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# Cooperation as a solution to shared resources in territorial use rights in fisheries

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**Abstract.** Territorial use rights in fisheries (TURFs) are coastal territories assigned to fishermen for the exclusive extraction of marine resources. Recent evidence shows that the incentives that arise from these systems can improve fisheries sustainability. Although research on TURFs has increased in recent years, important questions regarding the social and ecological dynamics underlying their success remain largely unanswered. In particular, in order to create new successful TURFs, it is critical to comprehend how fish movement over different distances affects the development of sustainable fishing practices within a TURF. In theory, excessive spillover outside a TURF will generate incentives to overharvest. However, many TURFs have proven successful even when targeted species move over distances far greater than the TURF's size. A common attribute among some of these successful systems is the presence of inter-TURF cooperation arrangements. This raises the question of how different levels and types of cooperation affect the motivations for overharvesting driven by the movement of fish outside the TURF. In this paper, we examine equilibrium yields under different levels of inter-TURF cooperation (from partial to full) and varying degrees of asymmetry across TURFs of both biological capacity and benefit-sharing. We find that partial cooperation can improve yields even with an unequal distribution of shared benefits and asymmetric carrying capacity. However, cooperation arrangements are unstable if the sharing agreement and biological asymmetries are misaligned. Remarkably, we find that asymmetry in the system can lead to the creation of voluntary no-take zones.

*Key words:* bio-economic model; catch shares; game theory; small-scale fisheries; social-ecological systems; spatial management; TURF.

## INTRODUCTION

Human population growth is particularly fast in coastal areas (Neumann et al. 2015). In the absence of effective management schemes, the increased dependency on fish as a global food source and income for local communities is causing coastal ecosystems to deteriorate (Vitousek et al. 1997, Pauly et al. 1998, 2005, Pauly and Zeller 2016). Ultimately, this situation not only affects the coastal environment but also the livelihoods of fishing communities (McClanahan et al. 2015). The development of innovative management tools can offer a solution to these problems. In recent years, catch shares have been widely studied as a solution to problems of overexploitation and inefficiency in fisheries (Grafton 1996, Grafton et al. 2006, Costello et al. 2008,

Griffith 2008, Birkenbach et al. 2017). A particular form of catch shares, called territorial use rights in fisheries (TURFs), has emerged as a very promising tool for the management of coastal fisheries. TURFs provide spatially explicit access rights to resource users, and empirical studies have shown they can provide the right set of conditions to achieve more sustainable and profitable artisanal coastal fisheries (Smith and Panayotou 1984, Uchida and Baba 2008, Costello and Kaffine 2010, Gelcich et al. 2010).

Although TURFs are increasingly used, there is still considerable uncertainty around the design characteristics that promote the best fishery outcomes. Many TURF systems around the world are relatively small in order to restrict the number of users. Although the role of group size in collective action is dependent on the local institutional arrangements (Ostrom 2009), small groups tend to be formed by members with homogenous social characteristics, which facilitates coordination, monitoring, and enforcement (Olson 1965, Agrawal and Goyal 2001, Agrawal 2002, Poteete and Ostrom 2004,

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Cancino 2007, Ostrom 2010). However, this poses a challenge since, in order to be successful, TURFs need to provide clear access rights. Since ocean ecosystems are highly connected systems where fish can escape the TURFs (a process known as spillover) and be captured in neighboring fishing grounds, the exclusivity can be compromised when TURFs are small. Hypothetically, fish spillover can have a great impact on fisher behavior, since expected losses from the TURF can induce a race to fish and drive overfishing (White and Costello 2011, Aceves-Bueno and Halpern 2018). How is the uncontrolled spillover problem solved?

One potential explanation for the unexpected success of small TURFs with high spillover levels is the development of partial cooperation schemes among TURFs. If two TURFs fully coordinate their harvests and share benefits, they can effectively act as a single larger TURF and reduce the incentives to race (Kaffine and Costello 2011). Often, however, cooperation is less than complete. Examples of inter-TURF partial cooperation can be found across a range of TURFs in Japan, Mexico, and Chile, where partial cooperation has emerged as either profit sharing (unitization), joint monitoring and enforcement, or shared marketing of catch. These arrangements entail varying degrees of cooperation, with many involving only partial sharing of the benefits of fishing (Cancino et al. 2007, Uchida and Baba 2008, Kaffine and Costello 2011).

Many of these arrangements are also characterized by biological and benefit-sharing asymmetry. The consequences of benefit-sharing asymmetries have been studied in a variety of cooperative settings (e.g., Osborne and Pitchik 1983, Darrough and Stoughton 1989, Lundberg and Pollak 1996). In TURFs, asymmetries can be expected due to differences in membership, access to markets, access to information, and government support. For example, in the Sakura-Ebi fishery in Japan, a pooling arrangement was set between the Yui Harbor and Ohigawamachi cooperatives. In this pooling arrangement, the income is spread equally among all 60 fishing units of both cooperatives, 42 of which belong to the Yui Harbor cooperative. In spite of this asymmetry in shared benefits distribution, this pooling system has been in place since 1967 and has allowed the Sakura-Ebi fishery to thrive as one of the most profitable in Japan (Uchida and Baba 2008).

