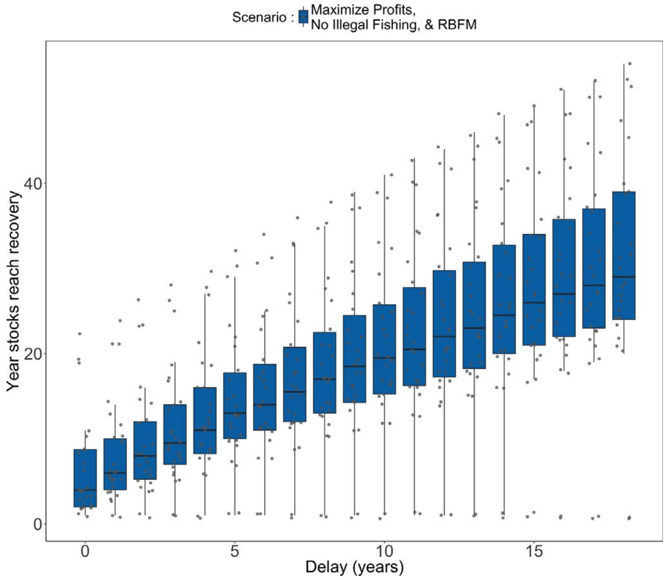

Fig. 5. The effect of delayed reform on fishery recovery under Scenario 4 (*Maximize Profits, No Illegal Fishing, & Rights Based Management*). This plot summarizes the year in which each fishery recovers under each delay. Only the 26 fisheries that eventually recover were include in this analysis.

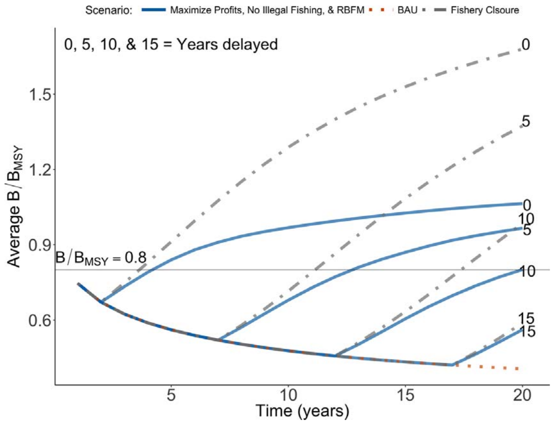

Fig. 6. Average B/B_{MSY} trajectories for three scenarios (*BAU*, Scenario 4 (*Maximize Profits, No Illegal Fishing, & RBFM*), and Fishery Closure) and four possible delays.

for the average B/B_{MSY} of all fisheries to reach 0.8 before the end of the time period under Scenario 4, the implementation delay cannot exceed 10 years [Fig. 6].

4. Discussion

4.1. Performance of alternative management scenarios

The results indicate that if maintained into the future, business-as-usual management will deplete Mexican fishery biomass to unhealthy levels, lead to significant harvest reductions, and almost entirely dissipate profits in the 28 fisheries examined. Aside from ecological impacts, this has potentially important negative implications on fishers, local communities, and export markets. Artisanal fishers, which operate 97.4% of Mexico's fishing vessels, depend on fish resources for their livelihoods [38]. In addition, artisanal fisheries have played important roles in alleviating local poverty and providing fish resources for local consumption [23,39]. Continued unsustainable fishing pressure could also affect fish availability in global markets, as Mexico has emerged as an important export nation.

While results surely differ across the diverse reforms examined, this study finds that the immediate implementation of any of the management reform scenarios examined [Table 1] is expected to outperform business-as-usual in terms of biomass, harvest, and profit indicators over time. All four alternative scenarios immediately lead to higher annual biomass compared to business-as-usual, although annual biomass levels under Scenario 1 (*No Illegal Fishing*) are significantly smaller than those under the other reforms. Although all of the scenarios that include a change in the harvest control policy (Scenarios 2, 3, and 4) lead to initial drops in both annual harvest and profit compared to business-as-usual, stock growth over time, coupled with more sustainable harvest policies, lead to significantly higher annual harvests and profits. Benefits to annual profit accrue quickly, with annual profits higher than those under business-as-usual and Scenario 1 starting in year 4 under Scenarios 3 and 4 (*Maximize Profits & RBFM* and *Maximize Profits, No Illegal Fishing, & RBFM*, respectively), and starting in year 6 under Scenario 2 (*Maximize Yield & No Illegal Fishing*). Although Scenario 1 profits are only slightly higher than those under business-as-usual, the scenario performs better when considering annual harvests. All four reforms eventually lead to annual harvests that exceed those under business-as-usual (year 1, 7, 11, and 13 under Scenarios 1, 4, 2, and 3, respectively). Scenario 3, which fails to control illegal fishing, performs the worst in year 20, suggesting that eliminating illegal fishing is an important reform if the goal is to increase the amount of legal harvest [Fig. 3]. The results indicate that implementing even a single management reform can lead to gains in annual biomass, harvest, and profit, and that different management changes can address different management goals.

