Modeling renewable natural resource management with heterogeneous collective action participation costs

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1 Introduction

Collective action solutions to environmental problems have been shown to be effective in such varied contexts as forestry, water management, and small scale fisheries (Ostrom, 1990). It is well understood through both theoretical literature and empirical evidence that sustained collective action faces challenges due to problems of coordination, disagreement over distributional effects, and temptation to free ride (Olson, 1965; Ostrom, 1990, and many others).

Long-term sustainable management of natural resources in a collective action context often takes the form of limitations on resource use, active management of the resource, and/or enforcement of exclusion of outsiders. Certain characteristics of the resource and resource-using community are understood to have significant impact on the likelihood of success of a collective action effort, e.g. a resource to which access is more easily excluded is easier to maintain through collective action. Other characteristics include condition of the resource, trust among the user community, experience with organizing within the community, and the strength of dependence upon the resource. Group size and group heterogeneity are also generally assumed to have a strong influence on the prospects of success for a collective action undertaking (Agrawal & Goyal, 2001; Poteete & Ostrom, 2004). Heterogeneity can impose a positive or a negative influence on establishing and maintaining cooperation depending on the context (Heckathorn, 1993); thus it is critical to specify the type of heterogeneity that is expected to influence collective action (Poteete & Ostrom, 2004).

Poteete and Ostrom (2004) describe situations in which locational differences (i.e. proximity to the resource) can impose high costs of participation in activities related to duties and benefits of resource use simply due to the difficulty of access (e.g. walking time). While locational heterogeneity would be expected to be detrimental to cooperation, institutional rules that account for such heterogeneity can overcome this effect (Varughese, 1999).

While the initial establishment of cooperation seems particularly perilous, even the ongoing cooperation of a previously-cooperating group can be disrupted when the user-resource system is perturbed away from an equilibrium (Huberman & Glance, 1995).

To explore the factors that may contribute to the collapse of established cooperation in an environmental context, I will model a multiple agent resource user community with homogeneous ability to extract a renewable natural resource but heterogeneous costs to participate in a collective action to maintain the natural resource. These participation costs might represent opportunity costs (e.g., participation in the collective action might preclude taking on a lucrative second job) or incurred costs (e.g., cost of personal equipment, materials, or fuel).

In Part 2 I develop a simple model for numerical analysis. In Part 3 I establish benchmarks based on simulations across a finite time span, including metrics of present value, rate of collapse to open access, and time (periods) to collapse; these are used to develop intuition around comparative statics related to these metrics. In Part 4 I discuss implications and potential policy options based on intuitions developed from the benchmarks. I conclude in part 5.

2 The model

For concreteness, here I will consider a fishing community with an established Territorial User Rights Fishery (TURF) concession, a rights-based management system that assigns spatial property rights over an otherwise common pool resource to incentivize sustainable management of the resource and improve welfare for users (Cancino et al., 2007; Costello et al., 2015; Wilen et al., 2012). To focus on the effects of participation cost heterogeneity, here I assume a simple situation in which users are all equal in ability to harvest a target shellfish species, with harvesting costs and profits shared across the community. As a requirement for membership, are all expected to participate in collective action to benefit the TURF. The TURF is well-estabished, with a known optimal harvest policy and effective exclusion of poachers due to collective patrolling of the fishing grounds.

An external organization such as a governmental agency has to date supported the collective action via subsidies or direct payments for effort. However, the organization has recently decided to invest elsewhere, leaving the fishing community responsible for the costs of maintaining the collective action patrols. While the community continues to share the costs and benefits of harvest, individual participants may bear different costs related to the patrol aspect, such as real costs of fuel or boat maintenance, or opportunity costs such as inability to take on a night job for extra income. If any community members decide to defect on their patrol duties, poachers will claim a portion of the stock, bringing the residual stock below the optimal escapement.

2.1 Fishery model

The fishery model I adopt is essentially identical to the model used by Clark (1973), though my notation differs and I apply it in a discrete-time dynamic model across n patches managed by a community of n fishers. At the end of each period, the residual stock in patch $i \in 1, ..., n$ grows according to a density dependent growth function of the escapement

$$x_{it+1} = G(e_{it}) = e_{it}(1 + r_i(1 - e_{it}/K_i)), \tag{1}$$

where x_{it+1} is the next-period stock in the patch, e_{it} is the escapement stock size in the patch, r_i is intrinsic growth rate of the stock species in patch i, and K_i is the carrying capacity of the species in the patch.

Each patch is identical in productivity, each fisher is equally skilled at fishing, and all fishers share profits from the fishery, so all benefit equally from the harvest itself. Each unit of harvest is sold at price p; fishers are price-takers as the level of harvest is not sufficient to affect the market price. However, cost of harvest is dependent on stock size – as stock density declines, more effort must be expended for each unit of harvest – such that $c_h(x_i) = B_i/x_i$ where $B_i = B$ is a constant. Profit for each patch in period t is then

$$\pi_{it} = \pi_{it}(e_{it}, x_{it}) = p(x_{it} - e_{it}) - \int_{e_{it}}^{x_{it}} \frac{B_i}{s} ds \tag{2}$$

Each period, the fisher harvests down to the escapement e_i determined based on an assumption of complete exclusion of outsiders from the fishing grounds; prior to $t = 0$, enforcement effort is subsidized such that complete exclusion holds and participation cost for each fisher is zero. Across all n patches in the TURF, the dynamic programming equation would be set up as:

$$V_t(x_t) = \sum_{i=1}^{n} \left(\max_{e_{it}} \left[p(x_{it} - e_{it}) - \int_{e_{it}}^{x_{it}} \frac{B}{s} ds + \delta V_{it+1}(G(e_{it})) \right] \right) \tag{3}$$

Using backward induction from time $t = T$ assuming $V_T(x_T) = 0$, and assuming all harvest generates profit for the TURF (i.e. no stock is taken by poachers), we can numerically determine a time-independent optimal escapement policy $e_i^* = x_{it} - h_{it}$ where e is escapement and h is harvest.

