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Revenue-sharing clubs provide economic insurance and incentives for sustainability in common-pool resource systems

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ABSTRACT

Harvesting behaviors of natural resource users, such as farmers, fishermen and aquaculturists, are shaped by season-to-season and day-to-day variability, or in other words risk. Here, we explore how risk-mitigation strategies can lead to sustainable use and improved management of common-pool natural resources. Over-exploitation of unmanaged natural resources, which lowers their long-term productivity, is a central challenge facing societies. While effective top-down management is a possible solution, it is not available if the resource is outside the jurisdictional bounds of any management entity, or if existing institutions cannot effectively impose sustainable-use rules. Under these conditions, alternative approaches to natural resource governance are required. Here, we study revenue-sharing clubs as a mechanism by which resource users can mitigate their income volatility and importantly, as a co-benefit, are also incentivized to reduce their effort, leading to reduced over-exploitation and improved resource governance. We use game theoretic analyses and agent-based modeling to determine the conditions in which revenue-sharing can be beneficial for resource management as well as resource users. We find that revenue-sharing agreements can emerge and lead to improvements in resource management when there is large variability in production/revenue and when this variability is uncorrelated across members of the revenue-sharing club. Further, we show that if members of the revenue-sharing collective can sell their product at a price premium, then the range of ecological and economic conditions under which revenue-sharing can be a tool for management greatly expands. These results have implications for the design of bottom-up management, where resource users themselves are incentivized to operate in ecologically sustainable and economically advantageous ways.

1. Introduction

In open-access natural resource systems, conventional bio-economic theory predicts over-exploitation, resulting in reductions to profitability and stock biomass (Gordon, 1954). Further, users of such resources are subject to economic risk resulting from resource or environmental stochasticity (Mumford et al., 2009). In this paper, we analyze a single mechanism that can lead to the resolution of both challenges. We examine cooperative revenue-sharing agreements, where a set of harvesters agree to share a fraction of their revenue equally with the group. These agreements act as insurance because they decrease temporal variability in profits. Revenue-sharing agreements also induce changes in harvester incentives because they create a free-rider problem: each harvester benefits from the effort of others, and members of a revenue-sharing club are disincentivized to (over)harvest because all club members retain only a fraction of their own revenue (Heintzelman et al., 2009). In most contexts, a free-rider problem is a major hurdle that prevents optimal outcomes, but in this context it can be beneficial (Kaffine and Costello, 2011). It reduces the incentive for over-exploitation and leads to greater profitability. We use an evolutionary game theoretic model to explore when revenue-sharing agreements can solve the dual challenges of over-exploitation and risk mitigation in common-pool resource systems.

In many common-pool resource systems there exist bottom-up institutions that collectively manage the level to which (shared) natural resources are exploited (Leslie et al., 2015; McCay et al., 2014; Ostrom, 1990). Qualitative frameworks exist to help elucidate the conditions in which these bottom-up approaches are most likely to emerge, and achieve sustainability (Ostrom, 2009). These

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frameworks suggest that in order to achieve long-term sustainability, flexibility that can be sub-optimal in the short run must be built in (Dietz et al., 2003). Another crucial component of successful bottom-up management is the structure of the institutional environment in which decisions are made. Behavioral economic experiments have shown that the mechanism by which decisions are made impacts the sustainability of outcomes in inter-generational public good and common-pool resource games (Fischer et al., 2004; Hauser et al., 2014) and that the presence of club goods can increase overall contributions in social dilemmas (Chakravarty and Fonseca, 2017). These findings are particularly relevant to cases where traditional top-down management through centralized institutions is limited. As such, the role of self-organized collective management is crucial in developing countries where government regulations are often weakly enforced (Andrew et al., 2007). It is also in these regions that risk, in the form of climate shocks or stochastic resource fluctuations, have particularly strong impacts on wellbeing (Schmidhuber and Tubiello, 2007).

When formal management is lacking, additional action can be taken by resource users. Often, this will be in the form of cooperation through collective management and information sharing, which has been shown to increase harvest efficiency (Barbier and Watson, 2016; Barnes et al., 2017; Evans and Weninger, 2014). Further, social norms for sustainable resource use can stabilize low harvesting effort in common-pool resource systems (Sethi and Somanathan, 1996; Tavoni et al., 2012). However, when norms are weak, there is often a tradeoff between achieving a stable harvesting norm and obtaining optimal resource management (Tilman et al., 2017). In addition, social norms often generate multiple stable states with the possibility of regime shifts (Lade et al., 2013), thus modeling the process by which populations can transition to collective management is critical. Here, we analyze how even in the absence of sustainable resource-use norms, revenue-sharing can act as a catalyst for transitioning to more formalized, norm-based collective management.

In economics and mathematical finance, the study of risk sharing has a long history (Arrow, 1971), with advances that are well summarized by Dana and Scarsini (2007) and Jouini et al. (2008). Applications of these theories have been useful for understanding collective insurance arrangements, including those in the maritime industry (Bennett, 2001). Risk management tools like production insurance, of the kind commonly used by farmers in the European Union and United States of America, are often not available in developing nations (Dercon, 2005; Roberts, 2005), or for food producers in common-pool resource systems, such as fishermen. Alternative forms of insurance, like individual and collective index insurance policies, have been proposed as alternatives for these groups, providing protection against risks at lower cost, and without moral hazard (Barnett and Mahul, 2007; Pacheco et al., 2016). Index insurance is a popular risk management tool for low-income agricultural communities (Müller et al., 2017) and pays policy holders when a measurable indicator that is correlated with expected losses crosses a set threshold. In doing so, index insurance avoids behavioral issues associated with false claims and moral hazard.

Importantly, access to risk management tools like insurance can alleviate the persistence of poverty traps by allowing relatively poor individuals and households of a given community, to make investments that would otherwise be too risky (Barnett et al., 2008). Index insurance is one example of a risk management tool that is being employed to provide this kind of financial aid. Others exist too, and many are based on informal agreements between individual food producers. For example, Kenyan pastoralists give each other access to their grazing lands when spatio-temporal variability in grazing land quality would otherwise lead to loss or low productivity of a herd (Dixit et al., 2013). This is a form of informal collective insurance that reduces the risk of livestock loss, and also improves the overall use of the grazing lands. This serves as an important example of communities self-organizing around risk, and acting cooperatively to minimize their shared risk, and ultimately improve the management of their environment.

Examples of self-organized collective insurance cooperatives are not limited to terrestrial systems. At sea, catch-pooling cooperatives mitigate risks in fisheries, especially when risks are uncorrelated among members of the cooperative (Sethi et al., 2012). In this paper, we study revenue-sharing collectives, a generalization of catch-pooling cooperatives. We use game theoretic analyses to generate baseline predictions and an agent-based evolutionary-game-theoretic framework to model the dynamics of revenue-sharing club membership, harvest effort, and the stock of the common-pool resource. When all harvesters are members of a revenue-sharing collective, the incentive structure mirrors that of a Pigouvian tax on harvest (where the tax income is redistributed equally) which is a general mechanism by which bioeconomic commons problems are resolved (Clark, 1976). However, in our framework, joining a club is voluntary, so the benefits of risk mitigation must outweigh the personal cost of sharing revenue with a group.

We answer two main questions. First, can revenue-sharing collectives emerge and be stable over time among a population of resource users? Second, how do revenue-sharing collectives impact harvesting behaviors in common-pool resource systems? We hypothesize that if revenue-sharing were adopted by users in a common-pool resource system, then, as a function of the fraction of revenue shared, incentives for over-exploitation may be mitigated. As we will show, revenue-sharing collectives create an incentive structure akin to a free-rider problem. That is, each harvester has an incentive to free-ride on the efforts of others and collect the benefits of the shared revenue stream. This counteracts the incentives for overexploitation that pervade common-pool resource systems, and also provides insurance against profit variability. Ultimately, our results shed light on the conditions under which revenue-sharing cooperatives can lead to the joint resolution of management and risk mitigation challenges, from the bottom up.

