Transboundary Marine Protected Areas

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Abstract

Countries exploiting transboundary fisheries face strong incentives for overexploitation. This basic economic insight has been validated empirically; transboundary fisheries tend to be in worse condition than fisheries in single nations. Attempts to solve this challenge through cross-country cooperation have been largely unsuccessful because competitive extraction is often more attractive than adhering to cooperative agreements. We explore the game-theoretic economics of an alternative solution, a transboundary marine protected area (TMPA), and derive the conditions under which it can improve profits and stock biomass, even in the presence of individually-rational non-cooperation across countries. We find that well-designed TMPAs have the potential to overcome non-cooperation across countries; this result is strengthened when stocks have relatively low growth rates. A TMPA can earn higher harvest benefits for both countries, increase stocks in both countries, and in many cases, can even reproduce the fully cooperative outcome.

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1 Introduction

Transboundary fish stocks, those shared by two or more countries, comprise a significant share of global fisheries (Hayashi 1993; McWhinnie 2009). Prominent examples include the anchoveta fishery shared by Chile and Peru (Agüero and Gonzalez 1996), the Arcto-Norwegian cod fishery shared between Norway and Russia (Armstrong and Flaaten 1991), and the snapper fishery shared by Indonesia and Australia (Blaber et al. 2005). Despite the 1982 UN Convention on the Law of the Sea, which encourages countries to cooperate with respect to management of shared stocks, there is little effective management attention bestowed on these fisheries. This comes as no surprise to economists: The striking lack of cooperation is likely a consequence of strong national incentives to join cooperative agreements and extract excessively from a shared resource (Barrett 2003; Walker et al. 2009). These observations have also played out empirically; many transboundary fisheries are significantly worse off, both in terms of yield and biomass in the water, than fisheries contained within a single country (McWhinnie 2009). An extreme version of this non-cooperation exists when stocks are completely contained on the high seas; this may represent the worst case scenario as there are no clear incentives for competing fishing countries to pursue long term sustainability (White and Costello 2014).

The challenges associated with transboundary fisheries have been addressed by economists using game theory (Levhari and Mirman 1980; Bailey, Sumaila, and Lindroos 2010; Hannesson 2011). This literature explores the implications of strategic behavior by multiple users over a single renewable resource. The main finding is that individual incentives usually lead all users to behave in an overly aggressive manner, overexploiting the resource and making everyone worse off compared to cooperative outcomes (Munro 2004). Although there are examples of regional fisheries management organizations for some transboundary stocks (e.g., the South Pacific Regional Fisheries Management Organization[1] and the Common Fisheries Policy of the European Union[2]), few real world examples of effective cooperative management

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[1] This organization has 14 member countries, mainly focusing in the management of Chilean jack mackerel (*Trachurus murphyi*) and Humboldt squid (*Dosidicus gigas*) in the South Pacific ocean. Additional information can be found at: `https://www.sprfmo.int`

[2] The CFP is the set of rules that guides the management of the stocks shared by the members

agreements exist and the driving force behind this lack of cooperation seems to accord with the basic economic logic presented above. In addition to the associated strategic incentives against cooperation, distinct motivations in each country, complex political landscapes, and a lack of effective international institutions to facilitate coordination have also impeded effective cooperative management (Bjørndal et al. 2000).

Although this historical experience may suggests cooperation between countries is unlikely, valuable theoretical (Benhabib and Radner 1992; Dutta and Sundaram 1993; Polasky et al. 2006) and empirical (Vollan and Ostrom 2010) observations have shown that cooperative outcomes are possible under the right conditions. Here, we complement these efforts by exploring the potential of an alternative approach to managing transboundary fisheries: a transboundary marine protected area (TMPA) sited on the border of the two jurisdictions. If harvest of the transboundary stock is effectively prohibited and enforced within the TMPA, then even when countries act non-cooperatively outside the TMPA, it can induce a reduction in fishing mortality while avoiding the complex process of creating and maintaining dynamic international political agreements. As new technology developments allow for real time spatial enforcement of fishing prohibitions at a fraction of the cost of traditional management controls (Sanchirico, Wilen, et al. 2007), TMPAs have the potential to become a realistic alternative to fishing agreements.[3] We show that in theory, the fully cooperative levels of fishing pressure can be induced by designating a TMPA of an appropriate size, even when countries are behaving non-cooperatively in the remaining fishing grounds. In addition, we discuss the general guidelines under which a negotiated TMPA size a là Weitzman (2014) can also be sustained and able to replicate first-best outcomes.

Marine Protected Areas (MPAs) are well established as an effective conservation tool (Lester et al. 2009), but their role in fisheries management has been actively contested (Hilborn et al. 2004). Although MPAs have been shown theoretically (Gaylord et al. 2005; White et al. 2008; Gaines et al. 2010) and empirically (Halpern, Lester, and Kellner 2009) to enhance fishery yields and/or profit under particular circumstances,

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of the European Union within its jurisdictional waters. Additional information can be found at: `http://ec.europa.eu/fisheries/cfp_en`

[3] An example of these technological advances can be found in the Global Fishing Watch Project, which allows monitoring of operations for more than 70,000 fishing vessels worldwide (Kroodsma et al. 2018).

these benefits are highly dependent on MPA size and location, as well as characteristics of the protected species and fishing regimes (Roberts et al. 2001; Gaines, Gaylord, and Largier 2003; Smith and Wilen 2003; Palumbi 2004; Sanchirico et al. 2006). In particular, these studies have previously identified dispersal benefits outweighing the opportunity costs of the closure as the key condition under which MPAs are most likely to result in any economic and yield benefits (Sanchirico and Wilen 2001; Janmaat 2005). This observation opens the possibility for benefits from a TMPA for transboundary fisheries that are highly susceptible to overexploitation, and in which there is the right degree of biological spillover across jurisdictions. Furthermore, transboundary protected areas have a rich history on land (Ali 2007; Lysenko, Besançon, and Savy 2007), demonstrating their institutional feasibility and providing examples of successful implementation. Even in marine systems, transboundary protected areas are gaining traction, although often more as a means to reduce conflict and deal with contested borders, than explicitly to solve overfishing per se (Mackelworth 2012).

The theoretical implications of MPAs in spatial settings have been previously explored by Sanchirico and Wilen (2001), Costello and Polasky (2004), Costello and Kaffine (2010), and others; and MPA impacts on yield (Hilborn et al. 2004; Hastings and Botsford 1999; Hart 2006; Hart and Sissenwine 2009) and profits (White et al. 2008; Sanchirico et al. 2006; Hart and Sissenwine 2009) have been examined in detail. This literature has provided great insights into the role of conservation for fisheries management, and our attempt is to expand it by specifically analyzing a transboundary setting in which countries can also negotiate over a single size TMPA. To our knowledge, only three previous studies have explored the notion of using marine protected areas for shared stocks. Herrera, Moeller, and Neubert (2016), who show that open access dynamics on the high seas will create de-facto marine reserves through competition. Sumaila (2002) who explores the use of MPAs for the North East Atlantic cod shared by Norway and Russia using numerical simulations, and Punt et al. (2010) who develop the theory for using MPAs in a static fishery model. Our paper extends these previous works in two ways. First, by using an analytical game theory model we derive the closed-form solution for a dynamic fishery game between two countries who jointly harvest a transboundary stock with and without a TMPA. Second, our model allows for symmetric and asymmetric conditions in both stock distribution and preferences across countries. Using game theory to account for strategic behavioral responses of fishers, we provide a theoretically-grounded characterization of fishing pressure by both parties and how strategic interactions (and therefore conservation and welfare outcomes) are likely to change in response to a TMPA and determine the outcome of a potential negotiation process between the two countries.

We model a spatially-heterogeneous transboundary fishery with a stylized fish stock spanning two exclusive economic zones (EEZ). To establish a no-TMPA baseline, we use dynamic game theory to explore the outcomes of non-cooperative exploitation by the two countries relative to a fully cooperative scenario in which total discounted individual benefits from fishing are maximized. We then evaluate the consequences of implementing a TMPA that spans the border of the two countries. While we solve the game for any size TMPA, we focus on the TMPA design that maximizes the joint welfare of the two countries. Because the whole premise of this paper is that countries act non-cooperatively, we approach this problem by assuming, for any TMPA size, that countries act non-cooperatively with respect to harvest outside the TMPA. We are able to show that under many circumstances, a well-designed TMPA can actually replicate the cooperative solution, even though countries behave non-cooperatively outside the TMPA. To explore how results might vary based on biological and economic characteristics, we model a range of different population growth rates, distributions, and discount factors for each country. We then turn to answer the question if countries will ever agree to implement the TMPA in the first place. We explore the likely situations in which a stable agreement can be reached by both nations, and discuss the policy implications. Overall, our results suggest that TMPAs can increase benefits in both countries by decreasing the negative externalities of non-cooperative behavior. Under a wide range of conditions, we find that TMPAs, either exogenously or endogenously determined, can diminish or completely eliminate the negative economic consequences of non-cooperative exploitation of a transboundary fishery and may thus be a tremendously effective alternative to attempting cooperative harvest agreements over these stocks.