To determine the open access escapement e_{iOA} for each patch i, we can simply find the stock size that, in steady state, equates the rent from harvest to the cost of harvest, driving profit to zero. Clark (1973) approximates open access equilibrium that dissipates rent R against cost C, in other words where profit $\pi_{it}(e_{it}, x_{it}) = 0$. However, solving numerically and using $C = \int_{e_i}^{x_i} \frac{B}{s} ds$, we can identify more accurately the escapement level for patch i where $R_i - C_i = 0$ by solving an implicit function of stock size at open access equilibrium:

$$\pi_{it}(e_{it}, x_{it}) = p(x_{it} - e_{it}) - \int_{e_{it}}^{x_{it}} \frac{B}{s} ds = 0 \tag{4}$$

$$\implies pG(x_{iOA}) = B \ln \frac{x_{iOA} + G(x_{iOA})}{x_{iOA}} \tag{5}$$

In the naive model, at time $t = 0$, the enforcement subsidy vanishes, allowing for the possibility of defection and thus poaching. Participants decide to defect in the current period t based on the benefits and costs of harvest and participation in prior period $t - 1$. For a community with n fishers across n patches, each defection leaves one patch unprotected and thus exposed to poaching. Assuming that poachers bear the same harvest cost as fishers and sell their ill-gotten harvest at the market price, they will reduce the stock in an exposed patch to the open access equilibrium for that patch, while protected patches will be harvested to the optimal escapement level.

The timing of events within each period and each patch is thus:

- Period t
  1) Each participant (i, corresponding to patch i) decides to defect in period t based on personal participation cost c_{pi} and individual benefit in prior period b_{it-1}.
  2) stock level x_{it} is observed.
  3) harvest occurs to the optimal escapement such that $h_{it} = x_{it} - e_i^*$.
  4) harvest is sold for profit $\pi_{it}(e_i^*, x_{it})$, generating overall benefit b, and summed and shared equally across all fishers.
  5) if participant defects, poaching occurs in the unprotected patch such that $e_{it} = e_{iOA} \leq e_i^*$.
  6) Total escapement from all patches, poached or protected, redistributes throughout the fishery such that e_{it} is uniform in each patch.
  7) For each patch i, escapement e_{it} grows such that $x_{it+1} = G(e_{it})$.
  8) participants observed defecting in this round are expelled and replaced with a new participant randomly drawn from the distribution.
- Period $t + 1$
  1) each participant makes a decision to cooperate or defect in this period, based on per-capita benefits accrued in period t, i.e. b_{it}.
  2) stock level x_{it+1} is observed.
  3) ...

2.2 Participation model

Participation in the fishery includes responsibilities to participate in the collective action provision of public good. But such cooperation, particularly ongoing cooperation, is made more difficult by the temptation to free ride if costs are high relative to benefits.

There is a large literature on conditional cooperation, beginning with Friedman (1971), to maintain cooperation in a repeated game. Several punishment schemes are often proposed, including a decentralized scheme in which if any defection is observed, all members agree to subsequently defect for one or more periods. If the collective action is intended to exclude outsiders, clearly this is not a good outcome for natural resource management, as it immediately results in no exclusion at all, and a collapse to open access; in any case, many of the challenges of establishing initial cooperation will rear up again at the conclusion of the punishment period. Instead I begin from an assumption of a centralized authority (e.g. a managing committee) with the ability to punish those observed defecting by expulsion from the group.

While all members benefit equally from fishing (sharing harvest costs and profits), each member may bear a different cost c_{pi} of participating in the collective action, e.g. differences in opportunity cost of time spent patrolling. These costs to individual fishers are independent of harvest and stock, and are initially randomly drawn from some distribution f.

Users whose participation costs are high might defect if their perceived one-shot benefit from defection exceeds the possible loss of a future stream of benefits if expelled from the community. Defection of the highest-cost participant may lead to the degradation of the resource, leading to reduced total benefits in the future, potentially inducing the defection of the next-highest-cost participant, and so in in a feedback loop that leads to the total collapse of cooperation. However, if defectors are expelled and replaced with sufficiently lower-cost participants, cooperation may be restored leading back to a collective action equilibrium. Factors that significantly affect the rate of collapse are group size, the distribution (mean and variance) of the participation costs, and the likelihood of expulsion for defection.

Each period, fishers will compare the long-term benefits from participating in the TURF with the costs of contributing to the public good. If every fisher participates in collective enforcement, then the total benefit to the TURF in each period is simply the profit of the TURF over an open access situation, which is simply the profit of the TURF (since open access profits devolve to zero).