2. Methods

2.1. Model

We model a population of n harvesters of a common-pool resource with stock biomass R. Each harvester invests $e_i \in (0, e_{max})$ effort in resource extraction. The imposed effort maximum could be due to management constraining effort, or technological limits making higher levels of effort infeasible. Effort is transformed into profit through revenue from the sale of the extracted resource and the cost of harvesting. To incorporate the effect of idiosyncratic risk, profit depends on the observed state of the resource, which can differ from its true, underlying value. We model the profit of an independent harvester i as

$$\pi_i = pqe_i(R + \epsilon_i) - we_i \tag{1}$$

where p is the fixed price received for each unit of resource sold, q is the ‘catchability’ of the resource (a measure that transforms effort into catch), w is the cost per unit effort, and ϵ_i the ith element of $\epsilon \sim N(0, \Sigma)$, a random variable that represents sampling errors of the resource stock or spatiotemporal variability of resource biomass. Catchability depends on the ecology of the resource, and the technology employed by resource users. Here, we assume that catchability is uniform across harvesters, and constant through time.

A harvester may also belong to a revenue-sharing collective. We let C be the set of club members, and c_i be an indicator variable such that $c_i = 1$ when $i \in C$. With this notation, we can write the strategy of a harvester as $S_i = \{c_i, e_i\}$. Harvesters within a revenue-sharing club split a fraction, γ, of their revenue equally with members of the collective. The value of γ is the same for all members of the revenue-sharing collective, thus we are assuming a degree of coordination within the club. The resulting profit of members of the revenue-sharing club is

$$\pi_i = \frac{\gamma}{|C|}\left(\sum_{j\in C} pqe_j(R+\epsilon_j)\right) + (1-\gamma)(pqe_i(R+\epsilon_i)) - we_i. \tag{2}$$

Now, we consider the utility of the fishers. We are interested in the role of revenue-sharing as insurance as well as management. For harvesters to benefit from insurance, they must be risk averse. Risk aversion arises in evolution because fitness is multiplicative, leading to selection for bet-hedging strategies (Stearns, 2000). We additionally build risk aversion into our model via an exponential utility function that allows for the modulation of risk aversion. We can write the utility of a fisher as

$$U_i = \begin{cases} (1-e^{-a\pi_i})/a & : a \neq 0 \\ \pi_i & : a = 0 \end{cases} \tag{3}$$

so that increasing a increases the risk aversion of all the fishers. It is important to note that as $a \to 0$ we approach risk-neutrality. For simplicity, we assume that each harvester has the same level of risk aversion, a. An important further direction is to consider heterogeneity in risk aversion across individuals, and its effects on the prevalence of revenue-sharing clubs. Risk aversion of this form incentivizes individuals to join a revenue-sharing club because for $a > 0$, U_i is concave. By Jensen's inequality, we have

$$E[U_i(x)] \leq U_i(E[x]) \tag{4}$$

for any random variable x and concave function U. In our model profit is a random variable because of stochasticity in resource harvesting, but joining a revenue-sharing collective can decrease profit variance, and thus increase in utility.

Using this framework, we model the dynamics of effort and club membership with a pairwise comparison process: at each time-step two individuals are chosen at random. The first individual compares their utility with that of the second individual, and the first harvester emulates the strategy of the second harvester with a probability that scales with the utility differential between them. The probability of transition from strategy S_i to strategy S_j is given by

$$Pr(S_i \to S_j) = \frac{1}{1+e^{-\delta(U_j - U_i)}} \tag{5}$$

where δ is a measure of the strength of selection (Traulsen et al., 2007). There is also a probability, μ, that a global mutation will occur and instead of switching (or not) to a new strategy, a random strategy (both effort and club membership) will be selected. Furthermore, when individual i emulates individual j there is a small error in copying the strategy (local mutation). Individuals always copy the club membership accurately, as this is easily observable and binary, but effort is copied with noise such that the new harvest effort of individual i is $e_i = e_j + \alpha$ where $\alpha \sim N(0, v^2)$.

Within this dynamic process, we also integrate feedbacks of harvesting on the state of the resource. Stocks of living common-pool resources are in constant flux due to the harvesting and growth of the resource. These dynamics alter the payoff structure, incentives for harvesting, and appeal of revenue-sharing clubs. Initially, we incorporate resource dynamics by assuming that they occur on a faster time scale than the strategy decisions of harvesters. This separation of time scales implies that we can write the resource level as

$$R = k\left(1 - \frac{qE}{r}\right), \tag{6}$$

the equilibrium level of the resource under the ecological harvesting model given by

$$\frac{dR}{dt} = rR\left(1 - \frac{R}{k}\right) - qRE \tag{7}$$

where r is the intrinsic rate of growth of the fish stock, k is the carrying capacity of the stock, q is the catchability of the resource, and E is the total harvesting effort of the population of fishers. Later, we explore the case where strategy updating and resource dynamics occur on the same timescale, adding complexity to the feedbacks between harvest strategies and the state of the resource. This harvest function assumes that catch is linear in both effort and stock abundance.

With this framework, we study the evolution of harvesting strategies within and outside a revenue-sharing club, as well as changes in overall club membership levels. These dynamics lead to changes in resource abundance that are of both management and ecological interest. In addition to modeling the temporal dynamics of harvesting effort and club membership for all harvesters, we also track aggregate behavior of the population. This yields patterns that give insight into the viability of revenue-sharing collectives as a function of ecological parameters, economic conditions and the design choices of revenue-sharing clubs, such as the fraction of revenue that is collectively shared.

2.2. Analytical benchmarks

To assess the impact of revenue-sharing on harvesting behavior we establish benchmarks to change the results of simulations with what is expected to occur in theory. First, we can calculate the Nash equilibrium individual harvesting effort under the assumption that harvesters seek to maximize expected utility, and that there is no revenue-sharing, ($\gamma = 0$). In general, we expect this level of effort to be favored by behavioral selection when there is no revenue-sharing club. However, this may not hold when the population size is small because inter-generational variance in utility may make variance in expected utility more important for driving the evolution of behavior within our simulation model.

To calculate the Nash equilibrium effort from the expected utility of independent harvesters, we start with the utility function from Eq. (3) and assume that the resource goes to equilibrium, and that every other harvester employs effort equal to $e_{\sim i}$ and $a \neq 0$. Under these assumptions, the utility of harvester i is

$$U_i(e_i, e_{\sim i}) = \frac{1}{a} - \frac{e^{-a\left(pqe_i\left(k\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)+\epsilon_i\right)-we_i\right)}}{a}. \tag{8}$$

Now we wish to calculate the expected value of U_i, given that $\epsilon_i \sim N(0, \sigma^2)$. We have

$$E[U_i(e_i, e_{\sim i})] = E\left[\frac{1}{a} - \frac{e^{-a\left(pqe_i\left(k\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)+\epsilon_i\right)-we_i\right)}}{a}\right], \tag{9}$$

which, by the linearity of the expected value operator, is equal to

$$E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{E\left[e^{-a\left(pqe_i\left(k\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)+\epsilon_i\right)-we_i\right)}\right]}{a}. \tag{10}$$

Other than ϵ_i, all elements within the expected value operator on the right-hand side of Eq. (10) are constants. Therefore, we can write

$$E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{e^{-a\left(pqe_ik\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)-we_i\right)}E[e^{-apqe_i\epsilon_i}]}{a}, \tag{11}$$

once again, by the linearity of the expected value operator. Finally, since ϵ_i is normally distributed, $e^{-apqe_i\epsilon_i}$ is log-normally distributed, with mean $e^{\frac{(apqe_i\sigma)^2}{2}}$. Therefore, the expected utility of harvester i, given that every other harvester employs effort $e_{\sim i}$ and $a \neq 0$, can be simplified to

$$E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{e^{awe_i}}{ae^{apqe_ik\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)}} e^{\frac{(apqe_i\sigma)^2}{2}} \tag{12}$$

where σ^2 is the variance in the resource that individuals face when harvesting. The final term in Eq. (12) is the influence of variance on expected utility. The rest of the terms represent the utility under certainty, since when $\sigma \to 0$ the final term in the expected utility goes to 1.

