## Title

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# Design trade-offs in rights-based management of small-scale fisheries

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**Abstract:** *Small-scale fisheries collectively have a large ecological footprint and are key sources of food security, especially in developing countries. Many of the data-intensive approaches to fishery management are infeasible in these fisheries, but a strategy that has emerged to overcome these challenges is the establishment of territorial user rights for fisheries (TURFs). In this approach, exclusive fishing zones are established for groups of stakeholders, which eliminates the race to fish with other groups. A key challenge, however, is setting the size of TURFs—too large and the number of stakeholders sharing them impedes collective action, and too small and the movement of target fish species in and out of the TURFs effectively removes the community's exclusive access. We assessed the size of 137 TURFs from across the globe relative to this design challenge by applying theoretical models that predict their performance. We estimated that roughly two-thirds of these TURFs were sized ideally to overcome the challenges posed by resource movement and fisher group size. However, for most of the remaining TURFs, all possible sizes were either too small to overcome the resource-movement challenge or too large to overcome the collective action challenge. Our results suggest these fisheries, which target mobile species in densely populated regions, may need additional interventions to be successful.*

**Keywords:** collective action, fish mobility, socioecological systems, territorial use rights for fisheries, TURFs

Diseño de Compensaciones en la Administración Basada en Derechos de las Pesquerías de Pequeña Escala

**Resumen:** *Las pesquerías de pequeña escala tienen una gran huella ecológica de manera colectiva y son fuentes importantes de seguridad alimenticia, especialmente en los países en desarrollo. Muchas de las estrategias cargadas de datos para la administración de las pesquerías son inviables en este tipo de pesquerías, pero una estrategia que ha emergido para sobrellevar estos retos es el establecimiento de los derechos de uso territorial para las pesquerías (TURFs, en inglés). Como parte de esta estrategia se establecen zonas exclusivas de pesca para los grupos de accionistas, lo que elimina la competencia por la pesca con otros grupos. Sin embargo, un reto importante es el establecimiento del tamaño de los TURFs – si son muy grandes, el número de accionistas que los comparten impide la acción colectiva; si son muy pequeños, el movimiento de las especies diana de peces dentro y fuera de los TURFs le retira efectivamente el acceso exclusivo a la comunidad. Evaluamos el tamaño de 137 TURFs ubicados en todo el mundo en relación con este reto del diseño aplicando modelos teóricos que pronosticaron su desempeño. Estimamos que aproximadamente dos tercios de estos TURFs tenían el tamaño ideal para superar los retos que presentan el movimiento del recurso y el tamaño del grupo pesquero. Sin embargo, para la mayoría de los TURFs restantes todos los tamaños posibles eran o muy pequeños para superar el reto del movimiento del recurso, o muy grandes para sobrellevar el reto de la acción colectiva. Nuestros resultados sugieren que estas pesquerías que se enfocan en especies móviles dentro de regiones pobladas densamente pueden requerir de intervenciones adicionales para ser exitosas.*

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***Article impact statement***: *Many areas allocated to exclusive fishing rights are designed inappropriately; changes are needed for this tool to address overfishing.*
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**Palabras Clave:** acción colectiva, derechos de uso territorial para las pesquerías, movilidad de peces, sistemas socio-ecológicos, TURFs

**摘要:** *小型渔业在整体上有很大的生态意义, 它们是食物保障的重要来源, 尤其是在发展中国家。然而, 渔业管理中的许多数据密集型的方法对小型渔业并不适用, 但是一项为克服这些挑战的策略应运而生, 即渔业领地使用权 (**territorial use rights for fisheries (TURFs)**)。这个方法为利益相关团体建立了专属捕鱼区, 以排除团体之间捕鱼竞争。然而, 如何设定 **TURFs** 的大小仍是一个关键的难题, **TURFs** 太大则共用的利益相关者太多, 会阻碍集体行动; 而太小目标鱼类会在 **TURFs** 间进进出出的移动, 团体实际上不能独享这些鱼类。我们通过应用理论模型来预测 **TURFs** 的情况, 评估了涉及这一设计挑战的全球 137个**TURFs** 的大小。我们估计其中约三分之二的 **TURFs** 大小合适, 可以应对鱼类资源的移动和渔民群体大小带来的问题。然而, 对于剩下的大多数 **TURFs** 来说, 所有可能的大小都要么太小 (面临鱼类资源移动的问题), 要么太大(难以克服集体行动的挑战)。我们的结果显示, 这些在人口密集的地区、以可移动鱼类为目标物种的渔业, 可能需要额外的干预措施才能取得成功。* **【翻译: 胡怡思; 审校: 聂永刚】**