Following Bendor and Mookherjee (1987), I model the cooperation/defection choice as an n-person prisoner's dilemma. Since plots and fishers are homogeneous, the per-participant contribution to the benefit is $b_{it} = \pi_t(e_i^*, x_{it}) = \frac{1}{n}\sum_{i=1}^{n} \pi_t(e_i^*, x_{it})$. If all other members are cooperating, the benefit to the ith member of cooperation is $b_{it} - c_{pi}$; if the ith member chooses to defect, he will earn a one-time defection premium of $c_{pi} - b_{it}/n$ but risk expulsion and therefore loss of all future benefits. To ensure a prisoner's dilemma, $b_{it} > c_{pi} > b_{it}/n$. If participants are observed perfectly ($p_{obs} = 1 \Rightarrow 100\%$ chance of punishment), then the future stream of benefits from cooperation must exceed the defection premium to ensure cooperation, otherwise the member will defect and not contribute to the public good; for imperfect observation ($p_{obs} \in (0, 1)$), the chance of expulsion decreases potential future benefits accordingly. Therefore, the participant will cooperate as long as

$$p_{obs} \times \frac{\delta}{1-\delta}(b_{it} - c_{pi}) > c_{pi} - \frac{b_{it}}{n} \tag{6}$$

This is consistent with a belief that all others will cooperate, but if the participant believes j others will defect, the premium increases to $c_{pi} - (j + 1)b_{it}/n$, making defection more likely. This also rests on the assumption that participants make their decision based on a belief that the benefit observed in period t will continue forward. If a participant believed the benefit would decrease in the future, it would reduce the left hand side and increase the righthand side, making defection more likely, and vice versa if the participant believed the benefit would increase.

Defectors, if observed, are expelled from the fishery and replaced with a new member from outside the current fishery, whose cost of participation is also drawn from distribution f. Over time, as higher-cost participants are expelled and often replaced with lower-cost participants, this will change the effective distribution of participation costs remaining within the fishery, driving down the mean and narrowing the spread.

3 Model outcomes

In the model as presented to this point, two possible equilibrium outcomes can be observed, given sufficient time to converge. On the one hand, if participants defect at a rate sufficient to reduce the benefit faster than defectors can be expelled and replaced, then the decline in benefits will ensure other defections, further decline in benefits, and so on until 100% of the community defects, and the TURF collapses into an open access condition. On the other hand, if initial defection rates are small and defectors are expelled and replaced quickly before large declines in benefits are incurred, then given sufficient time, all fishers with high participation costs will be forced out of the system and replaced with low-cost participants. This will result in a stable equilibrium at 100% participation, maximizing benefits.

3.1 Naive model outcomes

The distribution of participation costs c_{pi} will have a profound impact on the rate at which defections occur and thus the rate at which the TURF collapses into open access. Here I show outcomes for four different distributions, using a Monte Carlo method of 400 simulations across a fifteen year period, with initial cost vectors randomly drawn from the distribution for each simulation.

The following parameter values were used across all simulations:

$$\begin{aligned} \delta &= .95 && \text{discount factor} \\ r &= 0.3; K = 100 && \text{intrinsic growth rate; carrying capacity} \\ p &= 20; B = 200 && \text{unit price; harvest cost coefficient} \\ n_{fishers} &= 50 && \text{number of fishers in TURF} \\ obs\_rate &= .7 && \text{probability of getting caught defecting} \end{aligned}$$

Using these values we can calculate an open access equilibrium stock $x_{iOA} = 11.62$ (Fig. 1), and using backwards induction from $T = 30$ we can determine optimal escapement policy $e_i^* = 47.40$ and starting stock $x_i^* = 54.88$. Note that since the cost distributions are independent of stock and harvest, changes to the cost distribution has no effect on optimal escapement policy.

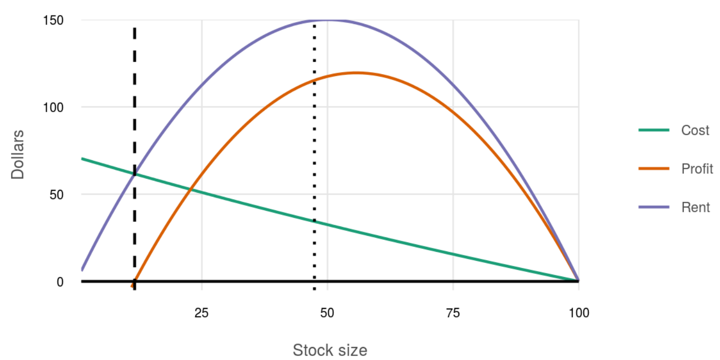

Figure 1: Rent, profit, harvest cost. Dashed vertical line represents open access equilibrium at which rents are dissipated; dotted vertical line represents optimal escapement to maximize long-term value.

