Does Climate Change Bolster the Case for Fishery Reform in Asia?

Christopher Costello*

I examine the estimated economic, ecological, and food security effects of future fishery management reform in Asia. Without climate change, most Asian fisheries stand to gain substantially from reforms. Optimizing fishery management could increase catch by 24% and profit by 34% over business-as-usual management. These benefits arise from fishing some stocks more conservatively and others more aggressively. Although climate change is expected to reduce carrying capacity in 55% of Asian fisheries, I find that under climate change large benefits from fishery management reform are maintained, though these benefits are heterogeneous. The case for reform remains strong for both catch and profit, though these numbers are slightly lower than in the no-climate change case. These results suggest that, to maximize economic output and food security, Asian fisheries will benefit substantially from the transition to catch shares or other economically rational fishery management institutions, despite the looming effects of climate change.

Keywords: Asia, climate change, fisheries, rights-based management
*JEL codes:* Q22, Q28

I. Introduction

Global fisheries have diverged sharply over recent decades. High governance, wealthy economies have largely adopted output controls or various forms of catch shares, which has helped fisheries in these economies overcome inefficiencies arising from overfishing (Worm et al. 2009) and capital stuffing (Homans and Wilen 1997), and allowed them to turn the corner toward sustainability (Costello, Gaines, and Lynham 2008) and profitability (Costello et al. 2016). But the world's largest fishing region, Asia, has instead largely pursued open access and input controls, achieving less long-run fishery management success (World Bank 2017). Recent estimates show that many Asian fisheries continue to languish under outdated management regimes and could benefit from economically optimized fishery management systems such as catch shares. World Bank (2017) estimates that

Figure 1. **Hypothetical Benefits of Economically Optimal Fishery Reforms for Select Economies**
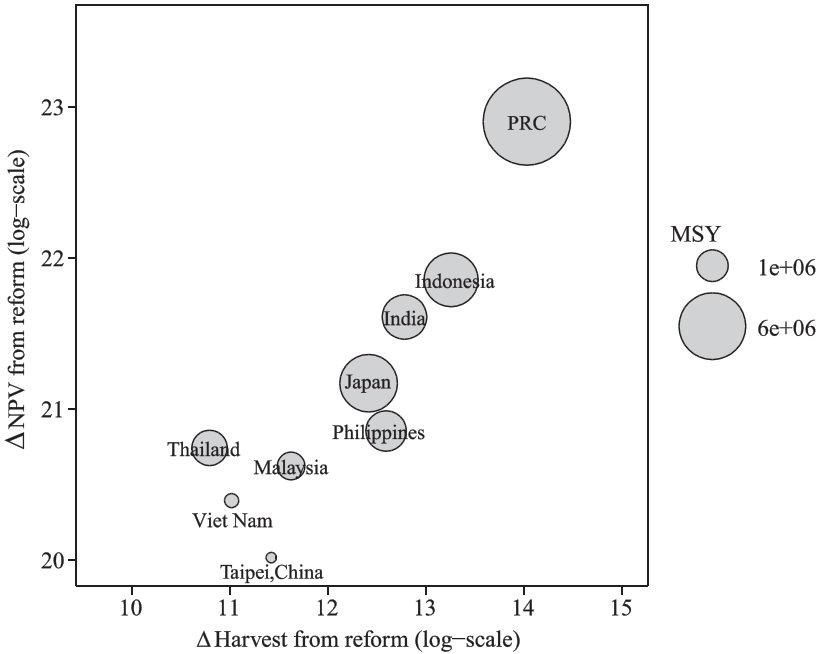
MSY = maximum sustainable yield, NPV = net present value, PRC = People's Republic of China.
Note: The figure shows the nine economies with the greatest gains in profit, which all happen to be in Asia.
Source: Calculated from data in Costello, Christopher, Daniel Ovando, Tyler Clavelle, C. Kent Strauss, Ray Hilborn, Michael C. Melnychuk, Trevor A. Branch, Steven D. Gaines, Cody S. Szuwalski, Reniel B. Cabral, Douglas N. Rader, and Amanda Leland. 2016. "Global Fishery Prospects Under Contrasting Management Regimes." *Proceedings of the National Academy of Sciences* 113 (18): 5125–29.

Asian fisheries lose $55 billion per year in inefficient management, which accounts for 65% of the estimated global loss of $85 billion. Figure 1 shows the potential gains from catch shares in the nine economies with the largest economic surplus, all of which are in Asia.

All of the aforementioned benefits of fishery reform were calculated assuming a stationary environment. Yet, climate change promises to dramatically alter the productivity and spatial distribution of most Asian fish stocks (Molinos et al. 2016). These climate-induced changes are expected to play out over the next 100 years or more, but are already starting to take hold. For example, range shifts have been noted in several of the world's oceans, coral bleaching appears to be accelerating, and the productivity of many stocks has sharply changed in recent years. These findings raise an important dilemma for Asian economies interested in the long-run sustainability, food security, and profitability of their fisheries: Should they aggressively pursue fishery management reforms in advance of the most

serious predicted effects of climate change? Or does the prospect of climate change weaken the case for reforms such that aggressive reform is no longer necessary?

To shed light on this dilemma, I join newly available data on Asian fishery status with state-of-the-art climate forecasts and bioeconomic models. I largely draw on data and methods in Gaines et al. (2018), though that paper does not single out any results for Asian fisheries, nor does it ask whether the case for reform is strengthened or weakened under climate change. This allows me to conduct a species-by-species analysis for 193 species of the most widely harvested fish in Asia, representing about 29 million metric tons in fish catch.[1]

I begin by estimating biological status and trends for each of these species; this is accomplished by combining retrospective regression approaches (Costello et al. 2012) with dynamic structural models (Martell and Froese 2013). I then use these data as inputs into a bioeconomic model that estimates the potential benefits—in terms of fish conservation, fishery profit, and fish catch—from adopting economically efficient fishery management practices in Asia in the absence of climate change. Essentially, this involves comparing projected fishery performance under business-as-usual (BAU) management with fishery performance under economically optimized management.[2] Results of that analysis largely corroborate previous findings. But because I am primarily interested in how climate change affects these calculations, I then couple to this analysis projections of climate effects on each of the species in my data set from Molinos et al. (2016). These climate models suggest that about 55% of Asian fisheries will experience reductions from climate change, and 29% will experience significant range shifts in the coming decades. By combining the fishery status, models, and climate effects, I can then estimate the potential benefits from adopting fishery management reforms in the face of climate change. Naturally, this involves solving for the economically optimal feedback control rule in each fishery. The final step is to ask whether the strong case for fishery reform is maintained, or undermined, in a future with significant climate change.

Overall, the strong case for fishery management reform is maintained in a world with significant climate change.[3] For the median fishery, both the economic and food provision cases for reform are slightly strengthened by climate change (though by less than 1 percentage point). However, because the effects are not symmetric, the aggregate case is somewhat weakened (by about 3 percentage points for harvest and 4 percentage points for value). While these results suggest that Asian fisheries would still do well to hasten the transition to economically optimized fishery management, they also point to substantial heterogeneity across fisheries due

---

[1]The species list (shown in the Appendix) is the set of species for which fish catch is reported to the Food and Agriculture Organization (FAO) in at least one of FAO regions 61, 71, or 57 (FAO 2014).

[2]To keep values comparable, I assume that price and cost parameters are the same under BAU and optimized fishery management, and that these parameters are unaffected by climate change.

[3]All results in this paper use the representative concentration pathway 6.0 scenario.

to differences in (i) current status of fish populations, (ii) BAU management, (iii) the biological effects of climate change, and (iv) anticipated geographic movement under climate projections. Taken together, these results suggest that for many Asian fisheries, climate change will strengthen the case for management reforms. But in some cases, I find that the case gets substantially weaker; in these places, motivating governments to undertake costly reforms will have to rely on other arguments or sources of reform capital.

The rest of this paper is organized as follows. Section II discusses the status and trends of major Asian fisheries, and their management. Section III provides theoretical guidance about the conditions under which climate change might strengthen, or weaken, the case for fishery management reform. Section IV then focuses on the empirical estimates of the effects of climate change on Asian fisheries. The estimates of reform with and without climate change are presented in section V. Finally, section VI concludes.