4.2. Cost of delayed reform

The results also indicate that while reform has the potential to improve economic, biological, and harvest indicators, delays have large costs. Results from this study corroborate previous findings that delays in fishery management reform can lead to unhealthy population levels in fish stocks and require longer time periods for fisheries to recover [14,17,18]. This work also reaffirms that delays reduce short and long-term harvest levels [14,17]. This is important, as delayed management reform is often influenced by an unwillingness to experience initial harvest cuts. This study also suggests, however, that initial harvest cuts will be necessary to ultimately achieve increases in annual profit, fish stock health, and long-term harvests. Indeed, without intervention, harvest levels are expected to decline to levels lower than those seen in any of the reforms examined. Thus, drops in harvest experienced during the first year of reform are expected to be followed by higher, stable harvest levels, and early implementation reduces the long-term losses associated with delays.

This work contributes to the existing literature on fishery yields by examining the economic costs of management delays in terms of losses to average annual profit (expressed here as an annual annuity). The results show that even a delay as short as 2 years leads to over a USD 20 million loss in the annuity, and the loss continues to increase as the reform delay increases. In the same way that reforms are resisted and delayed due to the unpopularity of making initial harvest cuts, the expected initial drops in profit also provide an incentive to delay reform. However, this study demonstrates not only that delays can result in significant economic losses, but also that over time, BAU will lead to extremely low annual profits compared to current conditions and the future under other management reforms (Figs. 2 and 3).

4.3. Broad implications

While this study focused on 28 Mexican fisheries, the general findings are expected to be robust and applicable to fishery management globally. Management reforms aimed at addressing unsustainable fishing pressure, reducing illegal fishing, and improving profitability by reducing fishing costs and increasing prices are expected to result in long-term benefits to stock size, harvest, and profit. However, the magnitude of benefits and relative performance of management reforms will vary from stock to stock. For example, a healthy stock already experiencing sustainable fishing pressure might experience more benefits from adopting RBFM than from only optimizing fishing pressure. In addition, the level of illegal fishing and the price and cost scalars associated with the implementation of RBFM will vary, and therefore their importance as potential management reforms will depend on the fishery and region. The decision of which reform to choose will ultimately depend on fishery managers' goals. For managers concerned with improving harvest, eliminating illegal fishing could be more important than implementing RBFM, though the results from this study strongly suggest that the combination of RBFM and combating illegal fishing gives rise to the greatest benefits.

5. Caveats and future work

There are a number of assumptions made in this study that affect the results in non-trivial ways. First, it is assumed that illegal fishing is represented by a constant level of fishing mortality. Under this assumption, larger fish stocks will attract more illegal harvest, but the harvest fraction itself will not change. This assumption is difficult to validate empirically and may not hold in reality. Alternative assumptions could be explored in future work. In addition, perfect compliance with fishery reforms is assumed, including the elimination of illegal fishing. For this study, it made sense to examine perfect compliance to bound the benefits from implementing reforms that target illegal fishing. While it seems intuitive that imperfect compliance would weaken the results presented here, future research could examine how the level of compliance affects projected benefits. Third, it is assumed that the underlying environment is stationary over the 20-year time horizon. A previous study has suggested that a changing environment due to climate change or other drivers could exacerbate the impacts associated with delayed management implementation, especially when the environmental shift causes a decline in productivity [17]. Future work could incorporate predictions regarding the effect of climate change on the studied stocks to determine if environmental change leads to even greater losses from delay.

While this study assumes both perfect management implementation and compliance, achieving this standard would be no small task. At least three unique challenges in the context of Mexican fisheries will need to be addressed. First, while this study focused on 28 specific fisheries, many more are in need of improvement. Second, the socioeconomic status of most fishers will complicate reform efforts. And third, to execute on these reforms, institutional capacity will need to be bolstered. Out of 175 assessed stocks in Mexico, most of which represent fisheries in the artisanal fishing sector, 30% are overexploited and almost 50% are at their maximum capacity [44]. Reforming these fisheries will entail considerable efforts by all parties involved including government agencies, non-governmental organizations (NGO), academia, and fishers. Strengthening of government institutions is needed to improve enforcement of current and future fishing regulations [45]. Both an increase in capacity building and enhancement of governance in fishing communities with active involvement of NGOs will also be a key element to addressing these and other barriers to reform in the context of Mexican fisheries [40,46].