Biological asymmetry is also common in coastal systems and leads to differential production capacity among TURFs. Such is the case for the Vigia Chico Cooperative in Punta Allen, Mexico. Fishermen in this cooperative have developed a unique fishing system involving *casitas*, concrete shades where lobsters aggregate in the search for shelter (Cunningham et al. 2013, Méndez-Medina et al. 2015). The carrying capacity of each TURF depends not only on the presence of natural suitable habitat, but also on the capacity of each TURF owner to invest in *casitas* for artificial habitat. Variation in investment has resulted in a system of TURFs with

different carrying capacities. Despite this asymmetry, fishermen in Punta Allen not only maintain sustainable levels of harvest, but have also developed conservation measures, such as the protection of reproductive females (Defeo and Castilla 2006). The reason for this behavior is that all individual TURF owners are part of the Vigia Chico cooperative. That cooperative system involves all of its members in decision making, monitoring, and enforcement. Furthermore, although TURF owners have full autonomy regarding the number of *casitas* and catch sizes inside their fishing areas (Cunningham et al. 2013; C. Méndez-Medina, *personal communication*), they partially cooperate by paying a fee to maintain the cooperative. In return, the cooperative provides infrastructure to process the catch, offers access to market and marketing tools, and absorbs all the costs of monitoring and enforcement (Cunningham et al. 2013).

We seek to better understand when partial cooperation such as that in Punta Allen can arise among TURF owners despite asymmetries in both biology and bargaining power. The interactions between spillover of fish and the level of inter-TURF partial cooperation have previously been analytically explored only along the margins, varying spillover at extreme levels of partial cooperation (full or absent) or changing levels of partial cooperation for a fixed level of spillover (Kaffine and Costello 2011). This approach does not allow the analysis of a wide range of stable partial cooperation scenarios. As a consequence, it limits our ability to fully explore the interconnected dynamics between movement and partial cooperation to develop appropriate guidelines for more effective TURF designs with different target species.

Here we rectify these shortcomings by numerically examining the effects of different partial cooperation levels. By examining coalitions with partial harvest pooling in symmetric and asymmetric scenarios, we are able to discern the magnitude of gains or losses compared to full cooperation. Our approach allows exploring the full interaction between the extents of fish movement and inter-TURF cooperation, to identify design guidelines that will enhance expected yields. We ask, when is cooperation among TURFs the best solution for the spillover problem? How do the gains from cooperation scale with the level of partial cooperation and fish distribution asymmetry? We find that partial cooperation will be beneficial for both TURF owners across a wide range of shared benefits distribution arrangements. However, with strong fish spillover, high levels of partial cooperation are necessary to achieve yields close to maximum sustainable yield (MSY). Interestingly, we find that asymmetrical systems can lead to the creation of voluntary fishery closures.

## METHODS

Based on White and Costello (2011), we use a bio-economic model that consists of two TURFs, each owned

by a group acting as a single agent. In the model, the adult stock density in patch  $i$  at time  $t$  ( $N_i^t$ ) evolves as follows:

$$N_i^{t+1} = (N_i^t + M_i^t)(1 - \delta) + \frac{S_i^t}{1 + \alpha_i S_i^t}.$$

here  $M_i^t$  is net migration into patch  $i$ ,  $\delta$  characterizes the natural annual mortality of adults (calculated as the inverse life span in years),  $S_i^t$  describes the density of settlers, and  $\alpha_i$  is a parameter describing the strength of density dependence. In particular,

$$\alpha_i = \frac{CR - 1}{CR\delta K_i},$$

where CR is the Goodyear compensation ratio. CR was fixed to 4, a value commonly used to represent coastal fish species (White and Costello 2011). A sensitivity analysis of the CR is presented in the supplementary information (Appendix S1: Fig. S1, S2).  $K_i$  is the carrying capacity in patch  $i$ . The carrying capacity is allowed to differ across patches so that we can study the influence of asymmetry (either inherent or influenced by investments, e.g., *casitas* in Punta Allen) on the viability of cooperation.

The production of settlers is determined by the following production function:

$$S_i^t = P_i(N_i^t + M_i^t),$$

where  $P_i$  is the per-capita larval production by adults in patch  $i$ :

$$P_i = \frac{\delta}{1 - \delta\alpha_i K_i}.$$

Adult net migration is a function of a migration parameter  $m$  and the difference in relative density between the two patches:

$$M_i^t = -M_j^t = m(N_i^t + N_j^t) \left( \frac{N_j^t}{K_j} - \frac{N_i^t}{K_i} \right).$$

Note,

$$N_i^{t+1} = N_i^t + M_i^t = (1 - m)N_i^t + m(N_i^t + N_j^t) \left[ \frac{N_j^t}{N_i^t + N_j^t} + \left( \frac{N_j^t}{K_j} - \frac{N_i^t}{K_i} \right) \right]$$

so that  $m$  can be thought of as the fraction of fish from both patches that swim around, with the fraction of swimmers that end up in  $i$  determined by the term in square brackets. Harvest occurs after adult movement and larval settlement. The harvest function in steady state conditions is represented by

$$Y_i^* = M_i^* + \frac{S_i^*}{1 + \alpha_i S_i^*} - \delta(N_i^* + M_i^*).$$

Each patch is managed by a single agent that selects the escapement level ( $N_i^*$ ) to maximize a yield-based objective. The agents choose harvest independently and simultaneously, taking the other owner's decision as

given; we therefore examine what choices the patch owners make in a Nash equilibrium.

