MANAGEMENT OF THE DISTRIBUTED FISHERY COMMONS

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Abstract. Open-access dynamics are a key concern for sustainable development, and central to fisheries collapses in many regions. This paper proposes the concept of "distributed commons" to help explain commons with imprecise boundaries, and both localized and cross-boundary impacts. It presents a theoretical model of distributed commons and explores implications for open-access management. In particular, the same management options that can be used for commons management can be combined in new ways in a distributed context. Models from groundwater use and heat diffusion provide a mathematical basis, which is used to parameterize a simple game theoretical model of cooperation. In this context, the Nash equilibrium that typically undermines cooperation offers additional options. In addition, a computational, agent-based model is presented through three experiments to investigate the role of mobility, decisions to join the commons, and local governing mechanisms. One key result from these experiments is that locally enforced MSY practices can still result in fishery collapse, but tit-for-tat behaviors can secure MSY even in the face of cheating. Finally, the consequences of the distributed commons perspective is applied to small-scale fishing communities, and used to inform co-management practices.

Fishery collapse is a global concern, affecting world food supply and economic prospects for fishing communities, and spilling across borders and across species. A growing set of policies are available address these problems, including catch quotas, marine reserves, and community management. However, a variety of systemic problems continue to hamper their deployment and effectiveness, including those stemming from the open-access nature of some fisheries.

Wild fish stocks are common pool resources (CPRs), with high subtractability of use (rivalry) and high difficulty of excluding users (Ostrom and Ostrom, 1977). They are also plagued with many characteristics considered unfavorable to community management, often including entrenched stakeholders, mistrust of science, high variability and uncertainties in stock sizes, complex migration patterns, orientations toward short-term gains, questions of sovereignty, counterproductive subsides, incentives to misreport catches, and ambiguous spatial boundaries. Despite this, some regions have had long histories of success (Pinho et al., 2012). This paper considers commons that share these characteristics and asks how further success might be possible.

While some commons are "well-mixed", such as CO_2 in the air or a small pasture, in many commons the distance between users is a key parameter. For example, fish stocks, timber, groundwater, water and air quality, and other ecosystem services are exploited and impacted heterogeneously across space, where the relevant stakeholders vary. Modeling and thinking about these resources in a non-distributed and non-spatial way can significantly distort our understanding of the system and the choices within it (Durrett and Levin, 1994, Smith and Wilen, 2003).

I argue that understanding the successes and failures of fishery commons demands a cross-scale perspective. Most CPR research focuses on the local level, where cooperative management has the greatest potential. Contemporary CPR theory ignores many influencing factors from the outside world, or considers them "as 'given' or as a 'black box'", independent of the activities of the local environment (Steins et al., 2000). This perspective has limitations, particularly for fisheries where much of the crucial ecological activity takes place on a wider scale.

To support this investigation, this paper develops the concept of the "distributed commons" in the context of fisheries management. A distributed commons differs from the traditional commons model in that the boundaries of the system are imprecise and resource users are affected most by impacts located nearby. This conception brings to the fore the role of perspective and scale (including cross-scale aspects) in understanding the political economies around management. I sketch several consequences of this new model of commons applied to fisheries management, along with the model's implications for the political economy surrounding local stakeholders, governing institutions, and their cross-scale interactions.

In the first section, the role and consequences of cross-scale issues are explored. Second, a general theory of distributed commons is developed. Third, the intuitions from these theoretical models are developed into an agent-based model, to explore three dynamic situations. Finally, some consequences of this theory are enumerated for fisheries management.

A Need for Cross-Scale Management

Scale, applied to social-ecological systems, refers to the spaciotemporal, quantitative, and analytical extent and resolution used in a perspective or analysis (Wiens, 1989, Gibson et al., 2000). Scale has long been a central issue in ecology. Aronson (1992) emphasizes that "variables such as abundance and diversity often behave unpredictably at one level of resolution but produce predictable patterns at another". For example, fish species distribution in the Great Barrier Reef is fairly random at the scale of a single patch or atoll reef, but shows predictable patterns at the scale of reef systems. Phytoplankton distribution shows a complicated set of patterns, dominated by local turbulence at the scale of kilometers, by ecosystem feedbacks on a wider scale, and oceanic flows on a still wider scale (Wiens, 1989).

Traditional CPR research focuses on the local scale for several reasons. Management at the local scale provides the greatest potential for communication and cooperation, stakeholder engagement, application of local knowledge, and agile adaptation (Ostrom et al., 1999). One branch of CPR research responds to the failures of management orchestrated by centralized institutions, which in many cases has encouraged unsustainable exploitation and undermined long-standing traditions of stewardship. A focus on the local scale affirms the local perspective, in which the concerns of users and their relationships are paramount.

There is also an implicit claim that local analyses are applicable to larger scales and remote contexts. First, it is argued that higher level features have little bearing on the institutions and outcomes at a local level (Elster, 1989, Furubotn and Richter, 1991). Further, Keohane and Ostrom (1995) argue that important facts of commons management are scale-invariant, so conclusions from local CPR studies can inform problems of global governance.

This paper makes a case that scales do matter, and that it is exactly the relationships between the local and the global that determine the scope of many commons issues. The emphasis on a local perspective is ineffective for commons rife with cross-boundary issues. Schlager et al. (1994) argues that cross-boundary migration aggravates many CPR problems:

> (1) users are more likely to attribute flow declines to the behavior of users elsewhere in the system; (2) the users in any one location cannot control the flow even if they act collectively; (3) because no one group can control the flow and capture the benefits of collective action, users in any one location are less likely to provide benefits for users elsewhere in the system by restraining their own appropriation activities; and (4) coordinating activities with users in other locations raises transaction costs.

The complexity of stock dynamics makes it very difficult to determine the effects fishers have on each other. As a result, the rules adopted by fishers often do not address the appropriation externalities at the heart of CPR problems, because the source of these problems extends beyond local fishing grounds. Leaving cross-boundary issues outside the scope of study undermines our ability to address the root of many CPR problems.[1]

Cross-scale issues are pervasive in complex social-ecological systems. Cash et al. (2006) identifies three common kinds of "scale challenges": "(1) the failure to recognize important scale and level interactions altogether, (2) the persistence of mismatches between levels and scales in human-environment systems, and (3) the failure to recognize heterogeneity in the way that scales are perceived and valued by different actors, even at the same level." Both "top-down" and "bottom-up" mechanisms exist in natural systems and their management. Emergent patterns drive the dynamics of higher levels,[2] while intervention into regional systems is impossible without warping the functioning of lower levels.

Rules naturally exist on many levels. Norberg et al. (2008) identifies the operational level, at which fishers make day-to-day decisions, as both smaller-scale and more pertinent than the collective choice ("local") level. Fishers regularly operate at more than one level, applying operational norms, helping decide collective choice rules, and providing input for regional rules. The cross-scale literature focuses on the relationship between fishing communities and the government or the market, but intermediate levels (such as middlemen) can also play crucial roles (Crona et al., 2010).