II. Status of and Trends in Asian Fisheries

Official data from the Food and Agriculture Organization (FAO) show a surprising and underrecognized trend in Asian versus non-Asian fish catch. While global catch has been relatively constant over the past few decades (at approximately 80 million metric tons per year), the fraction of global catch produced in Asia has steadily increased (Figure 2). Over the past 5 years, Asian catch has surpassed the rest of the world combined, which represents a dramatic feat for a region focused intently on increasing protein production from the sea (Cao et al. 2017). Yet, questions remain about the underlying reasons for this dramatic divergence in trends between Asia and non-Asian regions. The most common explanation is that Asia's catch is being propped up by increasingly aggressive fishing efforts. Under this explanation, fisheries are progressively being overfished and will eventually collapse. The second possibility is that many large Asian fisheries are thought to have fished-down their immense stocks of predatory fish and that this allows for a "predatory release" (Szuwalski et al. 2016). Under this explanation, catches of smaller-bodied fish can be sustained at a much higher level than was previously thought because their predator numbers have been reduced. But owing to the immense diversity in Asian fish species, fishery management institutions, and economic conditions, the truth is almost certainly somewhere in between.[4] The model I use here will not allow us to distinguish between these underlying causes, but it will allow us to track the likely species-by-species consequences of climate change on Asia's fisheries.

Drawing concrete conclusions about Asian fisheries is significantly hampered by the paucity of evidence on the biological status and trends for species

---

[4]See Cao et al. (2017) and Costello (2017) for further discussion of Asian fishery objectives and trends.

Figure 2.   **Fish Catch over Time—Asia versus the Rest of the World**
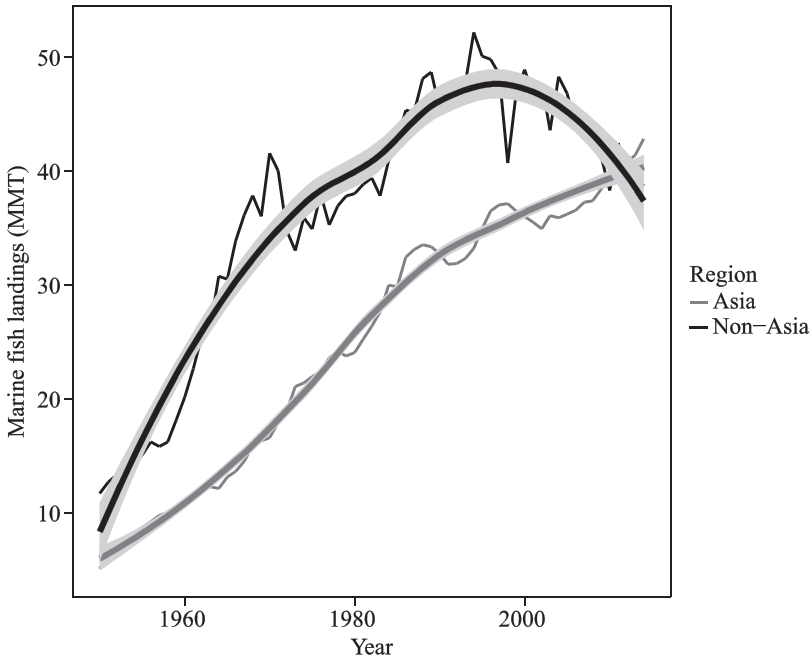
MMT = million metric tons.
Source: Food and Agriculture Organization (FAO). 2014. "The State of World Fisheries and Aquaculture." Technical Report of the Food and Agriculture Organization of the United Nations.

of fish harvested in Asia. While individual economies conduct some scientific surveys (Melnychuk et al. 2017), almost no Asian fisheries conduct or report stock assessments. While Asian fisheries supply over half of the global fish catch, among the more than 500 fish stocks represented in the global Ram Legacy Stock Assessment Database (Ricard et al. 2012), only about 1% are from Asia. To overcome these extreme data gaps, recent contributions have provided data-poor methods for estimating stock status and backing out the fishing mortality rate that is implied by reported fish catches. Costello et al. (2016) merge methods from Costello et al. (2012) and Martell and Froese (2013) to estimate current biological status (biomass of a fish stock relative to its biomass under maximum sustainable yield (MSY), denoted as B/B_{MSY}) and current fishing mortality rate (as a fraction of fishing mortality under MSY, denoted as F/F_{MSY}).

For an estimate of the current status of Asian stocks, we follow Gaines et al. (2018) and aggregate fisheries from Costello et al. (2016) at the species level, and extract species whose geographic range extends into Asian waters. Here I make some brief comments about the data underlying this analysis. Biomass and fishing mortality estimates are derived using a panel regression model (Costello et al. 2012)

as priors for a structural model from fishery science called the Catch–MSY method (Martell and Froese 2013). This model also provides estimates of the biological parameters for each individual stock, which are then aggregated at the species level for species known to exist in Asian waters. Catch data are from FAO (2014) and the Ram Legacy Stock Assessment Database (Ricard et al. 2012). Price and cost parameters are species-level aggregations from Costello et al. (2016); the resulting database of global fish prices has been published in Melnychuk et al. (2016) and cost parameters are derived to rationalize the level of fishing observed as formalized in Costello et al. (2016). The relevant climate data, which describe the spatial footprint of fish species now and in the future under alternative climate scenarios, are from Molinos et al. (2016), who estimate the change in ocean temperatures over time and associate that with species' temperature preferences to estimate the geographic range of a species in the future. After filtering for the species that reside in Asian waters, this leaves us with 193 species-level bioeconomic models with biological parameters, spatial distributions, and changes in each over time under different climate scenarios.[5]

The resulting 193 Asian fish species are displayed in Figure 3, where bubble size indicates the potential size of the species' fish catch (MSY) and shading foretells the future climate effects estimated from the climate model that will be described later (lighter shade for positive effects on carrying capacity and darker shade for negative effects on carrying capacity).[6] Using this approach, the median values for B/B_{MSY} and F/F_{MSY} are both near 1; this may initially suggest that Asian fisheries are in reasonable condition. But a closer inspection of Figure 3 reveals a stark contrast between two classes of fisheries. Those in the top left of Figure 3 are in poor condition. According to this model, these fisheries have been overfished, driving their biomass below levels that which would maximize food provision, and they continue to be fished at an excessive rate.[7] Many of the medium-sized and large Asian fisheries (bubble size), and the fisheries that will be negatively impacted by climate change (darker shade), are in this region of the figure. The second major group consists of fisheries in the bottom right of Figure 3. These fisheries appear to be underfished, at least so far as food production is concerned. Many of these biologically abundant species are expected to be positively affected by climate change. When combined, these features suggest that there may be important possibilities for future growth in some of these fisheries.

---

[5]I will not repeat here all of the data caveats from these previous papers. But it suffices to say that these estimates are subject to many qualifications, therefore all of these results should be viewed with some degree of caution.

[6]The unit of analysis in this article is technically a species of fish residing in Asian waters as extracted and reported from Gaines et al. (2018). For exposition, I also refer to species as either stocks or fisheries.

[7]As with most bioeconomic models, the one used here finds that the level of fish biomass that maximizes steady state fishery profit exceeds B_{MSY} by about 20%–30%.

Figure 3. **Status and Fishing Pressure for Asian Fish Stocks**
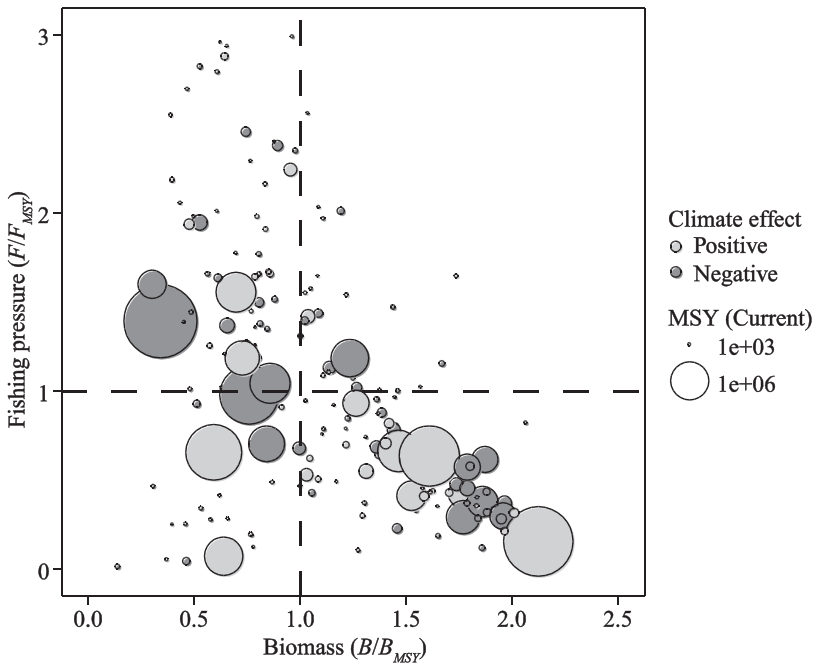
MSY = maximum sustainable yield.
Note: Size indicates MSY and shading indicates whether climate change is expected to have a positive (lighter shade) or negative (darker shade) effect on carrying capacity through 2100.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

III. Climate Change and Fishery Reforms—Theory

The basic question this paper poses is whether the case for fishery management reform that has been established in the absence of climate change will be maintained in a future with aggressive climate change. In this section, I develop the theory underpinning the empirical analysis that follows. Consider a single fishery in discrete-time with period-t biomass given by B_t. The fraction of the fish stock that is extracted in year t is given by F_t, so the harvest is given by $H_t = F_t B_t$. Price is assumed to be constant, p, and harvesting costs depend on aggregate fishing mortality, so cost is cF_t^B for some constants $c \geq 0$ and $\beta \geq 1$.[8]

---

[8]This nests the canonical bioeconomic model in which $\beta = 1$, but allows for the possibility that early applications of fishing effort are the most efficient; therefore, additional units of effort are increasingly costly.