To study inter-TURF partial cooperation in the model, we allow the objective that each owner maximizes to depend partly on yields in the other patch. Partial cooperation allows a more general approach that includes the fully cooperative and noncooperative scenarios, but it is able to also incorporate intermediate cooperation scenarios. For partial cooperation, the benefits of one patch depend on a portion of the harvest of the second patch (Kopel and Szidarovszky 2006). Patch owners still choose  $Y$  independently and simultaneously to maximize their own benefits, but their benefits are now determined by the sharing arrangement. In order to cooperate, both patches provide a portion of their catch to a common pool  $C$ :

$$C = \theta(Y_i + Y_j)$$

where  $\theta \in [0, 1]$  is a parameter determining the strength of partial cooperation. Setting  $\theta$  to zero represents no cooperation, and a value of one represents full cooperation. The distribution of shared benefits (dividend) for each patch from the pooled catch depends on the parameter  $\beta$  and is defined as

$$D_i = \beta C.$$

$$D_j = (1 - \beta)C.$$

With this setup, the benefits under partial cooperation for the patch owners are:

$$Y_{C_i} = (1 - \theta)Y_i + \beta C = (1 - (1 - \beta)\theta)Y_i + \beta\theta Y_j,$$

$$Y_{C_j} = (1 - \theta)Y_j + (1 - \beta)C = (1 - \beta\theta)Y_j + (1 - \beta)\theta Y_i.$$

In other words, each owner maximizes a weighted average of the yields in the two patches, with weights determined by  $\beta$  and  $\theta$ .

To consider whether a particular cooperative arrangement (choice of  $\beta$  and  $\theta$ ) is stable, we compare each patch owner's benefits to those she would receive if  $\theta = 0$ : the fully noncooperative outcome. If both patches earn higher benefits when cooperating than not, we consider partial cooperation to be stable (D'Aspremont et al. 1983). For much of our analysis, we treat  $\beta$  and  $\theta$  as fixed parameters, as if TURF owners were handed an agreement they could choose to sign or not. This helps retain focus on the potential for partial cooperation. In Appendix S1, we briefly consider how TURF owners might arrive at a specific choice of  $\beta$  and  $\theta$  through negotiation.

After studying this model in a general setting, we use it to analyze the spiny lobster (*Panulirus argus*) cooperative in Punta Allen (Fig. 1). The parameters used for this case study are presented in Table 1. The fishing grounds in that cooperative vary in size, with an average along-shore length of 1.4 km. The differences in area and in the presence of natural and artificial suitable area for lobster create asymmetry in the distribution of resources

among owners. In addition, the owners engage in partial cooperation, fishing separately but putting a portion of proceeds toward comarketing and other joint activities. Thus, this case study provides a rich opportunity for the application of our spatially asymmetric model of partial cooperation.

We calculate the movement of lobsters between patches ( $m$ ) based on the spiny lobster's home range relative to the average TURF size, according to the model of Kramer and Chapman (1999). For this case study, we use the average TURF length (1.4 km) and set the home range to 4 km, which is the largest movement performed by a lobster before their movement is considered nomadic (Bertelsen 2013). For consistency with previous application of similar models (White and Costello 2011, Aceves-Bueno et al. 2017), we use the inverse life span in years (Maxwell et al. 2007) as a measure of the species natural mortality.

## RESULTS

Our models show that partial cooperation can lessen the negative effects of fish spillover across TURFs on yields over wide ranges of fish mobility and degrees of cooperation.

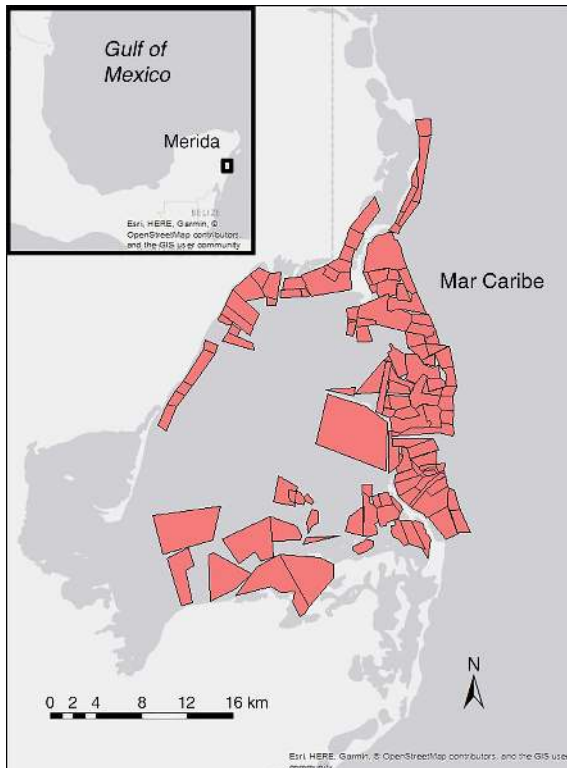


FIG. 1. Individual territorial use rights in fisheries (TURFs) of the Vigia Chico Cooperative in Punta Allen, Mexico. Adapted from a map provided by Comunidad y Biodiversidad A.C (COBI).

TABLE 1. Parameters used for the analysis of the Vigia Chico Cooperative territorial use rights in fisheries (TURFs).