The cross-scale impacts that government-scale policy has on the local scale are the best studied. Local fishing communities are affected by a wide range of outside factors, including regional environmental health, management policies, and market demands. In particular, national HDI, quota regimes, and the existence of protected areas have been identified as significant influences on the success of local management (Gutiérrez et al., 2011). Higher level institutions can strengthen local ones, through state legitimization, enabling legislation,

[1]Fishers are confronted with a wide variety of difficulties, including pervasive uncertainly (Schlager, 1994). I will not discuss issues, except as they pertain to scale and boundary issues. For example, a portion of fish stock variability is a consequence of fish movements, which is relevant to this exploration, while another part reflects underlying ecological dynamics, which is not.

[2]Emergence in an ecosystem describes the process by which "properties of the ecosystem at large spatial scales result from feedback interactions between components occurring at smaller scales" (van de Koppel et al., 2005).

cultural revitalization, capacity building, and institution building (Berkes, 2002). However, centralization and higher level management also frequently undermine local institutions. Co-management, defined as an institutional arrangement between government and communities, addresses this need for collaborative rules at different scales, and will be discussed in the last section.

The Distributed Commons

A distributed commons is a kind of non-excludable, rivalrous resource, with localized impacts from resource users. The distinction between this and the traditional commons is most relevant when considering scale issues. At a sufficiently local scale, a distributed commons– for example, a fishing area– is simply a commons with an ambiguous boundary, cross-boundary effects, and an open community of users. As with any commons, anyone in the community can access it for individual benefits, with the potentials for aggregate externalities, on one hand, and collective or autocratic management, on another. However, classic commons theory presumes that both the scope of the resource and the community with the potential to access it are clearly and completely defined, and relatively homogeneous (Young, 1995).

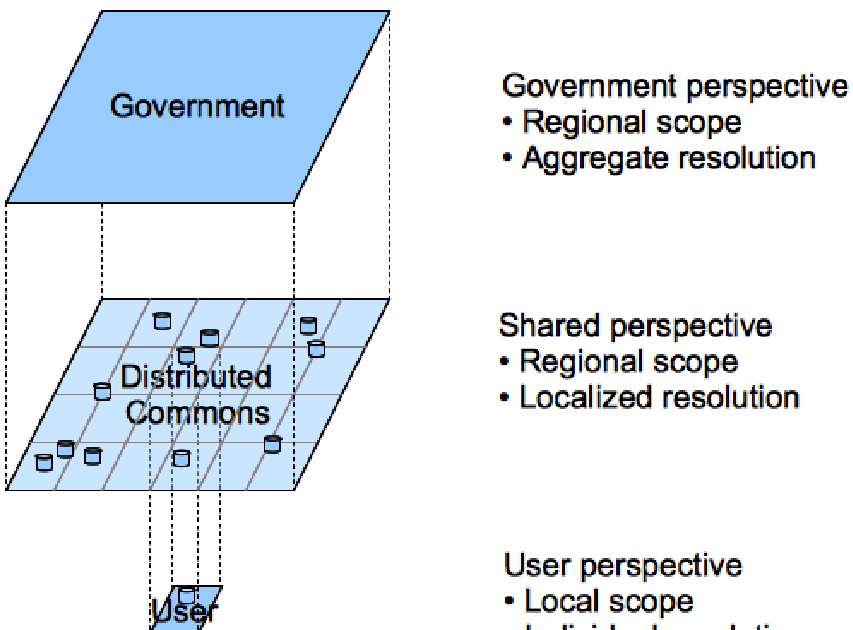


Figure 1. The distributed commons makes explicit the separate affects of scale and resolution. The governing institutions of a region emphasize the distributed nature of the commons' exploitation, while an individual user observes other users spread out at distances from it. While the prior resolution of a government is aggregate, due to its concern for aggregate measures like taxes and law, it can cultivate a localized resolution. The user's perspective is inherently on a local scale, but by recognizing the regional scope of its problems, it can better address them.

These assumptions are modified for distributed commons. System boundaries are imprecise because there are no clear border lines, because the system is open with flows passing in and out, and because of uncertainty in the underlying state and dynamics. There is also no clear boundary defining a scope of the commons relevant to a given stakeholder, and different stakeholders may have very different experiences of the resources available and community using them.

Questions of storage, mobility, and property are at the heart of distributed commons. This model contextualizes and provides insight into prior research on these issues. Schlager et al. (1994) explore the distributed aspects of commons through their the attributes of mobility and storage. They categorize all commons based on the presence or absence of these attributes, but some distinctions they draw seem unsatisfactory. For example, fisheries are classified as having "mobile units" and "without storage", while groundwater basins have "stationary units" and "storage". Both of these contexts have varying degrees of both "mobile units" and "storage", and in very similar ways. Water is far from stationary, although it seeps more slowly than fish swim. Furthermore, while water quantities are easier to measure and treat as stored, the spatial heterogeneity of geology imposes considerable uncertainty in many regions.

For Schlager et al. (1994), storage must be specific to a given resource user, with their prototypical example being the well. However, even with groundwater, water left in a well can be extracted by other users over time [REF]. Conversely, although fish are highly mobile, the probability of fish varies over space, and is higher in regions where they are underexploited. Unexploited regions can become sources of future fish [REF]. The storage capacity of fish is isomorphic to that of groundwater: in both cases, resource units that are left unharvested diffuse and a portion of them are likely to be available later.

Property rights and "assignment problems", central questions for classic commons, become difficult to establish in full. One's capacity to lay claim to a parcel of the greater commons is easier than to ensure that activities beyond that parcel do not impact it. Because of uncertainty, "fishers are more likely to use time, location, and gear restrictions, as opposed to quotas" (Schlager, 1994). Location restrictions appear to be the most common rule used in community managed fisheries. Boundary rules, which attempt to restrict access to only local fishers, are a natural response to the spatiotemporal variation of distributed fisheries, but applying them to this context is difficult.

Sources and sinks are also important elements in distributed commons. Resource users can be thought of as sinks located at particular points. For renewable resources[3], production occurs across a region, but often with localized "hot spots". For example, marine reserves can act as sources of fish in otherwise unmanaged fisheries, greatly increasing their sustainability (Gell and Roberts, 2003). For groundwater, recharge wells are gaining popularity as a management method, offsetting the growth of sinks by building more sources. A commons is overexploited when the sinks in a given region exceed the sources, and the degree of exploitation can differ across space.

The distributed commons has several conceptual advantages. It can help build an understanding of ecological issues, management issues, and the complexity between them. Strathmann et al. (2002) shows that many coastal species have very localized recruitment, suggesting that fish cannot be considered a single aggregate stock. This is supported by genetic

[3]Note that all CPRs with the potential for sustainability are renewable resources.

and mating studies and has important implications for resilience (Strathmann et al., 2002, Norberg et al., 2008). The spatial distribution of degraded ecosystem regions can have important consequences for the capacity of the ecosystem as a whole to recover from shocks (Hughes et al., 2005). Moreover, patterns of degradation are important determinants of whether SES systems experience regime shifts, reflecting the large-scale consequences that small-scale activities can have (Elmhirst et al., 2009).

