ECOLOGICAL, ECONOMIC AND SOCIAL MECHANISMS FOR COMMON-POOL RESOURCE MANAGEMENT

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Abstract

Sustainable solutions to global environmental problems, such as overfishing and climate change, will require long-term cooperation among nations and individuals. My thesis searches for policies and strategies that create stable, cooperative, solutions to local, regional and global environmental problems of the commons. I focus on common-pool resource management at the interface between ecology and economics. Overfishing in unmanaged fisheries has diminished fish stocks and harvests to the point that cooperative action could lead to an 8 to 40 percent increase in global fish yield. Food security will play an important role in maintaining global stability as the human population approaches 9 billion. Moreover, food security and climate change are linked: agriculture accounts for more than a third of global greenhouse gas emissions. All sources of greenhouse gas emissions must be brought under control via agreements among major emitting nations, a challenge that has not yet been successful in almost two decades. These global environmental challenges are unlikely to be adequately addressed without a theory that can explain the conditions for stable collective, cooperative global action. I analyze social, ecological and economic mechanisms that can stabilize cooperative action in the commons in order to advance our understanding of the ways in which tragedies of the commons can be averted.
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Chapter 1

Introduction

As world population approaches 9 billion, and economies develop, stress on the world’s ecosystems and atmosphere will continue to increase (Godfray et al., 2010). This presents challenges for management at local, regional and global scales. Specifically, problems of the commons arise in fisheries management, pollution control, and greenhouse gas emission reductions, all of which require collective action. In many of the world’s most pressing commons problems, institutions for management do not exist at the necessary scale or with the needed strength to enforce optimal policies for the use of the commons.

Overfishing currently diminishes fish yield such that optimal harvesting could lead to an 8 to 40 percent increase in global yield (Costello et al., 2012). Without intervention we can expect overfishing to increase. Traditional fisheries management relies on collecting information about fish stocks and using that information to set limits on how and where fishers can harvest. In addition to setting these limits, enforcement of the harvesting limits by third parties is also employed. This has been effective where applied, but it requires infrastructure that is not universal. Many unmanaged or unassessed fisheries are in the developing world, where the institutions needed to design and enforce top down management do not exist. In these fisheries,
bottom-up management, where agreements among individuals are self regulated, has
the greatest potential to increase both yield and the welfare of fishers. Fisheries
play important roles in food security as well as climate change because they provide
protein with low greenhouse gas impacts, depending on the harvesting technique. This
is important because agriculture accounts for more than a third of global greenhouse
gas emissions \cite{Nijdam2012,Foley2011}. Thus, efficient use of fisheries
resources has implications for both food security and climate change.

The atmosphere is the largest, truly global commons. The climate and health
consequences of overexploitation of the atmosphere impact every individual on the
planet. Negative consequences are already occurring, as air pollution alone causes
7 million deaths annually \cite{WHO2014}. We have the technological capability to limit greenhouse gas emissions and avoid many of the negative
consequences of climate change, but the adoption of these technologies is not suffi-
ciently widespread \cite{Pacala2004}. The challenge in climate, as in other
common-pool resource and public goods problems, is not that solutions do not exist,
rather that implementing these solutions is difficult \cite{Barrett2012}. The barriers to action on climate change are primarily political. Effective solutions
will require cooperative dilemmas to be overcome in a stable manner. The Paris
agreement is a step in this direction, but since action on climate change is costly and
the agreement is not legally binding, stronger agreements are necessary.

My thesis focuses on how social, ecological and economic interactions can facilitate
sustainable use of common-pool resources and provision of public goods. I study the
role that social and economic mechanisms can have in implementing and sustaining
cooperative behavior in common-pool resource systems. This advances our under-
standing of how the cooperative dilemmas associated with the world’s commons can
be overcome. I explore these questions with game theoretic and evolutionary game
theoretic techniques.
Cooperative dilemmas occur when individual incentives are not aligned with group optimization. Tension between individual and group optimization are ubiquitous in situations involving common property. This was classically conceptualized as the “tragedy of the commons”, where the quality of commonly held grazing lands is depleted because each herder had an individual incentive to add another grazer to the common land. Overexploitation occurs because each user of the common land only considers the negative effect that one extra grazer will have on themselves. All other users also bear the cost of overexploitation, leading to the degradation of the resource \cite{Hardin1968}. In the context of an open access fishery or the atmosphere, there is a similar tension between what would be best for the population, and how the economic incentives drive behavior \cite{Gordon1954}. Hardin concludes that in order to avoid the negative outcomes associated with the overexploitation of common lands, “mutual coercion, mutually agreed upon” is needed \cite{Hardin1968}.

Whenever the utility of an individual is a function of not only their own actions, but of other’s actions as well, it is possible for individual optimization to lead to inefficient outcomes \cite{VonNeumann1947}. Although there always exists a Nash equilibrium, where no player has an incentive to unilaterally change their strategy, there is no guarantee that the equilibrium is Pareto-optimal or efficient \cite{Nash1950}. In the case of a common-pool resource, as studied by \cite{Hardin1968} and \cite{Gordon1954}, individuals who maximize their own utility will overexploit the resource because they do not take into account the negative effect that their harvesting has on others. Many positive and negative interactions have these properties. They are studied with frequency dependent selection in evolutionary theory, as containing externalities in economics, or as being game theoretic. These fields attempt to understand what outcomes are likely to occur and how superior outcomes can be achieved. In the economic literature, one solution to the dilemma is well defined property rights and markets to trade these rights. It has been shown that even
in the face of externalities an optimal outcome will occur when property rights are well defined and transaction costs are low, because decision makers are forced to internalize the costs they impose on others (Coase [1960]). However, this approach entails privatization which has its own limitations. Privatization may not be effective when the resources in question are not easily excludable. In essence, strengthening and broadening property rights eliminates externalities and therefore leads to efficiency, but in many natural systems, the externalities are fundamental and irremovable.

Understanding the evolutionary origins of cooperation has long been of interest in biology. While the Nash equilibrium allows for analysis of possible equilibrium outcomes, from an evolutionary perspective, dynamics are also important. An evolutionary stable strategy (ESS) is a strategy that when held by a population can resist invasion by alternative strategies at low abundance. The conditions that define an ESS mirror those that define a Nash equilibrium of a symmetric game, but a refinement is needed to ensure stability to small perturbations (Maynard Smith 1974).

Many mechanisms have been proposed to explain the emergence of cooperative actions from an evolutionary perspective. Hamilton’s rule, derived from an inclusive fitness framework, was a means by which to explain altruistic actions toward relatives. Hamilton’s rule states that altruistic behaviors can evolve among kin when the cost benefit ratio of altruism is less than the relatedness of the individual to which the altruistic act is directed (Hamilton 1963, 1964). Other simple mechanisms may also explain the evolution of cooperative behavior.

Altruism and cooperation are often not one-shot behaviors. Analyses of repeated interactions between individuals led to the discovery that reciprocity can support cooperative altruistic actions. Trivers showed that if the cost of performing an altruistic act is small relative to the benefits the act confers, and if it is likely that a similar situation will arise with roles reversed, then reciprocal altruistic behavior to
be stable (Trivers, 1971). He suggested that warning calls are a good example of this. These calls are costly for the individual, but in the long run, they help to decrease the rate of predation on the individual if others also make warning calls. However, Trivers notes that reciprocal warning calls have the payoff structure of a prisoner’s dilemma. For probabilistically repeated games, or infinitely repeated games, if the discount rate or continuation probability give enough weight to the future, then it is possible to improve on the Nash equilibrium of the one-shot game. Any outcome that is at least as good for all players as a Nash equilibrium of the one-shot game can be a sub-game perfect Nash equilibrium of the repeated game if the future is sufficiently valued (Fudenberg and Maskin, 1986).

Empirical studies of repeated prisoner’s dilemma tournaments has shown that one of the best strategies in the repeated prisoner’s dilemma game is the “Tit For Tat” (TFT) strategy where a player begins by cooperating and then copies their opponent’s previous strategy (Axelrod and Hamilton, 1981). The consideration of rich, history-dependent strategies led to a great deal of study on TFT and related strategies such as generous TFT, and win-stay lose-shift (May, 1987; Nowak et al., 1993). In fact, no strategy can be evolutionarily stable in the repeated prisoner’s dilemma, there will always exist some special strategy that can invade regardless of the current strategy (Boyd and Lorberbaum, 1987).

In addition to repeated interactions as drivers for the evolution of cooperative behavior in prisoner’s dilemmas, spatial structure can also promote cooperation. Space and repetition have similarities. Playing games with neighbors and playing repeatedly with one or a few individuals means that interactions are likely to occur between known individuals. This opens the door for the development of reputation, as well as spatial patterning in observed dynamics. However, even in the absence of individual reputation or recognition, cooperation can persist in patches in a two strategy (always cooperate or always defect) prisoner’s dilemma played repeatedly on a lattice.
Indeed, under various conditions cooperation or defection can dominate or both can persist indefinitely (Nowak and May 1992; Nowak et al. 1994).