Parameter	Value	Source
Mean along shore length of the Vigia Chico Cooperative TURFs	1.43 km	map provided by Comunidad y Biodiversidad (COBI)
Spiny lobster ( <i>Panulirus argus</i> ) adult home range	4 km	Bertelsen (2013)
Spiny lobster ( <i>Panulirus argus</i> ) life span	20 yr	Maxwell et al. (2007)

Fig. 2 shows the overall yields of both patches resulting from all possible combinations of cooperation levels ( $\theta$ ) and different shared benefits distribution arrangements represented by the fraction of benefits assigned to patch  $i$  ( $\beta$ ). Intuitively, overall yields rise to maximum sustainable yield at full cooperation (Fig. 2).

Fig. 3 illustrates the benefits under partial cooperation to patches  $i$  and  $j$  under a range of scenarios, varying (1) the degree of fish movement between patches (lines per plot), (2) distribution of shared benefits (left to right), and (3) asymmetry in patch productivity (top vs. bottom). All benefits are shown relative to those received if the patch owners do not cooperate ( $\theta = 0$ ), shown by the gray horizontal line at 1, allowing identification of scenarios that lead to better (or worse) outcomes than full noncooperation. In general, the net benefits for both patches are higher for more mobile targeted species. In perfectly symmetric scenarios (Fig. 3E), both patches are equally benefited by cooperation. As both patches receive more under partial cooperation than noncooperation (benefits lie above the noncooperative line at 1), TURF owners could plausibly agree on partial cooperation across a range of  $\theta$  choices.

The prospects for partial cooperation in asymmetric systems (Fig. 3A–F) are more complex. Some patterns are intuitive: a patch owner benefits more from cooperation when she receives a greater share of pooled yields (left vs. center or right panels) and when the other patch is more biologically productive (top vs. bottom panels). Similarly, net benefits from cooperation remain positive under many combinations of asymmetry in biology and benefit sharing (Fig. 3A, B, D). However, if a TURF owner receives a small share of pooled benefits relative to the carrying capacity of her patch (Fig. 3C, F), partial cooperation may no longer be beneficial to her. In those cases, increases in the degree of profit-sharing  $\theta$  also may not lead to greater net benefits from cooperation. As a result, partial cooperation could not be stable if asymmetries in the biology and the sharing rules are sufficiently misaligned. In Appendix S1, we also examine a different role of asymmetry, studying how aversion to inequity may affect the behavior of TURF owners.



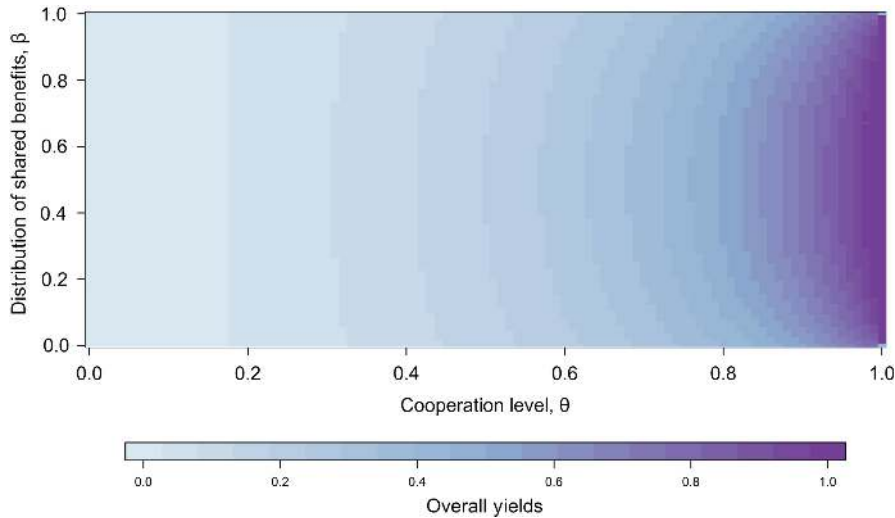


FIG. 2. Overall benefits for both patches under varying combinations of partial cooperation level ( $\theta$ ) and shared benefits distribution ( $\beta$ ) in a symmetric biological scenario (carrying capacity in patch  $i$ ,  $K_i = 0.5$ ), relative to yields under full noncooperation. Colors (blue to purple) indicate the increase in overall yields in the entire TURF system. Movement capacity ( $m$ ) is held constant at 0.5.

Figs. 4 and 5 examine the viability of partial cooperation in more detail, using movement parameters for the Punta Allen Spiny lobster TURFs. Fig. 4 illustrates the range of scenarios in which partial cooperation is stable, doing so in two steps. Each panel in the top row depicts the benefits for patch  $i$  relative to benefits without cooperation (the 1 isoquant) under different cooperation levels ( $\theta$ ) and different shared benefits arrangements ( $\beta$ ). The space under which patch  $i$  will prefer an agreement to noncooperation corresponds to the area where the net benefits from partial cooperation are positive (benefits are above the 1 isoquant). Intuitively, patch owner  $i$  is more likely to cooperate when receiving a higher share of pooled benefits. The different panels depict these incentives across a range of carrying capacities, suggesting patch  $i$  may find cooperation to be beneficial even when the distribution of shared benefits is highly unfavorable. The bottom row of plots in Fig. 4 takes this a step further, highlighting the regions of the parameter space in which *both* patch owners will find cooperation to be beneficial (light gray). Cooperation is stable across a range of scenarios, including many in which both biology and sharing rules are highly asymmetric.