This implies that period-t profit of the fishery is

$$\pi_t (F_t, B_t, K_t) = pH_t - cF_t^{\beta} \tag{1}$$

where I have made explicit the dependence on fishing mortality (F_t), biomass of the stock (B_t), and carrying capacity (K_t), which will capture the effects of climate change on the growth of the fish stock.

But the ecosystem places natural constraints on an economy's harvesting decisions. Let the growth of the fish stock be given by the following:

$$B_{t+1} = B(t) + \frac{\phi + 1}{\phi} gB_t \left(1 - \left(\frac{B_t}{K_t} \right)^{\phi} \right) - H_t \tag{2}$$

This biological growth equation (known as the Pella–Tomlinson model) contains three parameters: (i) g, which is related to the maximum (or "intrinsic") growth rate of the stock; (ii) ϕ, which governs the skewness of the familiar hump-shape of growth function; and (iii) K_t, which is the carrying capacity of the stock.[9] This functional form is quite general and nests two familiar examples. First, in equation (2), I have allowed the carrying capacity (K_t) to vary over time; in this paper, K_t reflects the climate state in year t. For example, if climate change is expected to reduce the overall suitable geographic range of a stock by 2% per year, I follow Gaines et al. (2018) and interpret this as a change in carrying capacity (so K_t declines by 2% per year). This interpretation of carrying capacity allows climate impacts to have year-by-year effects on fish stock growth. Second, the special case where $\phi = 1$ delivers the familiar logistic growth equation (with carrying capacity K_t and intrinsic growth rate $2g$).

Naturally, the consequences of climate change on any given fishery will hinge not only on the environmental effects, but also on the way in which the fishery is managed. As a measure of the economic benefit of fishery reform without climate change, I calculate the net present value (NPV) under the BAU fishing mortality rate (again without climate change); denoted as $\bar{F}_{-CC}$, these are the "Fishing Pressure" values in Figure 3 and are compared to the NPV under economically optimized fishery management, denoted as $F^*_{-CC}(B_t)$. To calculate the optimized feedback control rule, $F^*_{-CC}(B_t)$, I use a discrete-time dynamic programming approach, with numerical-value-function iteration and backward induction using $K_t = K_0$, thus assuming that climate change is not occurring. I work backward until the value and policy functions converge. I then forward simulate using the converged policy function from the starting conditions shown in Figure 3 to obtain $\bar{V}_{-CC}$ (NPV under BAU without climate change), V^*_{-CC} (optimized NPV without climate change), $\bar{H}_{-CC}$ (cumulative harvest 2012–2100 under BAU without climate change), and H^*_{-CC} (cumulative harvest 2012–2100 under optimized NPV without climate change).

---

[9] All parameters were extracted from Gaines et al. (2018).

In a similar manner, when climate change is present, I calculate the NPV and harvest under a BAU policy and an optimized policy. But which policies to use? For the optimized policy, since K_t can change each year in the climate change scenario, it could be treated as a state variable, which would give rise to a policy function that conditioned on K_t (as well as B_t). Under that fully adaptive assumption, the fully optimal policy function would take the form $F_{CC}^*(B_t, K_t)$, so effectively there would be a different optimized harvest control policy function every year that fully anticipated the future effects of climate change. While this may seem farfetched, it would provide a useful benchmark because it would represent the highest possible NPV that any fishery could attain under climate change. But, I do not conduct this additional optimization for three reasons. First, doing so would presume that the fishery manager had perfect foresight about climate effects in all fisheries over the next 80 years and was able to perfectly reoptimize her policy function every year in anticipation of those changes. This seems implausible because of information and policy constraints that often prevent such nimble policy responses. The second reason is that I have conducted this optimization for three fisheries (representing the 5th, 50th, and 95th percentiles of change in K due to climate change) and found that it makes almost no difference in the ultimate NPV of the fishery. The percentage increases in value from using the $F_{CC}^*(B_t, K_t)$ policy instead of the $F_{CC}^*(B_t)$ policy are 0.36%, 0.001%, and 0.02%, respectively, for the 5th, 50th, and 95th percentile fisheries; the commensurate differences in aggregate harvest in 2012–2020 are 3.9%, 0.01%, and 0.04%, respectively.[10] The final reason is that conducting this optimization for all 193 fisheries is very time consuming.

For these reasons, I continue to use the same optimized feedback control rule derived above, so $F_{CC}^*(B_t) = F_{-CC}^*(B_t)$ from the dynamic programming value function iteration procedure described above. For the BAU policy under climate change, I allow for the possibility raised in Gaines et al. (2018), who argue that range shifts induced by climate change could lead to institutional failures that increase fishing pressure. At the same time, it seems irrational to assume that fishing would extend beyond what is economically viable.

To capture these features, I analyze two different models of BAU fishing pressure (Table 1). In both models, BAU fishing pressure is initially $\bar{F}_{-CC}$ (as in the case without climate change). In the first model, I assume fishing pressure for shifting stocks gradually shifts to the open access level of fishing pressure (for which economic profit is zero in steady state) over time as range shifts take hold. In the second model, I assume BAU fishing pressure is unaffected by climate change, so $\bar{F}_{CC} = \bar{F}_{-CC}$ forever.

Across these models, I evaluate two different measures of fishery performance. The first is the NPV of the fishery from 2012 to 2100, and the second

---

[10]These fisheries are Pacific rudderfish (whose 2100 K is only 62% of its current K), Bartail flathead (whose 2100 K is 99.7% of its current K), and Akiami paste shrimp (whose 2100 K is 110% of its current K).

Table 1. **Fishing Policies with and without Climate Change**

		Climate Change?	
		No	**Yes**
Policy	BAU	$\bar{F}_{-CC}$	$\bar{F}_{-CC}$ to $\bar{F}_{OA}$ or $\bar{F}_{-CC}$ forever
	Optimized	$F^*_{-CC}(B_t)$	$F^*_{CC}(B_t)$

BAU = business as usual.
Source: Author's compilation.

is the cumulative harvest over the same time period. For any given fishery, these values will depend on the starting conditions (Figure 3), policy function (Table 1), and climate change impact on carrying capacity (Figure 6).

The NPV of the fishery under any climate trajectory and any policy function is given by

$$V = \sum_{t=0}^{T} \left(\frac{1}{1+r} \right)^t \pi_t (F_t, B_t, K_t) \tag{3}$$

where $r = 5\%$ is the discount rate and the equation is subject to equation (2). This implies that there are four relevant values to calculate for the NPV and four relevant values for H:

- NPV calculations
  - No climate change, BAU management $(\bar{V}_{-CC})$
  - No climate change, optimized management (V^*_{-CC})
  - Climate change, BAU management $(\bar{V}_{CC})$
  - Climate change, optimized management (V^*_{CC})

- Cumulative harvest calculations
  - No climate change, BAU management $(\bar{H}_{-CC})$
  - No climate change, optimized management (H^*_{-CC})
  - Climate change, BAU management $(\bar{H}_{CC})$
  - Climate change, optimized management (H^*_{CC})

This paper seeks to determine the first differences:

- percentage loss from failing to optimize management without climate change:

$$\Delta\Omega_{-CC} \equiv \frac{\Omega^*_{-CC} - \bar{\Omega}_{-CC}}{\Omega^*_{-CC}} (H^*_{CC}) \tag{4}$$

- percentage loss from failing to optimize management with climate change:

$$\Delta\Omega_{CC} \equiv \frac{\Omega^*_{CC} - \bar{\Omega}_{CC}}{\Omega^*_{-CC}} \tag{5}$$

where the outcome variable Ω can either be NPV (V) or cumulative harvest (H) from 2012 to 2100. For example, ΔV_{-CC} provides a measure of what is lost by adhering to BAU management, rather than optimizing the management of the fishery, in the absence of climate change.[11] These values are represented in Figure 7 (where BAU fishing pressure is given by the transition to open access for shifting stocks) and Figure 8 (where BAU fishing pressure is unchanged under climate change).