**关键词:** 渔业领地使用权 (TURFs), 集体行动, 鱼类的移动, 社会生态系统

## Introduction

Mismanagement of small-scale fisheries is one of the largest challenges faced by our oceans today. A widely advocated solution to overfishing in small-scale fisheries is territorial use rights for fisheries (TURFs). This approach allocates exclusive rights to a group of fishers to use all or a part of the resources in a particular area of the sea (Wilen et al. 2012). National governments from several countries have turned to such local-level governance institutions because of the potential benefits this strategy can provide to small-scale fishing communities (Agrawal 2005; Aceves-Bueno et al. 2017; Nguyen et al. 2017). Such systems recognize fishers as an integral and indispensable part of contemporary efforts to conserve environmental resources, especially when there are weak regulatory institutions. Unlike traditional management strategies, TURFs change overharvesting incentives prevalent in open access systems by allocating exclusive and secure access to marine resources (Costello 2012). Such rights motivate more sustainable management actions by TURF users because they ensure that future benefits from those actions are secured for TURF owners. The logic is that once a group of fishers has secure rights to a fishery, they will act as sole owners and manage the resource to obtain maximum long-term economic gains (Costello & Kaffine 2008).

In practice, TURFs will only achieve these goals if they are well-designed. There is a growing body of literature exploring the design factors that affect the success of self-organized resource regimes (Agrawal 2001; Ostrom 2009). For TURFs, one of the most basic design challenges is TURF size, which can affect performance via 2 distinct modes: collective action and resource dispersal.

Collective action is generally compromised as fisher group size increases (Olson 1965), suggesting smaller TURFs with fewer fishers may provide management benefits. This happens because the number of users within the system can influence many variables that affect self-organization (Agrawal 2002) and can also affect incentives to free ride (users who enjoy resource benefits without paying for costs). First, as groups become larger, the perception of individual contributions tends to decrease and transaction costs (communication, enforcement) tend to increase (Poteete & Ostrom 2004). This leads to greater incentives to free ride and diminishes the capacity of users to enforce regulations and punish defectors (Ostrom 2010). Second, as group size increases, the capacity to devise appropriate and legitimate management rules diminishes (Olson 1965) because larger groups tend to have greater heterogeneity of users (social, cultural, economic) (Poteete & Ostrom 2004) and diminished communication opportunities (Lopez & Villamayor-Tomas 2017). Overall, increases in TURF size create larger groups, which accentuate challenges for collective action and may dwarf the capacity of self-organizing systems to achieve optimal outcomes.

By contrast, movement of target species beyond the boundary of the TURF can create incentives to overharvest before fish leave the TURF (White & Costello 2011), suggesting larger TURFs may provide management benefits. Successful resource management depends on the size of TURFs relative to the natural spatial scales of dispersal (Janmaat 2005; White & Costello 2011). When fish swim or drift out of the bounds of a TURF, they become available to fishers outside the TURF. Boats lining the boundary of a TURF provide clear visible evidence of the loss of resources to others, which incentivizes TURF owners to harvest above sustainable levels rather than let the fish leave. Resources with high mobility can be more unpredictable, which affects the ability of users to set appropriate harvest rules. Overall, TURFs that are small relative to dispersal scales do not provide the correct biological incentives to optimally manage the resources.