The way in which interactions are clustered in space has important consequences for the spread of strategies and the maintenance of many strategies in a population. In order to study the effect of varying degrees of uniformity, Watts and Strogatz analyzed the impact of adding few or many random connections to regular graphs and found that even a small degree of randomness has substantial effects on dynamics (Watts and Strogatz 1998). Population structure, whether analyzed as games being played with neighbors, in set-structured populations, or, more generally, on graphs, has important effects on the evolution of strategies in cooperative dilemmas (Nowak et al. 2010; Tarnita et al. 2009). The insight that selection may act on different scales simultaneously can help to explain the evolution of cooperative behavior in structured populations with limited mixing (Wilson 1975; Traulsen and Nowak 2006; Fu et al. 2012). Cooperative groups perform better than non-cooperative ones, but non-cooperative individuals in a group perform better than cooperators within that group. The evolutionary outcome will depend on the relative strength of selection at each of these scales. Indeed, cancer highlights the fundamental tension between selection acting at the level of cells, versus at the level of the individual organism.

Many mechanisms have been proposed to explain the evolution of cooperation, and many situations exist where cooperative behavior is observed, across complexity gradients and levels of organization. From single celled bacteria to human societies, the effects of cooperative behavior have left imprints (Nadell et al. 2008b,a; Kiers et al. 2003; Milinski 1987; Fehr and Gächter 2002; Dixit et al. 2013). This, however, has not made it an easy phenomenon to explain, or use to our advantage in human systems desperately in need of cooperative solutions (Levin 2010). In order to apply concepts from the emergence of cooperation in biological systems to human systems, we need to consider the ecological, economic and social factors that shape
the patterns of behavior seen in common-pool resource and public goods problems in human societies.

Although a main take away from Hardin (1968), Coase (1960) and others was that government regulation or privatization was necessary to achieve positive outcomes in public goods and common-pool resource games, this has been increasingly recognized as an overly simplistic view that misses alternative ways in which people can organize and achieve efficient outcomes in a bottom up manner (Ostrom, 1990). There is much empirical evidence that people will enforce norms of behavior even if enforcement is individually costly, to support the provision of public goods (Fehr et al., 2002; Maier-Rigaud et al., 2010). However, there is evidence that punishment may not be the best mechanism to enforce norms, positive interactions and rewards can be more effective than punishment (Rand et al., 2009). In addition to the provision of public goods, there is evidence that some people are motivated by fairness and are willing to act to promote “fair” outcomes (Fehr and Schmidt, 1999; Nowak et al., 2000).

In addition to empirical evidence that humans are inclined to use punishment and reward as mechanisms to enforce norms, there is also theoretical evidence that this kind of behavior can stabilize cooperation in common-pool resources and public goods games. For a common-pool resource, where harvesters choose one of three strategies (enforcers who punish defectors, cooperators, or defectors) cooperation can be maintained when the initial fraction of enforcers is sufficiently large (Sethi and Somanathan, 1996). Similarly, social ostracism has been shown to be an effective mechanism to stabilize optimal use of resources, but these equilibria are sensitive to parameters and initial conditions, with the potential for critical transitions and tipping points (Tavoni et al., 2012; Lade et al., 2013; Schlüter et al., 2014). These research agendas have been motivated in part by a call for greater focus on bottom-up mechanisms that can promote sustainability in the commons, where depletion of both resources and profits is ubiquitous (Walker et al., 1990).
An example of increasing overexploitation of common-pool resources is small-scale fisheries in Sri Lanka. In the early 1900’s, there was a system set up on a local scale which regulated how and when local fishers were allowed to harvest fish. This system was stable for a long period of time, however as the local population grew and became connected to larger cities with roads, the norms of harvest, and accompanying profitability began to erode as outsiders entered the system (Gardner et al., 1990). This example highlights how bottom up forms of management are vulnerable to regime shifts when the underlying structure of the community changes. This raises concerns about the effect of globalization on existing community-based management regimes.

Common-pool resources are often considered as a single unified category. However, there are many different regimes of access and use rights in common-pool resources that have distinct qualitative effects on resource use. For example, common-pool resources can be owned by the government, by a local community, or by no one. Furthermore, within each of these categories, there can be differences in your right to harvest the resource, and your right to be involved in the process where the rules of the system are determined (Schlager and Ostrom, 1992). Moreover, social-ecological systems are complex adaptive systems, where adaptation happens in ecological, social and economic dimensions (Arrow et al., 2013). These nuances are highlighted in the case of Maine lobster fisheries where in addition to the de jure use rules of harvest, local de facto policies restrict the range where any fisher can set lobster traps, lest they face the destruction of their traps by other fishers (Acheson, 1975). In this case, regulation acts at different levels simultaneously and led to profitable harvests of lobster.

The notion that the most effective management mechanisms act at many levels of organization simultaneously, as in the case of Maine lobster, is an idea that was studied further by Ostrom and colleagues. They find that as the complexity of
common-pool resource systems increases, so do the institutions required for effective long term management (Becker and Ostrom 1995). This has been coined “polycentric governance”, and it is characterized by having regulations at multiple different scales so that the scale of management can match the scale of the problem. Inherent in the analyses of sustainability is a consideration of the attitudes about the value of the future. When deciding to use resources now, or save them for later, discounting becomes very important (Arrow and Levin 2009; Levin 2012). To summarize, the study of social-ecological systems has found that effective management of common-pool resources requires graduated punishment, low cost monitoring of behavior, governance at many scales, and rules of resource use which reflect current conditions (Dietz et al. 2003; Ostrom 2009).

My thesis explores and advances the theoretical underpinnings of common-pool resource management and public-goods provision in social-ecological systems. I apply evolutionary game theoretic and game theoretic techniques to problems of the commons at local, regional and global scales. First, I examine how norms and punishment can improve management in fisheries. Next, I model how agreements to share revenue among resource users can act as insurance against income volatility while improving resource use as a co-benefit. Then, I model action on climate change, specifically how a small coalition may be able to lead to broad action. Finally, I explore the consequences of pro-sociality on the provision of public goods in a structured population.
Chapter 2

Maintaining cooperation in social-ecological systems

Andrew R. Tilman, James R. Watson and Simon Levin

Abstract

Natural resources are vulnerable to over-exploitation in the absence of effective management. However, norms, enforced by social ostracism, can promote cooperation and increase stock biomass in common-pool resource systems. Unfortunately, the long-term sustainable use of a resource is not assured even if cooperation, maintained by ostracism and aimed at optimizing resource use, exists. Here, using the example of fisheries, we show that for a cooperative to be maintained by ostracism over time, it often must act inefficiently, choosing a ‘second-best’ strategy where the resource is over-harvested to some degree. Those cooperatives that aim for maximum sustainable profit, the ‘first-best’ harvest strategy, are more vulnerable to invasion by independent harvesters, leading to larger declines in the fish population. In contrast, second-best strategies emphasize the resistance to invasion by independent harvesters over maximizing yield or profit. Ultimately, this leads to greater long-run payoffs to the resource users as well as higher resource stock levels. This highlights the value of pragmatism in the design of cooperative institutions for managing natural resources.²

²The final publication is available at Springer via http://dx.doi.org/10.1007/s12080-016-0318-8
2.1 Introduction

Harvested populations are often vulnerable to the “tragedy of the commons” (Hardin, 1968) when strong externally imposed governance is absent. This is because the nature of common-pool resources creates incentives for over-exploitation (Gordon, 1954). This challenge of managing common-pool resources remains a central problem facing societies (Arrow et al., 1995; Levin and Lubchenco, 2008). Fisheries are prototypical common-pool resources, where over-harvesting diminishes stock levels, lowers yield, and decreases the welfare of all fishers (Ostrom et al., 1994). Improved management of common-pool resources can improve both the state of the resource and the welfare of its users by increasing stock levels as well as profits. However, this also increases the incentive for individuals to over-exploit the resource for short-term personal gain.

As an alternative to top-down management, where regulations are imposed by an external governance institution, collective-action agreements created and maintained by the resource users themselves can avert the tragedy of the commons (Ostrom, 1990, 2007). Hence, understanding when collective-action agreements—or more broadly, cooperation—might emerge among common-pool resource users is key to developing sustainable resource-use in these ways, and protecting fish stocks from collapse. Indeed, cooperation has been an enigmatic problem not just in social systems, but also in evolutionary biology since Darwin (1860). As in biology, the emergence and long-term maintenance of cooperation in common-pool resource systems depends greatly on the mechanisms that support the behavior, such as the norms of use that are followed by those who cooperate (Axelrod and Hamilton, 1981; Nowak, 2006). Further, for cooperation over sustainable resource use to persist, it must be robust to a wide variety of alternative and more individualistic strategies.

Here, we use fisheries that lack effective top-down regulation as a model case study to explore the ecological and social conditions necessary for the long-term persistence of sustainable collective-action agreements. Henceforth, we refer to the fisheries of
interest as “small-scale fisheries,” since many fisheries lacking effective governance are local operations in coastal communities of developing nations. Specifically, our work is relevant to those fisheries that have weak formal institutions, such as maritime laws and enforcement agencies, or those in remote locations out of sight of management (Pomeroy 1991). Such fisheries are thought to be a hidden but sizable source of fish catch (Andrew et al. 2007), employing some 37 million people world-wide. Further, improved management in these fisheries can have substantial positive impacts on human welfare, since in these regions there is often a greater reliance on fish for dietary protein.