And our main statistic of interest will be the difference in these differences, expressed as a percentage point change:

$$\Delta\Omega \equiv \Delta\Omega_{CC} - \Delta\Omega_{-CC} \tag{6}$$

For example, if $\Delta V = 5$ percentage points for a particular fishery, this would indicate that the case for fishery reform is 5 percentage points stronger in a world with climate change than it is in a world without climate change. Of course, we expect this statistic to be positive for some fisheries and negative for others. These values are represented in Figures 9 and 10 below.

Theoretical Guidance

Does theory provide any guidance about how we might expect climate change to affect the value of fishery management optimization? First, whether or not climate change occurs, we expect that optimizing the management of a fishery will lead to an increase in economic value. In other words, we expect $\Delta V_{-CC} > 0$ and $\Delta V_{CC} > 0$. And while we generally expect fishery profit and fishery catch to go hand-in-hand, fishing costs (c in equation 1) imply that it is possible for an intervention to increase profit but decrease catch.[12] But as a general rule, we expect $\Delta H_{-CC} > 0$ and $\Delta H_{CC} > 0$ for most fisheries; when these values are negative, we expect them to be small in absolute value.

But how will ΔV_{-CC} and ΔV_{CC} compare with each other? In other words, calculating $\Delta V \lessgtr 0$ will determine whether the presence of climate change increases or decreases the economic case for fishery management reform. Similarly, calculating $\Delta H \lessgtr 0$ will determine whether the presence of climate change increases or decreases the food production case for reform. While the answers will turn out to depend on current conditions, BAU management, and the dynamic effects of climate change for any particular fishery, some broad generalizations are possible. First, for fisheries that will experience a reduction in carrying capacity

---

[11]The denominators in equations (4) and (5) are the same. Normalizing both by the no-climate change scenario facilitates their comparison as percentage point differences later in the paper. Also note that the denominator is the optimized value Ω^*_{-cc} rather than the preoptimized value. This is because under some open access scenarios the preoptimized value can be negative so the percentage would not make sense. The interpretation of these values is the percentage loss from failing to optimize rather than the percentage gain from optimizing.

[12]For example, suppose the fishery is already managed to maximize sustainable yield. Then a management change to optimize NPV will necessarily decrease long-run catch.

Figure 4. **Steady-State Fishery Production with and without Climate Change for a Fishery with Globally Median Parameters**
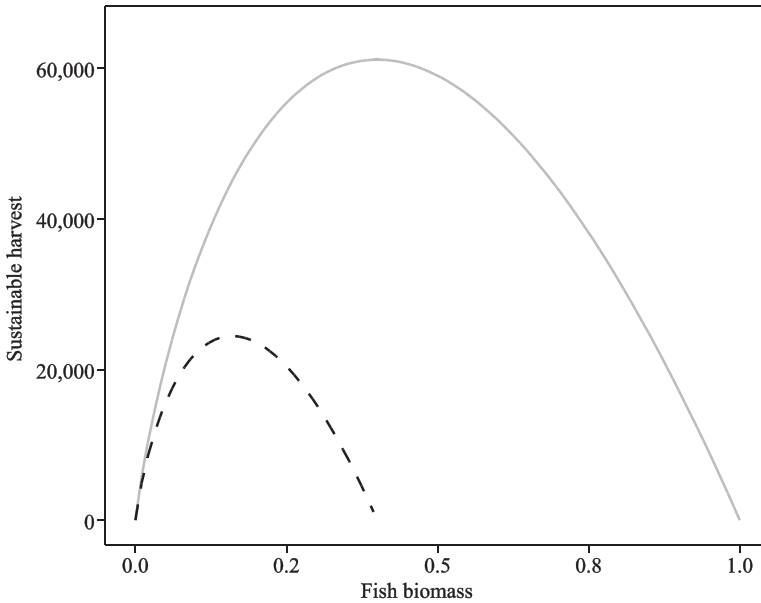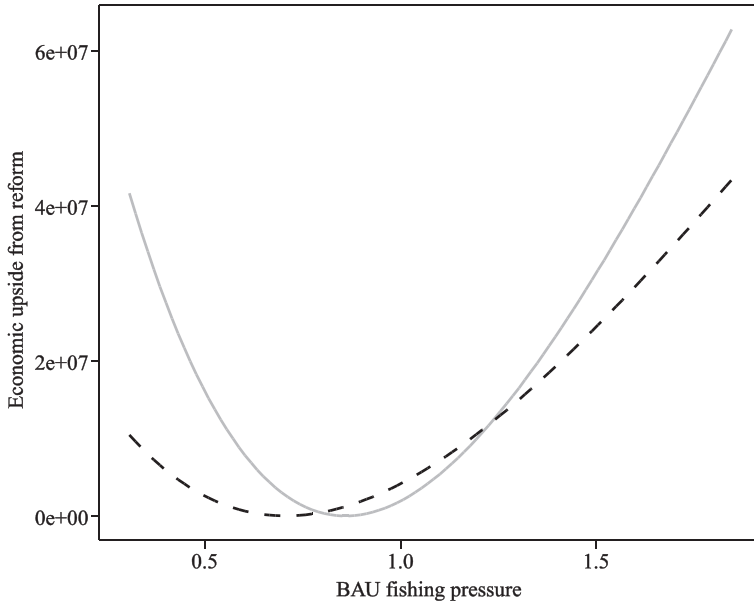
Note: The solid line is without climate change and the dashed line is with a hypothetical 60% reduction in carrying capacity from climate change.
Source: Author's calculations from globally median parameters extracted from Costello, Christopher, Daniel Ovando, Tyler Clavelle, C. Kent Strauss, Ray Hilborn, Michael C. Melnychuk, Trevor A. Branch, Steven D. Gaines, Cody S. Szuwalski, Reniel B. Cabral, Douglas N. Rader, and Amanda Leland. 2016. "Global Fishery Prospects Under Contrasting Management Regimes." *Proceedings of the National Academy of Sciences* 113 (18): 5125–29.

from climate change, it is reasonable to expect a reduction in both the maximum fish catch and the maximum value of the fishery. For example, Figure 4 shows the production function for a fishery with the median global parameters, where the solid line uses current parameters (no climate change) and the dashed line assumes a 60% reduction in carrying capacity resulting from climate change. Production with climate change is everywhere below production without climate change, reflecting the reduction in carrying capacity. This logic seems to suggest that fisheries that will suffer reductions in carrying capacity are likely to gain less from management reform than are fisheries that will experience increases in carrying capacity.

But this logic turns out to depend on the current level of fishing pressure. If BAU fishing pressure is very high (e.g., if the fishery is in open access equilibrium), then the logic holds firmly because the fishery is currently experiencing low (or zero) profit and low catch. Optimizing such a fishery eventually brings about positive increases whether or not climate change occurs, but climate change increases the case for reform only if it will increase carrying capacity. Alternatively,

Figure 5. **Steady-State Economic Upside from Reform for a Fishery with Globally Median Parameters**

BAU = business as usual.

Note: The solid line is without climate change and the dashed line is with a hypothetical 60% reduction in carrying capacity from climate change.

Source: Author's calculations from globally median parameters extracted from Costello, Christopher, Daniel Ovando, Tyler Clavelle, C. Kent Strauss, Ray Hilborn, Michael C. Melnychuk, Trevor A. Branch, Steven D. Gaines, Cody S. Szuwalski, Reniel B. Cabral, Douglas N. Rader, and Amanda Leland. 2016. "Global Fishery Prospects Under Contrasting Management Regimes." *Proceedings of the National Academy of Sciences* 113 (18): 5125–29.

if BAU fishing pressure is very low (take the extreme case when it is zero), then the logic also holds because under BAU both profit and catch are low (or zero). But for intermediate levels of fishing pressure, it turns out that the logic can break down. Figure 5 shows the increase in steady-state profit (again for a fishery with globally median parameters) that arises from fishery management reform as a function of BAU fishing pressure. The solid line depicts the upside from reform without climate change and the dashed line depicts it with a 60% drop in carrying capacity resulting from climate change. To see how a deleterious climate shock could actually increase the benefits from reform, consider the following example. Suppose BAU fishing pressure is about 0.9, which is near the profit-maximizing fishing pressure in the absence of climate change (solid line in Figure 5). In that case, the economic upside from reform (in the absence of climate change) is near zero. But how does the economic upside from reform change after a deleterious climate shock (dashed line)? After climate change, the optimal level of fishing pressure declines (to about 0.75) and the upside from reform, given that BAU fishing pressure is

0.9, is nonnegligible. This example is simply meant to illustrate the possibility that a negative climate shock does not necessarily imply a lower benefit from fishery management reform.