These opposing effects can pose challenges, especially in cases where TURF sizes that would be small enough to avoid collective action problems would not be large enough to avoid spillover problems created by species movement (Fig. 1). Thus, for fisheries targeting highly mobile species in regions with dense coastal human

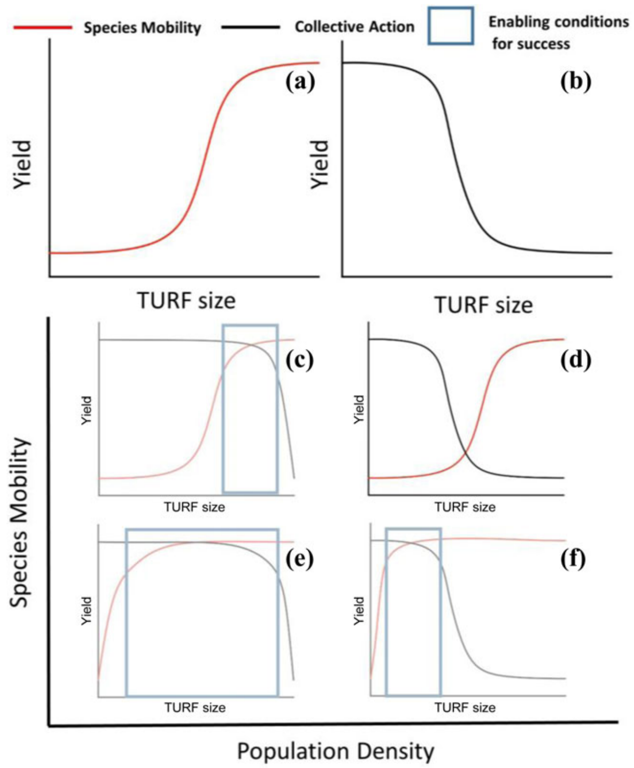


*Figure 1. Theoretical relationships between territorial use rights for fisheries (TURFs) size and resource outcomes in response to (a) resource mobility and (b) collective action; (c, e, f) scenarios in which TURFs across a range of sizes enable successful solutions to both problems simultaneously; and (d) a scenario in which there is an inherent trade-off between collective action and resource mobility problems. No TURF size in (d) would likely to have a good performance without other interventions.*

populations, TURFs may be ineffective unless additional interventions are made to overcome either spillover problems or the collective action problems. We assessed the prevalence of fisheries facing this challenge by applying theoretical models to predict the performance of 137 TURFs worldwide. Additionally, we considered possible solutions to overcome potential management challenges.

## Methods

We assembled a global database from peer-reviewed literature, governmental and nongovernmental reports, masters and PhD theses, and interviews of local stakeholders to assess where TURFs were with respect to these conceptual size guidelines (e.g., Auriemma et al. 2014; McCay et al. 2014). We compiled general data on TURFs from 30 countries (Supporting Information). For 19 of these countries, we were able to assemble a complete data set on a total of 137 TURFs where we obtained the requisite biological and social data to forecast their expected performance, including information on TURF size, primary species harvested, and group size. We constrained the number of TURFs from any given country in our database (maximum of 27 TURFs from Chile) to avoid bias related to any country-specific design guidelines. For example, countries, such as Chile, use TURFs only for sedentary species to address the problems related to mobility. Thus, including a larger sample from these countries would result in biased representation of TURFs worldwide. Of the 137 TURFs we used, 113 had information on all aspects and 24 had incomplete information on 1–2 aspects. For example, for some TURFs in Vanuatu, there was only information available on the main species harvested but not on fisher group size.