Governmentally enforced fisheries management has focused on optimization, identifying harvest rates that maximize (long-term) profits, or harvests (Hilborn and Walters 1992). Such approaches can succeed with the presence of fishery assessment and enforcement of top-down forms of governance such as quotas or total allowable catch limits (Costello et al. 2012). However, in the absence of strong governance, as in small-scale fisheries, this approach may fail due to a lack of compliance. Instead, the job of management and enforcement often falls into the hands of fishers themselves (Pomeroy 1991; Ostrom 2007). Application of Ostrom’s design principles to fisheries in Baja California has highlighted that the potential for bottom-up management varies across communities within this region (Leslie et al. 2015). In cases where the potential for bottom-up management is limited, maximizing the long-term profitability of the fishery—the “first-best” optimal outcome—may not be attainable because individual fishers may have an incentive to over-harvest for personal gain. Instead, a strategy for the cooperative that emphasizes the robustness of a beneficial resource-use norm, as opposed to economic optimality, may be better. This is called a “second-best” optimum because it represents the best management outcome that can be achieved given that the ability of the cooperative to enforce norms is limited.

In the long-run, when resource users employ a second-best harvesting strategy they will be better off, and so will the resource.

In this paper, we focus on how social norms and punishment can be used to facilitate self-organized management of a fishery, leading to increases in the resource stock. Previous work has analyzed how optimal use of a common-pool resource can be maintained as a subgame-perfect Nash equilibrium where punishment is incurred through reverting to the competitive state whenever there is any deviation from optimal harvesting (Tarui and Polasky, 2005). Here, we consider an evolutionary game-theoretic approach, where resource users—fishers—shift toward strategies that give higher individual utility, considering economic payoffs as well as the social and economic costs of both norm violation and enforcement. This evolutionary approach has been used to explore how norms and punishment can promote cooperative behavior (Sethi and Somanathan, 1996). In our case the evolutionary process reflects the emulation of successful harvesting strategies by individual fishers (Mangel et al., 2013). This paper also extends previous work on this topic (Tavoni et al., 2012; Lade et al., 2013; Schlüter et al., 2014) by incorporating a cost to punishment and by assessing how a cooperative can best choose a harvesting norm, achieving a balance between optimal harvesting and robustness to invasion by selfish, independent fishers.

We answer two questions. First, under what conditions can ostracism act as a mechanism to stabilize socially-optimal fishery harvests? Second, if the optimal harvest strategy is vulnerable to invasion or replacement by independent harvesters, is it possible to choose a resource-use norm that can stabilize the cooperative while improving the state of the resource? To answer these questions, we extend a model from Tavoni et al. (2012), and apply it to a living resource, focusing on how best to choose a harvesting norm. This modeling framework allows us to investigate the situation of a cooperative looking to enforce a socially-optimal fishing strategy, through ostracism, when there are individual incentives to harvest harder, diminishing all
other users’ catches. The social optimum occurs when the total profit summed across all the fishers is maximized. This level of total effort is not the same as the competitive Nash equilibrium level of effort, where no fisher has an incentive to change their harvesting practices unilaterally. The core of the problem is illustrated by figure 2.1: in the absence of enforcement, the maximally profitable social optimum will never be agreed to, since it does not align with the competitive Nash equilibrium, where the system is likely to end up if all fishers follow their individual incentives. As a result, the potential gains from cooperation will be lost, due to over-harvesting. Furthermore, this leads to a drop in the abundance of fish, which could be an ecological as well as practical concern.

Figure 2.1: Revenue and cost of the population of fishers across the total harvesting effort. The total profit of the fishers is the difference between the revenue and cost curves. When total effort is at the socially optimal level, the profit is maximized. However, at this level of total effort, each fisher has an incentive to increase her or his own effort, in order to get a larger share of the profit. The increase in total effort that results from these incentives leads to a decrease in total profits. At the Nash equilibrium level of total effort, no harvester has an incentive to change effort unilaterally, but very little profit remains.

In order to understand better how to overcome this challenge, we explore the conditions under which a norm-enforcing cooperative is robust to invasion by selfish, economically driven independent harvesters. If socially-optimal harvesting is not stabilized by the cooperative, we search for second-best solutions, those where the cooperative of norm enforcers chooses a greater harvest rate, one that is robust to
invasion by independent and selfish harvesters. We find that although there exist situations where optimal harvesting is stable, fishers in the cooperative are better off implementing pragmatic second-best policies that ensure no type of independent harvester can invade. Further, the state of the resource stock is also improved when a second-best strategy is employed by the fishers. Ultimately, our analysis shows that individuals who work in fisheries with weak enforcement can create sustainable systems by strategically selecting norms and enforcing those norms via social punishment or ostracism.

2.2 Model

2.2.1 Resource dynamics

We assume that the fish population grows logistically, and that, following the Gordon-Schaefer model, the harvest of fish is linear in both total effort and resource stock biomass:

\[
\frac{dR}{dt} = rR \left(1 - \frac{R}{k}\right) - qRE,
\]

where \(R\) is the biomass of the fish stock, \(r\) is the intrinsic rate of growth of the fish and \(k\) is the carrying capacity of the fish population. The parameter \(q\) is the catchability of the fish, which is the fraction of encountered fish that is caught by a fisher. The total harvesting effort of the resource users, \(E\), depends on the strategies of the individuals. We consider two alternative harvesting strategies that fishers choose between. The fishers can join a cooperative, harvest with per capita effort \(e_c\), and punish, via social ostracism, anyone who harvests with greater effort. Alternatively, fishers can be independent, and harvest with effort \(e_I > e_c\). Independent harvesters make more money, but also incur the cost of ostracism from those in the cooperative. We assume
that the number of resource users, \( n \), is fixed and write the fraction in the cooperative as \( f_c \). Thus, we can write the total harvesting effort as 
\[
E = (nf_ce_c + n(1-f_c)e_I).
\]

### 2.2.2 Strategy dynamics

The fraction of fishers with a particular strategy changes in accordance with the replicator equation, where the strategy that gives higher-than-average utility increases in frequency. Fishers receive a price, \( p \), for each unit of fish they harvest, and pay a cost, \( w \), for each unit of effort they invest in fishing. Hence, the profit of an individual is

\[
\pi_i = pqRe_i - we_i,
\]

with \( i = c, I \) for a cooperator, or independent, respectively. The profit from harvesting makes up one part of the fisher’s utility function.

The utilities of the cooperators and independents combine their direct profit from fishing with costs associated with violating and enforcing harvesting norms. Those in the cooperative punish independent harvesters in proportion to how much extra profit they receive due to their higher harvesting effort. Further, the magnitude of the punishment is also constrained by the size of the cooperative that is enforcing the norms of harvesting. Lastly, there is also a cost to the cooperative members for enforcing the norm. Given these assumptions, the utility of each strategy is:

\[
U_c = \pi_c - \gamma n(1-f_c)
\]

\[
U_I = \pi_I - \frac{\pi_I - \pi_c}{\pi_I} \omega(f_c),
\]

where \( \gamma \) is the unit cost of socially ostracizing or otherwise punishing someone, and \( \omega(f_c) \) is the ostracism function. The strength of ostracism is given by a non-decreasing function \( \omega(f_c) \), which satisfies \( \omega(0) \approx 0, \omega(1) \approx h, \omega'(0) \approx 0 \) and \( \omega'(1) \approx 0 \). These
restrictions imply that when very few individuals attempt to enforce a norm, it has no effect on others; but once enough individuals adhere to and enforce a norm it becomes costly to violate this norm. Further, once most of the population follows the norm, the cost of violating it plateaus at $h$. In numerical simulations, a Gompertz function, $\omega(f_c) = he^{ve^{fc}}$, is used where $v, g < 0$ are chosen to meet the above criteria. Qualitatively, $g$ determines the maximum slope of $\omega(f_c)$ with more negative values of $g$ leading to a steeper slope; and $v$ determines the critical mass of the population that must adhere to and enforce a norm before it is costly to violate, with less negative values of $v$ implying that a smaller fraction of the population is needed to reach this ‘critical mass’. The analytical results, however, do not depend on the exact form of the equation used, and hold for any function that satisfies the first set of conditions.

The replicator equation governs the dynamics of strategy choice, so we can write the rate of change of the fraction of the population in the cooperative as

$$\frac{df_c}{dt} = f_c(U_c - \bar{U}), \quad (2.4)$$

where $\bar{U} = f_cU_c + (1 - f_c)U_I$ is the average utility of the population. This means that when the utility of those in the cooperative is greater than the average utility of the population, the fraction of fishers in the cooperative will increase. Strategy and resource dynamics are coupled, so the fraction of fishers in the cooperative and the level of the resource stock both vary continuously in time. There are two strategies present in the population; thus, the dynamics of strategy choice can be simplified, and we can write our complete system as

$$\frac{dR}{dt} = R \left[ r \left(1 - \frac{R}{k}\right) - q(nf_ce_c + n(1 - f_c)e_I) \right], \quad (2.5a)$$

$$\frac{df_c}{dt} = f_c(1 - f_c)(U_c - U_I), \quad (2.5b)$$
keeping in mind that both $U_I$ and $U_c$ depend on $R$ and $f_c$. In figure 2.2 possible
dynamics of the system can be seen. In this case there are four equilibria, with sta-
ble equilibria marked with filled circles, and unstable equilibria marked with open
circles. The black solution curves illustrate dynamics that will be followed given par-
ticular initial conditions. In this example, there is a stable mixed equilibrium where
a fraction of the population belongs to the cooperative, and a fraction is composed
of independent fishers. We can see from the solution curves that when the fraction
of fishers in the cooperative is high, it is likely that the mixed equilibrium will be
reached. However, when members of the cooperative are few, or when the resource
stock is too great, independent harvesters will dominate the population. Further, the
dynamics also depend on the effort levels employed by the cooperative and by the
independent harvesters. To determine the range of plausible effort levels we establish
benchmarks, and bounds for effort. These serve to constrain the strategy space, and
allow measures of effort to be considered relative to the maximum sustainable profit
or Nash equilibrium level of effort.