To understand how cooperation might be operationalized in these settings, Fig. 5 shows the individual harvests of both patches under asymmetries in both benefit distribution and carrying capacity. In cases with either type of asymmetry, equilibrium harvests differ across patches. More interestingly, in many scenarios, the patch owner receiving a disproportionately high share of the pooled yields compared to her carrying capacity will stop harvesting entirely. Thus, partial cooperation may lead to voluntary conservation measures, including

closed areas. As with a marine protected area, the overall impact of these voluntary spatial closures depends on the redistribution of effort outside of the closed area.

In summary, our results show that (1) yields increase at higher levels of cooperation, (2) high levels of partial cooperation are necessary to observe substantial increases in yields, (3) partial cooperation can be advantageous to both patches even with an unequal distribution of shared benefits and asymmetric carrying capacity (particularly for highly mobile fish), (4) an uneven distribution of shared benefits can cause a reduction of the negotiation space, (5) cooperation arrangements are unstable if the sharing agreement and biological asymmetries are misaligned, and (6) asymmetry in the system can lead to the creation of voluntary no-take zones.

## DISCUSSION

As intuition would suggest, higher levels of partial cooperation lead to higher overall yields in the system. The gains from partial cooperation arise because stronger cooperation reduces the incentives for fishermen to overharvest (Levhari and Mirman 1980, Plourde 1989, Kopel and Szidarovszky 2006).

Perhaps surprisingly, the effect of partial cooperation on yields is minor until cooperation levels are quite high (Fig. 2). Strong improvements in yields require nearly full cooperation. This is a result of the strong competition for resources present with low levels of cooperation. When TURF owners pool only a small fraction of their catch, a large proportion of each owner's benefits comes from catch in her own patch, so the incentives to overharvest continue to dominate and the results do not differ greatly from the noncooperative case. A similar result

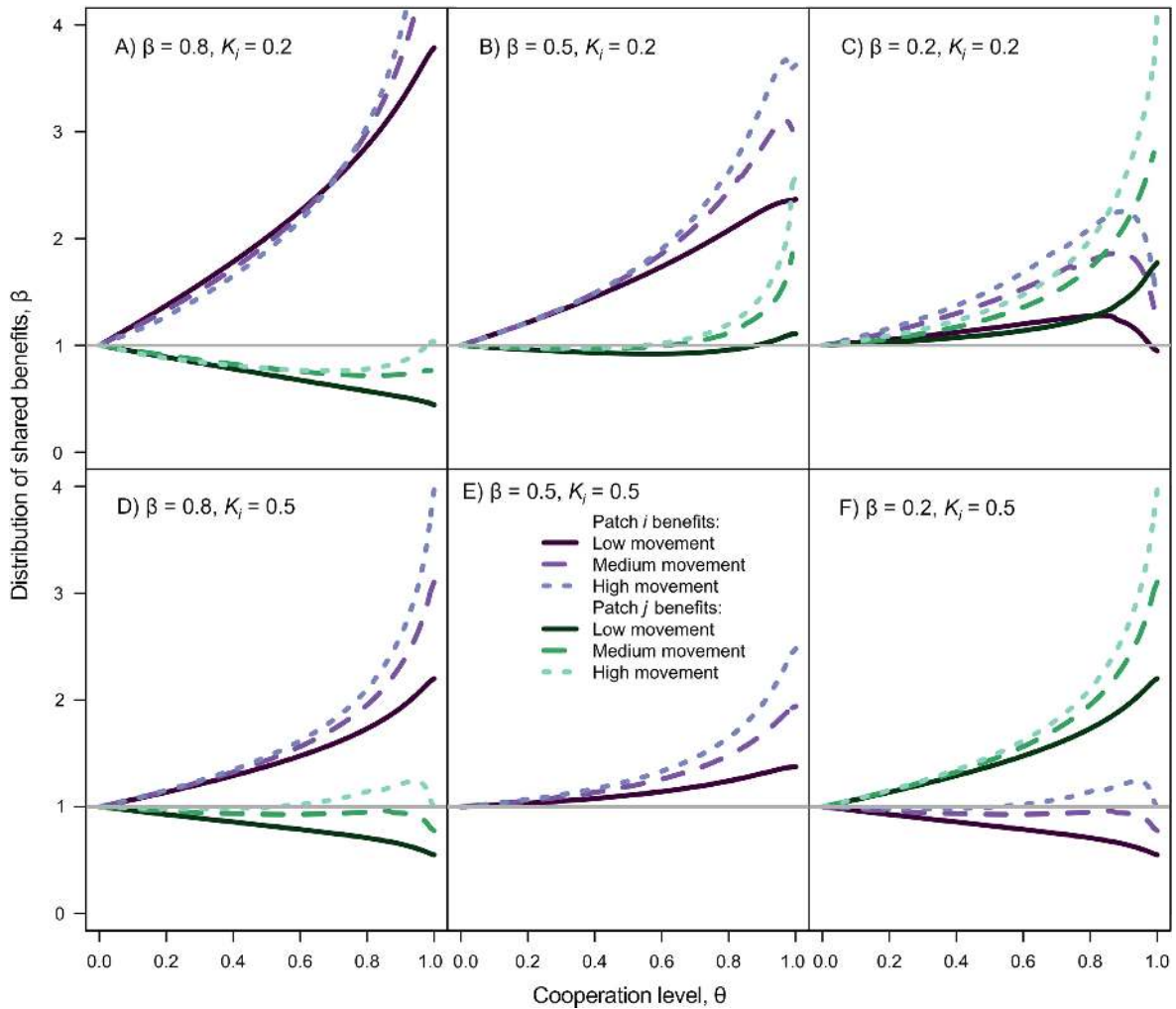


FIG. 3. Effect of fish mobility on patches *i* and *j* benefits under different asymmetry scenarios. Each panel (A–F) represents a scenario with a particular carrying capacity (*K*) and benefits distribution arrangement ( $\beta$ ). Carrying capacity and shared benefits distribution for patches *i* and *j* are set as complementary values (e.g.,  $K_i = 0.2, K_j = 0.8$ ).

has also been found in three-party coalition games, where the lack of cooperation by even one agent greatly diminishes the gains from cooperating in the system (Ishimura et al. 2013).