To calculate the predicted yield due to adult movement, we used a simple game-theoretic bioeconomic fisheries model developed by White and Costello (2011). This model considers the effect of TURF size relative to the scale of adult fish movement on potential yields. This 2-patch model simulates the behavior of noncooperative TURFs acting to maximize their yield and computes the expected Nash equilibrium of this competitive behavior. It calculates the potential loss in yield due to the dispersal of adult fish relative to a perfectly designed TURF (i.e., with no adult dispersal) that maximizes its yield (Supporting Information). Absolute yields clearly can increase with TURF size, but we scaled all evaluations of TURF performance relative to the maximum sustainable yield (MSY) for the TURF. We used species home range as a proxy for movement. This information was primarily extracted from the peer-reviewed literature. When data were not available in the literature, we used either values from species from the same family with similar characteristics or calculated the estimated home range from Kramer and Chapman (1999). This method estimated the home range of coastal species based on the species' maximum length. To simplify our model, we did not consider larval dispersal in our analysis. Uncertainty on population source–sink dynamics and data limitations can constrain managers' ability to properly align TURF spatial scale with scales of larval dispersal. Therefore, adult mobility is often the most important component driving management incentives of TURF owners.

To estimate predicted yields due to the number of users in a TURF, we assumed a negative logistic relationship (Eq. 1 in Supporting Information) to reflect the fact that groups above a certain size are expected to have performance similar to open access systems (Supporting Information). The shape and predicted yield values were derived from the literature and were context dependent. Several studies show how collective action outcomes decrease sharply with groups larger than a few hundred members (Dunbar 1998; Agrawal & Goyal 2001; Yang et al. 2013). We conservatively assumed group sizes of >200 fishers would decrease sharply in performance and reach yield levels expected in equilibrium open access fisheries (Costello et al. 2016) with group sizes of 400 or more fishers. We assumed that TURFs with large groups will have performance similar to open access systems to simplify the model. Given that the validity of these assumed values can be context dependent and that there is no consensus among scholars on forecasting the ideal group size to achieve optimal collective action outcomes (Yang et al. 2013) in specific cases, we also explored the sensitivity of conclusions to these presumed values.

Our model only considered effects of group size on TURF success. Collective action problems created by large group sizes can be overcome through strong leadership (Gutiérrez et al. 2011) or institutional support (Poteete & Ostrom 2004) (see Discussion). The objective of our model was, thus, to identify cases in which such additional governance interventions are needed.

All TURFs within the database were assigned to 1 of 3 categories according to their predicted performance with respect to collective action and resource mobility: optimally sized, resizing needed, and additional support needed. The optimally sized TURFs were those that had a predicted performance in or above the 0.75 quantile of predicted yields from both group size and resource mobility effects. The TURFs that needed resizing could potentially have high performance (0.75 quantile) on both dimensions with an appropriate change in TURF size. The TURFs that needed additional support could not achieve high performance simultaneously with respect to group size and resource mobility solely from changes in TURF size.

## Results

We estimated there were approximately 3700 TURFs worldwide, from which we gathered detailed information on 137. These TURFs had an average size of 367 km$^2$ (Supporting Information). The number of fishers varied greatly across TURFs (mean = 1995, median = 180, minimum = 11, maximum = 32,000). The TURFs were managed for species that differed greatly in adult mobility relative to TURF size; average predicted yield ranged from 33% to 100%. The effect of group size on average predicted yield from TURFs also varied greatly among TURFs; projected values ranged from 22% to 100% (Supporting Information).

### Adult Mobility

With respect to species mobility, the predicted yield for 137 TURFs worldwide followed the generally expected trend. Large TURFs had consistently high predicted yields, whereas small TURFs had a wide range of predicted outcomes, from very high yields to yields near 20% of MSY (Supporting Information). Although some TURFs were managed for species with high mobility relative to TURF size, most TURFs were managed for relatively sedentary species such as bivalves and crustaceans. In such cases, TURFs sizes were relatively small and did not create overharvest incentives. At the other extreme, several TURFs were managed for species that have extensive adult movement relative to the size of the TURF, resulting in low predicted yields relative to MSY. Countries, such as Brazil and Philippines, in many cases, manage for highly mobile species such as tunas, sharks, and sardines. In such cases, it is certain that the species will regularly move outside TURF boundaries and, thus, create incentives for fishers to overharvest the resource.