While CPR theory typically applies unitary conceptions of the system's state and the resource-using community, these abstractions are often problematic (Carlsson and Berkes, 2005). In contrast, the distributed commons model starts from a disaggregated view of the resource and its users, and thereby helps situate management options. For example, the necessary scope of management depends on the properties of the underlying resource. Management policies need to apply to larger or smaller regions based on the same resource characteristics that determine the degree of cross-boundary effects that users experience. Management of tuna requires international conventions since tuna are so mobile, while forest management may require only small buffer zones.

Empirical CPR studies find that heterogeneity in preferences and capability typically undermines cooperative governance (Johnson and Libecap, 1982). When heterogeneity in preferences is combined with a recognition of heterogeneity in membership– that not all users need to be in partnerships with all other users– new cooperative potential can be identified.

Distributed commons also make explicit the actors in the two-level games that characterize governance of global commons (Putnam 1988, Evans et al. 1993). Typically, two-level games involve the relationship between domestic constituents and international negotiations. Because the users of commons under the regimes constructed through international relations remain nationals or institutions of one state or another, commons on an international scale are a perfect example of a classic two-level game (Young, 1995). An equivalent dynamic occurs between regions in a single country, where the preferences of users of a distributed commons are necessary determinants of the policy national regimes that arise.

A Model of the Distributed Commons

Diagram 2-a of figure 2 shows a concrete model of a distributed commons. In contrast to a classic commons, where it is exactly the capacity for multiple users to simultaneously use a resource that is its defining feature and the source of its problems, the distributed commons is conceptually segmented into parcels under exploitation by at most one user or a single agent that represents a cooperative community. These parcels may fluidly shift in size and physical location, but it is not their simultaneous use that causes problems. Instead, the tragedy of the commons results from the compounded drain of many localized sinks. The compounding effects come from the cross-boundary movement of critical elements between the parcels. These elements may be the actual resource (e.g., fish and other mobile stocks), a necessary input (e.g., water for agriculture), or ecosystem services which rely on a wider domain (e.g., bee pollination services). The resulting tragedy may only apply to a region, or may be felt across the entire distributed commons.

For many real commons, this makes natural sense. The space that a boat physically occupies is inherently excludable– two boats cannot occupy the same space. For groundwater use, each well occupies a distinct column, and property rights typically keep some distance between them, but too many wells across a region cause overuse.

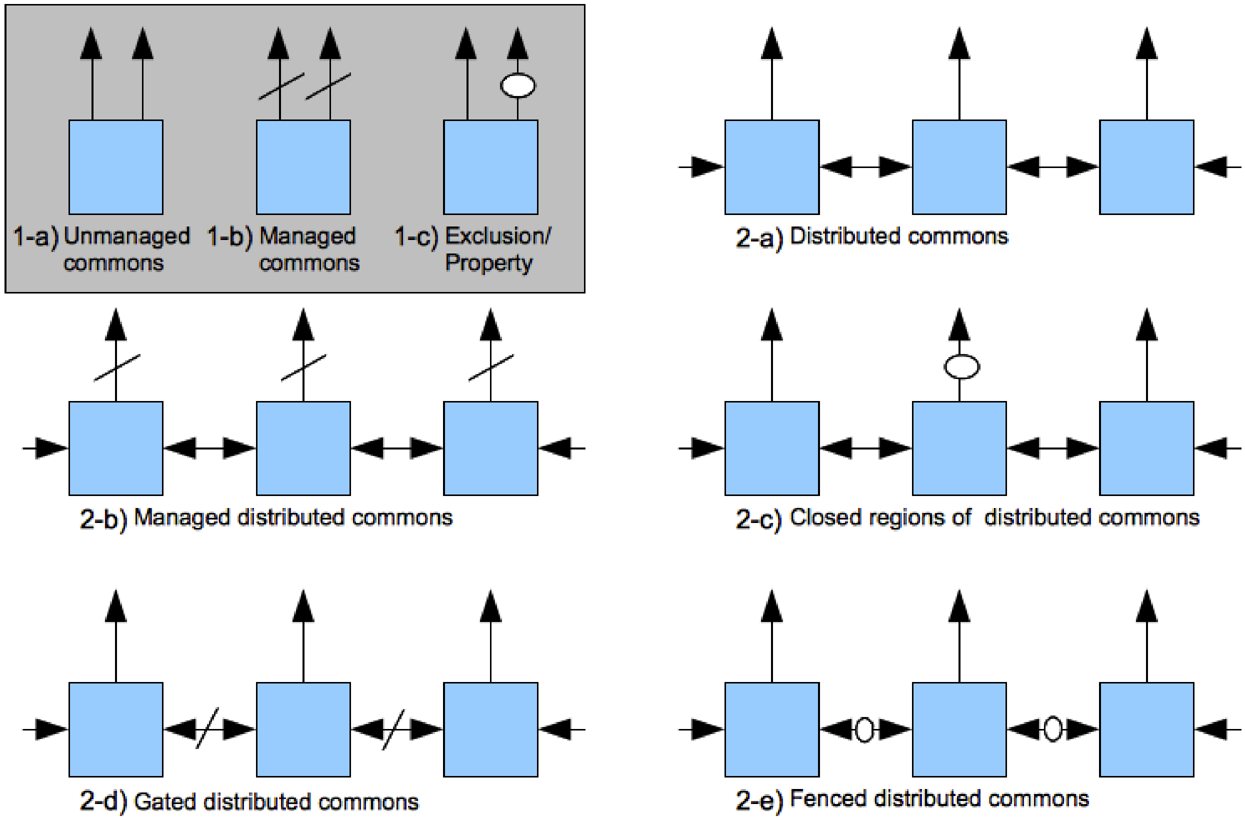


FIGURE 2. Classes of governance options for classical and distributed commons. The boxed schemas (1-a through 1-c) denote classic commons. These diagrams are meant to introduce a visual language of symbols used in the remaining diagrams, where the same approaches are applied in distributed fashion. The remaining diagrams show a general model for the distributed commons (2-a) and management options for it (2-b through 2-e). See text for descriptions.

The diagrams in figure 2 explore some basic classes of management strategies available for commons. The boxed figures refer to classical commons, where three potential institutional approaches are as follows.

Unmanaged commons (1-a): An unmanaged commons, with multiple users exploiting it simultaneously.

Managed commons (1-b): The exploitation of all users of the resource is limited through rules, such as quotas. The managed commons requires active monitoring and communication.

Exclusion/property (1-c): The tragedy of the commons is resolved by enforcing property rights, excluding all but a single agent or self-managing community of users.

For distributed commons, the same abstract approaches yield more options, due to the greater complexity of the model.

Distributed commons (2-a): Rather than imagining multiple users of one area, each area is exploited by at most user. Without communication, the tragedy of the commons is almost inescapable.

Managed distributed commons (2-b): All users within a region are managed, through limiting, monitoring, and communication.