Setting the partial derivative with respect to e_i of Eq. (12) equal to zero and then letting $e_{\sim i} = e_i$, and solving for e_i gives the Nash equilibrium level of effort for a population of independent harvesters. We have

$$e^*_{\text{Nash}} = \frac{r(pqk-w)}{(n+1)pq^2k + arp^2q^2\sigma^2} \tag{13}$$

when $pqk - w > 0$ and $e^*_{\text{Nash}} = 0$ otherwise. We ignore cases where $pqk - w < 0$ because these are the trivial cases where the resource cannot be economically harvested. Note that as the resource variance, σ^2, increases, the equilibrium level of harvesting declines because increased risk decreases the marginal gains from higher effort.

We can similarly calculate the level of effort that we expect if all individuals are members of a revenue-sharing club. We assume that the noise (in the level of the resource stock) that each harvester observers, ϵ_i, is independent. First, we find the expected utility of a focal individual in a revenue-sharing club, following the same steps as above. We have

$$E[U_i(e_i, e_{\sim i})]$$
$$= \frac{1}{a} - \frac{e^{awe_i} e^{\frac{n-1}{2n^2}(a\gamma pqe_{\sim i}\sigma)^2} e^{\frac{(a(1-\gamma+\gamma/n)pqe_i\sigma)^2}{2}}}{ae^{a\frac{n-1}{n}\gamma pqe_{\sim i}k\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)} e^{a(1-\gamma+\gamma/n)pqe_ik\left(1-\frac{q(e_i+(n-1)e_{\sim i})}{r}\right)}} \tag{14}$$

for the expected utility of a member of a cooperative when γ is the fraction of everyone's revenue that is shared equally among group members. We can use this to calculate the effort that we expect these individuals to employ at equilibrium following the same steps as above.

This effort level is

$$e^*_{\text{share}} = \frac{r\left(pqk\left(1-\gamma+\frac{\gamma}{n}\right)-w\right)}{pq^2k + npq^2k\left(1-\gamma+\frac{\gamma}{n}\right) + arp^2q^2\sigma^2\left(1-\gamma+\frac{\gamma}{n}\right)^2} \tag{15}$$

for $\gamma < \frac{n(pqk-w)}{(n-1)pqk}$ and 0 otherwise. This formula is consistent with e^*_{Nash} because when $\gamma = 0$, $e^*_{\text{share}} = e^*_{\text{Nash}}$. Just as the Nash level of effort does not align with the level of effort that would maximize the total utility of the population, the effort that results from a revenue-sharing club also does not necessarily align with socially optimal harvesting. We calculate socially optimal harvesting under revenue-sharing by letting $e_{\sim i} = e_i$ in Eq. (14), and setting the partial derivative with respect to e_i equal to zero. Solving this gives the optimal harvesting effort of a member of a revenue-sharing collective as

$$e^*_{\text{opt}} = \frac{r(pqk-w)}{2npq^2k + arp^2q^2\sigma^2\left(1-\gamma+\frac{\gamma}{n}\right)^2}, \tag{16}$$

which, counterintuitively, depends on the fraction of revenue shared, γ. This is because risk, in this context the variance of the observed resource stock, σ^2, alters harvesting behaviors, and is mitigated via revenue-sharing. High fractions of revenue-sharing with a large club size diminish the influence of risk on harvesting effort. The optimal level of effort, e^*_{opt}, may be a management target because it corresponds with aggregate harvesting that maximizes the total utility of all harvesters of the common-pool resources. Managers may also aim to maximize yield, as opposed to profit, if the supply of the resource to consumers is of primary concern. A revenue-sharing collective is defined by the fraction, γ, of revenue that is shared. As shown in Fig. 1, depending on γ, members of a collective may invest more harvest effort (or less) than would align with e^*_{opt}. Furthermore, collectives may face a tradeoff. If γ is too high, then the collective may not be attractive because free-riding will be rampant. On the other hand, if γ is too low, then the risk reduction and management benefits of revenue-sharing will be missed.

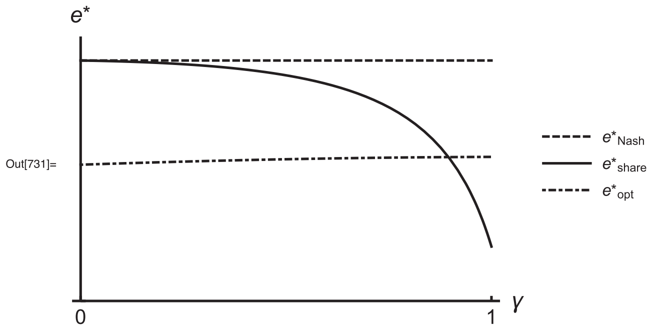


Fig. 1. Effort benchmarks as a function of γ, the fraction of revenue shared, showing that as γ increases, members of a revenue-sharing club will reduce their effort toward the optimal level. The intersection of the revenue-sharing effort with optimal effort occurs at an intermediate level of γ. e^*_{opt} is increasing in γ however, the magnitude of this increase is small relative to the changes in e^*_{share}.

2.3. Simulation experiments

To assess the efficacy of revenue-sharing collectives as a bottom-up governance institution, we systematically vary key parameters and observe the effect that this has on the prevalence of revenue-sharing clubs, the state of the resource stock, and the harvest effort employed. Primarily, we focus on the fraction of revenue shared, γ, and the degree of risk aversion, a. The degree of risk aversion is a measure of how much harvesters value reductions in income volatility, and as such should strongly influence the likelihood of the emergence of revenue-sharing clubs. From a management perspective, the fraction of revenues that are shared collectively, γ, is key tool for restraining over-harvesting. Taken together, the degree of risk aversion, and the fraction of revenue shared will give a good indication of the likelihood of revenue-sharing clubs emerging.

We observe the results from three perspectives. First, we show time series of the behavior of individual harvesters. In these figures, the effort of individual harvesters can be seen with colored dots, and average effort at every time step is shown in black. These figures show that even though the dynamics of individual harvesters are stochastic, at the population level patterns emerge.

In order to get a clearer view of these population level patterns, we aggregate behaviors through time to generate histograms showing the long-run distribution of effort employed by independent or revenue-sharing harvesters. These figures help illustrate how revenue-sharing agreements shift harvesting behavior toward lower, more sustainable levels.

Finally, we summarize the complexity of each of the above types of simulations by their impact on the average harvest effort, average resource level and average frequency of revenue-sharing clubs. This allows us to display results from many simulations, across ranges of parameter values. We analyze these long-term means across various parameter value combinations for γ and a.

We display the results as heat maps that highlight the conditions under which revenue-sharing collectives are most prevalent and lead to the greatest improvements in the use of unmanaged resources.

3. Results

In this section, we show simulations of the model and compare outcomes from them with predictions made about what strategies should be favored by selection. First, we examine the case where no harvesters share revenue. Here we expect Nash effort to be favored. We can assess if this holds by examining time series and histograms of simulations where all harvesters are independent and have no option of joining a revenue-sharing club. Next, we examine the case where all harvesters are members of a revenue-sharing club. In this case, we expect e^*_{share} to be favored by the evolutionary process.

Finally, we examine the case where club membership, as well as harvesting effort evolves. Under these dynamics, we do not have a good ex-ante expectation about what dynamics will result. However, we can break the coupled dynamics down to three separate regimes. When the population is dominated by a revenue-sharing club, we expect the dynamics to resemble that which occurs when independent harvesting is not possible. Similarly, when independent harvesters dominate, we expect the effort profiles to resemble that which results when only independent harvesting is possible. When there is a mixed population of independent harvesters and members of a revenue-sharing club, we do not have a good hypothesis about what strategies will emerge. For a low global mutation rate, transitions between the club dominated and independent dominated state may be fast relative to the time spent in each of these states, and the dynamics of the whole system can be decomposed into transitions between these two states. For higher mutation rates, significant time may be spent in this more complex internal regime.