2.2.3 Effort benchmarks

In this section, we establish levels of effort that serve as baselines for comparison.
First, we calculate the level of effort that maximizes the joint profit of all the fishers.
This is the socially optimal, or maximum sustainable rent, effort level. Next, we
calculate the Nash equilibrium level of effort, which leaves no fisher with an incentive
to deviate unilaterally.

Socially optimal harvesting effort maximizes the total profit summed across all the
fishers. To calculate this level of effort, we assume the resource goes to equilibrium,
and calculate the effort that leads to the greatest profit. Based on equation 2.1 the
biomass of fish at equilibrium is $R = k (1 - \frac{q}{n}e_i)$ when $E = ne_i$. This assumes ex
ante that all fishers share the same effort choice. Using this value for $R$, we maximize
equation 2.2 with respect to $e_i$ and find the socially optimal level of effort to be

$$e_{MSR} = \frac{r(pqk - w)}{2npq^2k}. \quad (2.6)$$

If each fisher harvests at $e_{MSR}$ (Maximum Sustainable Rent), the total long-term profit of the fishery will be maximized. However, in this case, each fisher will have an incentive to increase their own level of effort. Consider the Nash equilibrium level of effort, where no fisher has an incentive to change their effort unilaterally. This effort level is calculated by optimizing one’s own level of effort while assuming everyone else’s effort is fixed at some value. We assume that the fishers’ incentives are symmetric with respect to each other. Therefore, after optimization each fisher will choose the same level of effort. This gives us the Nash-equilibrium, or competitive-equilibrium,
effort-level of
\[ e_{\text{Nash}} = \frac{r(pqk - w)}{(n + 1)pq^2k} = \frac{2n}{n + 1} e_{\text{MSR}}. \] (2.7)

For \( n > 1 \), \( e_{\text{Nash}} > e_{\text{MSR}} \); and thus, at the Nash equilibrium, all fishers will receive less profit than at the socially optimal \( e_{\text{MSR}} \).

In a population of only independent harvesters, we expect every fisher to harvest at the Nash level of effort in the long run because this level of effort leaves no individual with an incentive to deviate. However, when there are cooperators present, an independent may have an incentive to increase her or his effort beyond the Nash level since the cooperators in the population harvest at a lower rate and keep the fish stock at a high level. Therefore, \( e_{\text{Nash}} \) is not a good upper bound for the effort of independents in mixed states with cooperators present. In order to set more realistic upper bounds on the effort that independents will employ, we will calculate the best response of a single independent to a population of cooperators. We are interested in the robustness of a cooperative to invasion by independent harvesters, and calculating the upper bound in this way reflects the configuration in which initial invasion of the cooperative by independent harvesters occurs.

### 2.2.4 Bounds on effort

The Nash equilibrium effort level is an insufficient upper bound for effort when there are fishers in the population who harvest at \( e_{\text{MSR}} \). In this section, we establish an upper bound on effort as the best response of a single independent harvester to a population of \( n - 1 \) fishers harvesting with effort \( e_{\text{MSR}} \). As before, the resource is assumed to be at equilibrium. In this case, the independent can write his or her profit function as \( \pi_I = pqke_I \left( 1 - \frac{q}{r} \left( (n - 1) e_{\text{MSR}} + e_I \right) \right) - we_I \). Maximizing \( \pi_I \) over \( e_I \) will
give the best response level of effort, $e_{Br}$. This level of effort is

$$e_{Br} = \frac{(n+1)r(pqk - w)}{4npq^2k} = e_{MSR} \frac{n+1}{2}. \quad (2.8)$$

Notice that $e_{Br}$ is greater than both $e_{MSR}$ and $e_{Nash}$. We expect that the effort level of an independent harvester will be greater than the effort of those in the cooperative, $e_{MSR}$, but at most the best response level of effort, $e_{Br}$. To bound the effort of independent harvesters in this range, we write

$$e_I = e_{MSR} \left(1 + \frac{n-1}{n+1}d_L\right) \quad (2.9)$$

where $d_L \in (0,(n+1)/2]$ is an effort-scaling parameter defined so that when $d_L = 0$, $e_I = e_{MSR}$; when $d_L = 1$, $e_I = e_{Nash}$; and when $d_L = \frac{n+1}{2}$, $e_I = e_{Br}$.

Regardless of the parameter-values used, the effort of independent harvesters can be judged by the value of $d_L$. For the cooperative equilibrium to be robustly stable at $e_{MSR}$, it must be resistant to invasion by independents for all values of $d_L \in (0,(n+1)/2]$. Analysis of resistance to invasion depends on the equilibria of the system and on the stability of the equilibria.

2.2.5 Equilibria

The intersections of the nullclines of the system define its equilibria. The resource nullclines are the set of points where $\frac{dR}{dt} = 0$ and are given by either $R = 0$ or

$$R = k \left(1 - \frac{qn}{r} (f_c e_c + (1-f_c)e_I)\right). \quad (2.10)$$

The strategy nullclines, where $\frac{df_c}{dt} = 0$ are given by the set of points where either $f_c = 0$, or $f_c = 1$, or

$$R = \frac{\omega(f_c)}{pqe_I} - \frac{n\gamma(1-f_c)}{pq(e_I-e_c)} + \frac{w}{pq}. \quad (2.11)$$
There are edge equilibria, where either all, or none, of the fishers are members of the cooperative. Also, there can be interior equilibria where both members of the cooperative and independent harvesters coexist.

We can analyze the stability of the edge equilibria by considering the Jacobian matrix of the system. For simplicity of notation, we shall denote \( \frac{dR}{dt} \) and \( \frac{df_c}{dt} \) from equation (2.5) as \( \dot{R} \) and \( \dot{f_c} \), respectively. The Jacobian matrix of the system is

\[
J = \begin{pmatrix}
\frac{\partial \dot{R}}{\partial R} & \frac{\partial \dot{R}}{\partial f_c} \\
\frac{\partial \dot{f_c}}{\partial R} & \frac{\partial \dot{f_c}}{\partial f_c}
\end{pmatrix}.
\] (2.12)

Standard stability analysis shows that the equilibrium where all are members of the cooperative is stable if and only if \( U_c > U_I \) at this equilibrium. Conversely, the equilibrium where all harvesters are independents is stable if and only if \( U_I > U_c \) at this equilibrium.

Now, we consider interior equilibria. We will show that stability at the interior equilibrium requires first that the slope of the resource nullcline be less than the slope of the strategy nullcline at the interior equilibrium, as can be seen in figure 2.2. Second, resource dynamics must be sufficiently fast relative to the strategy-decision dynamics. If both these conditions hold, an interior equilibrium will be stable. To illustrate this, we will consider the path derivative along the curve where \( \dot{R} = 0 \). Along this path, by construction, we know that the derivative is zero, and we can write this as \( \frac{\partial \dot{R}}{\partial R} \frac{\partial R}{\partial f_c} + \frac{\partial \dot{R}}{\partial f_c} = 0 \). Notice that \( \frac{\partial \dot{R}}{\partial f_c} \) is the slope of the resource nullcline, which we shall call \( S_R \). Similarly, taking the path derivative along the strategy nullcline will allow us to re-write the Jacobian of the system at an interior equilibrium as

\[
J = \begin{pmatrix}
\frac{\partial \dot{f_c}}{\partial R} - \frac{\partial \dot{R}}{\partial R} S_R \\
\frac{\partial \dot{f_c}}{\partial f_c} - \frac{\partial \dot{R}}{\partial f_c} S_{f_c}
\end{pmatrix},
\] (2.13)
where $S_{fc}$ is the slope of the strategy nullcline. Clearly, $\text{Det}(J) > 0$ when $\frac{\partial \dot{f}_c}{\partial R} \frac{\partial R}{\partial \dot{R}} (S_R - S_{fc}) > 0$; and since both $\frac{\partial \dot{f}_c}{\partial R}$ and $\frac{\partial R}{\partial \dot{R}}$ are negative, this reduces to $S_R > S_{fc}$. Also, the trace of the Jacobian must be negative for stability to occur. Thus, stability requires that $\frac{\partial \dot{R}}{\partial R} + \frac{\partial \dot{f}_c}{\partial f_c} < 0$. The value of $\frac{\partial \dot{R}}{\partial R}$ is negative, whereas $\frac{\partial \dot{f}_c}{\partial f_c}$ is positive. Therefore, stability depends on the relative magnitude of the these terms. When the magnitude of $\frac{\partial \dot{R}}{\partial R}$ is large relative to $\frac{\partial \dot{f}_c}{\partial f_c}$, the resource dynamics will be fast relative to the strategy dynamics and the interior equilibrium will be stable.