Closed regions of distributed commons (2-c): Some regions can be closed, providing sources to offset sinks elsewhere. This is equivalent to having protected areas for ecosystems or recharge wells for groundwater.

Gated distributed commons (2-d): The flow of materials between parcels is monitored and impeded, or equivalently, the material sizes of each parcel are managed.

Fenced distributed commons (2-e): The flow of materials between parcels can be shut off, or equivalently, their material sizes can be fixed, so that each parcel or distinct regions acts like classic (non-distributed) commons with a single user.

The diagram shows the distributed commons modeled on along a line, appropriate for a coast or a river, but a grid or network would better represent spatial regions. A network could also be used to represent more complicated interacting resource systems.

Mathematical Consequences

Methods used to study groundwater levels provide an simplified model for some of the interaction scenarios that are possible. Wells have well-known compounding effects, producing a cone of depression which is greater when combined than it would be individually. We can use this "cone of depression" concept to understand different exploitation scenarios and the sustainable yields that can be achieved under them. Figure 3 combines stock level graphs with yield graphs for the central stakeholder under four scenarios.

The most important consequences of the investigations in figure 3 are the changes in maximum yield, extreme yield, and potential for depletion. In diagram B, it is shown that a single user on a distributed commons can expect greater sustainable yields, as well as greater yields under exhaustive exploitation than under uniform exploitation, since the user continues to benefit from flows from either side. Diagram D shows the cone of depletion that occurs between users. As their use increases, the cross-border benefits from the depleted region between them diminishes.

The natural resolution of a distributed resource depends on the extent of cross-boundary effects. Useful resolutions of a distributed common could have a vast range, from small-scale agents to regional institutions working across the global commons (e.g., Berkes et al., 2006). Cross-boundary effects for a random walk of fish or the diffusion dynamics of groundwater can be modeled using the heat equation:

$$\frac{\partial u}{\partial t} - \alpha \nabla^2 u = g(u, x, t) - f(u, x, t)$$

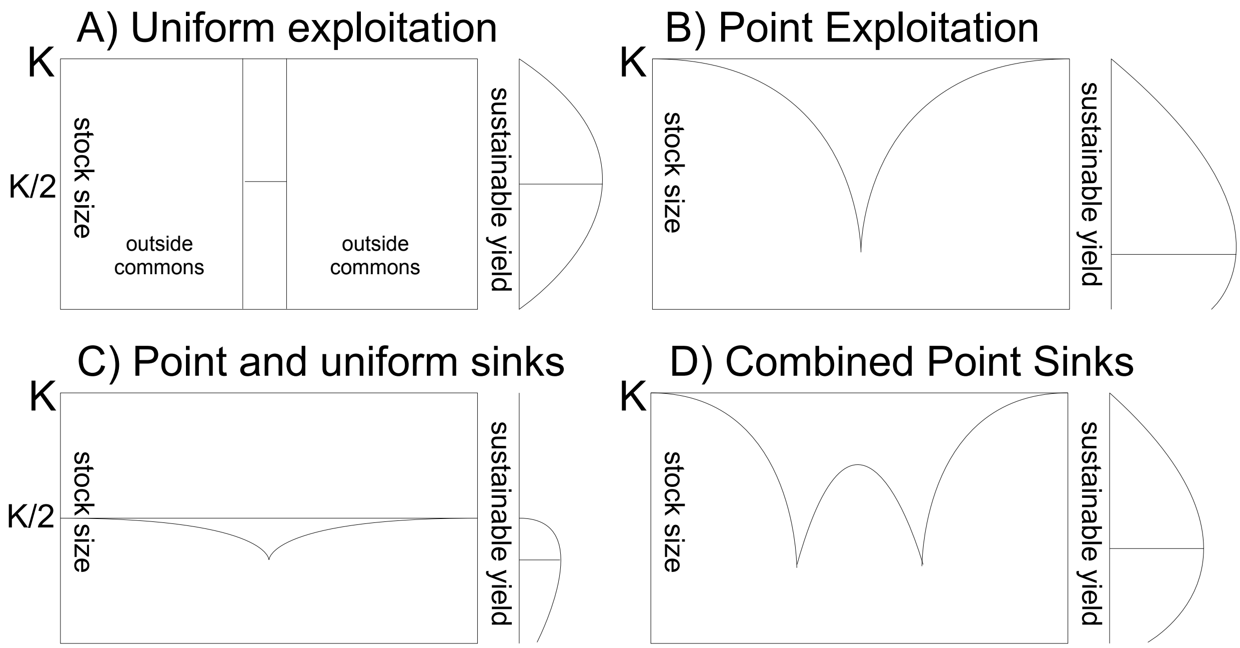


Figure 3. Examples of distributed commons exploitation at maximum sustainable yield, and the associated yield graphs. For each diagram, the box on the left shows resource levels across space, as they would be in a sustainable steady-state. To the right is the surplus at a given point expected at different choices of resource levels, with decreasing levels down. The peak of this second graph is the maximum sustainable yield (MSY). (A) shows conventional uniform exploitation, with MSY at a stock size of half the carrying capacity (under a logistic growth model). (B) has exploitation at a single point sink: the total MSY is greater, since stocks are flowing in from neighboring regions; the MSY stock may be higher or lower depending on characteristics of the resource. (C) shows a point sink under conditions where the total stock is already uniformly exploited: now both the maximum yield and the stock at that yield are much lower. (D) shows the effect of multiple point sinks, with an intermediate region of much lower stocks. In the extreme, the region between the two point sinks would be devoid of resources.

for a resource distribution in space and time, $u(\vec{x}, t)$, where α is related to the rate of diffusion, $g(u, x, t)$ is the rate of resource growth (like $g(u, x, t) = ru(1 - {}^{u}/_{K})$ for logistic growth), and $f(u, x, t)$ is the rate of resource extraction (like $f(u, x, t) = -c\delta(x)$ for a point extractor). Examples of the consequences of a set of extraction regimes are shown in figure 3.

Although there is no general, closed form for the resulting steady-state, the magnitude of impacts over space decays roughly according to a spatial exponential decay rate constant: D in $e^{-x/D}$, where D is related to α, the diffusion constant. In other words, the mobility of resources sets the natural length scale of a distributed resource. This result will be used in the next section to explore a spatial game on the commons.

The Distributed Prisoners Dilemma

As an example of the potential consequences resulting from a distributed model of the commons, we consider a prisoner's dilemma situation, with two fishery users. The general payout matrix for any prisoner's dilemma game is

	Coop	Expl
Coop	M, M	H, T
Expl	T, H	L, L

If both users cooperate (Coop), they get modest returns (M). If one tries sustainable harvesting (Coop) while the other does not (Expl), the returns to the cooperative harvester are very low (T). If both exploit to their full potential, they get equal low returns (L). For this model to produce a dominant strategy that results in L, L– that is, for this to represent a true prisoner's dilemma– the payouts must be such that $H > M > L > T$.