Using these values, we can also calculate the per-period per-capita benefit of the TURF based on the profit at starting stock x_i^* and optimal escapement e_i^* relative to profit at open access (= 0):

$$\pi(e_i^*, x_i^*) = p(x_i^* - e_i^*) - \int_{e_i^*}^{x_i^*} \frac{B}{s} ds = 120 \tag{7}$$

Per Bendor and Mookherjee (1987) and the requirements of a prisoner's dilemma, $b_{it} > c_{pi} > b_{it}/n$. Defining the overall range $\lambda \equiv b_{it} - \frac{b_{it}}{n_{fishers}}$ and $c_{min} \equiv \frac{b_{it}}{n_{fishers}}$, the four distributions in Fig. 2 correspond to:

A) Uniform: $C_p \sim U(\frac{b}{n}, b)$
B) Low-mean truncated normal: $C_p \sim N_t(\mu = .35\lambda + \frac{b}{n}, \sigma = .25\lambda)$
C) Mid-mean truncated normal: $C_p \sim N_t(\mu = .50\lambda + \frac{b}{n}, \sigma = .25\lambda)$
D) High-mean truncated normal: $C_p \sim N_t(\mu = .75\lambda + \frac{b}{n}, \sigma = .25\lambda)$

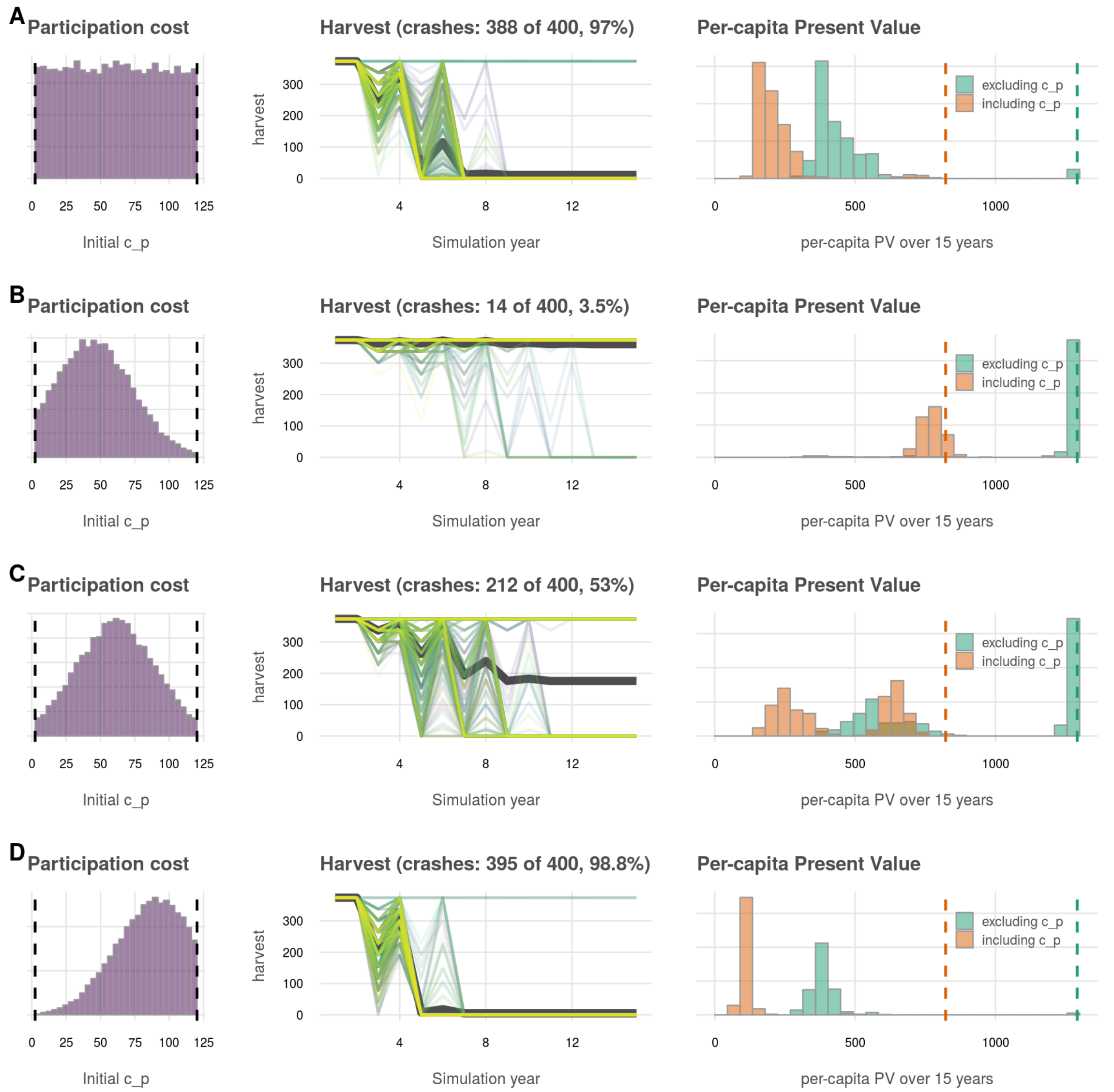

Figure 2: Initial distribution of participation costs, trajectories of simulated harvests, distribution of simulated net present values, for (A) uniform, (B) low-mean truncated normal, (C) mid-mean truncated normal, and (D) high-mean truncated normal distributions. Vertical bars on present value plots show present value for stable fishery (i.e. no poaching) ignoring participation costs (blue) and accounting for participation costs (orange) by assigning all fishers $c_p = \mathbb{E}[C_p]$

The results shown in Fig. 2 are fairly intuitive: uniformly distributed participation costs and high-mean normally distributed costs, with a large number of high-cost fishers who are likely to defect in early rounds, both demonstrate a high probability of collapse to open access conditions. As the mean of the normally-distributed costs drops, fewer high-cost fishers drives fewer defections, resulting in lower probabilities of collapse.