One important characteristic of several TURFs worldwide was that they were managed for multiple species that exhibit a wide range of biological characteristics. Consequently, in the same TURF there were sometimes species with high and low mobility, leading to different management incentives within the same area. From our database, 57% of the TURFs were managed for only 1 species, and the remaining TURFs were managed for ≥2 species. Based on the examples in our database, single-species TURFs generally focused on sedentary resources, whereas multiple-species TURFs commonly had harvests of both mobile and sedentary species.

By examining only the species mobility aspect of TURF design, 1 solution for increasing the predicted yield relative to MSY was to increase TURF size (Supporting Information). Large TURFs had lower predicted yield loss relative to small TURFs. For small TURFs, the predicted performance varied greatly, reflecting the wide variability in the biology of the species being harvested. Thus, many of the existing TURFs at the small end of the TURF size spectrum would likely benefit from increasing TURF size. For example, some TURFs in the Philippines had their main resource species that migrate long distances along the coastline. In this case, increasing TURF size to cover the entire home range of the species would increase the predicted yield. However, such increases in TURF size would undoubtedly also increase the number of users within the TURF, negatively affecting collective action outcomes.

### Group Size

The number of users varied greatly within and across countries (median = 180 fishers/TURF [Supporting Information], range 11–32 000). Although many TURFs had thousands of fishers, 70% of TURFs had fewer than 200 fishers. Therefore, most TURFs had group sizes that were small enough to facilitate collective action. For the other one-third of global TURFs, however, group sizes were sometimes enormous. In areas with high population density, even a relatively small TURF sometimes had thousands of users. For example, a Brazilian TURFs had up to 32 000 fishers in an area spanning about 50 km of shoreline. In contrast, large TURFs sometimes still had relatively few users. For example, Mexico had TURFs that stretched about 200 km along the shore. Yet, they still had fewer than 200 fishers. In the case of Mexico, there is considerable scope for expanding TURF size to match species mobility if necessary, due to the relatively low user density. By contrast, in Brazil the large population densities along the coastline compromise that option.

When the number of fishers was used to predict TURF performance, most TURFs had a predicted yield in the top quantile (Supporting Information). However, many TURFs had low predicted yields because of large group sizes. The TURFs of similar size across the entire range of observed TURF sizes sometimes had distinctly different predicted performance because of enormous variation in human population densities. Even relatively small TURFs located in areas with high population densities sometimes had low predicted performance. On the contrary, TURFs located in areas with low population densities sometimes had relatively large TURFs and still maintained high predicted yield.

To address the consequences of uncertainty regarding the appropriate group sizes for collective action, we tested a range of inflection points to assess how such changes affect our conclusions. Because the majority of TURFs that were predicted to have poor performance had thousands of users, categorization of most TURFs in our database did not change across a wide range of alternative assumptions about the size of groups that limited collective action. Consequently, the broad trends in predicted performance were relatively insensitive to the current uncertainty surrounding effects of group size on collective action.

#### Interaction between Collective Action and Resource Mobility

From all TURFs in our database with complete information ($n = 113$), 65% had all species in the optimally sized category, 18% had at least 1 species in the resizing needed category, and 30% had at least 1 species in the additional support needed category (Fig. 2). Therefore, the majority of TURFs from around the world had sizes that were simultaneously appropriate with respect to both collective action and resource mobility (optimally sized category). However, over one-third of examined TURFs did not provide the enabling conditions for success. Of these TURFs, a small fraction was predicted to achieve high performance on both dimensions solely from a change in TURF size (resizing needed category). The remaining TURFs were in the additional support needed category and would need to compensate for at least 1 driver of low predicted yield with other management solutions.