We define the fishery prisoners dilemma to have a payout for each user of the form

$$v_i = c_i - \mathbf{1}\{c_i + c_{-1} > S\} \left(\frac{c_i + c_{-i} - S}{2} + P \right)$$

where $\mathbf{1}\{\cdot\}$ is the indicator function (1 if $\cdot$ is true, else 0), c_i is the catch that user i aims for, S is the stock, and P is a penalty for causing a fishery collapse. For our analysis, let $S = 100$, c_i be either at a cooperative level, set to 40, or an exploitive level, at 80, and let $P = 20$. The resulting payouts under this function are,

	Coop	Expl
Coop	40, 40	50, 10 (*)
Expl	10, 50 (*)	30, 30 (*)

where (*) denotes a fishery collapse. This model satisfies the prisoner's dilemma criteria and rational agents will both select high levels of exploitation, causing lower total and individual payouts as well as fishery collapse. This payout function also produces intuitive results for a wide range of parameter values. Graph A of figure 4 shows the consequences of varying levels of exploitation by one user against a constant level by the other.

Next consider if there is a distance d between the two users, causing their compounding effects to decrease. We modify the payout equation only by adding an exponentially decreasing portion of the impact of the other user:

$$v_i = c_i - \mathbf{1}\{c_i + c_{-i}e^{-d} > S\} \left(\frac{c_i + c_{-i}e^{-d} - S}{2} + P \right)$$

As d increases, eventually choosing fishing sustainably under the assumption that the other user is exploiting will no longer result in the penalty of a fishery collapse. At this point, the exploitive strategy will no longer be dominant (since it is dominated by cooperation in the case where the other user is exploitive). At a further distance, cooperation will no longer be socially optimal, since the cross-user impacts will be smaller and the ecosystem use will be sustainable even when both users are exploitive. These regions are diagrammed in figure 4.

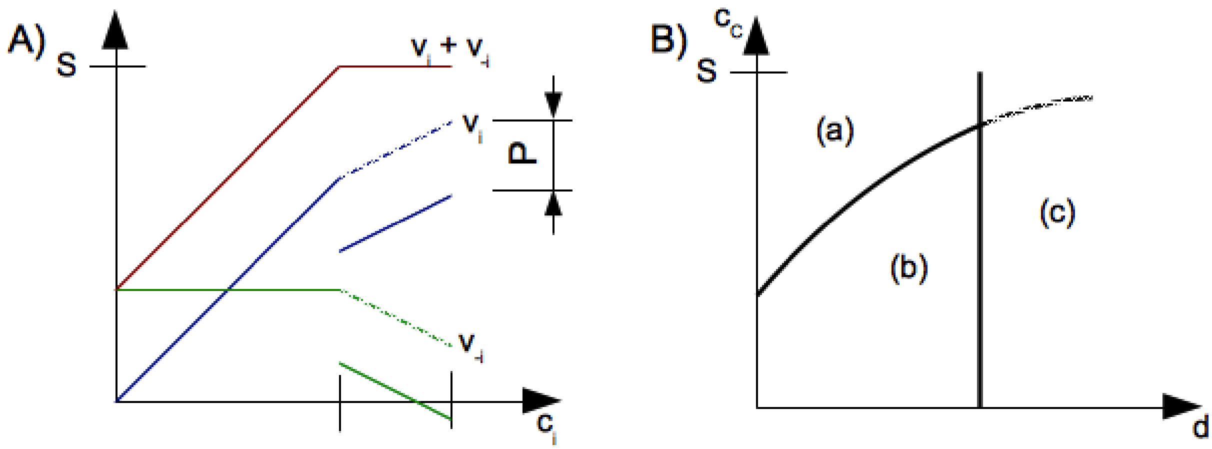


FIGURE 4. (A) shows the mechanics of the fishery prisoners dilemma payouts, varying the level of exploitation (c_i) against a constant exploitation by user $-i$. Up to $S - c_{-i}$, increases in exploitation lead to corresponding increases in value. After a level of $S - c_{-i}$, increases in exploitation are still beneficial, but the limited stock is shared. Also after this point, a penalty, P, drives down both payoffs. (B) shows three regions for the spatial game, based on the distance between users, d, and the "cooperative" level of exploitation, c_c. In region (c), even exploitive levels of use are sustainable, so cooperation is no longer socially optimal. For a given level of cooperative use, as d increases, the game transitions from region (a), characterized by the prisoners dilemma, to region (b) where exploitation is only weakly dominant.

Above, c_{-i} can be treated as the combined catch of all other resource users in a simple extension of the model. In either case, recognition of the distance between users here exposes some new opportunities to avoid the tragedy of the commons.

A Distributed Fishery Model

Agent-based modeling can be a useful tool to explore the consequences of the distributed commons model. I construct a simple model of an distributed fishery with autonomous agents derived from a Gordon-Shaefer model. The core principles of the model are as follows.

- The fishery is a one-dimensional array of cells, representing locations along a shore.
- Each cell in the array has its own stock of fish, which grows according to a logistic growth model: $\Delta_1 S_{it} = rS(1 - \frac{S_{it}}{K})$.
- Every time step, a portion of the stock in each cell diffuses to neighboring cells: $\Delta_2 S_{it} = \delta S_{i-1,t} + \delta S_{i+1,t} - 2\delta S_{it}$
- Agents occupy a grid cell in each time step, and can only harvest fish in that grid cell in that time step.

- Agents start with some wealth and pay costs according to their fishing effort and earn profits by catching fish. They go bankrupt (and exit the system) if their wealth reaches 0.
- All agents recieve the same price per ton of fish, opporate under the same opporating costs, and extract the same portion of the stock in their grid cell each time step: $C_t = (1 - e^{-E})S_t$ (this is the integral over one time period of the continuous equation $C(t) = ES(t)$ with $\dot{S} = -C(t)$).

The operating costs, fish price, and diffusion rate are chosen so that a user can only make a profit by either moving around the fishery or taking advantage of diffusion. I explore three experiments, by changing the rules by which agents move and harvest resources. They are,

(1) **Comparing the maximum occupancy of stationary and mobile fishers**

(2) **Exploring the consequences of local and global open-access rules**

(3) **Attempting to locally restrain fishing to maintain maximum sustainable yield (MSY)**

Maximum occupancy. Intuitively, a population of mobile fishers should be able to take better advantage of the resources available across a spatially distributed fishery than stationary fishers. However, I find that for evenly-spaced stationary users and under a range of biological and economic parameters, a greater number of stationary fishers can be maintained on a given fishery. This is due to the mobile fishers greater capacity to over-fish the entire region, compared to the benefit stationary fishers derive from implicitly protected areas. An example is shown in figure 5.

Open-access rules. The model can simulate an open-access commons by adding a new fisher to an existing grid cell if the unoccupied grid cells contain sufficient fish to cover the fisher's startup costs. The profit after a time T can be approximated as,

$$\pi_T = p(1 - e^{-ET})S_0 - cT$$

where p is the price per ton of fish, and c is the operating costs per timestep. The maximum value of this is,

$$\max_T \pi_T = \frac{c}{E}\left(1 - \log \frac{c}{pES_0}\right)$$

At each time step, if this maximum value is greater than the initial wealth of the fisher, then a new mobile fishing agent is constucted within the fishery.