Similarly, examining the mean time to collapse for each of these distributions (Table 1) shows that lower-mean distributions are not only less likely to collapse, but (for those simulations that result in collapse) the time to collapse is prolonged, potentially allowing more time to assess and address the problem:

Table 1: Mean years to crash

Distribution	Years to crash
Uniform	5.17
Low normal	8.86
Mid normal	7.03
High normal	4.14

Clearly, even a single period in which poaching occurs will reduce the present value of the fishery relative to the no-poaching condition. A crash will drastically reduce the present value, as once a crash occurs, all future values are reduced to zero. This can be seen in the right-hand column of Fig. 2 (present value plots), which shows a bimodal distribution: low-PV simulations in which a crash occurred, and high-PV simulations in which the fishery stabilized before collapse.

3.2 Comparative statics

Examining the decision rule by which fishers will decide to defect from participating in the collective enforcement of the TURF

$$p_{obs} \times \frac{\delta}{1-\delta}(b_{it} - c_{pi}) > c_{pi} - \frac{b_{it}}{n}$$

it is clear that several environmental factors will affect the likelihood of defection (as well as the net benefit provided by the harvest): the discount factor, observation rate, number of fishers, and the distribution of participation cost. We have already explored the effects of the mean participation cost in the previous section, but we have not yet explored the effects of the variance within the distribution.

The subsequent figures are based on simulations holding all parameters but one constant at the values defined in Section 3.1, and using a low-mean truncated normal distribution to define the starting participation costs. For each figure, only the parameter of interest changes. It must be noted that while each figure is based on a specific parameterization, the discussion of each is easily generalizable.

The effect of discount factor is intuitive: a decrease in δ indicates a heavier discounting of future profits, reducing the value of the future stream of benefits of remaining in the fishery. This makes each fisher more likely to defect on enforcement duties, exposing the fishery to poaching, reducing next-period benefits, and more likely resulting in a crash to open access.

Also quite intuitive is the effect of observation rate (Fig. 3). The higher likelihood that a potential defector will be observed and removed from the fishery, the higher the expected value of the lost future stream of benefits. This results in fewer defections, lower crash rate, and higher general expected present value of remaining in the fishery. Importantly, the non-linear relationship suggests that investments in improving observation rate should be carefully weighed against the benefits: above an observation rate of 50%, marginal gains in present value and marginal reductions in likelihood of a crash are quite small.

Theory and empirical evidence (Agrawal & Goyal, 2001; Poteete & Ostrom, 2004) predict that a larger pool of participants will face more difficulty in maintaining collective action. This is generally attributed to the difficulty of effectively observing a large group, as well as the perceived lower impact of individual contribution to the success of the collective action, resulting in higher incentives to free ride. The model presented here assumes that observation rate is inversely proportional to the number of fishers, such that when $n = 50$,

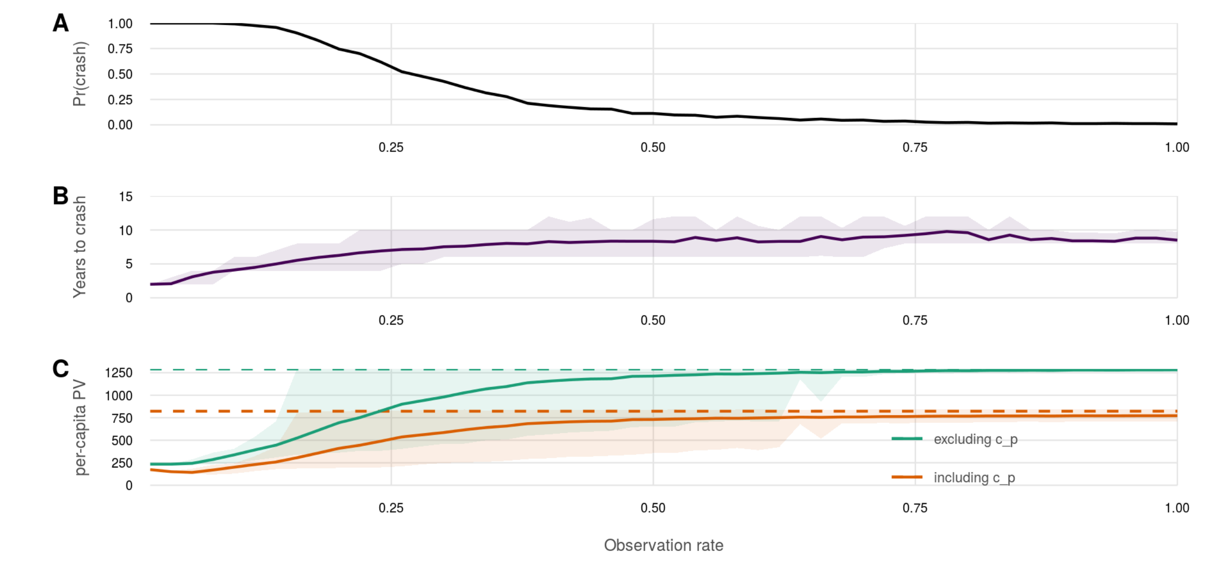

Figure 3: Effect of observation rate on (A) probability of collapse, (B) years to collapse, (C) net present value. Lines show mean value across 400 simulations; shaded areas show 0.05 and 0.95 quantile across 400 simulations.