3.1. Independent harvesting

In this section, we simulate the dynamical process in the absence of the possibility for revenue-sharing. This serves as a baseline case that recapitulates the tragedy of the commons in open access common-pool resources. In general, the simulations conform with theory, showing that in the long run, the Nash equilibrium level of harvesting is favored by selection, and that through time average harvest effort tracks the Nash equilibrium well. Individual effort is widely distributed about the Nash equilibrium, showing that even though aggregate behavior tracks the Nash equilibrium, individual effort does not. At low population sizes, aggregate effort diverges from the Nash equilibrium. We hypothesize that this divergence of our simulations from our predictions is a result of selection favoring strategies that maximize geometric mean fitness. Our analysis of the Nash equilibrium assumes that harvesters seek to maximize arithmetic mean fitness. The difference between these measures is greatest when the population of harvesters is small and it is under this scenario that our simulations do not conform to the Nash equilibrium. In Fig. 2, the simulation shows the dynamics of harvesting effort when harvesters share no revenue. In accordance with analytical theory, average effort tracks the Nash equilibrium well. To illustrate this, Fig. 3 shows a histogram of effort under independent harvesting. Next, we assess the effect that revenue-sharing has on harvesting, and seek to determine the degree of revenue-sharing that leads to optimal harvesting.

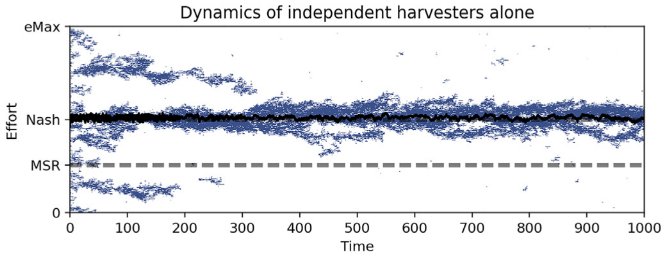


Fig. 2. Effort of individual harvesters (blue) and average effort at every point in time (black). The lower and upper horizontal lines correspond to the socially optimal and Nash equilibrium levels of effort, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

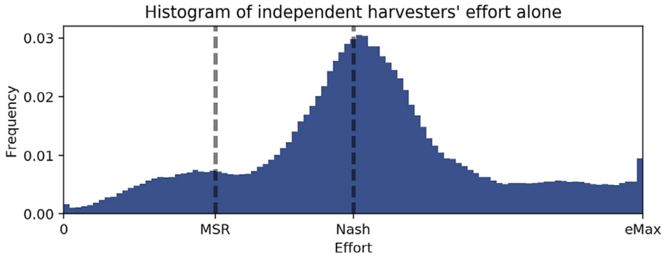


Fig. 3. Histogram of frequency of different effort levels. The left and right vertical lines correspond to the socially optimal and Nash equilibrium levels of effort, respectively.

3.2. Revenue-sharing

In this section, we explore the case where all harvesters are members of the revenue-sharing collective. We show that adherence to a revenue-sharing agreement can lead to optimal harvesting of a common-pool resource. The framework is the same as above, however, in this section all harvesters share a fraction of their revenue. The fraction that is shared influences harvester behavior. If no revenue is shared then harvesting will match the independent harvester case. If all revenue is shared, then harvesters may not find it worthwhile to invest any effort in resource extraction. Therefore, at some intermediate level of revenue shared, we expect harvester aggregate effort to align with the social optimum. We can calculate the fraction of revenue shared that leads to optimal harvesting by setting $e^*_{\text{opt}} = e^*_{\text{share}}$ and solving for γ. Assuming a large population size, we can concisely write the level of sharing that leads to optimal harvesting as

$$\gamma^* = \frac{pqk - w}{pqk + w}. \tag{17}$$

when $\gamma = \gamma^*$ we predict harvesting of those in a revenue-sharing club to align with the social optimum. Critically, the level of γ that leads to the social optimum depends on only a few parameters that are fundamental to the ecology of the resource, (k), and the economics of its harvest, (p, w, q). Although this level of gamma is only exact in the large population limit, it is a good approximation for most population sizes.

This is highlighted in Fig. 4. We let $\gamma = \gamma^*$ and average effort tracks the social optimum well, with a population size $n = 100$. Further, Fig. 5 shows that in the long run, harvesting with effort near the social optimum is favored by selection. This shows that revenue-sharing can lead to optimal management of a common-pool resource because it creates an incentive for fishers to reduce their own effort while benefiting from the harvesting effort of others, leading to reductions in total effort relative to the unmanaged case. This causes increases in abundance of the harvested species, and improvements in the profits and utility of all fishers. Further,

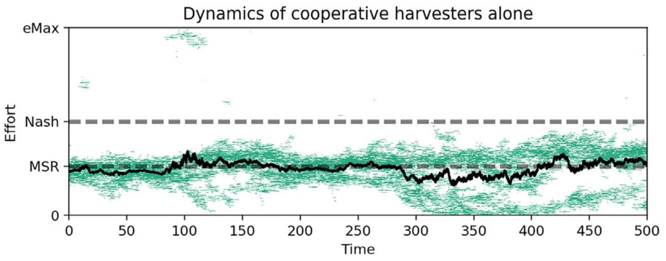


Fig. 4. Effort of individual harvesters in green and average effort at every point in time is shown in black. The lower and upper horizontal lines correspond to the socially optimal and Nash equilibrium levels of effort, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

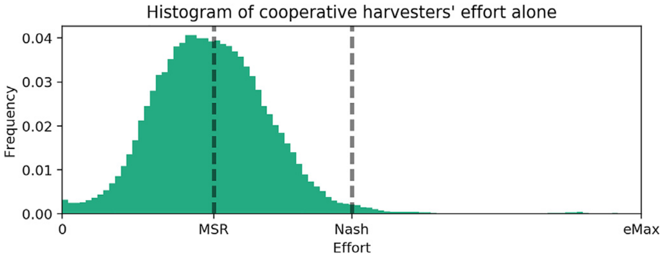


Fig. 5. Histogram of frequency of different effort levels for harvesters who are members of a revenue-sharing club. The left and right vertical lines correspond to the socially optimal and Nash equilibrium levels of effort, respectively.

revenue-sharing acts as an insurance mechanism against the risk of low harvests, and low profits. All else being equal, the utility of risk-averse harvesters increases with reductions in the variance of their revenue. For this reason, the variance reduction that results from revenue-sharing increases the utility of the harvesters.

3.3. Coupled dynamics of independent harvesters and club members

Our first result does not demonstrate if such revenue-sharing agreements will emerge and stabilize optimal harvesting of common-pool resources. For instance, independent harvesters may be able to invade and diminish the gains that result from revenue-sharing agreements. To evaluate this possibility, we now explore the effect of interactions between independent harvesters and a revenue-sharing club where we allow individuals to enter and exit the revenue-sharing agreement. In particular, we explore the full model with simulations of the dynamics and systematically sweep the parameter space to highlight conditions under which there is the greatest potential for revenue-sharing agreements to emerge and lead to improvements in resource harvesting. Simulations track the strategies, both club membership and harvesting effort, of all individuals through time.

This allows for the analysis of the statistical properties of strategy profiles in the long run. Initial dynamics can be complex, but in the long run, the average strategy choices favored by selection emerge. As an example, in Fig. 7 the efforts of individual independent harvesters and those in the revenue-sharing collective are plotted. When these effort trajectories are compared with the fraction of harvesters in the revenue-sharing club in Fig. 6, three apparent ‘regimes’ appear to dominate the dynamics: two states where either independent harvesters or those in the cooperative dominate, and a mixed state where both types coexist with highly polarized effort. Independent harvesters extract at maximal effort and those in the cooperative invest almost no effort.