The bioeconomic models I apply to Asian fisheries are substantially more complicated than the simple illustrative examples from Figures 4 to 5. The effects of climate change play out over time, starting conditions differ across fisheries, BAU and optimized policies have effects that evolve over time, and optimal policies are dynamically (not statically) optimized. While the intuition provided above can provide some guidance, it is ultimately an empirical question whether the presence of climate change will strengthen or weaken the case for management reform in any given Asian fishery.

IV. The Effects of Climate Change on Asian Fisheries

Following Gaines et al. (2018), the myriad effects of climate change on global fisheries can be distilled into two categories. The first, and most widely studied, is that climate change may alter the stock growth of a fishery, which is often interpreted as a change in carrying capacity. This can occur through changes in prey abundance, ocean temperatures, acidification, or via other mechanisms. The second consequence of climate change is that it can alter the spatial range of a species in the ocean. Even in the absence of carrying capacity changes, range shifts can have significant consequences to fishery sustainability because as a fish stock crosses international boundaries, institutional failures can lead to overexploitation.

I thus assume that the major effects of climate change can be captured by changes in carrying capacity and shifts in geographic range over time. Changes in the total geographic area suitable for a species correspond to changes in carrying capacity over time. Figure 6 shows the individual trajectories of carrying capacity for each of the 193 species in this analysis under a representative concentration pathway 6.0 climate change scenario; among these species, 55% will decline in carrying capacity and 45% will increase. The line thickness in Figure 6 corresponds to MSY (so it varies over time for each stock, in accordance with changes in K_t) and the shading corresponds to scaled K_t; all values are relative to the 2012 value. Among the species studied, 61% will experience a reduction in carrying capacity and/or significant range shifts as a result of climate change; the other 39% will experience positive effects.

To capture these effects of climate change on a species' carrying capacity and range, we must somehow translate them into the bioeconomic model presented above. First, we keep track of the carrying capacity in each year for each species (Figure 6), and this becomes an input into the model itself (see equation 2). To capture range shifts, we make no changes to the model when a stock is a stationary stock (that is, when it stays within a country's waters). But for the 29% of species

Figure 6. **Effects of Climate Change on Carrying Capacity of Asian Fish Stocks**
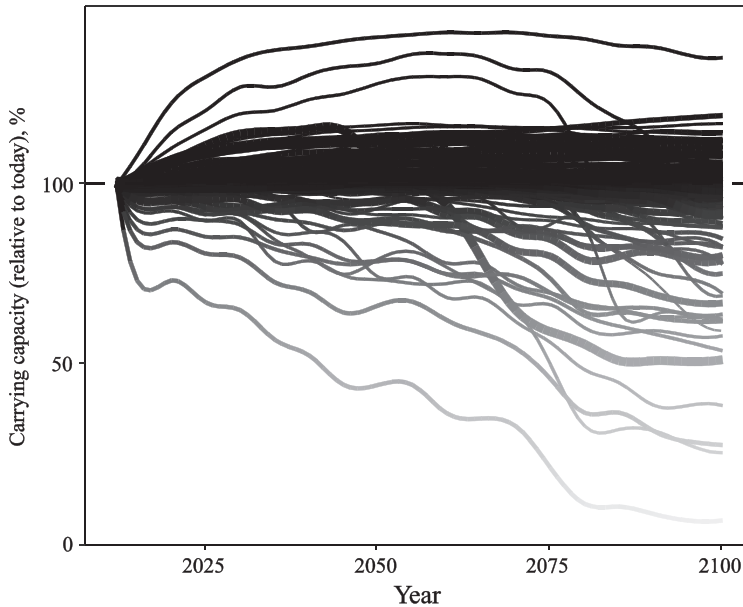
Notes: Each line represents an Asian fish species. Shading indicates carrying capacity (relative to 2012 value) and thickness indicates maximum sustainable yield (MSY) of the stock.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

that are shifting stocks, I run two scenarios. In the first scenario, the BAU fishery policy gets progressively worse as these transboundary shifts start to take hold. In the second scenario, fishing pressure for shifting stocks is unaffected by climate change. All of these assumptions are summarized as follows:

- Changes in fish stock growth
  - Changes in carrying capacity, *K*, over time: K_t (Figure 6) is an input to the biological model (equation 2) and thus to the forward simulations.
  - BAU policy under climate change: fish at the current fishing mortality rate (except for shifting stocks, see below)
  - Optimized policy under climate change: use the dynamically optimized harvest control rule under current conditions.

- Range shifts
  - "Stationary stocks" have policy functions as indicated above.
  - "Shifting stocks," or those that are expected to cross significantly into multiple jurisdictions (Gaines et al. 2018), are treated as follows:

- Under BAU, the initial fishing mortality rate is the current fishing mortality rate. It either gradually transitions to the fishing mortality rate under open access according to when the shifts are expected to occur, or it is maintained at the current fishing mortality rate; both scenarios are examined below.
- Under optimized management, the harvest policy is optimized (under current conditions), so range shifts are internalized into the policy.

## V. The Value of Fishery Management Reform for Asian Species

Detailed information on fishery management in Asia is extremely hard to come by. Most available evidence suggests that fishery management institutions are somewhat outdated and rely heavily on input controls such as season length; gear restrictions; and, in some cases, limited licenses. But there seem to be very few cases of feedback control rules, such as harvest control rules, that are now the backbone of fishery policy in Australia, Canada, the United States, and much of Europe and Latin America. I use the model described above to estimate the economic and food provision benefits of adopting fishery management reforms in Asian fisheries.

In the absence of climate change, the benefits of management reforms vary by fishery, but adopting economically rational fishery management generally increases both cumulative harvest (horizontal axis of Figure 7) and economic value (vertical axis of Figure 7) relative to BAU. The average effect of implementing optimized fishery management is expected to increase catch by about 24% and economic value by 34%, though these values range widely across fisheries. The comparable results in a world with climate change are shown in Figure 8, where the shading refers to whether climate change is expected to have a positive (lighter shade) or negative (darker shade) effect on fish stock growth. With climate change, the benefits of reform are still large (visually, there is little difference between Figures 7 and 8). But the average effects of reform are slightly muted here (reform increases catch by 21% and economic value by 30%). The next section explicitly focuses on the difference between these two sets of results.

How Does Climate Change Affect the Value of Fishery Reform in Asia?

The main question this paper seeks to ask is: does climate change undermine the case for fishery management reform in Asia? I conclude with an emphatic "no." Perhaps the best evidence is from Figure 8, which shows that there remains a large benefit of fishery management reform in nearly all Asian fisheries despite the onset of climate change. A more nuanced question is: does climate change strengthen or weaken the case for fishery management reform? Essentially, this amounts to the difference between Figure 8 and Figure 7, which is depicted in Figure 9 as percentage point changes for each individual fishery.

Figure 7.   **The Value of Reforming Asian Fisheries without Climate Change as a Fraction of Optimized Value without Climate Change**
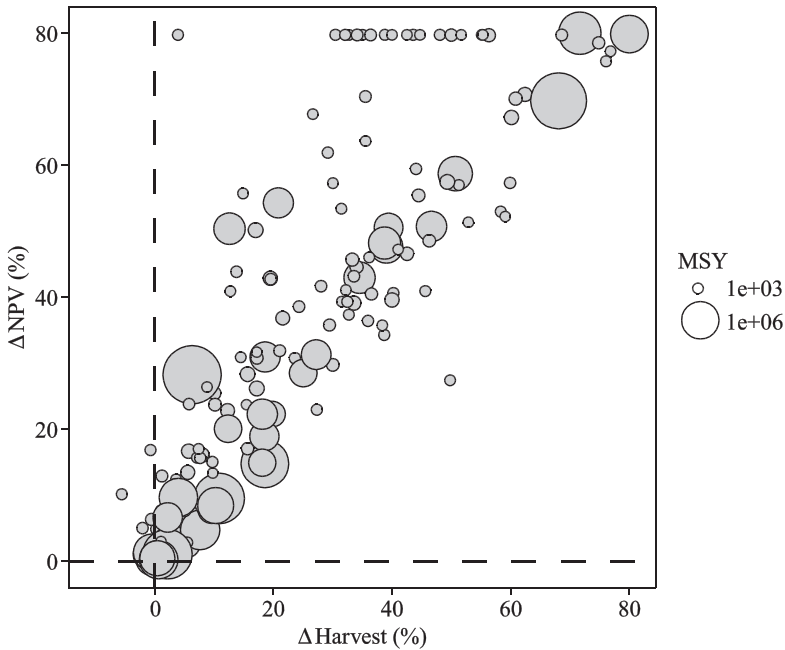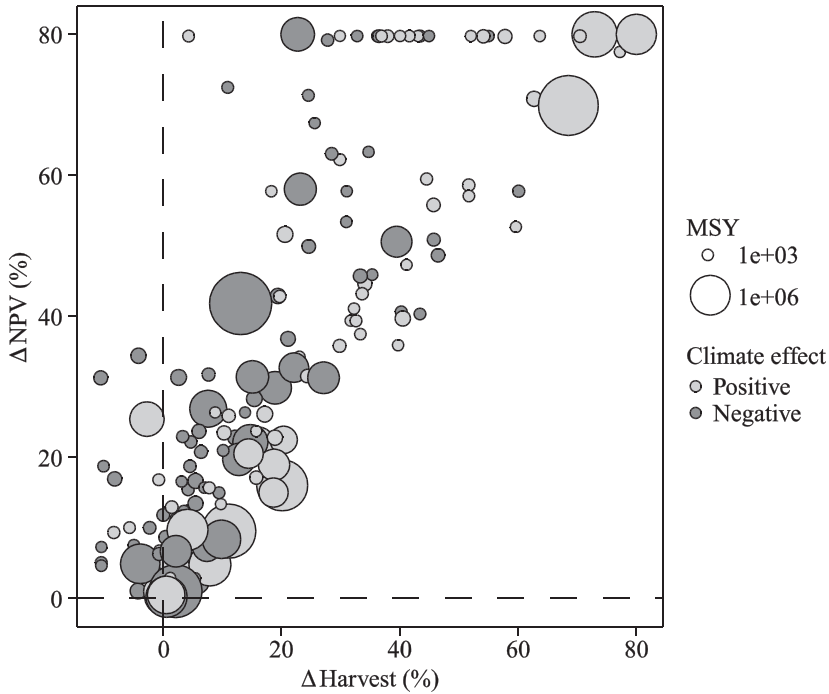