$obs\_rate = 0.70$ as in the previous section; obviously the observation rate reaches a maximum at 1.0. In this instantiation, while the mean participation cost decreases with n (since $C_p \sim N_t(\mu = .35\lambda + \frac{b}{n}, \sigma = .25\lambda)$, as n increases, $\frac{b}{n}$ decreases faster than $.35\lambda = .35(b - \frac{b}{n})$, therefore μ decreases), this effect is overwhelmed by the decrease in observation rate (Fig. 4).

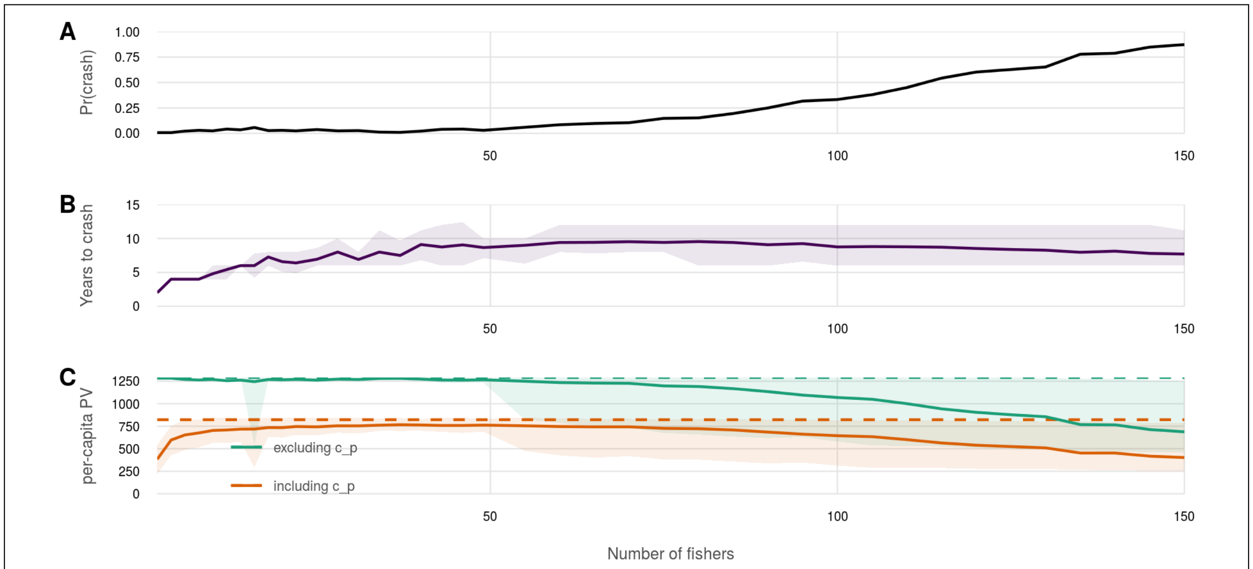

Figure 4: Effect of number of fishers on (A) probability of collapse, (B) years to collapse, (C) net present value. Lines show mean value across 400 simulations; shaded areas show 0.05 and 0.95 quantile across 400 simulations.

The variance or spread of participation costs within the fishery community also has a fairly intuitive effect on the dynamics of the collective enforcement. Fig. 1B-D explored the changes due to a shift in the mean of a truncated normal distribution while holding the variance constant. However, for any given mean, increasing the variance effectively spreads out the distribution around the mean, approaching a uniform distribution in the limit. As seen in Fig. 1A, a uniform distribution has a fairly high defection rate almost guaranteeing collapse of the fishery. Fig. 5 plots metrics against relative standard deviation, as a proportion of potential cost range $\lambda \equiv b_{it} - \frac{b_{it}}{n_{fishers}}$, for a fixed number of fishers ($n = 50$) and fixed mean participation cost $\mu = .35\lambda + \frac{b}{n}$.