These trajectories are illustrative of some dynamics of the system, however, to get a better understanding of the long-term frequencies of different strategies, we create histograms that show

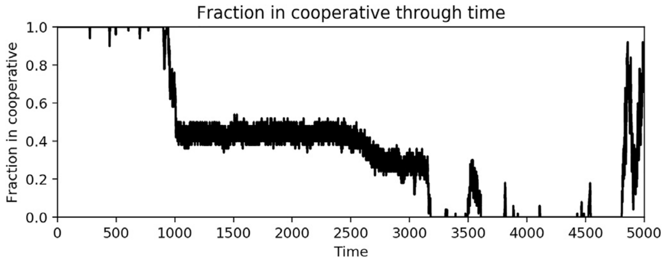


Fig. 6. Fraction of harvesters in the revenue-sharing collective through time.

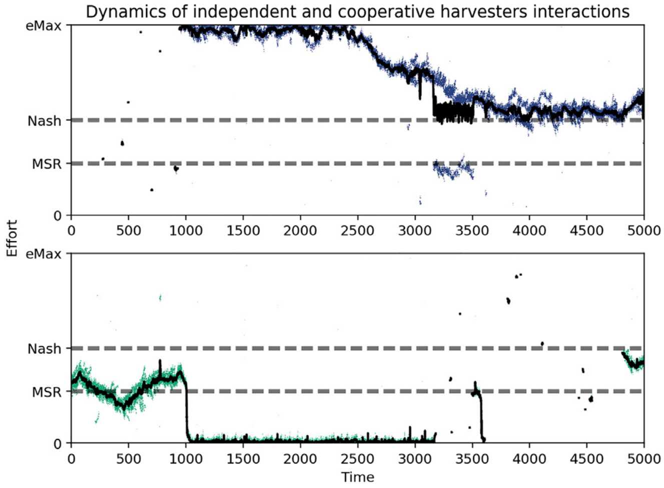


Fig. 7. Effort of independent harvesters (top panel) and those in the revenue-sharing collective (bottom panel). Average effort at every point in time is shown in black on each graph. The lower and upper horizontal lines correspond to the socially optimal and Nash equilibrium levels of effort.

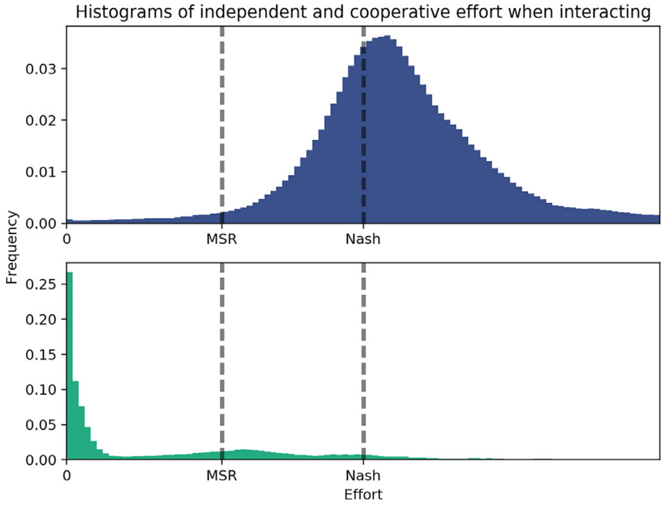
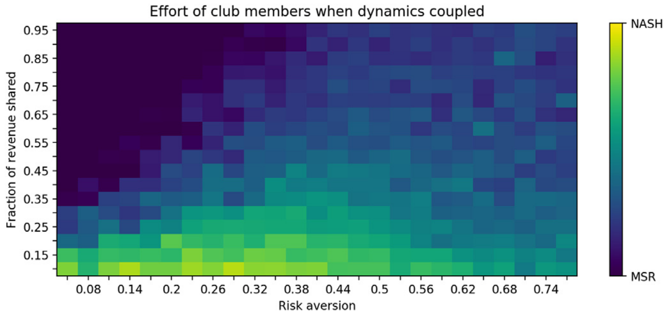


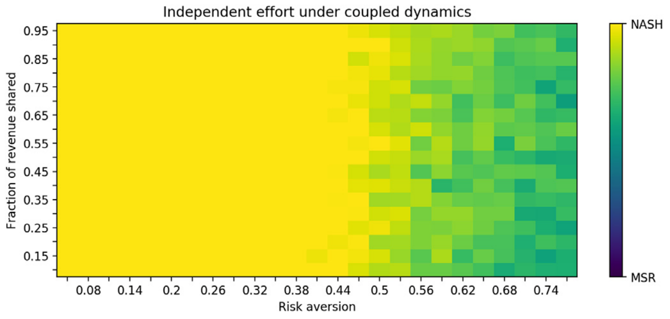
Fig. 8. Frequency of harvesting effort for independent fishers (top panel) and those in the revenue-sharing collective (bottom panel).

the effort choices of independent harvesters and those in the collective. In Fig. 8, the effort of those in the collective tends to be lower than those who harvest independently. This has critical implications for the effects of revenue-sharing agreements on the management of resources, if those in the collective decrease their harvesting effort, then this should lead to an increase in both fish stock level and the profitability of the fishery.

To evaluate how the management benefits of revenue-sharing depend on critical parameters, we vary the fraction of revenue

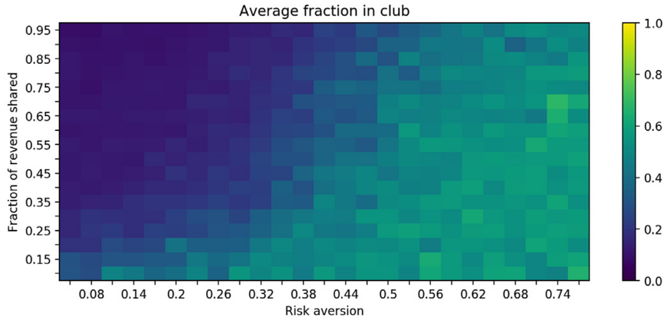


(a) Average effort of members of the revenue-sharing agreement

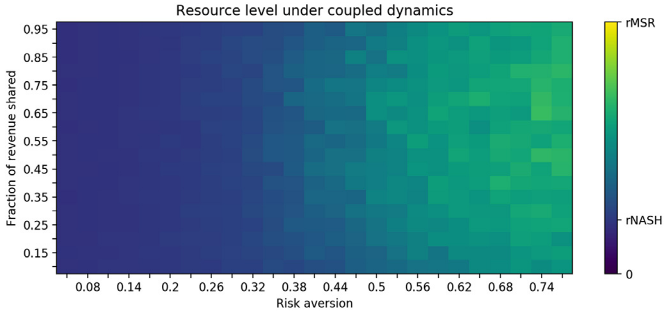


(b) Average effort of independent harvesters

Fig. 9. Average effort as a function of risk aversion and fraction of revenue shared.



(a) Average Frequency of revenue sharers



(b) Average resource stock level

Fig. 10. Prevalence of revenue sharers and average resource stock level.

shared, γ, and the degree of risk aversion, a. In Fig. 9, plots of average effort as a function of fraction of revenue shared and degree of risk aversion are shown.

Fig. 9 shows that members of the revenue-sharing club harvest with less effort than independent harvesters. Further, the degree of effort reduction by those in the collective increases in the fraction of revenue shared, γ, as expected. Fig. 10 quantifies the impact that this has on the state of the resource and the prevalence of revenue-sharing agreements. When the average fraction of the population that is part of a revenue-sharing agreement is higher, so are average resource stock levels. However, the benefits of revenue-sharing are minimal when γ is small. Revenue-sharing agreements are uncommon when risk aversion is low, but for higher levels of risk aversion, agreements become more common even if a significant fraction of revenue is shared. It is under these conditions that revenue-sharing will be most beneficial for management.