MSY = maximum sustainable yield, NPV = net present value.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

For stationary stocks (triangles in Figure 9), climate change only affects carrying capacity (it does not affect BAU management). For these stocks, the intuition provided in section III was that carrying capacity increases and the case for reform typically go hand-in-hand. Indeed, this seems to be the case for Asian fisheries: those for which carrying capacity shocks will be positive (lighter triangles) tend to have a stronger case for reform (in both harvest and economic value), and those for which carrying capacity shocks will be negative (darker triangles) tend to have a weaker case for reform. For stationary stocks, the overall conclusion is that climate change will generally bolster the case for fishery management reform in Asia.

But the story can be considerably different for Asian stocks for which we anticipate future range shifts resulting from climate change (circles in Figure 9, which reflect the assumption that BAU fishing pressure gradually shifts to open access for shifting stocks). For those stocks, climate change induces potentially devastating institutional failure, which drives a possibly large wedge between the

Figure 8.   **The Value of Reforming Asian Fisheries under Climate Change as a Fraction of Optimized Value without Climate Change**

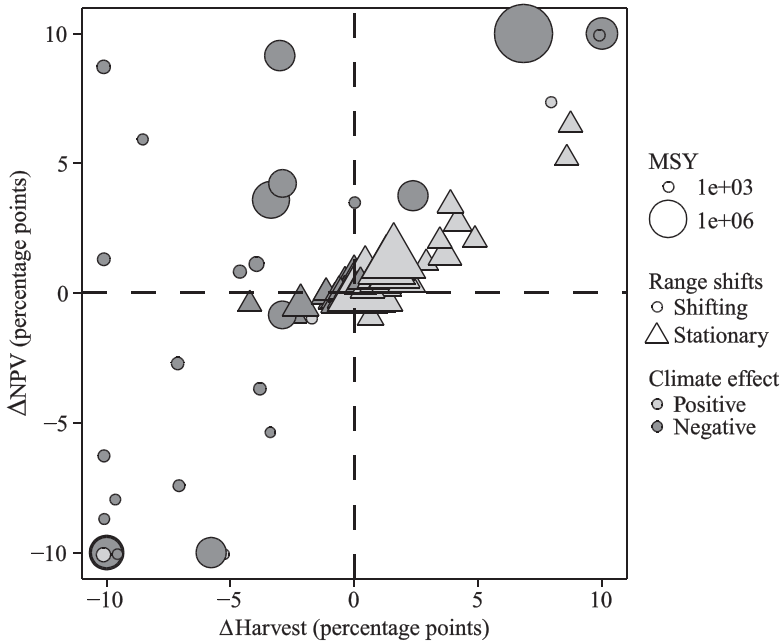MSY = maximum sustainable yield, NPV = net present value.
Note: Shading indicates whether climate change is expected to have a positive (lighter shade) or negative (darker shade) effect on carrying capacity through 2100.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances*. Forthcoming.

value of the fishery with and without reform. This complicates the calculus. While many shifting stocks are also negatively affected by climate change, the case for reform can either be strengthened (circles in upper right of Figure 9) or weakened (circles in lower left of Figure 9) by the onset of climate change. Taken together, these results suggest that despite climate change, the case for fishery reform remains strong in Asia, though the case can be weakened for some stocks.

To test the importance of the BAU assumption for shifting stocks, I repeat the same analysis for the alternative BAU scenario. In the results depicted in Figure 9, the BAU policy under climate change was for stationary stocks to continue at their current fishing mortality rate and for shifting stocks to transition to open access fishing pressure. The alternative is to treat shifting stocks in the same manner as stationary stocks (so they maintain the current fishing mortality rate). In that case, the basic story stands but the case for reform is even stronger. In both the

Figure 9. **Does Climate Change Strengthen the Case for Fishery Reform in Asia? BAU Fishing Pressure Gradually Shifts to Open Access for Shifting Stocks**
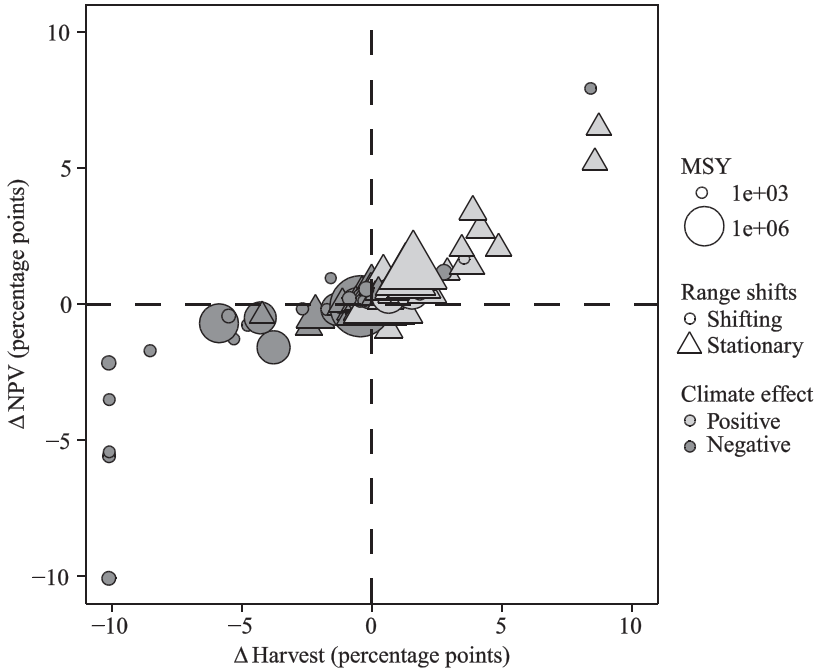

MSY = maximum sustainable yield, NPV = net present value.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

no-climate change and the climate change scenarios, the benefits of reform are 21%–24% (increase in harvest from reform) and 30%–34% (increase in economic value from reform), suggesting that climate change does not dramatically alter the case for reform. The fishery-by-fishery results for this scenario are depicted in Figure 10, which conform to the theoretical expectation that the case for reform will generally be strengthened for stocks that experience a positive climate shock (lighter shade) and weakened for stocks that experience a negative climate shock (darker shade).

Returning to the original BAU assumption, we can aggregate the data underlying Figure 9 to the FAO fish category level to provide a glimpse into the types of fish for which climate change is likely to strengthen or weaken the case for fishery reforms (recognizing that the case for reform remains strong in nearly all cases). Table 2 reports ΔH and ΔV for the seven fish categories with MSY > 1 million metric tons (reported as percentage point gains as a consequence of climate change). These data suggest that the case for reform is strengthened for the large class of cods, hakes, and haddocks, but weakened (sometimes substantially) for

Figure 10. **Does Climate Change Strengthen the Case for Fishery Reform in Asia?**

MSY = maximum sustainable yield, NPV = net present value.
Note: Plotted for all stocks under the alternative business-as-usual assumption (with climate change, all stocks are fished at their current fishing mortality rate).
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

Table 2. **Effect of Climate Change on the Case for Reform by Major Fish Category**

Category	Stocks (No.)	MSY (MMT)	BMSY (MMT)	ΔH	ΔV
Cod, hake, haddock	5	4.83	72.22	6.03	9.66
Misc. pelagic fishes	23	4.86	48.31	1.75	2.25
Misc. coastal fishes	36	1.48	21.58	−6.50	1.46
Herring, sardines, anchovy	11	3.98	82.49	−0.62	1.44
Tuna, bonito, billfish	18	6.06	35.74	−0.30	0.19
Misc. demersal fishes	21	4.45	36.87	−2.74	−5.59
Salmon, trout, smelt	5	1.02	17.75	−31.48	−23.18

BMSY = biomass under maximum sustainable yield, MMT = million metric tons, MSY = maximum sustainable yield.
Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.

other groups such as salmon and smelts. Some groups show the interesting pattern that the case for harvest is weakened but the case for economic value is strengthened (e.g., herrings, sardines, and anchovies). The table also provides the number of species composing each category and measures of fishery size (MSY) and overall biomass (BMSY). Four of the five largest classes of fish are expected to have a stronger economic rationale for reform with climate change than without climate change.