2.3 First-best optimum

In this section, we ask under what circumstances the cooperative can be stable, $f_c = 1$, when cooperators fix their effort level at the socially optimal level, $e_{MSR}$. For the equilibrium to be stable at this point, the utility of being a member of the cooperative must be greater than the utility of being an independent harvester, as shown above. This condition can be written generally as

$$e_c (pqR - w) > e_I (pqR - w) - h \frac{e_I - e_c}{e_I} \quad (2.14)$$

and simplified, in this case, to

$$\frac{2h}{e_I} > pqk - w \quad (2.15)$$

because we assumed that the ostracism function, $\omega(f_c)$, saturates at $h$ as $f_c \to 1$, that $e_c = e_{MSR}$, and that the resource goes to equilibrium, $R = \frac{pqk + w}{2pq}$. Furthermore, stability is only guaranteed when the cooperators are resistant to invasion from independents who harvest at any feasible level of effort, defined as $d_L \in (0, \frac{a+1}{2}]$. The greater the effort of the invading independents, the harder it is to resist invasion, as seen in condition 2.15. Therefore, if cooperators can resist invasion by independents
harvesting at the highest feasible level of effort, then the cooperative will be stable in all cases. Given this restriction, we can simply write the condition for stability of the cooperative if we define

\[ \Theta = \frac{r (pqk - w)^2}{pq^2 k}. \]  

(2.16)

The quantity \( \Theta \) combines properties of the market for the resource \((p)\), its ecological characteristics \((r, k)\), and properties of its harvest \((q, w)\) into a single term that characterizes the difficulty of supporting a cooperative. With this, the condition for stability of the cooperative can be expressed as

\[ \frac{8h}{\Theta} > \frac{n + 1}{n}. \]  

(2.17)

We can tell from condition 2.17 and equation 2.16 that although social ostracism can guarantee that cooperation is stable in many cases, it becomes increasingly difficult if the fish are fast growing (high \( r \)) and the maximum potential profit per unit effort, \( pqk - w \), is large. Furthermore, as the number of fishers increases, it is more likely that the cooperative can be maintained, as the right-hand side of condition 2.17 is decreasing in \( n \). When \( h \leq \frac{\Theta}{8} \) a first-best equilibrium cannot exist. If, however, \( h > \frac{\Theta}{8} \), we can simplify the expression for stability of the cooperative as

\[ n > \frac{1}{\frac{8h}{\Theta} - 1}. \]  

(2.18)

It is important to consider the cases where condition 2.17 does not hold. In these cases, it might be possible for the cooperative to set a higher level of effort and prevent the emergence of selfish, over-harvesting independents. In this second-best case, those in the cooperative forgo some profits that could be attained at MSR in order to guarantee that they can resist invasion by independents.
2.4 Second-best optimum

When the cooperative is not stable with $e_c = e_{MSR}$, it may still be possible for stability to occur when a higher harvesting effort is employed by those in the cooperative. In this section, we will allow the effort of the cooperators to be set between the social optimum and the Nash level. Then we find the lowest possible value of effort that guarantees the stability of cooperation against all possible types of independent harvesters. Identifying the lowest such value of effort is important because as the effort of those in the cooperative increases beyond $e_{MSR}$, their utility declines.

In keeping with previous notation, we define the effort of cooperators as

$$e_c = e_{MSR} \left( 1 + \frac{n - 1}{n + 1} c_L \right) \tag{2.19}$$

so that when $c_L \in [0, 1]$ the effort of those in the collective is between the socially optimal level and the Nash equilibrium level. Further, when the group of cooperators harvests with a higher level of effort, the best response of a single independent to a cooperative population decreases. This constricts the strategy space of independent harvesters, making the stability of the cooperative even more likely as $c_L$ increases.

We want the effort of independent harvesters to be greater than the effort of those in the collective and less than the best response of a single independent harvester to a population otherwise dominated by the cooperative. This upper bound is modified from equation 2.8 and is given by

$$e'_{Br} = e_{MSR} \left( 1 + \frac{n - 1}{n + 1} \left( \frac{n + 1}{2} - \frac{n - 1}{2} c_L \right) \right) \tag{2.20}$$

As a result, we can constrain the effort of independent harvesters to the desired range, $e_I \in (e_c, e'_{Br})$ by imposing the restriction $d_L \in \left( c_L, \frac{n + 1}{2} - \frac{n - 1}{2} c_L \right]$. The equilibrium where all fishers are cooperators ($f_c = 1, R = \frac{pqk+w}{2pq} - \frac{(pqk-w)(n-1)}{2pq(n+1)}c_L$) is stable.
when condition \(2.14\) holds. In this case, the expression can be simplified as

\[
\frac{2h}{e_I} > (pqk - w) \left(1 - \frac{n - 1}{n + 1} c_L \right) \quad (2.21)
\]

highlighting that increasing \(e_I\) makes stability harder to achieve. Therefore, the cooperative will be resistant to invasion by any type of independent harvester when it can resist invasion with \(d_L = \frac{n+1}{2} - \frac{n-1}{2} c_L\). Under this circumstance, the cooperative is stable when

\[
\frac{8n p q^2 k h}{r (pqk - w)^2} > (n + 1) \left(1 - \frac{n - 1}{n + 1} c_L \right) \left(1 - \left(\frac{n - 1}{n + 1}\right)^2 c_L \right) . \quad (2.22)
\]

This condition is easier to meet as \(c_L\) increases because the right-hand side is decreasing in \(c_L \in [0, 1]\). The expression can be simplified and expressed in terms of \(\Theta\) as

\[
\frac{8h}{\Theta} > \frac{n + 1}{n} \left(1 - \frac{n - 1}{n + 1} c_L \right) \left(1 - \left(\frac{n - 1}{n + 1}\right)^2 c_L \right) . \quad (2.23)
\]

To determine the boundary where improvement over the competitive state can occur with a second-best equilibrium, we will let \(c_L \to 1\) and simplify our expression. This gives us

\[
n > \sqrt{\frac{\Theta}{h}} - 1 \quad (2.24)
\]

as our condition that a second-best equilibrium exists for some \(c_L \in (0, 1)\). In contrast to the condition for stability of the first-best equilibrium, for any positive value of \(h\) there exists some value of \(n\) and \(c_L\) for which a stable second-best equilibrium exists. This means that if the community of resource users has some ability to punish, \(h > 0\), then a large enough community of resource users will be able to improve resource use relative to the competitive equilibrium. This shows how a combination of social pressure and wise management, which pragmatically prescribes greater than optimal harvesting, can be useful to promote and stabilize cooperative fishing practices. In
many marine systems, first-best and second-best solutions exist that can guarantee
the stability of a cooperative outcome while increasing the biomass of the fish stock
and the profit of the fishers relative to the competitive state. Furthermore, even
in situations where the strength of ostracism is limited, second-best solutions that
prevent invasion of independent fishers may still exist.

2.5 Relative utility of the second-best

When stable cooperation with a first-best strategy is not possible, a second-best
strategy can be employed. In this section, we compare the utility of those in the co-
operative when they employ either a first-best or second-best harvesting strategy. On
one hand attempting the first-best strategy can lead to a mixed equilibrium with in-
dependent harvesters present. Alternatively, a second-best strategy can be employed
by the cooperative, which will lead to the exclusion of independent harvesters. For
the second-best approach to be wise, it must lead to an increase in utility compared
to a first-best strategy at a mixed equilibrium, or one dominated by independent
harvesters.

In the Figure 2.3a and all subsequent figures, the lines that are gold correspond to
the state where all fishers are members of the cooperative, the blue lines correspond
to equilibria of the systems where there is a mix of independents and cooperators,
and the green lines correspond to equilibria of the system where only independents
are present. The solid lines and solid circles correspond to stable states, and dashed
lines and open circles to unstable states. Arrows indicate the dynamics of the system
off equilibrium.

As an example, in figure 2.3a for $c_L = 0$ only the independent-dominated state
is stable. As the value of $c_L$ increases, a stable mixed equilibrium exists, and even-
tually at $c_L \approx .3$, the state where all fishers are in the cooperative becomes stable.
Figure 2.3: Equilibria across $c_L \in [0, 1]$ ($c_L = 0$ implies the cooperative harvests at the social optimum, and $c_L = 1$ implies the Nash level of effort) with independent harvesters at the Nash equilibrium effort ($d_L = 1$). Gold curves correspond to cooperative dominated states. Blue curves correspond to mixed equilibria. Green curves correspond to states where independent harvesters dominate. Solid lines correspond to stable states, and dashed lines to unstable equilibria.
Figure 2.3b shows that it is at this value of $c_L$ that the fish stock is at its maximum stable abundance. Figure 2.3c shows the equilibrium utility that cooperators receive at all the equilibria. At the second-best optimum, the utility is approximately 90% of the maximum possible utility, significantly greater than what is attained in the states where there is a mix of those in the cooperative and independent types. This shows that the cost to the cooperative for using effort levels that are greater than what would be optimal is small and represents a payment for assurance that invasion of independent harvesters can be stopped. This highlights the potential power of pragmatic policies that balance the goal of optimal harvest against the need for stability of the cooperative to invasion. We showed that the second-best solution can be superior to failed attempts to implement optimal effort. Therefore, it is in the incentives of the cooperators to harvest at a level of effort that prevents the invasion of independents, yet does not overly deplete fish stock and dampen utility. This shows that the prevention of invasion of independent harvesters can have a highly favorable benefit-to-cost ratio.