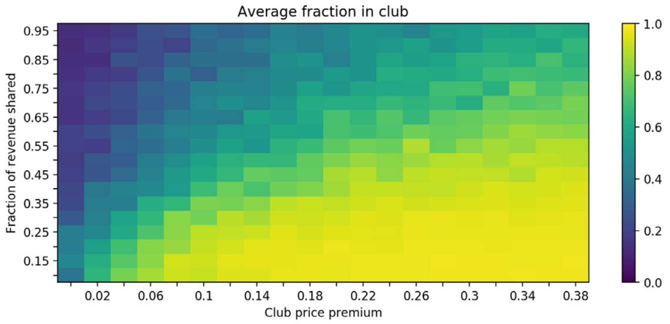


Fig. 11. Fraction of harvesters that are in a revenue-sharing collective through time.

3.4. Price premium

Although revenue-sharing collectives promote the emergence of improved harvesting practices under some circumstances, additional mechanisms may increase the range of parameters under which this results. One such mechanism is a price premium, where harvesters who are members of a revenue-sharing collective receive a higher price for their harvest than independent harvesters. A price premium could result from consumer demand for products that are viewed as environmentally friendly, or a desire by consumers or managers that food purchases contribute to the wellbeing of the those in the supply chain. These drivers can be seen in the increased prices that consumers are willing to pay for sustainably harvested timber, organically grown food or fair-trade products. In this section, we examine the relationship between the magnitude of the price premium and the prevalence of revenue-sharing clubs.

We have shown that revenue-sharing collectives are most common under high risk aversion and a low fraction of revenue-sharing. Improvements in management are greatest under high risk aversion and a moderate fraction of revenue-sharing. Here, we explore the potential for price premiums for harvest from a revenue-sharing collective to promote the stability of these clubs and enhance overall sustainability of resource use. We modify the model from previous sections by increasing the price that those in the revenue-sharing collective receive relative to independent harvesters. We simulate the average fraction of the population that is in a revenue-sharing collective as a function of the magnitude of price premium that they receive. As seen in Fig. 11, even small premiums can greatly increase the rate of revenue-sharing in the population. In this simulation, revenue-sharing is uncommon when there is no price premium, but when the price premium for resource harvested in the revenue-sharing collective is 12%, revenue-sharing dominates even when a high fraction of revenue is shared. This leads to increased resource stock biomass and harvester profits.

3.5. Coupled resource dynamics

In this section, we relax the assumption that resource dynamics occur on a fast timescale relative to strategy dynamics.

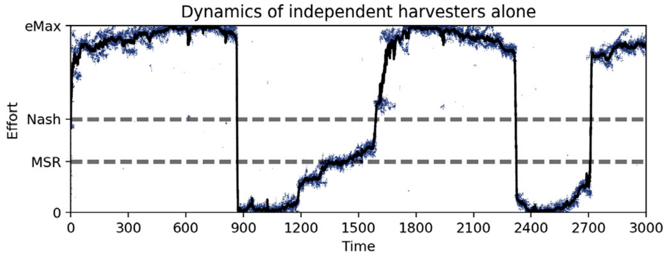


Fig. 12. Effort of a population of independent harvesters with slow resource dynamics.

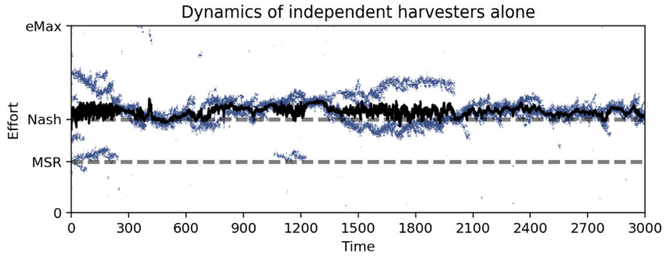


Fig. 13. Effort of a population of independent harvesters with fast resource dynamics.

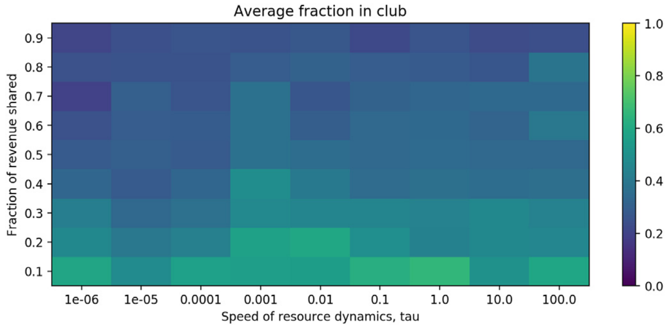


Fig. 14. Fraction in a revenue-sharing club as a function of the fraction of revenues shared, γ, and the speed of the resource dynamics relative to the strategy update process, τ.

This timescale separation simplifies the dynamics and provides a stronger signal to resource users of their impact on the state of the resource stock. For this reason, our initial analyses focused on the case were resource dynamics were fast. By relaxing the timescale separation, we can analyze the sensitivity of our results to this assumption. We systematically vary the relative timescales of the resource and the strategy update processes by modeling the resource R for time τ between each strategy update step. For large τ the resource approaches equilibrium between every strategy update, corresponding to our previous analyses. For small τ, many strategy update iterations may occur before the resource approaches its new equilibrium. In fact, the resource may systematically lag the strategy dynamics and never approach equilibrium. This time-lag may be destabilizing, possibly driving boom and bust resource dynamics.

For comparison, Fig. 12 shows that slow resource dynamics leads to alternations between very high and very low harvesting effort. These fluctuations coincide with long-term resource fluctuations. Holding all else equal, under fast resource dynamics (Fig. 13) These fluctuations do not occur. We analyze whether this has an overall impact on the results of previous sections.

Fig. 14 shows that there is not a strong impact of resource dynamics speed on the average fraction of harvesters who participate in a revenue-sharing club in the long-term. While the trajectories of resource biomass and harvest effort change, there appears to be minimal impact on long-term averages predicted under fast resource dynamics.

We find that while the relative timescales of resource dynamics and strategy dynamics does have a destabilizing effect on the strategy profiles and resource stock, the impact on long-term harvesting behaviors in aggregate is limited. This seems to indicate that the results of previous sections will hold even if the assumption of fast resource dynamics is not strictly met.

4. Discussion

Standard bio-economic theory prescribes taxes or tradable permits as a general solution to the commons problem (Clark, 1976). If the level of taxation is chosen to equal the size of the externality, then implementation of the tax will lead to optimal harvesting. A similar outcome occurs when the correct number of tradable permits are granted. We study a related mechanism of solving the commons problem, where individuals can voluntarily join a revenue-sharing club, which performs the same function as a revenue neutral tax on club members. Revenue sharing is a specific solution to the commons problem that shares similarities with general solutions, such as taxes. However, joining revenue-sharing club is not mandatory, so it will only be effective when most harvesters belong to the club. Further, the reduced effort that club membership induces is only beneficial when there is a compensatory response to decreased effort, as is the case in fisheries, and other living resource systems.

Another issue that is integral to bioeconomic analyses and a primary challenge of managing the commons is the degree to which the returns to better management are delayed. Our analysis of the degree of timescale separation indicates that this does not have a strong impact on long-run dynamics within our model. We suspect that this results because the delayed response of the resource makes it difficult for both independent and club harvesters to coordinate around an equilibrium strategy. This can lead to cyclic dynamics where each group overshoots the intended equilibrium and is replaced by the other group. This ultimately gives revenue-sharing clubs an opportunity to invade, after independent harvesters overshoot Nash equilibrium effort, causing an eventual resource collapse.

For harvesters of natural resources that are subject to stochastic variation, a revenue-sharing club can provide an immediate benefit via risk mitigation, and this immediate benefit can promote the emergence of clubs, which, in the end, result in improved management. While the immediate benefit of revenue-sharing is a club good, and available only to members of the group, the long-term benefits of increased stock biomass are a public good, and available to all harvesters. This tension makes revenue-sharing clubs vulnerable to collapse after they become established. Ultimately, for a club to be stable, the benefit of the club good (reduced risk) must outweigh the temptation to overexploit the resource unilaterally once the stock is rebuilt (the public good). The degree of benefit to management that such clubs provide is constrained by this tension.