VI. Conclusions

The focus of this paper has been on whether climate change undermines the case for fishery management reform in Asia. While the Asia-wide answer is "no," the answer for any given species turns out to hinge on the exact manner in which climate change will influence the species. For sedentary stocks, the main effect of climate change is on the carrying capacity, and thus the overall growth of the fish stock. If the carrying capacity of a stock is expected to decline under climate change, then the case for fishery reform is generally weakened; the opposite holds for cases when the carrying capacity will increase in the future. While the model results support this prediction, the weakening of the case for reform is quite small (less than 5 percentage point changes), even when climate change will have deleterious effects. The other significant implication of climate change, which has largely gone unnoticed by the previous literature, is that the ranges of some stocks will change. When fish stocks move into new jurisdictions, this can cause a race to fish and may result in worse outcomes than if the same stock had not crossed a jurisdictional boundary. Fisheries for which this second effect is present see a much wider range of outcomes, which largely hinge on how aggressively they are currently managed.

Overall, these results suggest that the vast majority of Asian fisheries, including its largest ones, would benefit economically and in terms of food security by engaging in fishery management reforms. Across Asia, I find that such reforms could lead to increases of 30% in the present value of fisheries and 21% in food provision, even under impending climate change. This implies that Asian fisheries should hasten the transition to sensible, economically rational fishery management under current climate conditions; this will simultaneously secure food and livelihoods across Asia's diverse fisheries, even in the face of climate change.

References

Cao, Ling, Yong Chen, Shuanglin Dong, Arthur Hanson, Bo Huang, Duncan Leadbitter, David C. Little, Ellen K. Pikitch, Yongsong Qiu, Yvonne Sadovy de Mitcheson, Ussif Rashid Sumaila, Meryl Williams, Guifang Xue, Yimin Ye, Wenbo Zhang, Yingqi Zhou, Ping Zhuang, and Rosamond L. Naylor. 2017. "Opportunity for Marine Fisheries Reform in China." *Proceedings of the National Academy of Sciences* 114 (3): 435–42.

Costello, Christopher. 2017. "Fish Harder; Catch More?" *Proceedings of the National Academy of Sciences* 114 (7): 1442–44.

Costello, Christopher, Steven D. Gaines, and John Lynham. 2008. "Can Catch Shares Prevent Fisheries Collapse?" *Science* 325 (896): 1678–81.

Costello, Christopher, Daniel Ovando, Tyler Clavelle, C. Kent Strauss, Ray Hilborn, Michael C. Melnychuk, Trevor A. Branch, Steven D. Gaines, Cody S. Szuwalski, Reniel B. Cabral, Douglas N. Rader, and Amanda Leland. 2016. "Global Fishery Prospects Under Contrasting Management Regimes." *Proceedings of the National Academy of Sciences* 113 (18): 5125–29.

Costello, Christopher, Daniel Ovando, Ray Hilborn, Steven Gaines, Olivier Deschenes, and Sarah E. Lester. 2012. "Status and Solutions for the World's Unassessed Fisheries." *Science* 338 (6106): 517–20.

Food and Agriculture Organization (FAO). 2014. "The State of World Fisheries and Aquaculture." Technical Report of the Food and Agriculture Organization of the United Nations.

Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change" *Science Advances*. Forthcoming.

Homans, Frances R., and James E. Wilen. 1997. "A Model of Regulated Open Access Resource Use." *Journal of Environmental Economics and Management* 32 (1): 1–21.

Martell, Steven, and Rainer Froese. 2013. "A Simple Method for Estimating MSY from Catch and Resilience." *Fish and Fisheries* 14 (4): 504–14.

Melnychuk, Michael C., Tyler Clavelle, Brandon Owashi, and Kent Strauss. 2016. "Reconstruction of Global Ex-Vessel Prices of Fished Species." Edited by Raúl Prellezo. *ICES Journal of Marine Science* 74 (1): 121–33.

Melnychuk, Michael C., Emily Peterson, Matthew Elliott, and Ray Hilborn. 2017. "Fisheries Management Impacts on Target Species Status." *Proceedings of the National Academy of Sciences* 114 (1): 178–83.

Molinos, Jorge García, Benjamin S. Halpern, David S. Schoeman, Christopher J. Brown, Wolfgang Kiessling, Pippa J. Moore, John M. Pandolfi, Elvira S. Poloczanska, Anthony J. Richardson, and Michael T. Burrows. 2016. "Climate Velocity and the Future Global Redistribution of Marine Biodiversity." *Nature Climate Change* 6 (1): 83–88.

Ricard, Daniel, Cóilín Minto, Olaf P. Jensen, and Julia K. Baum. 2012. "Examining the Knowledge Base and Status of Commercially Exploited Marine Species with the Ram Legacy Stock Assessment Database." *Fish and Fisheries* 13 (4): 380–98.

Szuwalski, Cody S., Matthew G. Burgess, Christopher Costello, and Steven D. Gaines. 2016. "High Fishery Catches through Trophic Cascades in China." *Proceedings of the National Academy of Sciences*. COI:10.1073/pnas.1612722114.

World Bank. 2017. *The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries. Environment and Development.* https://openknowledge.worldbank.org/handle/10986/24056.

Worm, Boris, Ray Hilborn, Julia K. Baum, Trevor A. Branch, Jeremy S. Collie, Christopher Costello, Michael J. Fogarty, Elizabeth A. Fulton, Jeffrey A. Hutchings, Simon Jennings, Olaf P. Jensen, Heike K. Lotze, Pamela M. Mace, Tim R. McClanahan, Cóilín Minto, Stephen R. Palumbi, Ana M. Parma, Daniel Ricard, Andrew A. Rosenberg, Reg Watson, and Dirk Zeller. 2009. "Rebuilding Global Fisheries." *Science* 325 (5940): 578–85.

Appendix

This table contains the scientific and common names for each of the 193 species in the Asia data set used in this paper. Among these are several names of economies, which represent aggregated species according to the Food and Agriculture Organization's not elsewhere included (nei) category (e.g., Singapore nei 110).

Table A1.   **Scientific and Common Names of Fisheries Used in this Analysis**

	Scientific Name	**Common Name**
1	Argyrosomus hololepidotus	Southern meagre (=Mulloway)
2	Stephanolepis cirrhifer	Threadsail filefish
3	Tenualosa toli	Toli shad
4	Atrobucca nibe	Blackmouth croaker
5	Konosirus punctatus	Dotted gizzard shad
6	Genypterus blacodes	Pink cusk-eel
7	Scomberomorus lineolatus	Streaked seerfish
8	Ruditapes philippinarum	Japanese carpet shell
9	Oncorhynchus gorbuscha	Pink (=Humpback) salmon
10	Nemipterus virgatus	Golden threadfin bream
11	Ilisha elongata	Elongate ilisha
12	Portunus trituberculatus	Gazami crab
13	Scomberomorus niphonius	Japanese Spanish mackerel
14	Todarodes pacificus	Japanese flying squid
15	Oncorhynchus tshawytscha	Chinook (=Spring=King) salmon
16	Muraenesox cinereus	Daggertooth pike conger
17	Psenopsis anomala	Pacific rudderfish
18	Tenualosa ilisha	Hilsa shad
19	Conger myriaster	Whitespotted conger
20	Clupanodon thrissa	Chinese gizzard shad
21	Mene maculata	Moonfish
22	Seriolella punctata	Silver warehou
23	Erimacrus isenbeckii	Hair crab
24	Pennahia argentata	Silver croaker
25	Berryteuthis magister	Schoolmaster gonate squid
26	Paralichthys olivaceus	Bastard halibut
27	Sardinella longiceps	Indian oil sardine
28	Pterygotrigla polyommata	Latchet(=Sharpbeak gurnard)
29	Atheresthes evermanni	Kamchatka flounder
30	Nemadactylus macropterus	Tarakihi
31	Lactarius lactarius	False trevally
32	Crassostrea gigas	Pacific cupped oyster
33	Trochus niloticus	Commercial top
34	Miichthys miiuy	Mi-iuy (brown) croaker
35	Sardinella lemuru	Bali sardinella
36	Psettodes erumei	Indian halibut
37	Chelidonichthys kumu	Bluefin gurnard
38	Jasus edwardsii	Red rock lobster

Continued.