2 Model

Consider a fish stock shared by two countries with index $i = \{A, B\}$. Countries seek to maximize harvest benefits, where each country has the required institutions to enforce total allowable catch within their jurisdiction, but institutions for joint management of the stock are absent. During time step t, there is a period of harvest and a period of reproduction. Once the stock has reproduced, it distributes uniformly through the fishing grounds; there is no migration during the harvest season.

2.1 Biological model

Let X_t and H_t denote the total fish stock and total harvest at time step t in this discrete time model. We assume that the biological dynamics are governed by a population growth parameter α à la Levhari and Mirman (1980), with the following form:

$$X_{t+1} = (X_t - H_t)^{\alpha};\ 0 < \alpha < 1 \tag{1}$$

Following harvest, the stock grows according to Equation (1) and then redistributes evenly across its habitat range. Note that $\partial X_{t+1}/\partial\alpha < 0$, so higher α implies a lower growth rate of the fish stock. For this reason, we will for the remainder of this paper refer to α as the "growth parameter" and $(1-\alpha)$ as the "growth rate." The size of the TMPA in country i is given by λ_i (expressed as a fraction of the entire fishing grounds across both jurisdictions), and the size of the fishing grounds available to country i outside the TMPA is given by $\gamma_i(\lambda_i)$. For example, $\gamma_i(0)$ depicts the fraction of area available for fishing in country i with no TMPA. Under uniform redistribution, the stock in each country's fishable jurisdiction at time t, x_{it}, is given by:

$$x_{it} = \gamma_i(\lambda_i)X_t \tag{2}$$

The size of the fishing grounds in country i ($\gamma_i(\lambda_i)$) can have several interpretations, including the fraction of the total habitat area in which the stock reside at all times, the fraction of relevant habitat available for post-spawning settlement, or the distribution of the stock after recruitment. Naturally, the larger is the TMPA, the smaller are the harvestable fishing grounds, so $\gamma_i' < 0$.

2.2 Economic model

We build on the fish war setup proposed by Levhari and Mirman (1980) to model competition among users. Each country has access only to its own fishing grounds, so harvest for country i is limited by the stock that is present in its respective territory (Hayashi 1993). Country i chooses its own harvest, h_{it}, from the available stock in its fishing grounds, and again, following Levhari and Mirman (1980) enjoys benefits (e.g., fishery profits) as a function of this harvest, as follows:

$$U_{it} = \log\left[h_{it}\right] \tag{3}$$

Using its own discount factor, β_i, the goal of each country is to maximize the present value of its own fishing benefits over an infinite horizon, recognizing that the other country is also acting in its own self interest. The resulting population of the fish stock depends on how intensively the two countries fish.

2.3 Transboundary Marine Protected Areas

Suppose now that a TMPA is established on the border between the two countries and that fishing is prohibited within its borders. The TMPA is designated as a fraction, $\lambda_i + \lambda_{-i} = \lambda_A + \lambda_B$, of the entire spatial distribution of the stock. In time period t, the total stock inside the TMPA, m_t, is given by:

$$m_t = (\lambda_A + \lambda_B)X_t \tag{4}$$

3 Results

We assume that countries determine harvest simultaneously by playing a Cournot duopoly game (Osborne 1994). This is analogous to countries simultaneously announcing their total allowable catch levels, number of permits issued, or other management schemes that regulate total harvest within their own fishing grounds. We focus our analysis first on the non-cooperative scenario; we then turn to the cooperative scenario.

3.1 Non-Cooperative Scenario

Levhari and Mirman (1980) did not address the possibility of a TMPA . In the absence of TMPAs, they found that the Cournot-Nash equilibrium harvest for each country depends only on the current stock levels, the population growth parameter, and the discount factors of each country. This will end up being a special case of our model (in which no TMPA is implemented and there is full mixing of the stock across jurisdictions). To extend their model to account for a TMPA, it will become useful to express harvest as a function of stock and escapement, e_{it}, where $h_{it} = x_{it} - e_{it}$. Our objective is to derive analytically the game theoretic interactions for any size TMPA. It turns out that this problem has an analytical solution that generalizes the results in Levhari and Mirman (1980). We find that the non-cooperative equilibrium in both countries takes a form similar to what was found in that paper, except that the slope of each country's harvest rate is modified by the presence of the TMPA and the fraction of the stock that distributes across each jurisdiction. In addition, our approach explicitly considers the existence of multiple corner solutions. [4] This result is formalized below:

Proposition 1. *Equilibrium non-cooperative dynamic escapement in country i's jurisdiction is a fixed fraction of the total stock, X_t, and is given by:*

$$\bar{e}_{it} = X_t\, \bar{f}_i(\lambda_i, \lambda_{-i}) \;\; ; \;\; i = \{A, B\} \tag{5}$$

with

$$\bar{f}_i(\bullet) = \begin{cases} \max\left\{0, \frac{\alpha\beta_i\gamma_i(\lambda_i) - \alpha\beta_{-i}(1-\alpha\beta_i)(\gamma_{-i}(\lambda_{-i})+\lambda_i+\lambda_{-i})}{1-(1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \bar{f}_{-i}(\bullet) > 0 \\ \\ \max\left\{0, \alpha\beta_i\gamma_i(\lambda_i) - (1-\alpha\beta_i)(\lambda_i + \lambda_{-i})\right\} & ; \quad \bar{f}_{-i}(\bullet) = 0 \end{cases} \tag{6}$$

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[4] To obtain the canonical result from Levhari and Mirman (1980), assume interior solutions, eliminate the existence of a TMPA by letting $\lambda_A = \lambda_B = 0$, and assume full mixing of the stock by letting $\gamma_A(0) = \gamma_B(0) = 1$. Applying these conditions to Equation (6) returns the classic result of their paper.

Proof. All proofs are provided in the Appendix.

Proposition (1) defines the dynamic Cournot-Nash equilibrium non-cooperative escapement for each country for any size and configuration of the TMPA. Note that the optimal policy in country i depends on the individual and total size of the TMPA, the growth parameter and each discount factor parameter. We refer to this result as the non-cooperative equilibrium (NCE).

3.2 Cooperative Scenario

In the absence of a TMPA, Levhari and Mirman (1980) have robustly determined that non-cooperative behavior leads to sub-optimal outcomes. We may anticipate a similar finding in the presence of a TMPA. Thus, we would like to compare the NCE to the benchmark case of the fully cooperative solution in which harvests are chosen to maximize the sum of the two individual country's discounted benefits. For completeness, our cooperative solution also generalizes previous results by allowing the presence of asymmetries across countries. Note that if harvests can be set cooperatively, there may be no need for a TMPA, but to remain consistent, we also provide the general solution for any size TMPA. The cooperative solution is formalized below:

Proposition 2. *Equilibrium cooperative dynamic escapement in country i's jurisdiction is a fixed fraction of the total level of stock, X_t, and is given by:*

$$\hat{e}_{it} = X_t \, \hat{f}_i(\lambda_i, \lambda_{-i}) \;\; ; \;\; i = \{A, B\} \tag{7}$$

with

$$\hat{f}_i(\bullet) = \begin{cases} \max\left\{0, \frac{\Delta\gamma_i(\lambda_i) - (1-\alpha\beta_i)(1-\alpha\beta_{-i})(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + 2(1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \hat{f}_{-i}(\bullet) > 0 \\ \\ \max\left\{0, \frac{\Lambda\gamma_i(\lambda_i) - (1-\alpha\beta_i)(1-\alpha\beta_{-i})(\lambda_i + \lambda_{-i})}{\alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + (1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \hat{f}_{-i}(\bullet) = 0 \end{cases} \tag{8}$$

and

$$\Delta = \alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + (1-\alpha\beta_i)(1-\alpha\beta_{-i}) \tag{9}$$

$$\Lambda = \alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) \tag{10}$$

Proposition (2) defines the optimal dynamic cooperative escapement for country i in the presence of any arbitrarily-sized TMPA. We refer to this result as the cooperative equilibrium (CE). Two important features of Proposition (2) must be highlighted. First, despite having written Equation (8) generally for any size TMPA, our comparisons between NCE and CE will be performed for the case where there is no TMPA in the cooperative scenario, $\hat{e}_{it} = X_t\hat{f}_i(0,0)$. Second, note that for any TMPA $(\lambda_i, \lambda_{-i})$, the fractional escapement in the CE (Equation (8)) differs and can be shown greater than the fractional escapement in the NCE (Equation (6)).