Our evolutionary agent-based model shows that revenue-sharing clubs can self-organize and emerge amongst common-pool resource harvesters because they provide revenue insurance and stabilize income. As a co-benefit, revenue-sharing clubs also reduce the incentive of each harvester to overexploit the resource. This can lead to improved usage of the resource, but it also incentivizes free-riding behaviors that can undermine the stability of the revenue-sharing club. Critically however, unlike most other common-pool resource systems where free-riding leads to harm, here it leads to reduced harvest effort which ultimately leads to a greater total harvest rate more closely aligned with optimal resource management. To explore the balance between the positive and negative effects of revenue-sharing on harvesting behaviors, we systematically varied the fraction of revenue that was pooled and divided equally among members of the revenue-sharing club. When all harvesters are members of a revenue-sharing club, harvesting can be aligned with the socially optimal harvesting strategy, as long as the correct fraction of revenue is shared. When harvesters can choose both their effort level and whether or not to join a revenue-sharing club, the situation is more complex. If harvesters are highly risk averse, and an intermediate fraction of revenue is shared, then revenue-sharing clubs can lead to modest improvements in the management of common-pool resources. Furthermore, if revenue-sharing club members receive a higher price for their product when sold, then the conditions under which revenue-sharing clubs emerge (and which have positive effects on the resource) expand greatly.

Our results show that revenue-sharing agreements can be an important catalyst for bottom-up governance in social ecological systems. In contrast to traditional management, revenue-sharing agreements do not rely on coercion or external enforcement. Rather, agreements are joined voluntarily and reductions in harvest effort result from individuals pursuing their own self-interest. Our model does not specify exactly how a revenue-sharing club would be implemented, and we assume that adherence to the sharing regime occurs without costs. In practice, mechanisms from simple cash-in-hand procedures, to contractual agreements could be employed. The success of revenue-sharing agreements may increase in conjunction with alternative bottom-up management strategies, and will depend on how easily adherence can be achieved. Similarly, we do not model the process by which a price premium occurs, but we imagine that support fromnon-governmental agencies could be procured, especially as the revenue-sharing agreement will lead to improved resource governance. Revenue-sharing clubs could also work in concert with fisheries management organizations, where in addition to setting quota limits, management could help develop mechanisms for achieving price premiums within revenue-sharing clubs. Ultimately, we envision price premiums as an extremely useful tool for this form of management because they strongly incentives club membership.

Just as management via social norms requires individuals to take costly actions to enforce harvesting practices via punishment or ostracism, management via revenue-sharing requires that the harvest is accurately measured and split. With revenue-sharing, bottom-up management might be able to emerge even in communities where the strong social bonds needed to enforce norms are not present. On the other hand, the process of establishing and managing a revenue-sharing club may strengthen social ties among members and allow for further improvement and stabilization of management via social norms. In this way, revenue-sharing clubs may plant the seeds of more formalized (collective action) management institutions. While improved common-pool resource governance is the co-benefit of the insurance provided by the revenue-sharing collective, the main benefit to the harvesters is the reduction in income risk. This is often a pre-condition for long-term business success and growth, and in some cases poverty alleviation and food security. With revenue-sharing agreements, both ends can be achieved in concert though a single mechanism.

Our work is relevant to common-pool resource systems, most notably small-scale (artisanal) fisheries in the developing world, which often lack strong formal governance institutions and/or the means to enforce policies. In this context, revenue-sharing clubs among harvesters from a community may be a useful alternative approach for fishers to improve harvesting practices. The focus would be on creating market mechanisms for guaranteeing a price premium for fishers who join/create revenue-sharing collectives. Further, in addition to artisanal fishing communities, these revenue-sharing agreements may also be useful within managed fisheries (in developed countries say). Under total allowable catch management, a race to fish often occurs, but this could be mitigated with revenue-sharing.

Although this work applies most directly to fisheries management, the approach is applicable to many common-pool resource systems. For the benefits of revenue-sharing to be present, however, harvest of the resource at any point in time must not be perfectly correlated across individuals. This will hold for spatially patchy resources, but not for spatially uniform but seasonal resources. Under the former setting, revenue-sharing can lead to joint environmental and economic wins. It is worth noting that many food producers have natural risk management tools based upon these characteristics on their environment. For example, fishermen are known to operate in a variety of fisheries, spread throughout the year, so that they smooth their income over this time-frame (Kasperski and Holland, 2013). Similarly, small-holder agriculturalists in developing regions often grow polycultures as a way to spread their risk in production. Also worth noting is that there are problems associated with presenting alternative risk management tools to food producers, as it can lead to changes in approaches to risk management. For example, a farmer may shift to monoculture if part of a revenue-sharing collective. This is an important example of moral hazard (Müller et al., 2017).

Another important caveat of our work is that within our modeling framework, we have assumed that harvesters are symmetric, each having identical abilities of harvesting and levels of risk aversion. Further, we model a single revenue-sharing club that any harvester can enter or exit. This implies that all individuals are identical and that members of the club cannot exclude anyone. Also, we also assume that the fraction of revenue shared, γ, is set by the club. If individual resource users could select their own γ, deterioration of contributions would be expected. In practice, monitoring of contributions within the club will be necessary to assure that members do not under-contribute to the club. A related simplification we employ is assuming that the level of risk aversion is the same for all harvesters. In reality, there may be variation among harvesters in their degree of risk aversion, and this variation could impact individuals decision to enter or leave the system, opening a new dimension of dynamical responses were the level of risk aversion can co-evolve with resource use strategies. In future work, heterogeneity among harvesters in their ability level and degree of risk aversion could be studied, and the agent-based nature of our simulation methods are amenable to such investigations. Further, in reality it may be the case that multiple (small) revenue-sharing clubs will be operational in a given common-pool resource system, and this may be more effective than a single large one. Identifying under what environmental and human-behavioral conditions this is so is the next step in this line of research.

In sum, governance of common-pool resources is one of the central challenges facing societies today. Many such resources are located in regions of the world where formal top-down management institutions either do not exist or are ineffective. Further, trans-boundary problems, where the harvested resource spans many (international) jurisdictional boundaries or management institutions, are prevalent. For example, as in the case of high seas fisheries, many common-pool resources fall outside the reach of any nation's governance institutions. These challenges call for novel approaches to bottom-up governance. In this paper, we have examined a new financial tool – revenue-sharing collectives – and have determined in part the social and ecological conditions that are most favorable for its use for management. We find that highly variable resources can be managed this way if harvesters are sufficiently risk averse and a moderate fraction of their revenue is shared. If resources harvested within a revenue-sharing collective can be sold at a price premium, then the conditions under which revenue-sharing clubs can emerge and be stable over time is greatly expanded. In general, we show that risk mitigation strategies can be used as a catalyst for common-pool resource harvesters to cooperatively self-govern, leading to both economic and environmental wins.