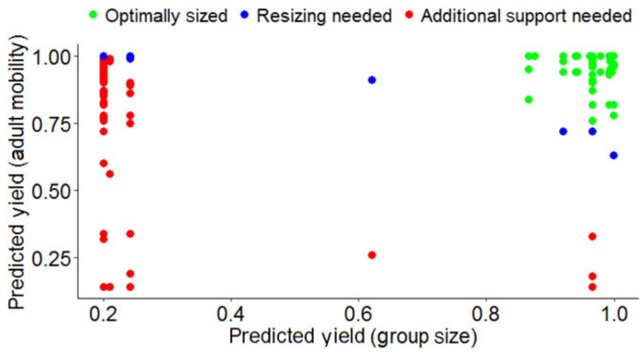


*Figure 2. Interaction between predicted fisheries yield relative to maximum sustainable yield as functions of adult fish mobility and fisher group size. Different colors represent different TURF categories (optimally sized, both dimensions with predicted yield in the 0.75 quantile; resizing needed, TURF size can be adjusted to achieve high performance [above 0.75 quantile] along both dimensions; additional support needed, high performance on both dimensions cannot be achieved solely with a change in TURF size).*

## Discussion

The twin challenges of species mobility and collective action among large groups pose challenges to sizing TURFs. Despite these challenges, a majority of TURFs from our database had sizes that we project will foster their success. About two-thirds of the TURFs had high predicted yields that were uncompromised by either collective action or resource mobility (optimally sized category). Therefore, such TURFs had the enabling success conditions and were predicted to have high performance indicators. The TURFs in this category were mostly managed for sedentary species, such as bivalves, mollusks, or crustaceans, allowing establishment of small TURFs with low number of users. Another class of TURFs in this category was located in areas with low population density, allowing TURFs to be large enough to retain even relatively mobile species while still maintaining small groups of TURF owners.

We projected that about 18% of TURFs had at least 1 species with overharvesting incentives that could be improved solely by changing their size (resizing needed category). Because of low population densities or low adult mobility, there will be a range of TURF sizes that can have small groups, while being large enough to retain adult mobility. When TURFs are managed for sedentary species, their areas can be reduced to decrease group size and still maintain incentives for sustainable management. For example, in Vanuatu some TURFs were managed for species with low mobility (e.g., mollusks) and had group sizes of thousands of fishers. In such cases, it might be more efficient to subdivide TURFs into many