2.5.1 Second-best effort against a range of independent effort

We have shown that for a fixed level of effort employed by independents, it can be in the best interests of those in the cooperative to prescribe higher effort so that the cooperative state becomes stable. A related question is how second-best solutions perform against varying levels of independent effort. We know that if $c_L$ is chosen to meet condition 2.22 it will be impossible for independents to invade at a reasonable level of effort, but the value of $c_L$ needed to guarantee stability across the widest range of potential independent efforts may drive the resource to low levels, and limit the potential for large profits by the fishers. On the other hand, lower values of $c_L$ can prevent invasion by independents up to a reasonably high level of effort. When time or gear limitations, such as high initial capital investment, prevent fishing at
extremely high levels of effort, this may be sufficient. In figure 2.4a we can see that for \( c_L = .5 \), where a value of \( c_L \approx .95 \) could prevent invasion for any independent effort, the cooperative state is still stable up to \( d_L \approx 2 \), which may be sufficient if increasing effort beyond this is not technically feasible. Figure 2.4a shows that even if independent harvesters invade the fishery, their numbers will be low at equilibrium. But, this does not mean that they will not greatly impact the resource and the utility of harvesters, as seen in figure 2.4b and figure 2.4c. Lastly, the utility of cooperators is just over 1.1 when employing the second-best strategy with \( c_L = .5 \), given these parameters when independent harvesters do not invade; this is less than the maximum attainable utility of about 1.5, yet far greater than the Nash equilibrium level of utility where nearly all the profits are dissipated.

2.6 Discussion

Many of the successes of traditional fisheries management have come through the implementation of limits on fishing strategies and effort levels by strong institutions that enforce compliance to rules and regulations (Hilborn and Walters, 1992; Hilborn, 2012). Though often successful, this governance model is not always an option in areas of the world where infrastructure and institutions are weak or absent (Pomeroy, 1991). However, it often is precisely in these regions that improved fishery management is of great importance because people in these regions have greater reliance on fish for dietary protein and food security.

As a consequence, methods are needed to manage marine systems sustainably in the absence of top-down regulation. These bottom-up forms of governance institutions are typically made among resource users themselves, facilitating cooperation to achieve sustainable collective-action (Ostrom et al., 1994). A key mechanism for these bottom-up forms of governance can be social ostracism (Tavoni et al., 2012). Here we
Figure 2.4: Equilibria across the level of effort of independents, $d_L$, with the effort of those in the cooperative fixed at $c_L = .5$. Gold Curves correspond to states where the cooperative dominates. Blue curves represent mixed states, and green curves represent states where independent harvesters dominate. Dashed curves correspond to unstable states, and solid curves correspond to stable ones.
show that socially ostracizing those who over-harvest fish can impose sufficient costs on selfish fishers, leading to stable cooperatives that harvest sustainably. There do exist cases where ostracism is not strong enough to stabilize optimal fishing effort, and in these cases, it is possible that a higher level of effort—one that is suboptimal, yet superior to the competitive equilibrium—exists for which independents cannot invade the population. When this harvest norm is chosen, ostracism need not be carried out regularly, since no harvester has an incentive to violate the norms of use prescribed by the cooperative. For these reasons, we suggest that effective management, based on collective-action agreements, should be pragmatic and value long-term stability over aiming for maximum sustainable profit.

There is ample evidence that cooperative behavior does occur in commons such as small-scale fisheries (Mangel et al., 2013), and in this paper, we have found that the norms of resource-use, set by a cooperative, determine its success. These findings highlight important principles unique to the management for a common resource via social ostracism and punishment. We show that to implement a bottom-up approach to management, it is important to consider the harvesting norms of a community, and how the social bonds between users constrain the ability of a cooperative to persist. We take as a given the workings of the social system of some commons, and determine from this the best harvesting norm for a cooperative to employ. Indeed, Elinor Ostrom highlighted a list of key design principles for effective bottom-up management (Ostrom, 2007). These principles are important determinants of successful bottom-up management, and they also relate to our theoretical results. For example, effective self-governance is said to be supported by resource-use rules that are adapted to local conditions. With respect to the work presented here, this is akin to adjusting the extraction norm so that it is in line with what will lead to a stable cooperative. Further, trust and reciprocity are known to be important for effective governance (Ostrom, 2009). In our analyses, we similarly see that the strength of
social punishment constrains the stability of optimal harvest rates; trust, and the
tendency for reciprocity within a community are key drivers of the ability to both
cooperate effectively and punish strongly. Hence, in a community where reciprocal
behaviors and trust are prevalent, there is likely much to be lost by being cast as an
outsider. The ancillary benefits of membership to the strong community will be lost
and the severity of the punishment will likely deter deviation from the norms set by
the community.

2.7 Conclusions

We have shown that when managing a common-pool resource such as a fishery for
robust cooperative behavior it is critical to consider the incentives of individualistic
harvesters, and their potential to erode cooperative behavior. We show that main-
tenance of first-best harvest practices is often not possible because a cooperative is
likely to face many different alternative independent strategies. This is highlighted
by condition 2.17, which shows that only for sufficiently strong ostracism can the
first-best optimum be robust to invasion by any possible independent type.

There are also significant negative consequences to attempting to implement op-
timal resource-use when this leads to mixed equilibria, where both users in the co-
operative and those that are independent and selfish coexist, or when it leads to the
dominance of selfish harvesters. First, this can lead to decreased resource stock lev-
els, depending on the nature of the species of interest, which could be undesirable
from an ecological/conservation perspective. Also, these states are associated with
depressed utility levels for all the resource users. Lastly, in the mixed states all the
resource users suffer the disutility of applying and facing ostracism. Together, these
consequences of failed attempts to achieve the first-best make a strong case for an
approach that is focused on the robustness of the cooperative to invasion, rather than the economic optimality of the harvesting norm of the cooperative.

These negative outcomes can be avoided by employing a second-best strategy where the harvest norm of the cooperative is chosen such that there is never an incentive to become an independent harvester. Choosing the norm that achieves stability, and minimally exceeds the optimal level of effort, leads to the greatest possible stable levels of the resource, as well as the highest possible stable utility levels for all of the fishers. For management of a living common-pool resource via social punishment, optimal harvest rates are often not ideal and we assert that the second-best is often actually the best.
## 2.A Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>$R$</td>
<td>Fish stock biomass</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Fraction of cooperators</td>
</tr>
<tr>
<td>$r$</td>
<td>Intrinsic growth rate of fish population</td>
</tr>
<tr>
<td>$k$</td>
<td>Carrying capacity of fish</td>
</tr>
<tr>
<td>$q$</td>
<td>Catchability of fish</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of fishers</td>
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<tr>
<td>$e_i$</td>
<td>Effort of strategy $i$</td>
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<tr>
<td>$\pi_i$</td>
<td>Profit of strategy $i$</td>
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<tr>
<td>$U_i$</td>
<td>Utility of strategy $i$</td>
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<tr>
<td>$p$</td>
<td>Unit price of fish</td>
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<tr>
<td>$w$</td>
<td>Unit cost of effort</td>
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<td>$\omega(f_c)$</td>
<td>Ostracism function</td>
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<tr>
<td>$h$</td>
<td>Maximum value of ostracism function</td>
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<td>$d_L$</td>
<td>Relative effort of independent harvesters</td>
</tr>
<tr>
<td>$c_L$</td>
<td>Relative effort level of cooperators</td>
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<tr>
<td>$S_R$</td>
<td>Slope of resource nullcline</td>
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<tr>
<td>$S_{f_c}$</td>
<td>Slope of strategy nullcline</td>
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<td>$\gamma$</td>
<td>Cost to ostracize an individual</td>
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Chapter 3

Risk aversion and revenue-sharing agreements can lead to cooperative self-regulation

Andrew Tilman, James Watson and Simon Levin

Abstract

Day-to-day and season-to-season variability in harvest by natural resource users, for example farmers, fishermen and aquaculturalists, is an important driver of their behavior. Here, we explore how risk-mitigation strategies can lead to sustainable use and improved management of 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 lies outside the jurisdictional bounds of any management entity, or if existing institutions cannot effectively impose sustainable-use rules. We study an alternative approach where harvesters join revenue-sharing collectives to mitigate risk and, as a co-benefit, are also incentivized to reduce their effort toward the optimal level. We find that when there is high resource variability, but this volatility is not highly correlated across harvesters in the collective, revenue-sharing agreements can emerge and lead to improvements in resource management. Further, we show that if sustainably-harvested resources from a revenue-sharing collective can be sold as differentiated products with 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.

3.1 Introduction

In open-access natural resource systems, conventional economic theory predicts over-exploitation, resulting in reductions to profitability and stock biomass. Further, users of such resources are subject to economic risk resulting from resource stochasticity. 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 where each harvester benefits from the effort of others. Members of a revenue-sharing collective have a reduced incentive to harvest because everyone retains only a fraction of their own revenue. In this context, the free-rider problem can be beneficial because it reduces the incentive for over-exploitation and can lead to greater profitability. In this paper, 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.

The work of Ostrom and others has shown that in many common-pool resource systems there exist bottom-up institutions that collectively manage the level to which (shared) natural resources are exploited (Ostrom, 1990). Indeed, the role of collective management is crucial in developing countries where governmental institutions are often weak and have limited ability to enforce sustainable practices (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).

Further, risk management tools like production insurance (of the kind commonly used by farmers in the EU and US for example) are often not available (Dercon, 2005; Roberts, 2005). Alternative forms of insurance, like individual and collective index insurance policies, have been proposed as alternatives to provide protection against these risks at lower cost, and without moral hazard (Barnett and Mahul, 2007; Pacheco et al., 2016). Index insurance pays policy holders when a measurable indicator that is correlated with expected losses crosses a set threshold. For example, extreme heat is correlated with crop loss. Index insurance will pay policy holders when an extreme heat event occurs regardless of actual losses. For this reason, index insurance avoids moral hazard. Purchasing the insurance policy does not affect the incentives for policy holders. Access to insurance is thought to be one mechanism that can alleviate the persistence of poverty traps by allowing poor individuals and households to make investments that would otherwise be too risky (Barnett et al., 2008). Other mechanisms of insurance have also been studied. Kenyan pastoralists allow 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 collective insurance that reduces the risk of livestock loss, but also improves the overall use of the grazing lands; highlighting the potential for insurance to be deployed for the improvement of natural resource management.