3.3 Designing TMPAs to Match Cooperative Escapement

Here we show that, if designed properly, a TMPA with non-cooperation in the fishable area can lead to the same total escapement as in the cooperative equilibrium. Taking the size protected in country $-i$ as given, the TMPA size in country i that achieves the same total escapement in the fishery when countries behave non-cooperatively is formalized below:

Corollary 1. *With non-cooperation across countries and taking λ_{-i} as given, the size of the TMPA in country i that achieves the total CE escapement, λ_i^*, is implicitly defined by:*

$$\lambda_i^* = \Big(\hat{f}_i(0,0) - \bar{f}_i(\lambda_i^*, \lambda_{-i})\Big) + \Big(\hat{f}_{-i}(0,0) - \bar{f}_{-i}(\lambda_{-i}, \lambda_i^*)\Big) - \lambda_{-i} \tag{11}$$

Corollary (1) characterizes the one-sided TMPA that induces the fishery to match the same level escapement as in the CE, or first-best, when countries behave non-cooperatively. The result is intuitive as it simply forces countries, through the establishment of a TMPA, to leave more resource in the water. Note, however, that strategic responses play a role in how effective the TMPA is going to be. Figure (1) provides a numerical example of this result. It plots the fraction protected in country

i as a function of the fraction protected in country $-i$ so the fishery matches the total escapement of the CE, while varying the growth rate (panel A) and the distribution of the stock across jurisdictions (panel B). Plotting fractions is useful because is a relative measure of size.

Several points are worth noting from Figure (1). First, the relationship between fractions protected is linear with negative slope. In other words, there are multiple ways to distribute the size of the TMPA across jurisdictions that exactly match CE escapement. One possible way to achieve that outcome is when countries protect the same percentage in each jurisdiction, which is represented by the 45°line. For a visualization, consider the case in which the stock is equally distributed and country $-i$ protects 25 percent of its fishing grounds (Fig. 1 - panel A). If the stock were to grow at rate 0.5, 66 percent of country i's fishing grounds must be protected to match the CE (Panel A - point a). The same outcome, however, can be achieved if both countries protect 45 percent of their fishing grounds (Panel A - point b).

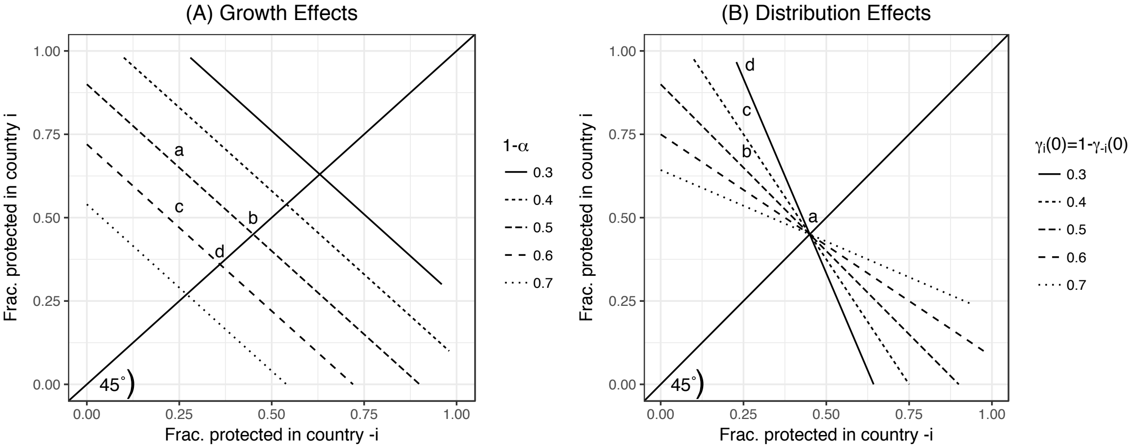

Figure 1: **Combinations of TMPAs in countries i and $-i$ that reproduce the total escapement of the first-best under no cooperation, varying the growth rate (panel A), and the distribution (panel B)**. Fractions protected in both countries are plotted for (A) different growth rates $1-\alpha$, and (B) different distributions of the stock across jurisdictions, $\gamma_i(0)$. Plot (A) assumes $\gamma_i(0) = \gamma_{-i}(0) = 0.5$ and $\beta_i = \beta_{-i} = 0.90$, plot (b) assumes $1 - \alpha = 0.5$ and also $\beta_i(0) = \beta_{-i}(0) = 0.5$.

Second, stocks that grow faster require less protection to replicate the escapement of the CE. This result is intuitive, lower growth rates mean countries have less of an incentive to leave stock in the water and the stock is also less able to withstand overfishing. We can visualize this result by examining how the changes in growth rate, $1 - \alpha$, shift the linear relationship of the different combinations (Fig. 1 - panel A). For example, if country $-i$ protects 25 percent of its fishing grounds and the grow rate increases from 0.5 to 0.6, the protection required in country i decreases from 66 (Panel A - point a) to 48 percent (Panel A - point c). Further, if countries protect the same percentage, an increase in the growth rate now reduces the required level of protection from 45 (Panel A - point b) to 36 percent (Panel A - point d).

Third, asymmetry in the distribution of the stock introduces asymmetry in the the required fractions to protect. Graphically, we can examine point a in panel B of Figure 1. The combination matching the CE escapement, regardless of the distribution, is 45 percent. But if country $-i$ protects a lesser share, country i would have to protect relatively more as its share of the fishing grounds decreases. For example, fix country $-i$ at protecting 25 percent. Under symmetric distribution, country i would have to protect 66 percent to match total CE escapement (Panel B - point b). That percentage increases to 75 (Panel B - point c) and 93 percent (Panel B - point d) as the share of stock residing in country i's reduces from 40 to 30 percent, respectively.

The combination rule switches if country $-i$ were to protect more than 45 percent. That is, country i will have to protect relatively less as its share of the fishing grounds decreases. Evidently, this is a consequence of the uniform distribution we have assumed in this model. The CE seeks a fixed level of escapement, and larger percentages of smaller areas can match smaller percentages of larger areas and vice versa. See the Appendix for an additional description when the stock's distribution is even more skewed toward one country.

These results show how a TMPA could be designed so as to achieve the same escapement as when countries behave cooperatively. We find that stocks with lower growth rates require more protection and that CE escapement can be achieved with a common percentage protected in both countries, regardless of the distribution of the stock. These allocations, however, do not consider the individual or total value of the fishery. Intuitively, strategic interactions must play a role and matching on total escapement does not necessarily mean that the first-best is also achieved. We cover this topic in the section below.

3.4 Designing TMPAs to Match Total Cooperative Performance

In this section we show that, if designed properly, a TMPA with non-cooperation in the fishable area can lead to the same total economic performance as in the cooperative equilibrium. It will be useful to define country i's discounted sum of utilities as $J_i(\lambda_i, \lambda_{-i})$. Following the notation above, $\bar{f}(\bullet)$ and $\hat{f}(\bullet)$, we use bars to denote the NCE and hats denote the CE, respectively. Taking the size protected in country $-i$ as given, the TMPA size in country i that achieves the same total economic performance in the fishery when countries behave non-cooperatively is formalized below:

Corollary 2. *With non-cooperation across countries and taking λ_{-i} as given, the size of the TMPA in country i that achieves the total CE performance, λ_i^{**}, is implicitly defined by:*

$$\bar{J}_i(\lambda_i^{**}, \lambda_{-i}) + \bar{J}_{-i}(\lambda_{-i}, \lambda_i^{**}) = \hat{J}_i(0,0) + \hat{J}_{-i}(0,0) \tag{12}$$

Corollary (2) characterizes the one-sided TMPA that induces the fishery to match the same level performance as in the CE, or first-best, when countries behave non-cooperatively. The difference with Corollary (1) lies on the fact that an additional unit of protection, which results in an additional unit of escapement, may lead to a unit loss in harvest. A marginal decrease in harvest then results in losses that increase at an increasing rate in terms of utility. This relationship implies that to match CE performance, countries need to have their exact CE level of harvest, or that the losses of one of them are exponentially captured by the other.