This experiment is run both by treating all fish stocks as an aggregate, and by making the decision based only on individual grid cell statuses (see figure 6). In the simulation, both rules initially operate identically. After fishing agents begin to go bankrupt, new fishing agents are continuously added under the bulk open-access rule, while the local access rule allows the fishery to recover before new fishing agents are added. However, in the local open-access rule, the open-access tragedy reoccurs after a period of recovery (between time steps 165 and 170).

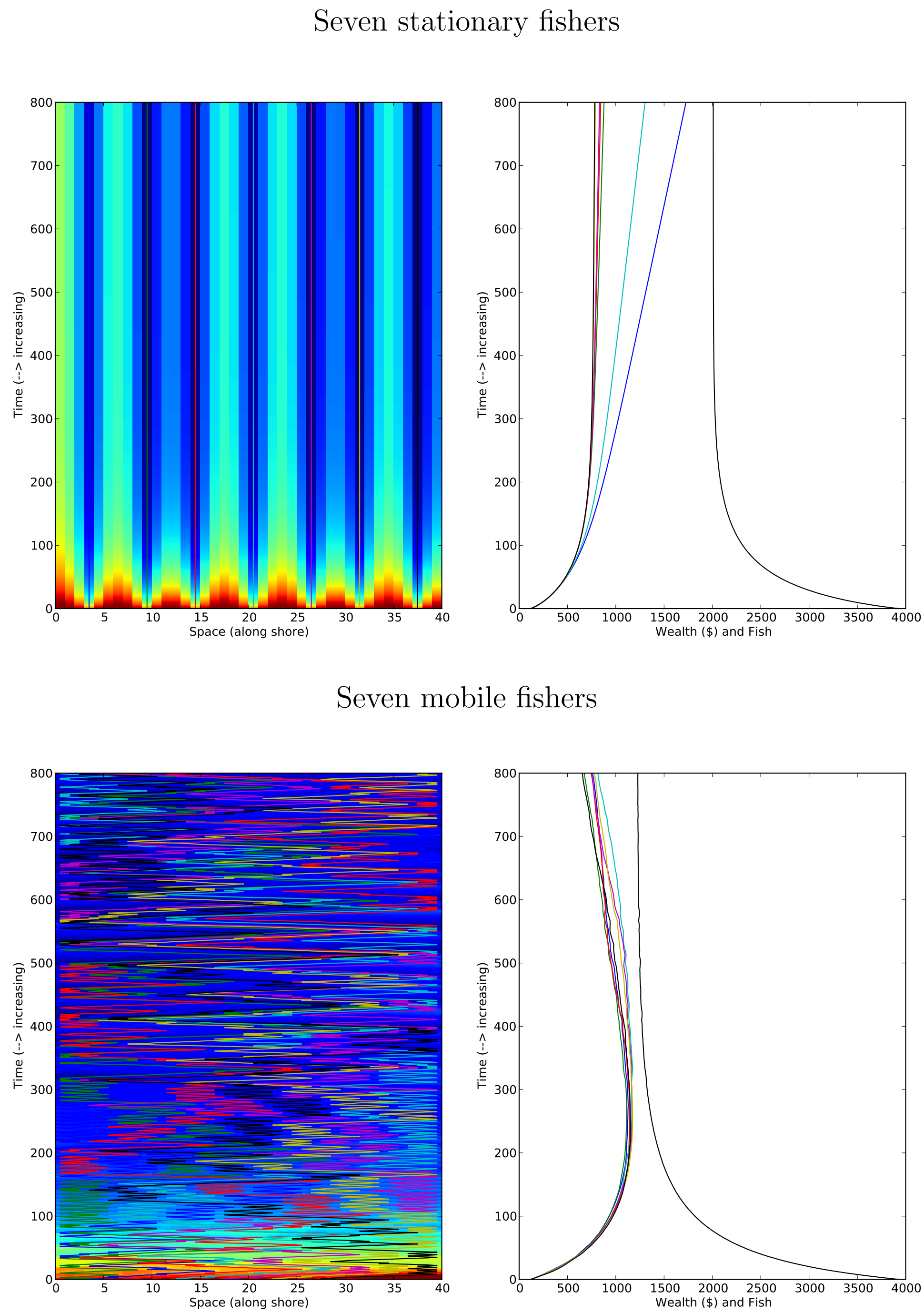
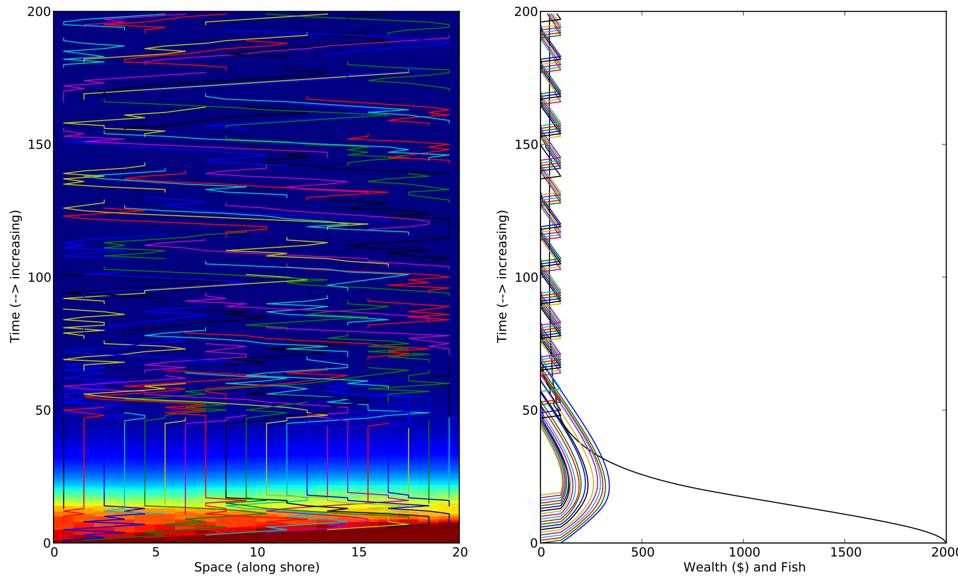


FIGURE 5. Each row is a time step, for 40 grid cells across 800 time steps. Background grid colors represent the density of fish biomass in each cell. Lines show the location of each fisher, and correspond to the colored lines in the right graphs. **Top:** For stationary fishers, the grid cells occupied by the fishers are quickly depleted, but having 2-3 neighboring unfished grid cells provides sufficient diffusion to support the fishers. For this arrangement, the aggregate fish population asymptotes at MSY. **Bottom:** Mobile fishers move to grid cells with high fish biomass, which allows them to extract more biomass. The fishers' wealth lines peak at over $1000, but then decline as the fish stocks are no longer sufficient to support them.