In this paper, we model an alternative strategy of risk management for natural resource harvesters: revenue-sharing collectives. We use an evolutionary game theoretic framework to answer the following questions: can revenue-sharing collectives emerge among a population of resource users? How do revenue-sharing collectives impact harvesting behaviors in common-pool resource systems? These two questions are of interest because we hypothesize that if revenue-sharing were adopted by users in a
natural resource system, then, depending on the fraction of revenue shared, revenue-sharing may counteract the incentive for over-exploitation that plagues open-access resources. Revenue-sharing creates an incentive structure akin to a free-rider problem. 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 over-exploitation that pervade common-pool resource systems, while also providing insurance against profit variability. Whether this results in improved management will depend on whether such revenue-sharing collectives are stable though time. Ultimately, our results highlight the potential for revenue-sharing cooperatives to lead to the joint resolution of management and risk mitigation challenges, from the bottom up.

3.2 Methods

3.2.1 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 unfeasible. Effort is transformed into profit through revenue from the sale of the extracted resource and the cost of harvesting. We model the profit of an independent harvester $i$ as

$$\pi_i = pqe_i(R + \epsilon_i) - we_i$$

(3.1)

where $p$ is the price received on the market for each unit of resource sold, $q$ is the ‘catch-ability’ of the resource (a measure that transforms effort into catch), $w$ is the cost per unit effort, and $\epsilon_i \sim N(0, \Sigma)$ is a term that results from sampling errors of the resource stock and may be due to spatiotemporal variability of the resource.
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, \( \gamma \), of their revenue equally with members of the collective. As a result, the profit of members of the revenue-sharing club can be written as

\[
\pi_i = \frac{\gamma}{|C|} \left( \sum_{j \in C} pq e_j (R + \epsilon_j) \right) + (1 - \gamma) (pq e_i (R + \epsilon_i)) - we_i. \tag{3.2}
\]

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

\[
U_i = \begin{cases} 
(1 - e^{-a\pi_i}) / a & : a \neq 0 \\
\pi_i & : a = 0
\end{cases} \tag{3.3}
\]

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

\[
E[U_i(x)] \leq U_i(E[x]) \tag{3.4}
\]
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 Fermi process: at each time-step two individuals are chosen at random and one compares its utility to the other. This individual emulates the strategy of the other harvester with a probability that is determined by the utility differential between them. The probability of transition from strategy $S_i$ to strategy $S_j$ is given by

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

where $\delta$ is a measure of the strength of selection. There is also a probability, $\mu$, 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 $\alpha \sim N(0, \nu^2)$.

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

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

(3.6)
the equilibrium level of the resource under the simple ecological harvesting model

given by

\[
\frac{dR}{dt} = rR \left(1 - \frac{R}{k}\right) - qRE
\]  

(3.7)

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. Different functional responses of harvest to effort can also be explored, but we analyze this simplest case.

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.

3.2.2 Analytical benchmarks

To assess the impact of revenue-sharing on harvesting behavior we establish benchmarks to compare 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 equation 3.3 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

\[
U_i(e_i, e_{\sim i}) = \frac{1}{a} - \frac{e^{-a(pqe_i(k(1 - \frac{nq(e_i + (n-1)e_{\sim i})}{r}) + e_i) - we_i)}}{a}.
\] (3.8)

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

\[
E[U_i(e_i, e_{\sim i})] = E\left[ \frac{1}{a} - \frac{e^{-a(pqe_i(k(1 - \frac{nq(e_i + (n-1)e_{\sim i})}{r}) + e_i) - we_i)}}{a} \right],
\] (3.9)

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

\[
E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{E\left[ e^{-a(pqe_i(k(1 - \frac{nq(e_i + (n-1)e_{\sim i})}{r}) + e_i) - we_i)}}{a} \right].
\] (3.10)

Other than \( \epsilon_i \), all elements within the expected value operator on the right-hand side of equation 3.10 are constants. Therefore, we can write

\[
E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{E\left[ e^{-a(pqe_i(k(1 - \frac{nq(e_i + (n-1)e_{\sim i})}{r}) + e_i) - we_i)}}{a} \right].
\] (3.11)

once again, by the linearity of the expected value operator. Finally, since \( \epsilon_i \) is normally distributed, \( e^{-apqe_i, \epsilon_i} \) is log-normally distributed, with mean \( e^{\frac{apqe_i, \epsilon_i^2}{2}} \). 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

\[
E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{e^{aw e_i}}{ac^{apq, k} \left(1 - \frac{q(e_i + (n-1)e_{\sim i})}{r}\right)} e^{\left(\frac{(apq, e_i)^2}{2}\right)}
\]  

(3.12)

where \( \sigma^2 \) is the variance in the resource that individuals face when harvesting. The final term in equation \( 3.12 \) 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 equation \( 3.12 \) 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

\[
e_{\text{Nash}}^* = \frac{r(pqk - w)}{(n + 1)pqk^2 + arp^2q^2\sigma^2}
\]  

(3.13)

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, \( \sigma^2 \), 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 observes, \( \epsilon_i \), 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

\[
E[U_i(e_i, e_{\sim i})] = \frac{1}{a} - \frac{e^{aw e_i}}{ac^{apq, k} \left(1 - \frac{q(e_i + (n-1)e_{\sim i})}{r}\right)} e^{\left(\frac{(apq, e_i)^2}{2}\right)}
\]  

(3.14)

for the expected utility of a member of a cooperative when \( \gamma \) 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

\[ e_{\text{share}}^* = \frac{r \left( pqk \left( 1 - \gamma + \frac{2}{n} \right) - w \right)}{pq^2k + npq^2k \left( 1 - \gamma + \frac{2}{n} \right) + arp^2 q^2 \sigma^2 \left( 1 - \gamma + \frac{2}{n} \right)^2} \]  

(3.15)

for \( \gamma < \frac{n(pqk - w)}{(n-1)pqk} \) and 0 otherwise. This formula is consistent with \( e_{\text{Nash}}^* \) 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 equation (3.14), 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

\[ e_{\text{opt}}^* = \frac{r (pqk - w)}{2npq^2k + arp^2 q^2 \sigma^2 \left( 1 - \gamma + \frac{2}{n} \right)^2}, \]

(3.16)

which, counterintuitively, depends on the fraction of revenue shared, \( \gamma \). This is because risk, in this context the variance of the observed resource stock, \( \sigma^2 \), 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, \( e_{\text{opt}}^* \), 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, \( \gamma \), of revenue that is shared. Depending on \( \gamma \), members of a collective may invest more harvest effort (or less) than would align with \( e_{\text{opt}}^* \). Furthermore, collectives may face a tradeoff. If \( \gamma \) is too high, then the collective
may not be attractive because free-riding will be rampant. On the other hand, if $\gamma$
is too low, then the risk reduction and management benefits of revenue-sharing will be missed.

### 3.2.3 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. We observe the results from three perspectives. First, we show time series of the behavior of individuals. Next, we aggregate behaviors through time and generate histograms of the distributions of effort employed by independent harvesters and club members. Finally, we analyze long-term means across many parameter combinations, generating heat maps that highlight the conditions under which revenue-sharing collectives are most effective and improving use of unmanaged resources.

### 3.3 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 $e_{\text{share}}^*$ 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.

3.3.1 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 figure 3.1, 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, figure 3.2 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.

Figure 3.1: 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.

Figure 3.2: 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.
3.3.2 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 $\gamma$. Assuming a large population size, we can concisely write the level of sharing that leads to optimal harvesting as

$$\gamma^* = \frac{pqk - w}{pqk + w}. \quad (3.17)$$

when $\gamma = \gamma^*$ we predict harvesting of those in a revenue-sharing club to align with the social optimum. Critically, the level of $\gamma$ 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 figure 3.3. We let $\gamma = \gamma^*$ and average effort tracks the social optimum well, with a population size $n = 100$. Further, figure 3.4 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 benefitting from the harvesting effort of others, leading to reductions in total effort relative to the unmanaged case. This causes increases in abundance of the
Figure 3.3: 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.

Figure 3.4: 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.

harvested species, and improvements in the profits and utility of all fishers. Further, 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.
3.3.3 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 figure 3.6 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 figure 3.5, 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 the effort choices of independent harvesters and those in the collective. In figure 3.7, the effort of those in the collective tends to be lower
Figure 3.5: Fraction of harvesters in the revenue-sharing collective through time

Figure 3.6: Effort of independent harvesters (blue) and those in the revenue-sharing collective (green). 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.
Figure 3.7: Frequency of harvesting effort for independent fishers (blue) and those in the revenue-sharing collective (green).

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 shared, $\gamma$, and the degree of risk aversion, $a$. In figure 3.8, plots of average effort as a function of fraction of revenue shared and degree of risk aversion are shown.