Table A1. *Continued.*

	Scientific Name	Common Name
39	Rastrelliger brachysoma	Short mackerel
40	Rexea solandri	Silver gemfish
41	Ammodytes personatus	Pacific sandlance
42	Singapore	nei_110
43	Seriolella brama	Common warehou
44	Sillago flindersi	Flinders' sillago
45	Arctoscopus japonicus	Japanese sandfish
46	Callorhinchus milii	Ghost shark
47	Makaira nigricans	Blue marlin
48	Chanos chanos	Milkfish
49	Cromileptes altivelis	Humpback grouper
50	Thailand	nei_122
51	Palau	nei_92
52	Haliotis rubra	Blacklip abalone
53	Megalops cyprinoides	Indo-Pacific tarpon
54	Oncorhynchus nerka	Sockeye (=Red) salmon
55	Cololabis saira	Pacific saury
56	Plectropomus leopardus	Leopard coralgrouper
57	Acanthocybium solandri	Wahoo
58	Amblygaster sirm	Spotted sardinella
59	Arripis trutta	Australian salmon
60	People's Republic of China	nei_20
61	Pagrus auratus	Silver seabream
62	Sillago sihama	Silver sillago
63	Cambodia	nei_15
64	Isurus oxyrinchus	Shortfin mako
65	Lates calcarifer	Barramundi (=Giant seaperch)
66	Trachysalambria curvirostris	Southern rough shrimp
67	Taipei,China	nei_120
68	Ruvettus pretiosus	Oilfish
69	Scylla serrata	Indo-Pacific swamp crab
70	Mugil cephalus	Flathead grey mullet
71	Selaroides leptolepis	Yellowstripe scad
72	Euthynnus affinis	Kawakawa
73	Republic of Korea	nei_115
74	Prionace glauca	Blue shark
75	Tonga	nei_124
76	Epinephelus merra	Honeycomb grouper
77	Oncorhynchus keta	Chum (=Keta=Dog) salmon
78	Portunus pelagicus	Blue swimming crab
79	Decapterus russelli	Indian scad
80	Rastrelliger kanagurta	Indian mackerel
81	Eleutheronema tetradactylum	Fourfinger threadfin
82	Pomadasys argenteus	Silver grunt
83	Thunnus obesus	Bigeye tuna
84	Melicertus latisulcatus	Western king prawn
85	Pseudopleuronectes herzensteini	Yellow striped flounder
86	Vanuatu	nei_133
87	Platycephalus conatus	Deep-water flathead

Continued.

Table A1.   *Continued.*

	Scientific Name	Common Name
88	Platycephalus indicus	Bartail flathead
89	Indonesia	nei_56
90	Saurida tumbil	Greater lizardfish
91	Selar crumenophthalmus	Bigeye scad
92	Fiji	nei_39
93	Istiompax indica	Black marlin
94	Penaeus semisulcatus	Green tiger prawn
95	Trachurus declivis	Greenback horse mackerel
96	Herklotsichthys quadrimaculatus	Bluestripe herring
97	Scomber australasicus	Blue mackerel
98	Chirocentrus dorab	Dorab wolf-herring
99	Japan	nei_63
100	Timor-Leste	nei_32
101	Federated States of Micronesia	nei_78
102	Megalaspis cordyla	Torpedo scad
103	Zenopsis nebulosa	Mirror dory
104	Beryx decadactylus	Alfonsino
105	Tetrapturus angustirostris	Shortbill spearfish
106	Penaeus monodon	Giant tiger prawn
107	Marsupenaeus japonicus	Kuruma prawn
108	Thunnus albacares	Yellowfin tuna
109	Oncorhynchus kisutch	Coho (=Silver) salmon
110	Zeus faber	John dory
111	Scomberomorus commerson	Narrow-barred Spanish mackerel
112	Istiophorus platypterus	Indo-Pacific sailfish
113	Katsuwonus pelamis	Skipjack tuna
114	Sepioteuthis lessoniana	Bigfin reef squid
115	Thyrsites atun	Snoek
116	Cephalopholis boenak	Chocolate hind
117	Decapterus maruadsi	Japanese scad
118	Kajikia audax	Striped marlin
119	Thunnus alalunga	Albacore
120	Harpadon nehereus	Bombay-duck
121	Philippines	nei_96
122	Pellona ditchela	Indian pellona
123	Mustelus antarcticus	Gummy shark
124	Drepane punctata	Spotted sicklefish
125	Lutjanus argentimaculatus	Mangrove red snapper
126	Carcharhinus longimanus	Oceanic whitetip shark
127	Hoplostethus atlanticus	Orange roughy
128	Kiribati	nei_65
129	Malaysia	nei_73
130	Sri Lanka	nei_117
131	Solomon Islands	nei_112
132	Platycephalus richardsoni	Tiger flathead
133	India	nei_55
134	Carcharhinus falciformis	Silky shark
135	Thenus orientalis	Flathead lobster
136	Ommastrephes bartramii	Neon flying squid

Continued.

Table A1. *Continued.*

	Scientific Name	Common Name
137	Anoplopoma fimbria	Sablefish
138	Panulirus longipes	Longlegged spiny lobster
139	Macruronus novaezelandiae	Blue grenadier
140	Elagatis bipinnulata	Rainbow runner
141	Eleginus gracilis	Saffron cod
142	Epinephelus tauvina	Greasy grouper
143	Seriolina nigrofasciata	Blackbanded trevally
144	Anodontostoma chacunda	Chacunda gizzard shad
145	Sphyraena barracuda	Great barracuda
146	Xiphias gladius	Swordfish
147	Tegillarca granosa	Blood cockle
148	Trichiurus lepturus	Largehead hairtail
149	Centroberyx gerrardi	Bight redfish
150	Arripis georgianus	Ruff
151	Sphyraena jello	Pickhandle barracuda
152	Sardinella gibbosa	Goldstripe sardinella
153	Ariomma indicum	Indian dirtfish
154	Australia	nei_6
155	Papua New Guinea	nei_94
156	Rachycentron canadum	Cobia
157	Scomberomorus guttatus	Indo-Pacific king mackerel
158	Priacanthus macracanthus	Red bigeye
159	Pampus argenteus	Silver pomfret
160	Dussumieria elopsoides	Slender rainbow sardine
161	Acetes japonicus	Akiami paste shrimp
162	Rhynchobatus australiae	Whitespotted wedgefish
163	Coryphaena hippurus	Common dolphinfish
164	Cheilinus undulatus	Humphead wrasse
165	Mallotus villosus	Capelin
166	Thunnus orientalis	Pacific bluefin tuna
167	Fenneropenaeus chinensis	Fleshy prawn
168	Scomber japonicus	Chub mackerel
169	Bregmaceros mcclellandi	Unicorn cod
170	Pleurogrammus azonus	Okhotsk atka mackerel
171	Sardinops sagax	South American pilchard
172	Paralithodes camtschaticus	Red king crab
173	Russian Federation	nei_101
174	Metapenaeus joyneri	Shiba shrimp
175	Democratic People's Rep. of Korea	nei_88
176	Myanmar	nei_82
177	Hilsa kelee	Kelee shad
178	Lateolabrax japonicus	Japanese seabass
179	Engraulis japonicus	Japanese anchovy
180	Gadus macrocephalus	Pacific cod
181	Thunnus tonggol	Longtail tuna
182	Perna viridis	Green mussel
183	Sardinella zunasi	Japanese sardinella
184	Fenneropenaeus penicillatus	Redtail prawn
185	Paralithodes platypus	Blue king crab
186	Larimichthys crocea	Large yellow croaker

Continued.

Table A1. *Continued.*

	Scientific Name	Common Name
187	Larimichthys polyactis	Yellow croaker
188	Theragra chalcogramma	Alaska pollock (=Walleye poll.)
189	Dussumieria acuta	Rainbow sardine
190	Parastromateus niger	Black pomfret
191	Pseudocaranx dentex	White trevally
192	Trachurus japonicus	Japanese jack mackerel
193	Pagrus major	Japanese seabream

Source: Author's analysis of data from Gaines, Steven, Christopher Costello, Brandon Owashi, Tracey Mangin, Jennifer Bone, Jorge Garcia Molinos, Merrick Burden, Heather Dennis, Ben Halpern, Carrie Kappel, Kristen Kleisner, and Dan Ovando. 2018. "Fixing Fisheries Management Could Offset Many Negative Effects of Climate Change." *Science Advances.* Forthcoming.