In addition, future work could include the governance and administrative components affecting entry to reformed fisheries. The improved outcomes expected from the implementation of RBFM can incentivize those not previously involved in a fishery to enter it illegally. For example, one may consider a strong pressure by neighboring communities to enter a fishery (mainly illegally) once a stock has been rebuilding, especially if landed fish prices have increased. To prevent this situation, management reform will clearly necessitate strengthening the governance of fishers through capacity building, allocation of resources to secure science-based management reform, and some form of resource ownership. Successful Mexican fisheries reform will almost surely rely on sound, long-term planning, and clear recognition of the importance of fishing communities and the fishing industry. A key element could be to actively promote increased capacity at the community level and promoting governance, co-management, and sustainable fishing [40].

Finally, this study has not explicitly addressed the costs associated with the design and implementation of different types of management reforms. These costs could be significant, especially if reforms require improvements in enforcement and surveillance. These are typically the most expensive management services, because they can require expensive equipment and are labor intensive [41,42]. This suggests that a management reform aimed at eliminating illegal fishing could be quite expensive if it relies on a prevalent and successful enforcement regime, especially in a country like Mexico with an extended coastline, limited enforcement capacity, and generally marginalized artisanal fishers for whom fishing is often the only short-term economic alternative. However, a recent study found that it may be possible to finance improved enforcement through a suite of sustainable financing mechanisms including a landings tax, license fee, tourism tax, and fines from illegal fishing [43]. More research is needed to quantify the costs associated with reform design and implementation – such information could be incorporated in future analysis to inform a comprehensive cost benefit analysis of alternative approaches to fishery management reform in Mexico.

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Appendix

See Tables A1 and A2 here.

Table A1
List of species included in this study.

Common name (Sp.)	Common name (Eng.)	Location (if specified)	Scientific name	Family
Sardina Monterrey	Pacific sardine	Gulf of California	*Sardinops sagax*	Clupeidae
Camarón azul	Blue shrimp	Gulf of California	*Litopenaeus stylirostris*	Penaeidae
Sierra	Spanish mackerel	Sonora	*Scomberomorus* spp.	Scombridae
Tiburón de puntas negras	Black tip shark	Gulf of Mexico	*Carcharhinus limbatus*	Carcharhinidae
Tiburones	Sharks	Gulf of Mexico		
Atún aleta amarilla	Yellowfin tuna	Pacific	*Thunnus albacares*	Scombridae
Calamar gigante	Jumbo squid	Gulf of California	*Dosidicus gigas*	Ommastrephidae
Pulpo	California two-spot octopus	Sonora and Baja California	*Octopus bimaculatus*	Octopodidae
Jurel	Skipjack	Pacific	*Seriola* spp.	Carangidae
Medusa bola de cañón	Cannonball jellyfish	Gulf of California	*Stomolophus meleagris*	Stomolophidae
Almeja generosa	Geoduck	Upper Gulf (Gulf of California)	*Panopea globosa*	Hiatellidae
Curvina golfina	Gulf corvina	Upper Gulf (Gulf of California)	*Cynoscion othonopterus*	Sciaenidae
Merluza	Pacific whiting	Gulf of California	*Merluccius productus*	Merlucciidae
Callo de hacha	Penshell scallop	Bahía de Kino, Sonora	*Atrina tuberculosa*	Pinnidae
Huachinango	Red snapper	BC, Sonora, and Sinaloa	*Lutjanus peru*	Lutjanidae
Langosta	Spiny lobster	Atlantic and Pacific	*Panulirus interruptus*	Palinuridae
Mero	Red grouper	Campeche	*Epinephelus morio*	Serranidae
Robalo	Snook	Sinaloa	*Centropomus robalito*	Centropomidae
Dorado	Mahi-mahi	Pacific	*Coryphaena* spp.	*Coryphaenidae*
Abulón azul	Green abalone	North Pacific	*Haliotis fulgens*	Haliotis
Pepino de mar	Brown sea cucumber	Gulf of California	*Isostichopus fuscus*	Stichopodidae
Jaiba café	Brown swimming crab	Sonora and Sinaloa	*Callinectes bellicosus*	Portunidae
Caracol rosado	Queen conch	Yucatán Peninsula	*Strombus gigas*	Strombidae
Almeja chocolata	Chocolate clam	Baja California Sur	*Megapteria squalida*	Veneridae
Almeja mano de león	Lion-paw clam	Baja California Sur	*Lyropecten subnodosus*	Pectinidae
Caracol chino	Black murex	Sonora	*Hexaplex nigritus*	Muricidae
Langostilla	Pelagic red crab	Baja California Sur	*Pleuroncodes planipes*	Munididae
Pez cochito	Triggerfish	Sonora	*Balistes polylepis*	Balistidae