To add flexibility to our results, we also consider second-best scenarios. In other words, cases in which TMPAs lead to better economic outcomes than the pure NCE. This analysis is done by taking protection in country $-i$ as given, and then choosing the amount of protection in country i that maximizes the sum of discounted utilities. Choosing the TMPA that achieves the first, or a second-best, is equivalent to:

$$\underset{0 \leq \lambda_i < \gamma_i(0)}{\arg\max} \{\bar{J}_i(\lambda_i, \lambda_{-i}) + \bar{J}_{-i}(\lambda_{-i}, \lambda_i)\} \tag{13}$$

Figure (2) provides a numerical example of this result. It plots the protected fraction in country i as a function of the fraction protected in country $-i$ so the fishery maximizes the sum of the discounted utilities, while varying the growth rate (panel A) and the distribution of the stock across jurisdictions (panel B). In addition, we also highlight the combinations that achieve at least 99% of the economic performance of the first-best.

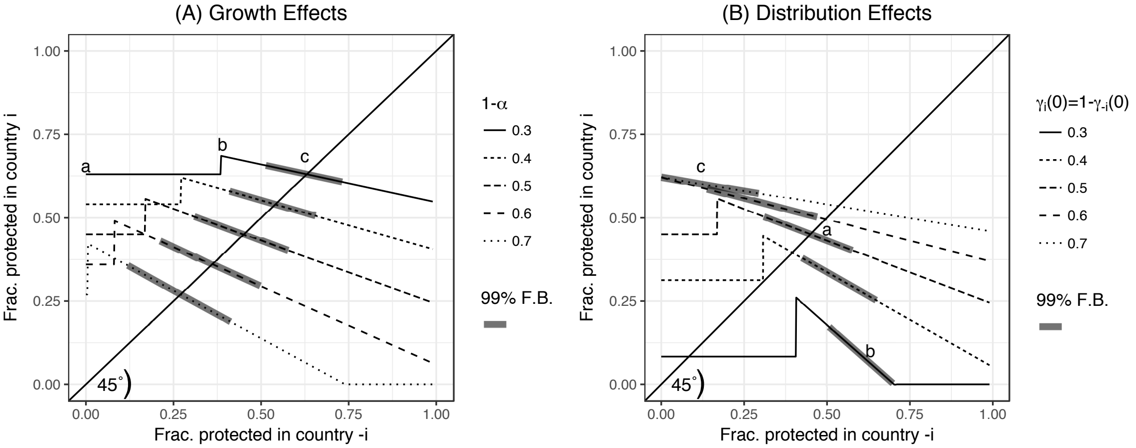

Figure 2: **Combinations of TMPAs in countries i and $-i$ that maximize the social value of the fishery under no cooperation, varying the growth rate (panel A), and the distribution (panel B)**. Fractions protected in both countries are plotted for (A) different growth rates $1-\alpha$, and (B) different distributions of the stock across jurisdictions, $\gamma_i(0)$. The highlighted sections indicate the combinations that achieve at least 99% of the value generated in the first-best. Plot (A) assumes $\gamma_i(0) = \gamma_{-i}(0) = 0.5$ and $\beta_i = \beta_{-i} = 0.90$, plot (b) assumes $1-\alpha = 0.5$ and also $\beta_i(0) = \beta_{-i}(0) = 0.5$.

From this figure, it is evident that altering the objective of the TMPA also changes the design principle. Combinations that achieve the same escapement as the CE do not necessarily maximize the value of the fishery. To visualize the design principle, consider a stock growing at rate 0.3 in panel A of Figure (2). If country $-i$ protects 0 to 38 percent of its fishing grounds, the level of protection in country i that maximizes the total value of the fishery is always 68 percent (Panel A - point a). At that point, country i is already constrained by the TMPA. Country $-i$ is aware of this, and reducing its fishable area only leads to reducing its own escapement further. At 38 percent, however, country $-i$ becomes constrained and the combinations start to generate tradeoffs between the two nations (Panel A - point b). In the neighborhood of the 45°line, the TMPA approaches the performance of the first-best (Panel A - point c).

Overall, the observation is that stocks that grow at faster rates require more protection to approach, and potentially match the performance of the first-best (Fig. 2 - panel A). It also follows that the range of combinations that come close to replicating the first-best is increasing in the growth rate. This pattern is a consequence of faster rates being able to compensate for the short-term loss in harvest due to decreases in the fishable area.

Introducing asymmetric distribution alters these results. To maximize the value of the fishery, the country with the biggest share hast to protect relatively more of its fishing grounds. Consider the case of symmetric distribution in Figure (2), with each country protecting 45 percent (Panel B - point a). Now, suppose that country i's share is 30 percent instead. To match the first-best, country i now has to protect only eight percent, while country $-i$ has to protect 60 percent (Panel B - point b). The protection requirement switches when country i's share is 70 percent (Panel B - point c).

A question that arises is why the fraction protected doesn't converge to zero when the fishery is mostly contained in one country. One would expect the country with the larger share to behave as a sole owner, and that is what happens in the NCE as $\gamma_i(0)$ approaches one. This fact would suggest that the TMPA becomes less useful, and that its size should converge to zero. Our result differs from this prescription by the fact that our first-best is not a sole owner solution, but a cooperative exploitation that considers the utility in both nations. The Inada conditions associated with the individual utility functions imply that a small increase in the harvest of the smaller country has a large total marginal contribution. This effect leads to strictly positive TMPAs, even when the distribution is heavily skewed (Fig. 2 - panel B). Note, however, that as the distribution becomes more asymmetric, protection in country with the largest share converges to an upper value (Panel B - point b), while protection in the other country converges to zero (Panel B - point c).

These results show how a TMPA could be designed so as to achieve the same economic performance as when countries behave cooperatively. We find that stocks with lower growth rates require more protection, and that both countries need to be constrained to approach the first-best. Changes in distributions also indicate that countries with the biggest share should always protect more to maximize the value of the fishery. The question that remains unanswered is if countries were to ever agree to have the TMPA established, and if so, why don't they? We provide some answers to these questions, and derive a potential solution in the section below.

3.5 Negotiating Over a Common Protection TMPA Size

The previous section established that an appropriately-sized TMPA could be designed to induce a fishery with non-cooperative countries to perform *as if* they were acting cooperatively. This section examines the possibility of countries willingly agreeing to establish a TMPA. In particular, we ask if countries will voluntarily ever choose to protect their own fishing grounds.

If countries are left to their own devices, the NCE is the optimal response and there will never be any level of protection. The way in which we propose to tackle this problem is by inducing negotiation. In particular, we build on the idea proposed by Barrett (2003) and Weitzman (2014), who explore the feasibility of negotiating a single price in the presence of a global externality. Weitzman (2014) shows that in the case of climate change, negotiating over a single internationally binding minimum carbon price decreases self-interest and forces countries to internalize the externality.

In the case of a TMPA, the obvious candidate for a single-negotiation point is the fraction protected in each country's fishing ground; recall that fractions protected are a relative measure of size. According to Weitzman (2014), an ideal negotiating instrument should be able to i) induce cost-effectiveness, ii) be a one dimensional focal point, and iii) embody a countervailing force against self-interest. The task is now to show that negotiating over a single TMPA size satisfies these properties.

Contrasted against a single fishing mortality rate agreement, the first requirement is the weak point for TMPAs. Closing fishing grounds could induce congestion, and individual vessel profits will be relatively lower than simply reducing fishing mortality. On the other hand, credibly cross-monitoring and cross-enforcing individual landings also generate costs. Which option leads to cost-effectiveness then depends on how these two sources of cost compare to each other. One factor that may tilt the scale in favor of TMPAs, however, is that freely available data on the geospatial distribution of global fishing vessels could allow to control spatial effort at a fraction of the cost of standard landing enforcements (Kroodsma et al. 2018).

The second and third conditions are satisfied as countries decide over a binding common TMPA size for both of them. Any voting mechanism will concentrate efforts toward a single dimension, and transaction costs will be effectively reduced. More importantly, both countries have an incentive to make the other fish less and themselves more. These two incentives balance each other in their decision, and may have the potential to lead to second-, and even first-best outcomes depending on how the externality and the instrument affects both negotiating parties.

To show how these claims hold in the case of a TMPA, we implement a bilateral negotiation process. We do not explore the conditions that bring countries to the negotiating table, or how they decide on implementation, but on how they act when given the opportunity to propose a mutually binding size TMPA.