Bulk open-access rule



Local open-access rule

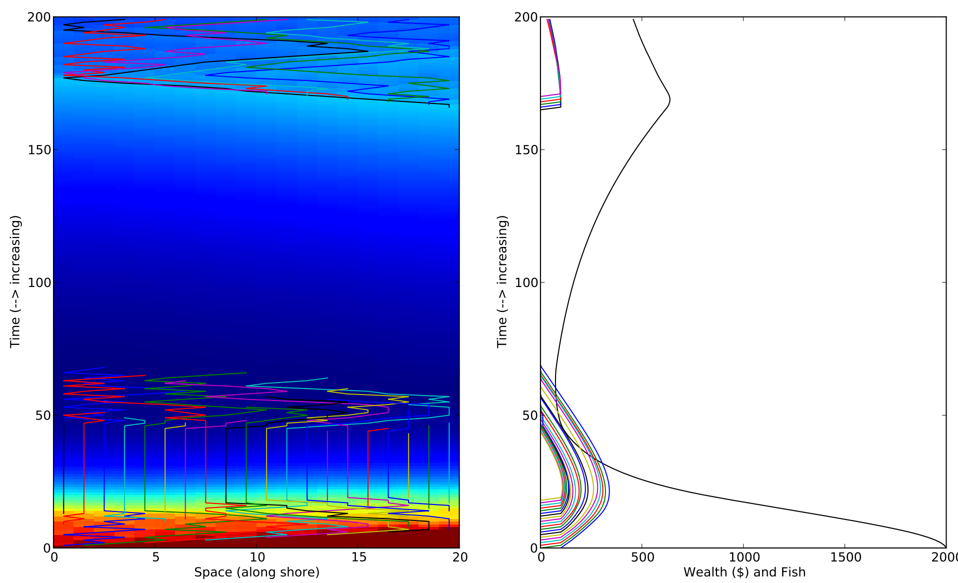


FIGURE 6. The first 45 time steps are identical between the two experiments: A new fisher is added each time step until all locations are occupied. Between timesteps 20 and 45, the agents fish down the stocks until agents begin to go bankrupt. **Top:** Under the bulk open-access rule, new fishing agents are continously added whenever there is a free location, despite the negative slope in their wealth trajectories. **Bottom:** Under local open-access, the fishery recovers for about 100 time steps, until new fishers can join the fishery without having a negative wealth slope.

Maximum sustainable yield (MSY) management. I now allow fishing agents to "go on vacation", a state where they continue to occupy a grid cell but no longer fish and have reduced operating costs. For example, a fishery with seasonally inforced vacations can support greater numbers of fishers. In this scenario, I require that fishers stop harvesting if their local stock levels fall much below MSY, defined as half of the carrying capacity (see figure 7). The result is a fishery that in aggregate maintains stocks near MSY, but at a social cost: while some fishing agents go on vacation due to their local conditions, others can continue to operate, and eventually take advantage of the vacationing fishers by harvesting their diffusing stocks. As a result, the stocks in the vacationing agents' grid cells never reach a high enough level for them to return to fishing, and they eventually go bankrupt.

As a solution, I add a new rule, "tit-for-tat". Vacationing fishers continue to monitor the region around them. If they see another fishing agent operating within their neighborhood, they return to fishing themselves, even if their local conditions have no attained MSY. Instead of resulting in greater collapse, this forces all of the fishing agents to synchronize their vacations, ensuring both stable fish poulations and equitable management. This works because the rouge fishers who would otherwise exploit these vacationing fishers are bound by the same MSY rule, they simply precieve different local conditions. Finally, a more aggressive form of the "tit-for-tat" behavior can be used to "starve" fishers who do not follow the MSY vacation rule, by fishing in close proximity to them.

The "tit-for-tat" rule also operates effectively under open-access rules. While initially too many fishers join the fishery, after a few have gone bankrupt, the remainder maintain the fishery near MSY.

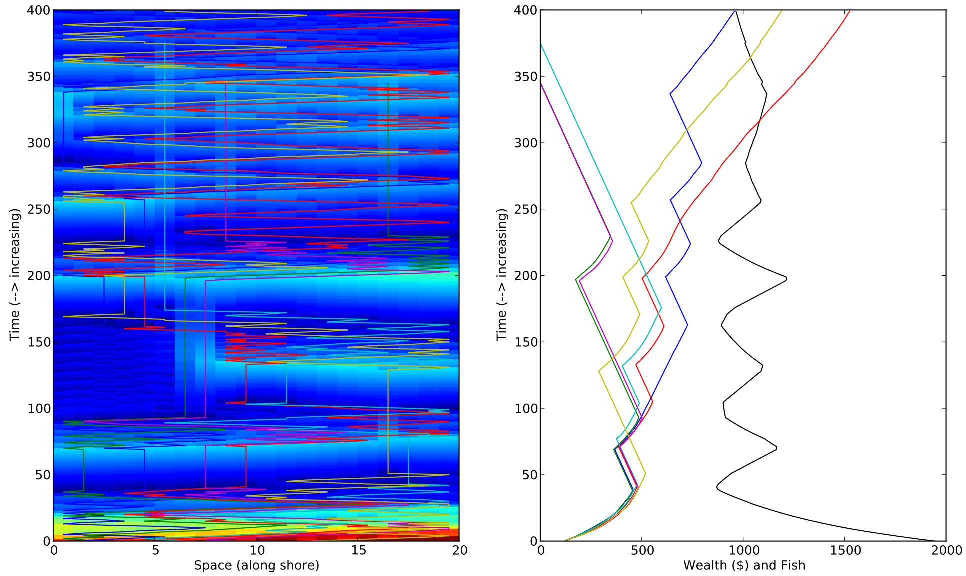
Fishery Governance for a Distributed Commons

Local fishing communities bear huge costs from fishery collapse. While many communities historically developed commons management practices to maintain their resources sustainably, a combination of government policies, market changes, and environmental cross-border effects act to undermined these regimes. This section investigates some of ways that the distributed commons perspective illuminates responses that local fishing communities have to these difficult issues. How can local communities encourage overarching regulatory regimes that then support their ability to self-organize sustainable fisheries?

Addressing this equation requires understanding the perspective of both governments and users within local communities. An example of conflict between these perspectives revolves around "outsiders", entities whose cross-border effects impact the commons. One source of outsiders is the international commercial fishing industry which over the last century has had an increasing impact on coastal fisheries in Africa (Alder and Sumaila, 2004). The government and local communities may have very different perceptions on the nature of outsiders and their consequences. For example, the agents which are "outsiders" for the fishery may actually be national institutions, such as impacts from agricultural or industrial sectors.