We find the distribution of shared benefits does not have to be equal ( $\beta = 0.5$ ) to develop stable, mutually beneficial cooperative arrangements, particularly for highly mobile species (Fig. 3); movement intensifies the dependency of one TURF on the other. Fig. 4 illustrates the range of conditions under which both players gain from cooperation (light gray), the “negotiation space.” In other conditions (white space), at least one of the two players is better off not cooperating. We find the negotiation space to be quite large for simulations modeled after the Punta Allen lobster TURFs. Which combination of  $\beta$  and  $\theta$  the TURF owners would choose within that negotiation space is not the focus of our analysis; we aim only to demonstrate the potential for partial cooperation. However, in Appendix S1 we discuss

candidate mechanisms by which owners might arrive at a specific set of agreement parameters.

The relationship between the size of the negotiation space and the degree of yield pooling reflects the two potentially counteracting effects of cooperation. Increased cooperation raises overall yields by reducing overharvesting, but it also increases the fraction of each patch owner’s benefits that depends upon the distribution of shared benefits parameter  $\beta$ . For small  $\theta$ , the first effect dominates the negotiation space increases with the level of cooperation and overall yields increase. With a larger overall harvest to share, players are willing to tolerate more asymmetry in how pooled yields are distributed. However, at high levels of  $\theta$ , the negotiation region ultimately shrinks again (Figs. 4, 5). At those high levels of partial cooperation, the shared benefits distribution parameter  $\beta$  affects nearly all harvest caught by both players, and the benefits for the patch owner with low allocation eventually drop below those under