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Appendix A. Parameters and variables

Parameter	Description
R	Resource biomass
f_c	Fraction of resource users in the revenue-sharing collective
γ	Fraction of revenue shared among members of collective
a	Degree of risk aversion of resource users
r	Intrinsic growth rate of the resource
k	Carrying capacity of the resource
q	Catchability of the resource
n	Population size of resource users
e_i	Effort of harvester i
π_i	Profit of harvester i
U_i	Utility of harvester i
p	Price per unit of resource sold
w	Cost per unit of effort
σ_i^2	Variance of resource sampling noise
c_{ij}	Covariance of resource sampling noise between harvesters i and j
ϵ_i	Normally distributed resource sampling noise for harvester i
C	Set of revenue-sharing club members
c_i	Indicator variable of club membership for individual i
S_i	Strategy of harvester i, composed of effort and club membership (e_i, c_i)
δ	Strength of selection
α	Normally distributed, small error in effort emulation during update process
μ	Probability that a random strategy is chosen during update process (mutation)
τ	Resource simulation duration between successive strategy update events

Appendix B. Figure parameters

Figure	γ	a	r	k	q	n	p	w	σ^2	c	δ	α	μ	τ
1	0 – 1	0.3	2	1300	0.9	12	2	125	1500	0	N/A	N/A	N/A	N/A
2	*N/A*	0.5	3	650	0.2	125	7	300	120	0	1.5	0.001	0.0006	N/A
3	*N/A*	0.65	3	1000	0.5	100	1	100	2000	0	2.5	0.001	0.0004	N/A
4	2/3	0.65	3	1000	0.5	100	1	100	2000	0	2.5	0.001	0.0004	N/A
5	2/3	0.65	3	1000	0.5	100	1	100	2000	0	2.5	0.001	0.0004	N/A
6	2/3	0.65	3	1000	0.5	50	1	100	2000	0	2.5	0.001	0.0004	N/A
7	2/3	0.65	3	1000	0.5	50	1	100	2000	0	2.5	0.001	0.0004	N/A
8	2/3	0.65	3	1000	0.5	100	1	100	2000	0	2.5	0.001	0.0004	N/A
9	0.1–0.95	0.05–0.77	3	1000	0.5	50	1	50	1000	0	0.5	0.005	0.008	N/A
10	0.1–0.95	0.05–0.77	3	1000	0.5	50	1	50	1000	0	0.5	0.005	0.008	N/A
11	0.1–0.95	0.3	3	1000	0.5	50	1	50	1000	0	0.5	0.005	0.008	N/A
12	2/3	0.65	3	1000	0.5	50	1	100	2000	0	2.5	0.001	0.0004	10^{-5}
13	2/3	0.65	3	1000	0.5	50	1	100	2000	0	2.5	0.001	0.0004	1
14	0.1–0.9	0.3	3	1000	0.5	45	1	50	2000	0	0.5	0.005	0.008	$10^{-6} - 10^{2}$

References

Andrew, N.L., Béné, C., Hall, S.J., Allison, E.H., Heck, S., Ratner, B.D., 2007. Diagnosis and management of small-scale fisheries in developing countries. Fish Fish. 8 (3), 227–240.

Arrow, K.J., 1971. Essays in the Theory of Risk-Bearing. Markham Publishing Co., Chicago.

Barbier, M., Watson, J.R., 2016. The spatial dynamics of predators and the benefits and costs of sharing information. PLoS Comput. Biol. 12 (10), e1005147.

Barnes, M.L., Arita, S., Kalberg, K., Leung, P., 2017. When does it pay to cooperate? Strategic information exchange in the harvest of common-pool fishery resources. Ecol. Econ. 131, 1–11.

Barnett, B.J., Barrett, C.B., Skees, J.R., 2008. Poverty traps and index-based risk transfer products. World Dev. 36 (10), 1766–1785.

Barnett, B.J., Mahul, O., 2007. Weather index insurance for agriculture and rural areas in lower-income countries. Am. J. Agric. Econ. 89 (5), 1241–1247.

Bennett, P., 2001. Mutual risk: P&I insurance clubs and maritime safety and environmental performance. Mar. Policy 25 (1), 13–21.

Chakravarty, S., Fonseca, M.A., 2017. Discrimination via exclusion: an experiment on group identity and club goods. J. Pub. Econ. Theory 19 (1), 244–263.

Clark, C.W., 1976. Mathematical Bioeconomics, the Optimal Control of Renewable Resources. Wiley, NY.

Dana, R.-A., Scarsini, M., 2007. Optimal risk sharing with background risk. J. Econ. Theory 133 (1), 152–176.

Dercon, S., 2005. Risk, insurance and poverty: a review. In: Insurance Against Poverty, pp. 9–37.

Dietz, T., Ostrom, E., Stern, P.C., 2003. The struggle to govern the commons. Science 302 (5652), 1907–1912.

Dixit, A.K., Levin, S.A., Rubenstein, D.I., 2013. Reciprocal insurance among Kenyan pastoralists. Theor. Ecol. 6 (2), 173–187.

Evans, K.S., Weninger, Q., 2014. Information sharing and cooperative search in fisheries. Environ. Resour. Econ. 58 (3), 353–372.

Fischer, M.-E., Irlenbusch, B., Sadrieh, A., 2004. An intergenerational common pool resource experiment. J. Environ. Econ. Manag. 48 (2), 811–836.

Gordon, H.S., 1954. The economic theory of a common-property resource: the fishery. J.Polit.Economy 62 (2), 124–142.

Hauser, O.P., Rand, D.G., Peysakhovich, A., Nowak, M.A., 2014. Cooperating with the future. Nature 511 (7508), 220.

Heintzelman, M.D., Salant, S.W., Schott, S., 2009. Putting free-riding to work: a partnership solution to the common-property problem. J. Environ. Econ. Manag. 57 (3), 309–320.

Jouini, E., Schachermayer, W., Touzi, N., 2008. Optimal risk sharing for law invariant monetary utility functions. Math. Finance 18 (2), 269–292.

Kaffine, D.T., Costello, C., 2011. Unitization of spatially connected renewable resources. BE J. Econ. Anal. Policy 11 (1).

Kasperski, S., Holland, D.S., 2013. Income diversification and risk for fishermen. Proc. Natl. Acad. Sci. 110 (6), 2076–2081.

Lade, S.J., Tavoni, A., Levin, S.A., Schlüter, M., 2013. Regime shifts in a social-ecological system. Theor. Ecol. 6 (3), 359–372.

Leslie, H.M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K.C., Cota-Nieto, J.J., Erisman, B.E., Finkbeiner, E., Hinojosa-Arango, G., Moreno-Báez, M., Nagavarapu, S., Reddy, S.M.W., Sánchez-Rodríguez, A., Siegel, K., Ulibarria-Valenzuela, J.J., Weaver, A.H., Aburto-Oropeza, O., 2015. Operationalizing the social-ecological systems framework to assess sustainability. Proc. Natl. Acad. Sci. 112 (19), 5979–5984. doi:10.1073/pnas.1414640112.

McCay, B.J., Micheli, F., Ponce-Díaz, G., Murray, G., Shester, G., Ramirez-Sanchez, S., Weisman, W., 2014. Cooperatives, concessions, and co-management on the pacific coast of mexico. Mar. Policy 44, 49–59.

Müller, B., Johnson, L., Kreuer, D., 2017. Maladaptive outcomes of climate insurance in agriculture. Glob. Environ. Change 46, 23–33.

Mumford, J., Leach, A., Levontin, P., Kell, L., 2009. Insurance mechanisms to mediate economic risks in marine fisheries. ICES J. Mar. Sci. 66 (5), 950–959.

Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.

Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325 (5939), 419–422.

Pacheco, J.M., Santos, F.C., Levin, S.A., 2016. Evolutionary dynamics of collective index insurance. J. Math. Biol. 72 (4), 997–1010.

Roberts, R.A., 2005. Insurance of Crops in Developing Countries, Vol. 159. Food & Agriculture Org.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. 104 (50), 19703–19708.

Sethi, R., Somanathan, E., 1996. The evolution of social norms in common property resource use. Am. Econ. Rev. 86 (4), 766–788.

Sethi, S.A., Dalton, M., Hilborn, R., 2012. Managing harvest risk with catch-pooling cooperatives. ICES J. Mar. Sci. 69 (6), 1038–1044.

Stearns, S.C., 2000. Daniel Bernoulli (1738): evolution and economics under risk. J. Biosci. 25 (3), 221–228.

Tavoni, A., Schlüter, M., Levin, S., 2012. The survival of the conformist: social pressure and renewable resource management. J. Theor. Biol. 299, 152–161.

Tilman, A.R., Watson, J.R., Levin, S., 2017. Maintaining cooperation in social-ecological systems. Theor. Ecol. 10 (2), 155–165.

Traulsen, A., Pacheco, J.M., Nowak, M.A., 2007. Pairwise comparison and selection temperature in evolutionary game dynamics. J. Theor. Biol. 246 (3), 522–529. doi:10.1016/j.jtbi.2007.01.002.