Define η as the size, or fraction protected in each of the fishing grounds. $\gamma_i(\lambda_i)$ can now be denoted as $\gamma_i(\eta)$, and $J_i(\lambda_i, \lambda_{-i})$ as $J_i(\eta)$. The η that maximizes the NCE country i's discounted utility, η_i^*, is then given by:

$$\eta_i^* = \underset{0 \leq \eta < 1}{\arg\max}\{\bar{J}_i(\eta)\} \tag{14}$$

Suppose further that countries have previously agreed to a blind-auction voting mechanism. First, both countries propose their η^* simultaneously. Then, some function of the two values, such as the average or the minimum, is implemented. It follows that a strictly positive value of η^* will be proposed *if and only if* the country is made better off. Because optimal escapement is state independent, η^* does not depend on the current state of the stock and countries have no incentive to deviate from their proposed percentages. The outcome of the bidding process is shown in Figure 3, in which we graph η^* as a function of the growth rate and a country's share of the fishing grounds.

To see how the incentives for negotiation work, consider the case of symmetric distribution first (Fig. 3 - panel A). Under this scenario, both countries vote for the same common protected percentage, which makes both of them better off and also

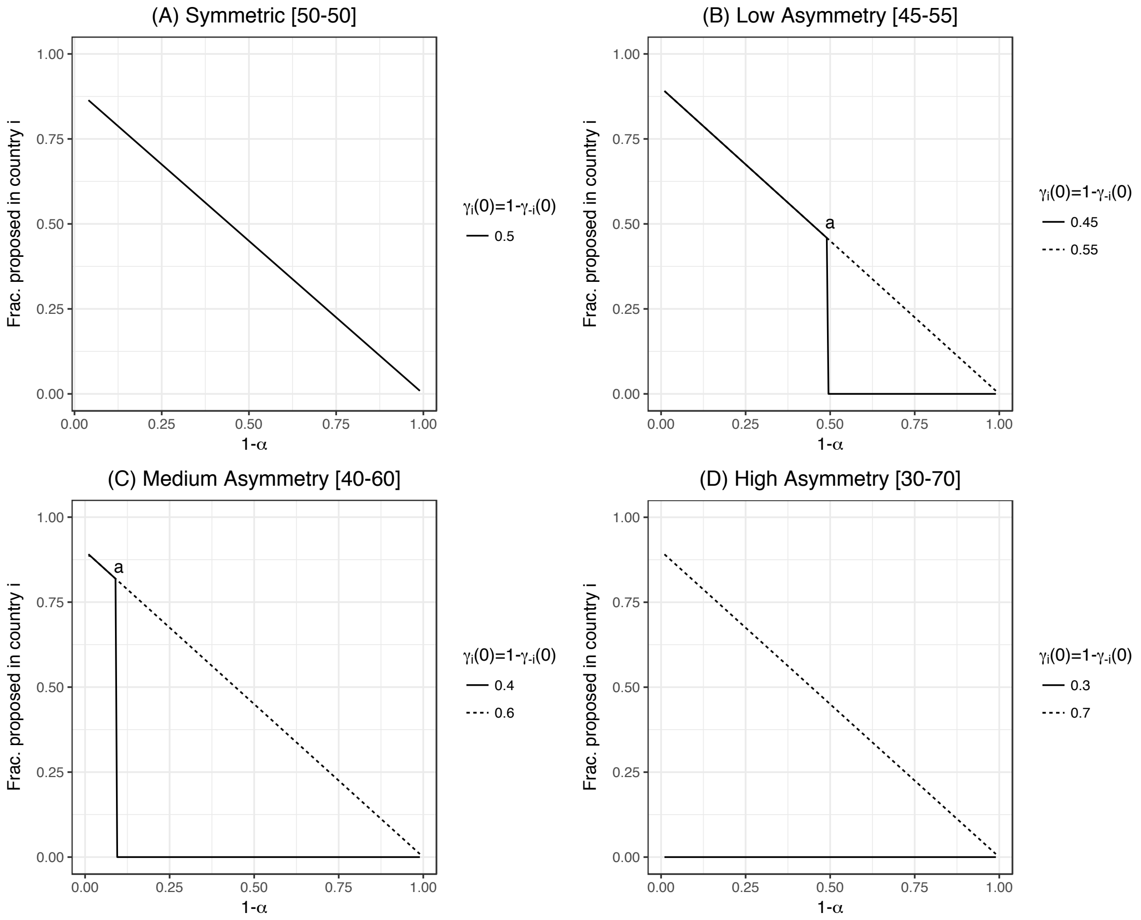

Figure 3: **Proposed TMPA size as a function of the growth rate for symmetric (panel A) and asymmetric distributions (panels B-D)**. Proposed TMPA sizes are plotted with respect to different growth rates $1 - \alpha$, when (A) the stock is equally distributed across both jurisdictions, (B) when one country has 55 percent of the fishing grounds, (C) when one country has 60 percent of the fishing grounds, and (D) when one country has 70 percent of the fishing grounds. All panels assume $\beta_i = \beta_{-i} = 0.90$.

achieves the first-best. As noted earlier, this size is decreasing in the growth rate. This result is expected, as noted by Weitzman (2014) in the case of a global externality, a single negotiation mechanism can also balance and cancel out the fishing externality, even when countries behave selfishly. Symmetry aids this outcome by balancing the gains and losses from decreasing fishing grounds evenly across the two countries.

Introducing asymmetric distribution diminishes the potential of an agreement. Consider the case when there is low asymmetry in the distribution of the stock (Fig. 3 - panel B). The country with the larger share (dotted line) will always vote to have a TMPA. Implicitly, that behavior follows from the incentive to reduce the influence of the smaller country on the stock. On the other hand, the country with the smallest share (solid line) only votes to have a TMPA when the stock grows at lower rates. As the growth rate increases its relative losses in fishing grounds overcome the gains of additional escapement, and then there is no TMPA size that can improve the NCE (Panel B - point a). Notwithstanding these differences, when both countries vote to establish a TMPA, the proposed sizes coincide.

Figure (3) also shows how further increases in distribution asymmetry eventually break down the incentives in the country with the smaller share. With medium distribution asymmetry (Fig. 3 - panel C), this country will only vote to have a TMPA only when the growth rate of the stock is extremely low (Panel C - point a). In the case of high asymmetry (Fig. 3 - panel D), all incentives for protection go away and the smaller country will never vote to impose a common size TMPA.

These results show how incentives condition a potential vote, and that TMPAs could indeed be mutually agreed upon by both countries. The likelihood for agreement increases for stocks that have low growth rates and that are more evenly distributed across jurisdictions. In other words, countries are more willing to voluntarily constrain themselves and the others as the fishing externality increases. In the next section we discuss the policy implication of these results, as well as the main caveats present in our analysis.

4 Discussion

Transboundary fisheries pose a significant management challenge for nearly all coastal nations. For diverse regions and taxa (Lear and Parsons 1993; Schaefer 1995; Maquire 2006; Maurihungirire 2008), there are incentives for countries to harvest these fisheries too aggressively. We show that in the absence of effective cooperation, well designed spatial closures spanning the border between countries could provide an effective solution. Moreover, we also show that implementing a single negotiation mechanism can lead to the establishment of TMPAs, even when countries behave selfishly.

Our main result is that TMPAs have the potential to alleviate the consequences of non-cooperative behavior in transboundary fisheries. This improvement can occur both when TMPAs are exogenously imposed, conditional on being properly designed, or when countries negotiate over a common fraction to protect in their own fishing grounds. The effectiveness of the negotiation depends on the extent of asymmetry between countries. In the symmetric case, both countries face the same conditions, and sharing the burden of the TMPA leads to the first-best outcome. Asymmetric distribution limits this potential because the losses from non-cooperation and the burden of the TMPA are not equally distributed, and the required levels of protection that make both countries better off cannot longer be achieved by a common percentage.

These results provide some useful insights for the strategic use of MPAs in transboundary fisheries. In terms of species characteristics, TMPAs could be effectively used for fisheries that have moderate to low population growth rates, such as many demersal and benthic fisheries, especially if they are relatively evenly distributed across countries. The total number of candidate fisheries worldwide that fit these characteristics is large, and the long term impacts could be substantial if TMPAs are properly enforced (Hilborn et al. 2004; Gaines et al. 2010; Halpern 2003; Klein et al. 2008). More importantly, the presence of ancillary benefits (e.g., habitat effects, pure biodiversity conservation, and recreation) opens the door for TMPAs to be considered as a viable comprehensive management measure for transboundary fisheries (Lauck et al. 1998; Sanchirico 2004; Armstrong 2007).