Table A2
Fishery specific parameters used in study.

Species	Scientific name	*g*	*K* (MT)	Initial B/B_{MSY}	Initial total F/F_{MSY}	$f_{L,0}$	Price ($/MT)	γ_P	γ_C
Pacific sardine	*Sardinops sagax*	0.17	6980198.73	0.90	1.63	0.94	84	0.90	1.10
Blue shrimp	*Litopenaeus stylirostris*	0.20	75531.55	0.70	2.09	0.81	4903	0.80	1.20
Spanish mackerel	*Scomberomorus sierra*	0.24	16789.41	0.50	3.52	0.91	1089	0.80	1.30
Black tip shark	*Carcharhinus limbatus*	0.03	79691.90	0.70	3.83	0.92	1276	0.90	1.30
Sharks		0.04	2409.34	0.60	1.97	0.85	1368	0.90	1.30
Yellowfin Tuna	*Thunnus albacares*	0.03	9155828.24	0.85	1.93	0.95	661	0.80	1.20
Jumbo quid	*Dosidicus gigas*	0.25	902459.53	0.80	2.24	0.91	333	0.70	1.30
California two-spot octopus	*Octopus bimaculatus*	0.21	3615.34	0.30	5.05	0.92	3145	0.90	1.30
Skipjack	*Seriola* spp.	0.02	148878.66	0.80	2.75	0.89	636	0.80	1.10
Cannonball jellyfish	*Stomolophus meleagris*	0.24	173233.18	0.80	1.98	0.80	219	0.70	1.40
Geoduck	*Panopea globosa*	0.02	107586.47	0.50	3.52	0.93	1757	0.85	1.20
Gulf corvina	*Cynoscion othonopterus*	0.11	77435.37	0.90	1.88	0.89	985	0.60	1.40
Pacific whiting	*Merluccius productus*	0.06	3682.82	1.30	1.01	0.80	688	0.90	1.20
Penshell scallop	*Pinna rugosa*	0.03	1159.59	0.71	2.82	0.89	18906	0.80	1.30
Red snapper	*Lutjanus peru*	0.03	44067.40	0.80	2.24	0.87	3247	0.90	1.10
Spiny lobster	*Panulirus interruptus*	0.03	67507.05	0.90	1.37	0.85	11019	0.90	1.10
Red grouper	*Epinephelus morio*	0.06	505113.43	0.80	2.49	0.92	2511	0.80	1.30
Snook	*Centropomus robalito*	0.08	7047.87	0.40	4.53	0.93	3415	0.90	1.10
Mahi-mahi	*Coryphaena* spp.	0.11	88235.75	0.91	2.14	0.72	2578	0.60	1.20
Green abalone	*Haliotis sorenseni*	0.02	169681.40	1.15	0.31	0.84	19271	0.90	1.20
Brown sea cucumber	*Isostichopus fuscus*	0.02	2691.34	0.48	5.39	0.89	1988	0.80	1.10
Brown swimming crab	*Callinectes bellicosus*	0.17	63507.75	0.90	3.19	0.91	958	0.75	1.30
Queen conch	*Strombus gigas*	0.06	7847.74	0.15	5.95	0.97	6875	0.80	1.40
Chocolate clam	*Megapitaria squalida*	0.04	33491.22	0.80	2.75	0.89	590	0.90	1.20
Lion-paw scallop	*Nodipecten subnodosus*	0.05	6705.10	0.94	2.12	0.93	12031	0.80	1.40
Black murex	*Hyporthodus nigritus*	0.06	14757.40	0.50	4.92	0.92	1806	0.90	1.10
Pelagic red crab	*Pleuroncodes planipes*	0.24	5027.44	1.50	0.58	0.91	770	0.95	1.10
Triggerfish	*Ballistes polylepis*	0.04	20392.85	0.30	4.62	0.91	1719	0.90	1.10

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