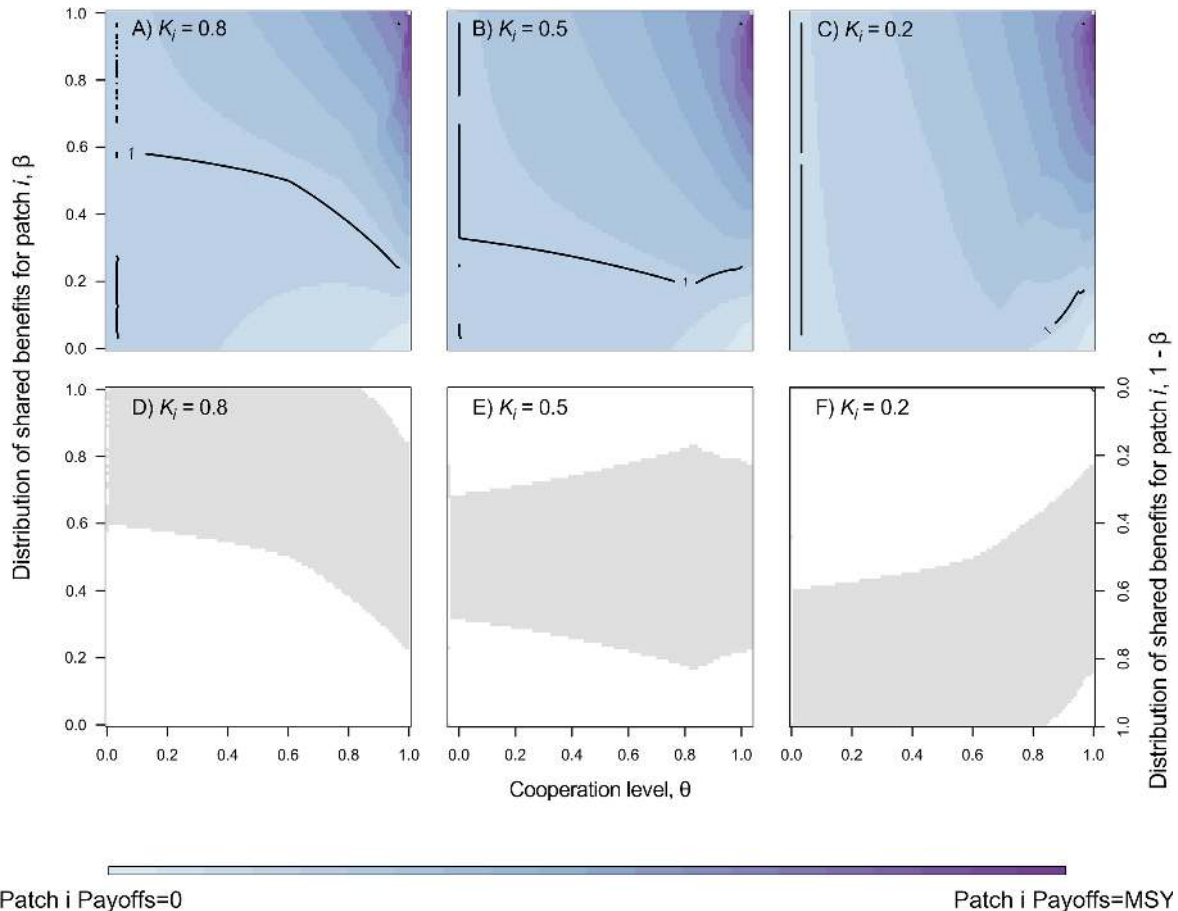


FIG. 4. Benefits with varying distribution of shared benefits and partial cooperation levels. The top row (A–C) shows benefits for patch  $i$  (low benefits, blue; high benefits, purple). The black line (1 isocline) represents the benefits obtained by patch  $i$  under full noncooperation ( $\theta = 0$ ); values below this line represent outputs less favorable than noncooperation for patch  $i$ . In the bottom row (D–F), light gray areas represent the negotiation region, in which both players are better off under cooperation at the specified values of  $\theta$  and  $\beta$ . Movement capacity ( $m$ ) is held constant at 0.5.

noncooperation. As a result, high levels of cooperation provide no additional benefits to the losing patch, reducing the overall negotiation space.

Examining the individual harvests of each patch under partial cooperation illuminates how such an agreement falling within the negotiation space might work. Fig. 5 shows the patch-level harvests ( $Y_i^*$ ,  $Y_j^*$ ) as a multiple of noncooperative Nash equilibrium harvests ( $\theta = 0$ ) under different shared benefits distribution arrangements ( $\beta$ ) and cooperation levels ( $\theta$ ). When the distribution of shared benefits puts patch owners on roughly equal footing by rectifying differences in (or reflecting equality of) carrying capacity, the owners harvest at similar multiples of the noncooperative levels (Fig. 5, panels A and E). The rest of the panels show the dramatic effect of asymmetry (Fig. 5, panels B, C, D, F). Interestingly, in all these cases, the patch owner who gains more from cooperation than the other, the “winner”, will reduce her harvests or stop fishing entirely, creating an artificial no-take zone.

These voluntary no-take zones arise due to productivity gains from increasing the density gradient between patches. A large difference in adult density across patches, such as that created when one patch is closed and the other heavily fished, increases adult movement. This has an important impact on yields due to the concave form of the recruitment function  $S$  for  $S > 0$ : shifting adults from the denser to the less dense patch can increase overall recruitment. Thus, closing one patch creates a sink–source dynamic that favors the overall productivity of the system. Provided that a sufficient fraction of the benefits from this boosted recruitment ultimately return to the owner closing her patch, that owner will gain from such an arrangement. Similar results have been found in previous spatially explicit, non-game-theoretic bio-economic models, in which closures are economically beneficial with “increases in dispersal rate” when the closed area is acting as the source (Sanchirico et al. 2006). However, these results erode in systems where recruitment is less dependent on local