In addition, traditional approaches for managing transboundary fisheries require institutions that facilitate coordinated management and cooperation between countries. Such institutions are commonly unsuccessful (Hilborn, Orensanz, and Parma 2005), and they can have significant costs of implementation and operation. In some cases these costs can exceed several millions of dollars, when considering registration systems for fish landings, monitoring and enforcement measures, and research capacity necessary for stock assessments and total allowable catch recommendations (Schrank, Arnason, and Hannesson 2003). Using TMPAs as a management tool could also be desirable because closing a fraction of the fishing grounds and enforcing it through currently available vessel monitoring systems may prove easier and cheaper to implement than standard measures. Although implementing a TMPA will also require a negotiation process and enforcement costs of its own (Balmford et al. 2004), the appeal of the ancillary benefits provided by TMPAs could make their implementation politically more feasible, and even more desirable than traditional fishing agreements.

Our observations, however, are not free of caveats. In an effort to increase the tractability of the problem, we steer away from details regarding the species' dynamics as well as the social and institutional dynamics of the fishery in each country. Despite these omissions, this is a useful starting point that demonstrates some of the basic rules likely guiding the effectiveness of TMPAs in solving the widespread problem of transboundary fisheries. Potential extensions that could guide specific case-by-case analysis include the inclusion of larval dispersal, adult movement, other life-history traits and habitat heterogeneity (Sanchirico and Wilen 1999; Neubert 2003; Brock and Xepapadeas 2010). Sound policy making regarding TMPAs will greatly benefit from future tactical models that take into account these complex assumptions.

The benefits of TMPAs, as with any fishing agreement, will take time to be realized (Ovando, Dougherty, and Wilson 2016). This problem may create politically-motivated incentives to oppose reforms of any kind and continue the status quo, even if this position is counterproductive in the long run. TMPAs could overcome this short term hurdle by using instruments such as side payments (Bjørndal et al. 2000; Kaitala and Munro 1993; Arnason, Magnusson, and Agnarsson 2000) and external loans. These could be justified by both fishing goals and the ancillary benefits of a TMPA. Side payments could come from the country that achieves gains faster after the TMPA is implemented, thus lowering the resistance of the country that is most negatively impacted in the short term. As an alternative, an external organization could provide funding or loans to compensate for short term losses, making both countries indifferent to, or even supportive of the reform. Given the potential for economic and conservation benefits that are predicted to follow, a finance plan could be supported by international banks or conservation focused NGOs.

Finally, and under the assumptions of our model, the fishery will be unaffected if a TMPA is not sufficiently large to constrain harvest. This is also true for countries that cooperate, as the optimal harvest takes into account how much of the stock is being buffered in the TMPA. This result implies that cooperatively managed transboundary fisheries may be able to implement moderately-sized TMPAs with little or no effect on harvest, creating the opportunity for cooperating countries to capture conservation benefits without compromising production goals. Furthermore, our focus on a single species fishery can and should be expanded to fisheries that comprise multiple species. If well designed, a TMPA could both ease multispecies management challenges and have larger cumulative benefits by increasing biodiversity and overall harvest (Hastings, Gaines, and Costello 2017). If sizes and locations where positive effects are obtained do not overlap among the species, however, there will be tradeoffs across the gains and losses for different fisheries. Addressing these multispecies issues is an area ripe for further analysis and innovation in studying transboundary fishery problems.

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5 Appendix

5.1 Proofs

5.1.1 Proof of Proposition 1

Under a non-cooperative scenario, each country seeks to maximize its discounted benefit taking as given the other country's harvest. Let x_{it} be the fish stock, and e_{it} the escapement level in country's i jurisdiction at time t. The harvest h_{it} is given by $h_{it} = x_{it} - e_{it}$, and benefit is $\log[h_{it}] = \log[x_{it} - e_{it}]$. Let m_t be the fish stock inside the TMPA.

Consider a fishery that lasts only for two periods, $T-1$ and T. There is no value in fishing after period T, so each country will harvest all the stock in their jurisdiction, $e_{iT} = 0$. The benefit of this harvest is given by:

$$V_{iT}(X_T) = \log[h_{iT}] = \log[x_{iT}] \tag{15}$$

Proceeding via backward induction in period $T-1$, each country chooses its harvest level to maximize the dynamic programming equation:

$$V_{iT-1}(X_{T-1}) = \max_{e_{iT-1}} \{\log[x_{iT-1} - e_{iT-1}] + \beta_i V_{iT}(X_T)\} \tag{16}$$

Where β_i is the discount factor for country i. Substituting (15) into (16) then gives:

$$V_{iT-1}(X_{T-1}) = \max_{e_{iT-1}} \Big\{ \log[x_{iT-1} - e_{iT-1}] + \beta_i \log[x_{iT}] \Big\} \tag{17}$$

We assume that harvest precedes reproduction, and that finally a fraction $\gamma_i(\lambda_i)$ returns to jurisdiction i, and a fraction $\lambda_i + \lambda_{-i} = \lambda_i + \lambda_{-i}$ returns to the TMPA. The stock available for country i at time T is then given by $x_{iT} = \gamma_i(\lambda_i)(e_{iT-1} + e_{-iT-1} + m_{T-1})^{\alpha}$. Inserting these dynamics into equation (17), we have the dynamic programming equation for the two period transboundary fishery:

$$\begin{aligned} V_{iT-1}(X_{T-1}) = \quad & \max_{e_{iT-1}} \Big\{ \log[x_{iT-1} - e_{iT-1}] \\ & +\beta_i \log\left[\gamma_i(\lambda_i)(e_{iT-1} + e_{-iT-1} + m_{T-1})^{\alpha}\right] \Big\} \end{aligned} \tag{18}$$

The first order conditions for country i are then given by the following expression:

$$e_{iT-1} = \frac{\alpha\beta_i x_{iT-1} - e_{-iT-1} - m_{T-1}}{\alpha\beta_i + 1} \tag{19}$$

If both countries act non-cooperatively the non-cooperative escapement level that each country applies in its jurisdiction is given by:

$$e_{iT-1} = \frac{\alpha\beta_i(\alpha\beta_{-i} + 1)x_{iT-1} - \alpha\beta_{-i}(x_{-iT-1} + m_{T-1})}{(\alpha\beta_i + 1)(\alpha\beta_{-i} + 1) - 1} \tag{20}$$

Given that the distribution of the stock is determined by λ_i and λ_{-i}, let $X_{T-1} = (e_{iT-2} + e_{-iT-2} + m_{T-2})^{\alpha}$, $x_{iT-1} = \gamma_i(\lambda_i)X_{T-1}$, and $m_{T-1} = \lambda_i + \lambda_{-i}X_{T-1}$. Hence, the final expression for escapement can be re-written as:

$$e_{iT-1} = X_{T-1}\frac{\alpha\beta_i(\alpha\beta_{-i} + 1)\gamma_i(\lambda_i) - \alpha\beta_{-i}(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{(\alpha\beta_i + 1)(\alpha\beta_{-i} + 1) - 1} \tag{21}$$

Where the present value benefit each country perceives from this strategy is given by:

$$V_{iT-1}(X_{T-1}) = \log[x_{iT-1} - e_{iT-1}] + \beta_i \log\left[\gamma_i(\lambda_i)X_T^{\alpha}\right] \tag{22}$$

Substituting equation (21) into (22), and rearranging terms we get that the maximum benefit for the two period non-cooperative fishery can be expressed as:

$$V_{iT-1}(X_{T-1}) = (\alpha\beta_i + 1)\log[X_{T-1}] + C_i \tag{23}$$

$$C_i = \log\left[\frac{\alpha\beta_{-i}\gamma_i(\lambda_i)^{\beta_i}(\gamma_i(\lambda_i) + \gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{(\alpha\beta_i + 1)(\alpha\beta_{-i} + 1) - 1}\right] \tag{24}$$

Working backwards in time, each country faces the following maximization problem:

$$V_{iT-2}(X_{T-2}) = \max_{e_{iT-2}} \{\log[x_{iT-2} - e_{iT-2}] + \beta_i V_{iT-1}(X_{T-1})\} \tag{25}$$

Recall that $X_{T-1} = (e_{iT-2} + e_{-iT-2} + m_{T-2})^{\alpha}$. Hence, the first order conditions for the escapement level of country i at time $T-2$ are given by:

$$e_{iT-2} = \frac{(\alpha\beta_i + (\alpha\beta_i)^2)x_{iT-2} - e_{-iT-2} - m_{T-2}}{\alpha\beta_i + (\alpha\beta_i)^2 + 1} \tag{26}$$