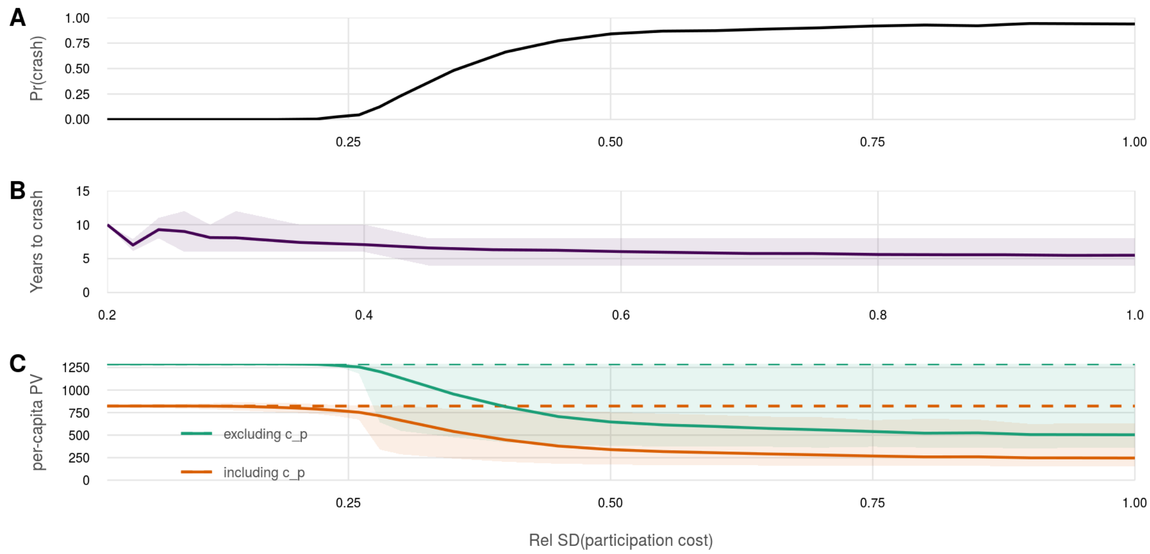

Figure 5: Effect of relative standard deviation of participation cost on (A) probability of collapse, (B) years to collapse, (C) net present value. Lines show mean value across 400 simulations; shaded areas show 0.05 and 0.95 quantile across 400 simulations.

4 Implications

From this simplified analysis many interesting implications arise. To begin with, we can explore the effects of several TURF management policies intended to reduce or eliminate the rate of defection, and thus ensure the long-term stability and value of the fishery. From a starting point at which an established TURF is facing the end of a subsidy for collective enforcement, we must consider the population of fishers to be given, and thus must work with participation costs determined by the population's cost distribution. However, from a starting point prior to the establishment of the TURF in the first place, we can consider policies that *ex ante* affect the cost distribution of the fishers participating in the TURF. Finally, we can probe the decision rule fishers use to decide whether to defect or cooperate to identify some interesting issues.

4.1 Implications for TURF management

Assuming a situation in which an external agency has over time facilitated the development of a cooperative fishery through generous subsidies for collective enforcement, the cost of participation is hardly a concern for individual fishers. However, upon the demise of the subsidy, and without additional policy in place, each fisher would suddenly be responsible for his or her individual participation costs, resulting in the possible collapse of the fishery as demonstrated in the naive model. However, presuming that there is already in place an authority (e.g. managing committee) with the ability to monitor fishers and expel defectors, there may be an opportunity for this authority to act as a social planner to distribute the costs and benefits in such a way as to prevent defection.

First let us assume a social planner with complete and perfect information about the participation costs of all fishers. If she were to hold back enough profit from the fishing harvest to cover the participation costs of all fishers, our dynamic programming equation would include a participation cost term c_{pi}:

$$V_t(x_t) = \sum_{i=1}^{n} \left(\max_{e_{it}} \left[p(x_{it} - e_{it}) - \int_{e_{it}}^{x_{it}} \frac{B}{s} ds - c_{pi} + \delta V_{it+1}(G(e_{it})) \right] \right) \tag{8}$$

Since the cost of participation for each fisher is independent of the stock size or the harvest, the c_{pi} term drops out of the first-order conditions required to maximize the value function; the participation cost similarly has no impact on the open access equilibrium stock size. While the participation costs clearly affect the value, they do not affect the patch-specific policy functions e_i^*. In this situation, the participation costs are perfectly internalized by the fishery, which is illustrated in Fig. 3C as the difference between the green line (c_p subsidized) and orange line (c_p internalized).

Unfortunately, it is not realistic to think that the social planner can observe the participation costs of the individual fishers, even if she is aware of the distribution of costs in the population. With participation costs imperfectly observed, fishers would be likely to overstate their personal costs, resulting in overpayment and an inefficient outcome. If instead the social planner were to hold back some portion of profits and pay these back to fishers in equal amounts, there would again be inefficiencies: low-cost fishers would receive more than required to maintain their participation, while high-cost fishers may not receive enough to deter them from defecting.

A policy that treated participation in collective enforcement as a tradeable obligation could allow fishers with high participation costs (e.g., opportunity for a high-wage second job outside of fishing hours) to pay another fisher to cover their obligation (e.g., take a second shift on patrol). The threshold cost between high-cost and low-cost fishers, i.e. the participation cost at which the fisher is indifferent between cooperation and defection, can be determined from equation (6) by setting the two sides equal:

$$p_{obs} \times \frac{\delta}{1-\delta}(b_{it} - c_{pi}) = c_{pi} - \frac{b_{it}}{n}$$

and then rearranging to determine the threshold cost c_p^τ:

$$c_p^\tau = \frac{b\left(\frac{1}{n} + \frac{\delta}{1-\delta} p_{obs}\right)}{\left(1 + \frac{\delta}{1-\delta} p_{obs}\right)} \tag{9}$$

As long as there were sufficient low-cost fishers willing to be paid to take on the obligations of the high-cost fishers, defection could be avoided entirely.

In fact, tradeable obligations could be quite efficient if transaction costs were low and marginal participation costs (i.e. opportunity cost of taking on an extra patrol shift, presumably an increasing and convex function of the number of shifts) of low-cost fishers were sufficiently low, such that even fishers below the defection threshold could still find benefit in paying a lower-cost fisher to patrol while they reap the benefits of avoiding their participation cost. Bilateral trades or a double auction mechanism (for example) could facilitate such a system, which would clearly be Pareto dominant over a strict non-tradeable obligation even ignoring the impacts of poaching.