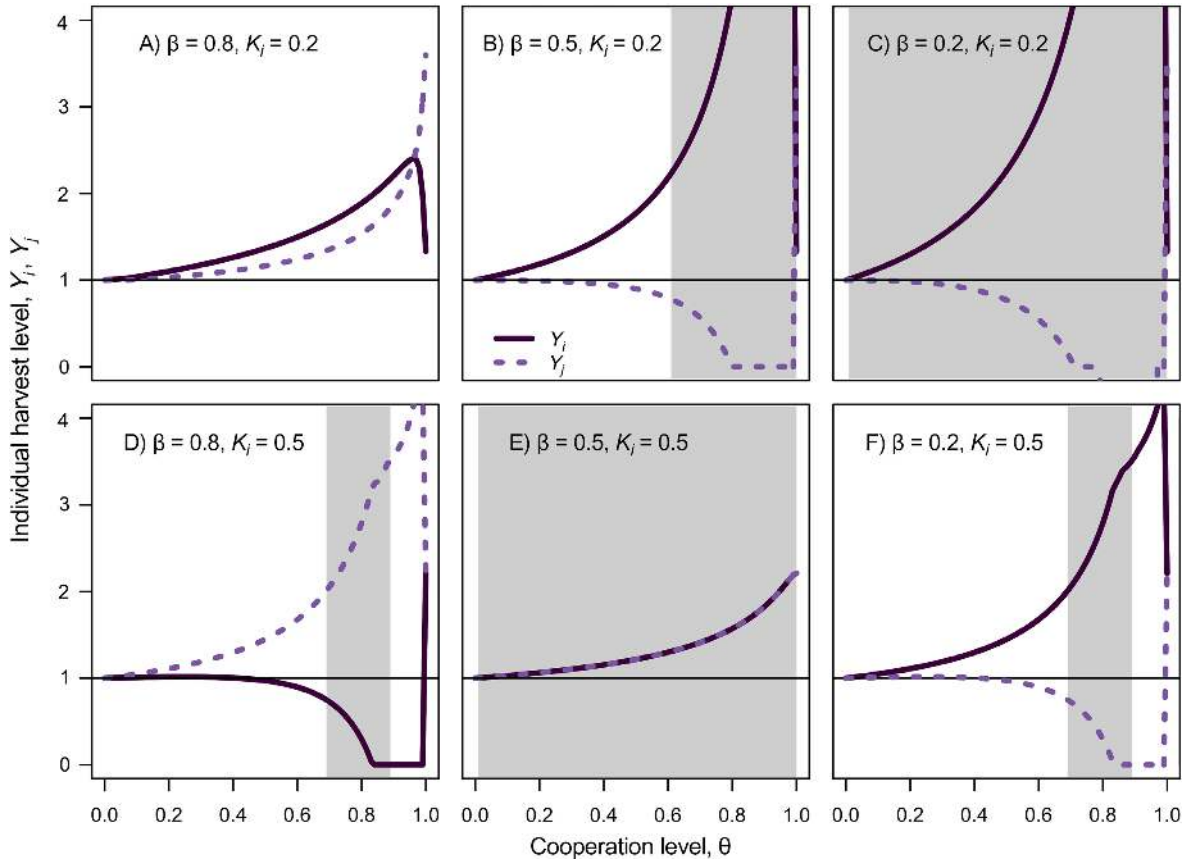


FIG. 5. Individual harvests of each patch ( $Y_i^*, Y_j^*$ ) relative to noncooperative harvest levels under different scenarios of benefits distribution ( $\beta$ ), partial cooperation ( $\theta$ ), and asymmetric carrying capacity ( $K_i$  vs.  $K_j$ ). Each panel (A–F) represents a scenario with a particular carrying capacity ( $K$ ) and benefits distribution arrangement ( $\beta$ ). Movement capacity ( $m$ ) is held constant at 0.5.

adult density, since harvest choices have little effect on the density of settlers. In such case, only high cooperation scenarios lead to voluntary closures (Appendix S1).

The plausibility of these closures, or other highly asymmetric harvesting arrangements, deserves further exploration. If TURF owners maximize profits, convex costs or downward-sloping demand are likely to make such highly asymmetric arrangements less attractive. However, observed effort levels in TURFs systems are relatively low (as evidenced by the fishermen’s reliance on other livelihood alternatives) and cost functions tend to be fairly flat (Uchida and Baba 2008, Wilen et al. 2012, Headley et al. 2017). Additionally, neighboring cooperatives may coordinate fishing activities and share costs (e.g., the Sakura Ebi fishery; see Uchida and Baba 2008). Thus even if one TURF is voluntarily closed, members of that community could be employed as fishers in the other patch, rendering overall costs less convex. If prices are also roughly constant (e.g., TURFs sell into national or export markets), then net price is approximately fixed and our model’s predictions of voluntary TURF closures are plausible. Still, further research under a wider range of cost and market demand

assumptions could refine predictions about if and when voluntary closures might arise.

Taken together, these results provide intuition about when and how partial cooperation might arise among TURF owners. Although previous analytical studies typically focus on full rather than partial cooperation for efficiency reasons (e.g., Kaffine and Costello 2011), partial cooperation is both prevalent and worthy of study for many reasons. While first-best solutions are desirable, they may not be feasible due to practical constraints. Partial cooperation can be a more feasible solution if information about catch levels is poor, enforcement capacity is limited, or if the level of trust among users is low. Furthermore, although higher equilibrium yields are found at perfect cooperation levels, higher fishing effort (employment) under partial cooperation can be desirable in systems where job security is a priority (Cheung and Sumaila 2008, Péreau et al. 2012). Lastly, partial cooperation can reduce social conflicts in heterogeneous social landscapes, where the most efficient boats can be negatively affected by sharing with less skillful fishers (Deacon et al. 2010, Deacon 2012).

All these advantages illuminate why partial cooperation systems have emerged in several settings. A good example in Mexico is the fishing federations to which many Mexican TURFs systems belong. Fishing cooperatives, such as the members of the FEDECOOP, dedicate a portion of their profits to the federation, which, in return, secures government support and facilitates access to markets (Kaffine and Costello 2011, McCay et al. 2014, McCay 2017). These arrangements are also often successful: the complex partial cooperation arrangement in the Vigía Chico cooperative in Punta Allen has helped this fishery become a reference in artisanal fisheries sustainability literature and one of the few MSC certified artisanal fisheries (Cunningham et al. 2013). Members share profits through the payment of approximately MX\$25,000 in seasonal quota (Suverza 2008), which corresponds to the profits of more than four fishing trips (~32% of a median of 12.5 trips) considering variable (Headley et al. 2017) and fixed costs (Pérez 2004). Since 1982, the Pescadores de Vigía Chico has been the most productive fishing cooperative in the Mexican Caribbean. This fishery has been able to maintain stable catches and effort through strong collective action that allowed the creation of effort control and conservation measures, such as the prohibition of scuba and hookah (Sosa-Cordero et al. 2008).

The success and stability of the Vigía Chico cooperative echoes our model's main findings: partial cooperation can be stable across a range of sharing arrangements. More subtly, we document how the benefits and stability of partial cooperation depend on the life history characteristics of the species, the level of cooperation, and alignment of asymmetries in both biology and sharing arrangements.

These results provide a new perspective on characteristics that determine the success of TURF systems. In the past, partial cooperation schemes have emerged, but typically only after the fishery collapsed in the first place. This paper provides guidance on when the degree of resource interdependency across TURFs is large enough (fish movement capacity is large relative to TURF size) for partial cooperation to be attractive. If so, partial cooperation could help avoid collapse rather than being a response to it.

Although partial cooperation is present in some of the most successful TURF systems, prior work offers little guidance on when such agreements might arise. Our study sheds light on how partial cooperation affects the operation of spatially explicit access rights for interconnected coastal resources. In particular, our model explores how partial cooperation can mitigate inefficiencies resulting from fish spillover under different biological and distributional inequities. Furthermore, through an analysis of the Punta Allen lobster fishery, we add to the understanding of successful instances of partial cooperation. Together, these results can inform the implementation of future TURF systems.

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