By solving this problem simultaneously and using our previous definitions, each country under the non-cooperative scenario will set its optimal escapement as:

$$\bar{e}_{iT-2} = X_{T-2}\frac{(\alpha\beta_i+(\alpha\beta_i)^2)(\alpha\beta_{-i}+(\alpha\beta_{-i})^2+1)\gamma_i(\lambda_i)-(\alpha\beta_{-i}+(\alpha\beta_{-i})^2)(\gamma_{-i}(\lambda_{-i})+\lambda_i+\lambda_{-i})}{(\alpha\beta_i+(\alpha\beta_i)^2+1)(\alpha\beta_{-i}+(\alpha\beta_{-i})^2+1)-1} \tag{27}$$

From this expression, it is clear that when the fishery lasts $n+1$ periods, the optimal escapement response under the non-cooperative scenario is given by:

$$e_{iT-n} = X_{T-n}\frac{\left(\frac{\alpha\beta_i-(\alpha\beta_i)^{n+1}}{1-\alpha\beta_i}\,\frac{1-(\alpha\beta_{-i})^{n+1}}{1-\alpha\beta_{-i}}\right)\gamma_i(\lambda_i)-\left(\frac{\alpha\beta_{-i}-(\alpha\beta_{-i})^{n+1}}{1-\alpha\beta_{-i}}\right)(\gamma_{-i}(\lambda_{-i})+\lambda_i+\lambda_{-i})}{\left(\frac{1-(\alpha\beta_i)^{n+1}}{1-(\alpha\beta_i)}\,\frac{1-(\alpha\beta_{-i})^{n+1}}{1-(\alpha\beta_{-i})}\right)-1} \tag{28}$$

As the fishery extends over time, let $X_t = X_{T-n}$ represent the fish stock at the time when each country decides its harvest policy taking into consideration that the fishery will last for $n+1$ periods. Finally, as n goes to infinity we get that the optimal escapement under a non-cooperative scenario is:

$$e_{it} = X_t\frac{\alpha\beta_i\gamma_i(\lambda_i) - \alpha\beta_{-i}(1-\alpha\beta_i)(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{1-(1-\alpha\beta_i)(1-\alpha\beta_{-i})} \tag{29}$$

Note that interior optimal non-cooperative harvest is a constant fraction of the stock. As expected, the non-cooperative harvest satisfies the original result provided by Levhari and Mirman (1980) whenever there is no TMPA and the stock is fully mixed across jurisdictions.

Now we turn to examine corners solutions. First, note that e_{it} is decreasing in the size of the TMPA and country $-i$'s jurisdiction. This relationship implies that as the available fishing grounds decrease in country i, its optimal extraction strategy is to fish monotonically more aggressively. At some level then, escapement in country i's fishing grounds is effectively zero.

If one country's optimal dynamic non-cooperative escapement is zero, then second country's strategy must take that limitation into account. Using the same process above, it is straight forward to show that country i's optimal escapement, when country $-i$ is at a corner, is given by:

$$e_{it} = X_t \left(\alpha\beta_i\gamma_i(\lambda_i) - (1-\alpha\beta_i)(\lambda_i + \lambda_{-i})\right) \tag{30}$$

Optimal dynamic non-cooperative escapement in country i can be then fully characterized by:

$$\bar{e}_{it} = X_t\, \bar{f}_i(\bullet) \tag{31}$$

with

$$\bar{f}_i(\bullet) = \begin{cases} \max\left\{0, \frac{\alpha\beta_i\gamma_i(\lambda_i) - \alpha\beta_{-i}(1-\alpha\beta_i)(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{1-(1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \bar{f}_{-i}(\bullet) > 0 \\ \\ \max\left\{0, \alpha\beta_i\gamma_i(\lambda_i) - (1-\alpha\beta_i)(\lambda_i + \lambda_{-i})\right\} & ; \quad \bar{f}_{-i}(\bullet) = 0 \end{cases} \tag{32}$$

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5.1.2 Proof of Proposition 2

Under a cooperative scenario, both countries seek to maximize total joint discounted benefit as function of the harvest in each jurisdiction. Consider a fishery that lasts only two periods, $T-1$ and T, respectively. There is no value in fishing after period T, so each country will harvest all the stock in their jurisdictions, $e_{iT} = 0$. The benefit of this harvest is given by:

$$V_{iT}(X_T) = \log[h_{iT}] = \log[x_{iT}] \tag{33}$$

For period $T-1$, both countries choose their harvest level in order to maximize the following dynamic programming equation for periods T and $T-1$:

$$\begin{aligned} V_{iT-1}(X_{T-1}) = \; & \max_{e_{iT-1}} \Big\{ \log[x_{iT-1} - e_{iT-1}] + \beta_i V_{iT}(X_T) \\ & + \log[x_{-iT-1} - e_{-iT-1}] + \beta_{-i} V_T^{-i}(X_T) \Big\} \end{aligned} \tag{34}$$

Substituting (33) into (34):

$$\begin{aligned} V_{iT-1}(X_{T-1}) = \; & \max_{e_{iT-1}} \Big\{ \log[x_{iT-1} - e_{iT-1}] + \beta_i \log[x_{iT}] \\ & + \log[x_{-iT-1} - e_{-iT-1}] + \beta_{-i} \log[x_{-iT}] \Big\} \end{aligned} \tag{35}$$

Inserting the biology gives:

$$\begin{aligned} V_{iT-1}(X_{T-1}) = \; & \max_{e_{iT-1}} \Bigg\{ \log[x_{iT-1} - e_{iT-1}] \\ & + \beta_i \log\left[\gamma_i(\lambda_i)(e_{iT-1} + e_{-iT-1} + m_{T-1})^{\alpha}\right] \\ & + \log[x_{-iT-1} - e_{-iT-1}] \\ & + \beta_{-i} \log\left[\gamma_{-i}(\lambda_{-i})(e_{iT-1} + e_{-iT-1} + m_{T-1})^{\alpha}\right] \Bigg\} \end{aligned} \tag{36}$$

Where the first order condition for country i is given by the following expression:

$$e_{iT-1} = \frac{\alpha(\beta_i + \beta_{-i}) x_{iT-1} - e_{-iT-1} - m_{T-1}}{\alpha(\beta_i + \beta_{-i}) + 1} \tag{37}$$

As both countries solve equation (37), the cooperative escapement level that each country applies in its jurisdiction is given by:

$$e_{iT-1} = \frac{\left(\alpha(\beta_i + \beta_{-i}) + 1\right) x_{iT-1} - x_{-iT-1} - m_{T-1}}{\alpha(\beta_i + \beta_{-i}) + 2} \tag{38}$$

Given that the distribution of the stock is determined by $\gamma_i(\lambda_i)$, let $X_{T-1} = (e_{iT-2} + e_{-iT-2} + m_{T-2})^{\alpha}$ and $x_{iT-1} = \gamma_i(\lambda_i) X_{T-1}$. Hence, the final expression for escapement can be re-written as:

$$e_{iT-1} = X_{T-1} \frac{(\alpha(\beta_i + \beta_{-i}) + 1)\gamma_i(\lambda_i) - (\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\alpha(\beta_i + \beta_{-i}) + 2} \tag{39}$$

The joint benefit both countries perceive from this strategy is then given by:

$$\begin{aligned} V_{iT-1}(X_{T-1}) &= \log\left[x_{iT-1} - e_{iT-1}\right] + \beta_i \log\left[\gamma_i(\lambda_i)(X_T)^{\alpha}\right] \\ &\quad + \log\left[x_{-iT-1} - x_{-iT-1}\right] + \beta_{-i} \log\left[\gamma_{-i}(\lambda_{-i})(X_T)^{\alpha}\right] \end{aligned} \tag{40}$$

Substituting equation (39) into (40), and rearranging terms we get that the maximum benefit for the two period cooperative fishery can be expressed as:

$$\begin{aligned} V(X_{T-1}) &= (\alpha\beta_i + 1)\log[X_{T-1}] + C_i' \\ &\quad + (\alpha\beta_{-i} + 1)\log[X_{T-1}] + C_{-i}' \end{aligned} \tag{41}$$

$$C_i' = \log\left[\frac{\gamma_i(\lambda_i)^{\alpha\beta_i}(\gamma_i(\lambda_i) + \gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\alpha(\beta_i + \beta_{-i}) + 2}\right] \tag{42}$$