The policies discussed previously assume a pre-determined pool of fishers already established in the fishery, with their concomitant distribution of participation costs. However, if attention were paid to participation costs at the initial establishment of the fishery, a pool of fishers could be selected that minimize participation costs in the first place and thus minimize or eliminate the possibility of defection. One simple mechanism to achieve this would be a non-trivial buy-in price, determined for example as the market clearing price in a double auction that offers shares in the TURF. Gibson and Koontz (1998) note the positive effect of a high buy-in price (coupled with limited recovery of investment upon exit) on sustained forest conservation in Indiana. An auction of member shares in a TURF would ensure allocation of shares to those who place the highest value on membership, which would (all else equal) suggest those with the lowest participation costs. Note this does not preclude the use of other management policies described above, such as tradeable obligations, but merely shifts the baseline of participation costs to a more favorable starting point from the standpoint of sustaining the fishery.

While here I have focused on a single established community with centralized management and internal profit sharing, Kaffine and Costello (2011) point toward unitization, i.e. contractual profit sharing among decentralized harvesters with spatial externalities in a connected network of resource patches, as a potential mechanism by which cooperation may develop. Unitization internalizes some or all of the spatial externalities of their harvest decisions, leading to better social outcomes which are then shared across the participants. Their analysis of unitization with endogenous participation bears similarities to the model I have adapted from Bendor and Mookherjee (1987). They conclude that voluntary coordination through profit sharing can arise organically, though in a system with spatial heterogeneity it may be challenging for participants to agree upon the redistribution of profits.

4.2 Community values in collective action

Certainly a reward/punishment scheme is helpful for sustaining cooperation in collective action, but trust is another critical component (Heckathorn, 1996; Ostrom, 1990; Poteete & Ostrom, 2004). What inferences about trust can we make from our model? The original statement of the cooperation decision rule (eq. 6, restated here) assumed that the participant believes all others will cooperate, and that the current period benefit will otherwise continue into the future:

$$p_{obs} \times \frac{\delta}{1-\delta}(b_{it} - c_{pi}) > c_{pi} - \frac{b_{it}}{n} \tag{10}$$

Relaxing these assumptions, we can generalize the rule for cooperation:

$$p_{obs} \times \sum_{t=t_c+1}^{\infty} \delta^{t-t_c}(b_{it}(j) - c_{pi}) > c_{pi} - (j+1)\frac{b_{i,t_c}}{n} \tag{11}$$

where t_c is the current time period.

As noted previously, if the fisher believes j others will defect (a lack of trust in others in the community), then the defection premium (right hand side) increases, adding $\frac{b_{it}}{n}$ for each additional presumed defector in this round. In addition, if one believes others will defect, then it follows that the next-period benefit b_{it_c+1} will be lower, reducing the expected value of benefit loss due to expulsion. While the idea of lack of trust eroding cooperation is quite intuitive, this shows a mechanism by which this might occur, and potentially could be used to highlight the value of trust-building exercises within the community.

Heterogeneity in costs and benefits can lead to perceptions of unfairness depending on how the community or institution account for it. Literature on social preferences around inequality (Bolton & Ockenfels, 2000; Charness & Rabin, 2002; e.g. Fehr & Schmidt, 1999) suggests inequitable processes and outcomes potentially reduce utility of benefits, particularly for those on the receiving end of disadvantageous inequality. Open, transparent, and representative institutions are critical to avoiding perceived inequity, making it easier to sustain long term cooperation.

Finally, social norms, while not generally sufficiently powerful on their own to sustain cooperation, can affect the costs associated with defection above and beyond the simple calculus of financial considerations. For example, a fisher who defects may be expelled from the fishery yet still remain in the community, facing disapproval and disfavor in unrelated day to day interactions with community members. This cost of social opprobrium adds to the potential financial loss for defection; intuitively, a tight-knit community thus promotes cooperation.

5 Conclusion

Here I explored heterogeneity in participation costs that fed back into the population stock, but the conceptual model could be generalized further to affect other aspects of the system: for example, instead of collective enforcement to exclude poachers (to maintain optimal escapement), the collective action could involve habitat restoration (to improve carrying capacity) or culturing larvae (to decrease early life-stage mortality). Multiple collective action opportunities, with different costs of participation, could allow participants to self-sort to minimize costs across the community. Instead of heterogeneity in participation costs, perhaps the individual patches are heterogeneous in productivity, or the fishers differ in their harvesting costs. As currently designed, the model is deterministic in all aspects except for participation cost; resilience of the system could be further explored by including stochastic shocks and/or uncertainty in resource productivity. And certainly the model need not apply only to TURFs, but could easily be generalized to other contexts such as forestry or irrigation rights. The base model could readily be extended to explore each of these ideas in more depth.

Importantly, the heterogeneity of costs and benefits need not solely reflect financial values. Studies and models of "critical mass" facilitating collective action (e.g. Heckathorn, 1993; Oliver et al., 1985; Olson, 1965) allow for heterogeneity in *interest* in the public good as well as heterogeneity in resources and costs associated with public good provision. Community members that value an environmental heritage above and beyond the financial rewards for harvest, such as a strong land (or ocean) ethic or deep sense of place, are likely to perceive greater benefits to collective action, and thus be moved toward sustained cooperation.

This simple model of heterogeneous participation costs shows results that echo expectations and empirical evidence around the success and failure of collective management of renewable natural resources. Clearly many other factors play into such situations, but understanding this as a potential mechanism can inform the design of institutions to better sustain long-term cooperation in conservation.

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