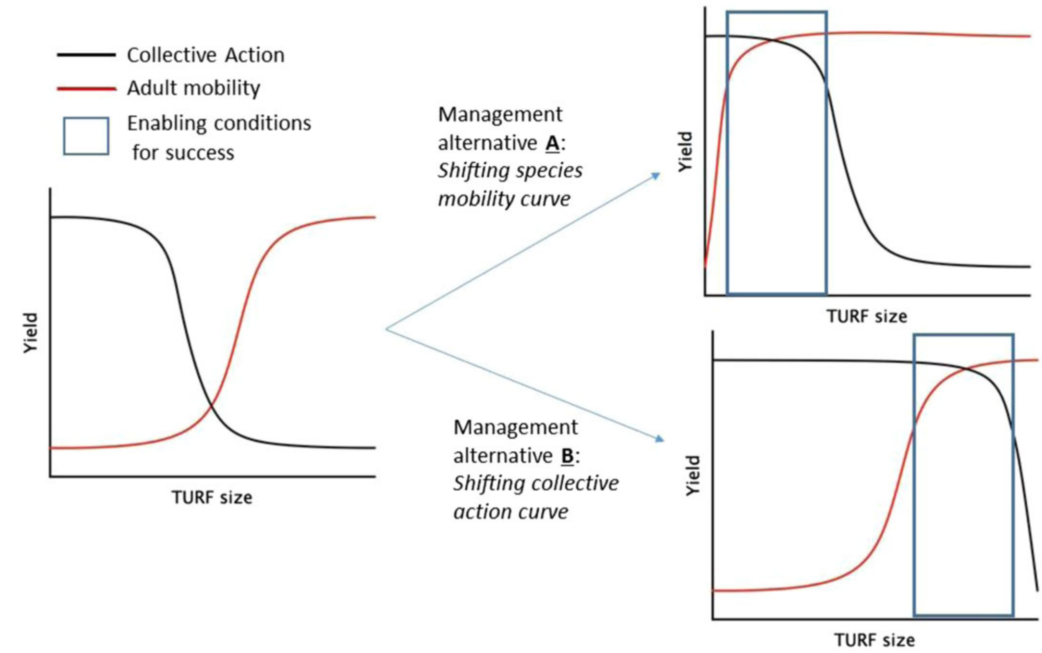


*Figure 3. Potential effects that 2 types of management alternatives could have on fisher collective action factors (e.g., leadership) and species mobility. Shifting collective action curve means that such management alternatives provide conditions in which large groups can succeed. Shifting species mobility curve means such management alternatives alter negative consequences of fish mobility.*

smaller TURFs to manage these sedentary species more sustainably. Smaller TURFs would reduce free riders in communities that manage resources with low mobility, thus, incentivizing more effective and sustainable management. In contrast, areas with low population densities can have relatively large TURFs to deal with more mobile species while simultaneously maintaining small group sizes. For example, in Mexico some TURFs had relatively large areas with small groups. Thus, adjusting TURF size to solve 1 problem does not inevitably compromises the other. Changing TURF size could be a relatively simple fix to provide the proper management incentives.

For the remaining TURFs (~30%), we projected that adjusting TURF size alone would not address both the collective action and the species mobility problems simultaneously (additional support needed category). Therefore, more sophisticated and complementary management alternatives are needed (Fig. 3).

The first set of potential solutions to these challenges involves introducing new institutions, which reduces the challenges posed by species spillover without increasing the TURF size. For example, creating a TURF network where multiple TURFs coordinate their management could produce an outcome that effectively functions as a larger TURF without the problems of collective action within each TURF. In such cases, TURF networks could maximize overall yield by assigning quotas to each individual TURF or by sharing profits across TURFs. Thus, fishes will still move out of each individual TURF, but the resulting overharvesting incentives will be reduced or eliminated. However, when fishes frequently move out of each individual TURF, the success of this strategy depends on successful coordination among all TURFs within the network. Such coordination might be challenged by heterogeneity in the quality of different TURFs in the network, insufficient communication or coordination among individual TURFs, or increased risk of cheaters. Enforcement across TURFs can also be challenging because each TURF will have different owners.

Despite these potential challenges to TURF networks, effective coordination has been observed in TURF systems in Japan and Mexico (Wilen et al. 2012; McCay et al. 2014), where species mobility would otherwise be expected to incentivize overharvest. These systems developed sophisticated management schemes to coordinate management across the network that incentivizes cooperation and maximizes outcomes. For example, the Sakuraebi shrimp TURF network in Japan created a profit sharing system (Wilen et al. 2012). Under this management scheme, harvest is pooled across all TURFs in the network and net returns are redistributed according to prearranged rules (Uchida & Baba 2008; Wilen et al. 2012). This management system decreases the incentive to overharvest because fishes that leave a TURF but are caught elsewhere in the network still provide benefit to all TURFs owners. Therefore, when there is a system in place to promote cooperation, TURF networks have the potential to alter negative consequences of fish mobility and maximize potential outcomes.

The second set of solutions addresses the collective action challenges within large user groups when reducing TURF size is not possible. Improving the collective action capacity of TURFs is complex and requires an enhancement of community organization within the TURF. A deep knowledge of the social system is required to identify what elements of collective action need improvement. There are a number of ways by which large groups have overcome coordination problems, and we see examples in TURF systems as well. The first, and perhaps most widespread in the literature, is through effective leadership and a nested governance structure (Olson 1965; Agrawal 2006). As group size increases, an effective leader can bring different communities together and enhances the likelihood of shared goals (Olson 1965). To produce such leaders, institutions could invest in leadership training. Additionally, the governance structure inside the TURF can be designed to facilitate communication across different communities (Olson 1965). Effective communication is a key to build trust among users and to design effective and fair rules (Olson 1965). For example, a country's exclusive economic zone can be viewed as essentially a large TURF, where each country has exclusive rights to exploit the natural resources within 200 miles from the coast. Because of the large area and high number of users, management is usually designated to states or municipalities that are then supervised by or coordinated with the federal government. Through this analogy, TURF systems could be nested into several communities where the leaders from each area collectively form a single central body, where the decisions are made. For example, the TURFs in Brazil have up to 32 000 users spread over up to 50 communities. One potential path forward would be for these TURFs to develop a governance structure that promotes more effective communication through nested tiers of social organization (Zhou et al. 2005). Therefore, deep knowledge of the social system and, subsequently, development of nested tiers of appropriate social organization are the heart of successful governance in large groups.