Working backwards in time, both countries face the following maximization problem:

$$\begin{aligned} V_{iT-2}(X_{T-2}) = \quad & \max_{e_{iT-1}} \Big\{ \log[x_{iT-2} - e_{iT-2}] \\ & +\beta_i \left((\alpha\beta_i + 1)\log[X_{T-1}] + C_i'\right) \\ & + \log[x_{-iT-2} - e_{-iT-2}] \\ & +\beta_{-i}((\alpha\beta_{-i} + 1)\log[X_{T-1}] + C_{-i}')\Big\} \end{aligned} \tag{43}$$

Recall that $X_{T-1} = (e_{iT-2} + e_{-iT-2})^{\alpha}$. Hence, the first order conditions for the escapement level of country i at time $T-2$ are given by:

$$e_{iT-2} = \frac{\left(\alpha(\beta_i + \beta_{-i}) + \alpha^2(\beta_i^2 + \beta_{-i}^2)\right)x_{iT-2} - (e_{-iT-2} + m_{T-2})}{\left(\alpha(\beta_i + \beta_{-i}) + \alpha^2(\beta_i^2 + \beta_{-i}^2)\right) + 1} \tag{44}$$

By solving this problem simultaneously and using our previous definitions, each country under the cooperative scheme will set its optimal escapement as:

$$e_{iT-2} = \frac{\left(\left(\alpha(\beta_i+\beta_{-i})+\alpha^2(\beta_i^2+\beta_{-i}^2)\right)+1\right)x_{iT-2}-(x_{-iT-2}+m_{T-2})}{\left(\alpha(\beta_i+\beta_{-i})+\alpha^2(\beta_i^2+\beta_{-i}^2)\right)+2} \tag{45}$$

From this expression, it is clear that when the fishery lasts $n+1$ periods, the optimal escapement response under the cooperative scenario is given by:

$$e_{iT-n} = X_{T-n} \frac{\left(\left(\frac{\alpha\beta_i - (\alpha\beta_i)^{n+1}}{1-\alpha\beta_i}\right) + \left(\frac{\alpha\beta_{-i} - (\alpha\beta_{-i})^{n+1}}{1-\alpha\beta_{-i}}\right) + 1\right)\gamma_i(\lambda_i) - (\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\left(\frac{1-(\alpha\beta_i)^{n+1}}{1-\alpha\beta_i}\right) + \left(\frac{1-(\alpha\beta_{-i})^{n+1}}{1-\alpha\beta_{-i}}\right)} \tag{46}$$

As the fishery extends over time, let $X_t = X_{T-n}$ to represent the fish stock at the time when each country decides its harvest policy taking into consideration that the fishery will last for $n+1$ periods. As n goes to infinity we get that the optimal escapement under the cooperative scenario is:

$$e_{it} = X_t \frac{\Delta\gamma_i(\lambda_i) - (1-\alpha\beta_i)(1-\alpha\beta_{-i})(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + 2(1-\alpha\beta_i)(1-\alpha\beta_{-i})} \tag{47}$$

with

$$\Delta = \alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + (1-\alpha\beta_i)(1-\alpha\beta_{-i}) \tag{48}$$

Analogous to the non-cooperative solution, the optimal dynamic cooperative extracts a constant fraction of the stock over time. Finally, it also necessary to take into account bi-lateral corner solutions. Following the same procedure, it is straight forward to show that the full characterization of optimal dynamic escapement is then given by:

$$\hat{e}_{it} = X_t \, \hat{f}_i(\lambda_i, \lambda_{-i}) \tag{49}$$

with

$$\hat{f}_i(\bullet) = \begin{cases} \max\left\{0, \frac{\Delta\gamma_i(\lambda_i) - (1-\alpha\beta_i)(1-\alpha\beta_{-i})(\gamma_{-i}(\lambda_{-i}) + \lambda_i + \lambda_{-i})}{\alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + 2(1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \hat{f}_{-i}(\bullet) > 0 \\ \\ \max\left\{0, \frac{\Lambda\gamma_i(\lambda_i) - (1-\alpha\beta_i)(1-\alpha\beta_{-i})(\lambda_i + \lambda_{-i})}{\alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) + (1-\alpha\beta_i)(1-\alpha\beta_{-i})}\right\} & ; \quad \hat{f}_{-i}(\bullet) = 0 \end{cases} \tag{50}$$

with

$$\Lambda = \alpha\beta_i(1-\alpha\beta_{-i}) + \alpha\beta_{-i}(1-\alpha\beta_i) \tag{51}$$

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5.2 Matching Cooperative Escapement with Highly Asymmetric Distributions

In the case of highly asymmetric distributions, the results in the main body of the paper are slightly modified. In particular, that the common level of protection matching CE escapement is insensitive to the stock's distribution. Recall that the main results suggest that one percentage of common protection was able to match the CE for all of the distribution combinations evaluated, $0.3 \leq \gamma_i(0) \leq 0.7$. In Figure (4) we expand that range and show this condition stops holding.

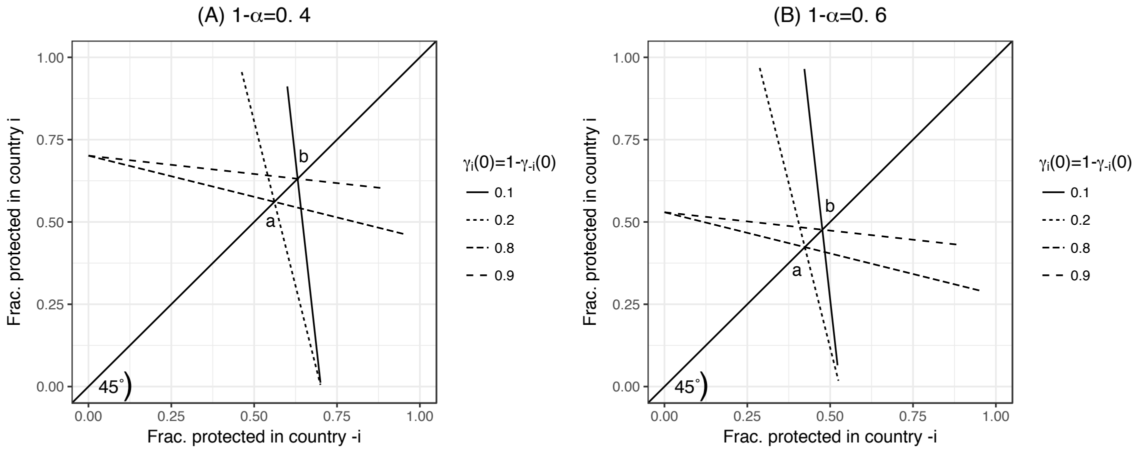

Figure 4: **Combinations of TMPAs in countries i and $-i$ that reproduce the total escapement of the first-best under no cooperation varying the growth rate for highly asymmetric distributions**. Fractions protected in both countries are plotted for different distributions of the stock across jurisdictions, $\gamma_i(0)$, and across two different growth rates, $1-\alpha$. Panel A assumes $1-\alpha = 0.5$, while panel B assumes $1-\alpha = 0.5$. Both plots assume $\beta_i(0) = \beta_{-i}(0) = 0.5$.

The figure plots the combinations of fractions protected in country i and country $-i$ that replicate the total escapement level of the CE in the case of highly asymmetric distributions. Consider panel A, in which the stock grows at rate 0.4. If 80 percent of the fishing grounds are in one country's jurisdiction, then both of them will have to protect 55 percent to achieve the same escapement as the CE (Panel A - point a). If the same country were to have 90 percent of the fishing grounds instead, the required common protection increases to 63 percent.

Changes in the growth rate shift this relationship. Panel B of Figure (4) shows how increasing the growth rate from 0.4 to 0.6 reduces the required common protection to achieve the the cooperative escapement. Note that the slopes of the relationship do not change, they only shift along the x-axis.

Highly asymmetric distributions change the combinations that achieve the CE because the first-best considers harvest in both countries. When the distribution of the stock forces one country into a corner, even if it behaves cooperatively, the first-best takes into account that limitation and makes the unconstrained country to behave even more conservatively. Recall that a marginal increase in harvest for the country fishing less has a greater marginal contribution to the total value of the fishery, so the losses are optimally compensated across the two nations. Designing a TMPA that replicates that outcome has to follow the same principle. In other words, the TMPA has more of the country with the larger share, hence the steep - flat slopes in potential combinations, or by protecting a larger common percentage in both countries. Slope remain consistent because these combinations seek to match escapement with the CE, and because of the uniform distribution assumption, additional units protected in each jurisdiction have the same net effect.