The remainder of this discussion applies a focus on a particular stakeholder. For a fishing community that desires sustainable management (and knows what that entails by virtue of a historical tradition, learning about other successes, or outside facilitation), that desire can

Local MSY rule



Local MSY/Tit-for-tat rule

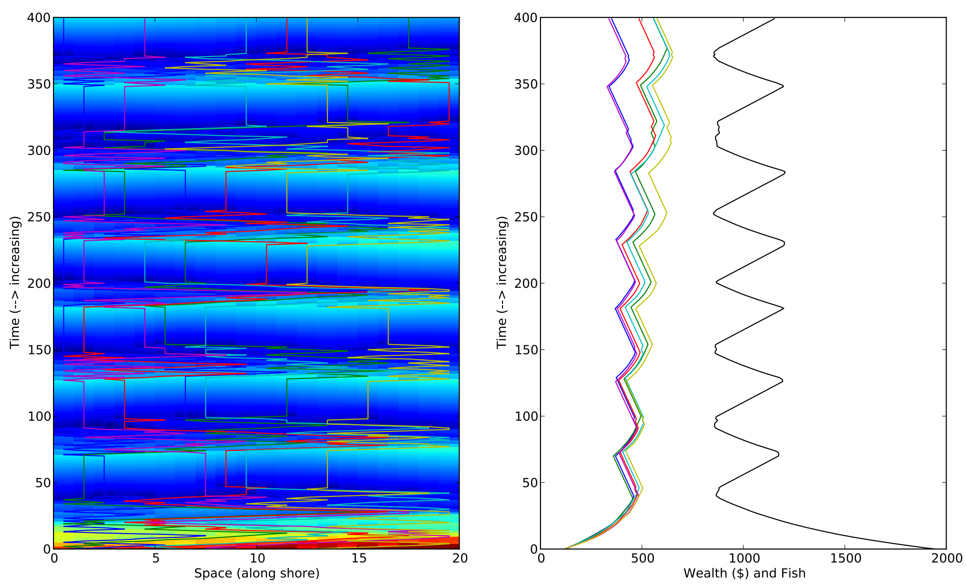


FIGURE 7. **Top:** Local MSY management allows fishers to be taken advantage of and never return from vacation. This happens to the green, purple, and cyan fishers between timesteps 230 and 400. **Bottom:** Local MSY/Tit-for-tat management forces fishing agents to synchronize their vacations. When only some fishers go on vacation, as happens between time step 310 and 320, others return from vacation and fish down the fishery until all fishing agents must go on vacation.

be said to have a "nucleus"– a core group with the capacity to deliberate on their situation. The scale on which the nucleus operates defines the local scale. At that local scale and in the region of the central stakeholder, an array of other users coexist, cooperate, and compete. Other members of the distributed commons are at various distances from that nucleus: some use a fishing region which only partially overlaps; others have closer affiliations with outside nuclei.

In the interests of maximizing well-being or tax revenue, the government's first priority for a renewable resource is to maximizing the total sustainable or economic yield. Depending on the characteristics of the fish species, this requires a combination of gear restrictions (to protect vital life stages or supporting species), ITQs (or other restrictions on total catch), and marine reserves (to protect vital habitats). Often, however, only a portion of the necessary practices are implemented, reflecting the political economy around entrenched stakeholders and poor communication between fishers and management groups.

The management concerns from the perspective of the nucleus are different from the government's. These include a reliable livelihood (through a social safety net), the elimination of outside drains, and support for self-management. Scientific information would also serve these goals, but the current distrust that many fishers have for the scientific community obstructs this avenue.

Two questions are critical for the nucleus. The first is what changes in the conditions of access and usage would best support a better fishing regime. A wide range of institutional regimes coexist within the vast distributed commons that is global marine and coastal fisheries. These include catch restriction regimes (such as quotas and gear restrictions), spatial restriction regimes (such as MPAs, use rights, and exclusive economic zones), community management regimes (which variously focus on decision-making and conflict-resolving practices), and co-management regimes (which apply combinations of the three other types). Cooperative community institutions may themselves impose catch restrictions and spatial restrictions, or be embedded into a larger region where such restrictions exist. In addition, these regimes may include governance architectures and boundary institutions that specify the roles of stakeholders, scientists, economists, special interest groups (like environmental NGOs), the national bureaucracy and international community.

The research on commons suggests the best options that an overarching governance body has for encouraging community self-organization: for example, it can close the commons (through a quota system), or enforce boundaries on the commons (with a police force). A more inclusive approach asks how government can support effective local institutions. Pinkerton (1989) notes that governments can support local institutions through data gathering, protection from environmental damage, and enforcement. Gutiérrez et al. (2011) identifies empirically the management characteristics that lead to effective co-management of fisheries, including leadership, quotas, cohesion, and protected areas. Gibson (2000) shows that the capacity for and laws supporting local property rights and rule-making plays an important role in conservation. Ostrom (2009) identifies the size of the resource system, its productivity, its predictability, the mobility of its units, the number of users, leadership, norms and social capital, knowledge, importance of the resource, and the ability to create rules as important factors determining the capacity of users to self-organize. The insight that social inequality results in poorer ecosystem management (Klooster, 2000, Holland et al., 2009) may also be explored through this lens. For classic commons, these many factors determine whether the expected benefits of managing the commons exceed the perceived costs. For a distributed commons, that result can differ in space, and the factors determine the potential scope of such management regimes.

Communities need to identify zones with leadership, equality, good communication, and the whole host of factors which support community management. Within the regional institutions, they need rights, legitimacy, and support from groups with a wider scope of information. Wilson (1982) notes that "gear conflicts or other forms of physical interference [arise] because fishermen often find it advantageous to fish very close to one another." This fact helps the establishment of local management regimes: the repeated encounters in prime fishing spots are conducive to cooperation (Schlager, 1994).

The second issue confronting the nucleus concerns methods for encouraging these changes. I will not address tactical options, which might include campaigning, lobbying, or mobilization of scientific support. The consequences of this cross-level power relation is studied in the literature on two-level games (Putnam, 1988). Zürn (1993) argues for the importance of domestic actions in regime formation (cited in Young, 1995).

In addition, the spatially heterogeneous nature of the commons provides an powerful incentive to devolve power to local authorities. Local users not only have greater knowledge of the environmental dynamics around them, but have a capacity to recognize the local social dynamics as well. On the other hand, regional authorities are better equipped to recognize regional level issues. This suggests a potential not only for a mutually beneficial information exchange, but for local users to extract rent (or better, drive power shifts) from their knowledge.

Berkes (2002) notes that "the balance of evidence from the commons literature of the past few decades is that neither purely local-level management nor purely higher level management works well by itself." Co-management, the institutionalize cooperation between regional and local governance, is a solution for handling cross-scale issues (Berkes, 2006). Co-management has the potential to mitigate the weaknesses of the management techniques used by different levels of institutions (Pomeroy and Berkes, 1997).

The distributed commons provides a natural perspective for a co-management regime, for both the government and local communities– but with different resolutions. For users within local communities, the agents of the distributed common are individual fishers. For the government, the agents are communities and commercial fishers. Many users can be encapsulated behind a single market, a single revenue stream, and aggregate metrics of well-being. At either resolution, cross-boundary and cross-scale issues continue to motivate a non-unitary vision of the commons.

By applying a model of distributed commons at local, regional, and international levels, the diverse needs and issues of fisheries management become clearer. The relevant users, resources, preferences, and impacts are all non-unitary and vary over space. Recognizing these variations can help identify places with greater potential for sustainable governance, and produce the cross-border effects which will support other regions in becoming sustainable as well.

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