When TURFs entail rights to fish multiple species, management alternatives to address design problems may vary according to the resource. This situation is expected when TURFs are managed for species with different mobility characteristics. For example, some TURFs in Brazil have thousands of fishers and are managed for both sedentary (such as, crab) and mobile (such as, mullet) species. While sedentary species allow TURF size reduction to decrease group size challenges (resizing needed category), this change in TURF size would exacerbate the problem for more mobile species. In such cases, a combination of smaller TURFs that coordinates across TURFs for more mobile species could provide better management incentives to all species. Alternatively, TURFs could prioritize management alternatives based on the economic importance of the different resources they manage.

Other important factors influencing collective action can be affected by TURF size and are independent of the number of users. Factors, such as heterogeneity of users, face-to-face or repeated interactions, and enforcement costs can be affected when small groups are spread over large areas (Poteete & Ostrom 2004). Under such conditions, increasing TURF size may increase the distance between communities, thus, increasing interaction costs and the chance of having different social, cultural, or economic characteristics, regardless of group size. Increasing heterogeneity among users can increase transaction costs and potential conflicts of distribution of benefits and costs. Decreasing the frequency of face-to-face interactions among TURF users can significantly decrease their trust level, in turn, diminishing the likelihood that individuals keep their promises to cooperate. Additionally, enforcement costs often have a direct relationship with area; larger TURFs have much higher costs than smaller TURFs (Davis et al. 2014). Increasing such costs can decrease the ability of TURF owners to exclude other users, thus, decreasing management incentives and resource outcomes. Therefore, even though we did not consider such factors, they can be affected by TURF size and will only reinforce the group size effect.

Percentage of TURFs in any given category may change if other countries are included in an analysis such as ours. Although we controlled for potential biases in our database by constraining the number of TURFs from any given country, including TURFs from other countries might change the worldwide percentages of TURFs within each design category. For example, Fiji has about 385 TURFs, but we only had detailed information on 2 of them. However, regardless of actual worldwide percentages, our database demonstrates that there will be TURFs in all categories and those with a significant number of TURFs need additional interventions to provide the enabling conditions for success.

Our results are theoretical predictions about performance, not empirical estimates of actual TURF performance. To date, there are very few empirical studies of actual TURF performance (González et al. 2006; Gelcich et al. 2012; Aceves-Bueno et al. 2017). As a result, formal comparisons of predicted and actual performance are not currently possible. Collecting empirical evidence on the performance of TURFs worldwide will allow us to assess whether fisheries performance varies predictably with TURF size or the management alternatives discussed here for cases with inherent trade-offs with TURF size are already effectively addressing the opposing challenges of fish mobility and collective action. Empirical analyses may also identify other innovative solutions that have addressed these potential trade-offs successfully. Future research could focus on the strength of institutional and governance structures within each TURF or country, especially those with large group sizes. Although we await such empirical evaluations, our theoretical predictions provide a useful framework for designing new TURFs and prioritizing additional interventions in existing TURFs to avoid the negative impacts of too much fish movement or too little collective action.

## Acknowledgments

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## Supporting Information

Yield prediction (Appendices S1, S2, & S3), a summary of data (Appendix S4), and the number of fishers relative to predicted yield (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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