Figure 3.8 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, $\gamma$, as expected. Figure 3.9 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
Figure 3.8: Average effort as a function of risk aversion and fraction of revenue shared

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

(b) Average effort of independent harvesters
part of a revenue-sharing agreement is higher, so are average resource stock levels. However, the benefits of revenue-sharing are minimal when $\gamma$ 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.

### 3.3.4 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 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
Figure 3.9: Prevalence of revenue sharers and average resource stock level
as a function of the magnitude of price premium that they receive. As seen in figure 3.10, 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.

3.3.5 Coupled resource dynamics

In this section, we relax the assumption that resource dynamics occur on a fast timescale relative to strategy dynamics. 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 $\tau$ between each strategy update step. For large $\tau$ the resource approaches equilibrium between every strategy update, corresponding to our previous analyses. For small $\tau$, 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, figure 3.11 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 (figure 3.12) these fluctuations do not occur. We analyze whether this has an overall impact on the results of previous sections.
Figure 3.13 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.

3.4 Discussion

Our model of common-pool resource harvesting shows that individuals who join a revenue-sharing club can receive a more stable income and greater utility than non-members if the appropriate portion of profits are shared. Importantly, we allowed harvesters to engage in revenue-sharing where a fixed fraction of revenue was pooled and divided equally among members of the revenue-sharing club. Revenue-sharing acts as a form of insurance against variability in profit that arises through sampling noise. We show that in addition to acting as an insurance mechanism, revenue-sharing also introduces a free-rider problem. However, unlike most systems where free-riding leads to harm, here it creates an incentive to harvest less, ultimately leading to a greater total harvest rate more closely aligned with optimal resource management.

We show that when all harvesters are members of a revenue-sharing club, harvesting can be aligned with the socially optimal harvesting strategy if the correct fraction of revenue is shared. Even when harvesters can choose both their effort level and whether to join a revenue-sharing club, if harvesters are more risk averse,
Figure 3.10: Fraction of harvesters that are in a revenue-sharing collective through time

Figure 3.11: Effort of a population of independent harvesters with slow resource dynamics
Figure 3.12: Effort of a population of independent harvesters with fast resource dynamics

Figure 3.13: Fraction in a revenue-sharing club as a function of the fraction of revenues shared, $\gamma$, and the speed of the resource dynamics relative to the strategy update process, $\tau$. 
and a moderate fraction of revenue is shared, then revenue-sharing clubs can lead to overall improvements in the management of common-pool resources. Furthermore, if resources harvested by members of a revenue-sharing club receive a higher price when sold, then the conditions under which revenue-sharing clubs emerge (and have positive effects on the resource) expand greatly.

These results show that revenue-sharing agreements can be an important tool 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, 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 as opposed to alternative bottom-up management strategies will depend on how easily adherence can be achieved. Similarly, we do not model the process by which a price premium emerges. Indeed, we envision price premiums as a useful tool for this form of management because they strongly incentives club membership. Revenue-sharing clubs could work well 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.

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.

Within a revenue-sharing club, management improvements are a co-benefit of the risk-management (i.e. insurance) that is provided. Insurance against risk is often a pre-condition for long-term planning that is necessary for sustainable resource management. With revenue-sharing agreements, both ends can be achieved in concert though a single mechanism.

Our work is relevant to several specific 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 risk clubs. 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 settings, revenue-sharing can lead to joint environmental and economic wins.

Within our framework, we assume that harvesters are symmetric, each having identical abilities of harvesting and levels of risk aversion. 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. In future work,
heterogeneity among harvesters in their ability level and degree of risk aversion could be studied. Further, it might be that multiple small revenue-sharing clubs will be more effective than a single large one.

Governance of common-pool resources is one of the central challenges facing societies. Many such resources are located in regions of the world where management institutions either do not exist or are ineffective. Further, trans-boundary problems, where resource ranges span many nations or management institutions, are prevalent. Lastly, 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 examine one financial tool, revenue-sharing collectives, and determine the 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 dominate are greatly expanded. We show that risk mitigation strategies can emerge among users of common-pool resources and that cooperative self-regulation can result.
## 3.A Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tr>
<td>$R$</td>
<td>Resource biomass</td>
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<tr>
<td>$f_c$</td>
<td>Fraction in revenue-sharing collective</td>
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<tr>
<td>$r$</td>
<td>Intrinsic growth resource</td>
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<td>$k$</td>
<td>Carrying capacity of resource</td>
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<td>Catch-ability of fish</td>
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<td>Unit cost of effort</td>
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<td>$c_{ij}$</td>
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<td>Multivariate normally distributed resource noise</td>
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<td>$C$</td>
<td>Set of revenue-sharing club members</td>
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<td>$c_i$</td>
<td>Indicator variable of club membership for individual $i$</td>
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<td>Strategy of harvester $i$, composed of effort and club membership choice</td>
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<td>$\gamma$</td>
<td>Fraction of revenue shared</td>
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<tr>
<td>$\delta$</td>
<td>Strength of selection</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Error in effort choice made via emulation of other’s strategy</td>
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Chapter 4

Climate action via a small coalition

ANDREW TILMAN, SIMON LEVIN AND MICHAEL OPPENHEIMER

Abstract

Decades of negotiation have not led to a legally binding global agreement for the reduction of greenhouse gas emissions. We model an alternative approach where a small coalition of nations forge an agreement that incentivizes others to act. We couple carbon mitigation with trade sanctions on non-compliant nations. We find that a small coalition of nations that imposing tariffs on imports from non-compliant nations can switch the cost-benefit analyses of emission reduction policies. This will be especially strong if the coalition is composed of the world’s major economies because the magnitude of the shift in the incentives depends on the amount of the global economy following the policy, not the number of nations following it. The impact of trade sanctions occurs both when a policy is based on a performance standard for each nation and when based on a more equitable metric, per capita emissions of each nation. Finally, in both scenarios, a climate-change coalition will tend to attract more nations. The growth in the size of the coalition makes it beneficial for even more nations to join the coalition. This indicates that climate action, based on a small coalition may have the potential to lead to broad action.

4.1 Introduction

Despite over two decades of negotiations, no legally binding global agreement has been reached for the reduction of greenhouse gas emissions. While the Paris Agree-
ment is a significant advance, it serves primarily as a symbol that many nations are taking climate change more seriously. Under the Paris Agreement, nations submitted nationally determined contributions (NDC’s) to climate change mitigation. Under the agreement, enforcement of these contributions, and the levels of mitigation that they entail relies on ‘naming and shaming’. This limits the ability of the agreement to compel individual nations into potentially costly action. Further, it has been shown that the NDC’s put forth, even if adhered to by all nations, will fail to limit warming to the $2^\circ$C target (Rogelj et al., 2016). Avoiding the damages associated with exceeding this threshold will require additional action. In this paper, we model how a small coalition may be able to tip the scales toward increased action on climate change.

As an alternative to an elusive global agreement, we model how a small coalition of nations could forge an agreement that incentivizes others to act by coupling carbon mitigation with trade sanctions on non-compliant nations. This is similar to the approach of climate clubs, which has been shown to be an alternative pathway for action on climate change (Nordhaus, 2015). The challenge of addressing climate change is driven by the structure the earth system. Greenhouse gas emissions have global impacts, so the social cost of each individual’s emissions is shared by all. This makes action on climate change a global public goods game, where everyone, and each nation has little incentive to unilaterally lower their emissions even though joint action is mutually beneficial. Challenges with this structure are difficult to address without governance at a scale that matches the public good in question. We do not have this luxury with climate change. International agreements have been successful when additional mechanisms are incorporated that alter the incentive structure and result in a self-enforcing agreement, as with the Montreal Protocol (Barrett, 2003). The purpose of sanctions in our model is to change the structure of climate change action from a public goods game to a coordination game. In coordination games,
beyond a critical threshold of action, all nations are better off joining the agreement, and taking action.

In this paper, we model how combining carbon mitigation with tariffs on trade would impact the ability of a small coalition to spur global action on climate change. A recent proposal by prominent republicans calls for a carbon tax in lieu of climate regulations and proposes to impose border adjustment taxes on imports from regions of the world that do not have a carbon tax or other carbon mitigation policy (Baker et al., 2017). The authors claim that the border adjustment will deter free-riding, but it is not clear that one nation acting alone will be sufficient to achieve this end. In particular, as the proportion of nations that have policies implementing a carbon tax, cap and trade system or other major climate regulation combined with a border adjustment tax or tariff on non-compliant nations increases, there is the potential that all nations may find it in their own self-interest to act on climate change. In this paper, we build a model that captures the major features of such a coalition of nations, to better understand the key parameters that would determine the success or failure of the proposed policy to spread and lead to sustained global action on climate change.

The main goal of this paper is to create a simple model that captures the essence of the incentives that nations face in their decision of how to act (or whether to act) on climate change mitigation. This decision is complex. Nations vary in their vulnerability to climate change, face different costs for action, are at different stages of development, and are heterogeneous in many other critical dimensions that influence their willingness to act on climate change. We focus on heterogeneity in population size and per capita wealth as two key axes around which to center our analysis.
4.2 Framework

4.2.1 Emissions

We model the emissions from $n$ nations based off the properties of their economies. Following the Kaya identity, each nation has current emissions, $F_i$, that emerge from their population size, $P_i$, current per capita GDP, $W_i$, and emissions per unit of GDP, $I_i$ with the form

$$F_i = P_i W_i I_i \quad (4.1)$$

where emissions per unit GDP, $I_i$, combines the energy intensity of the economy and the energy efficiency of the economy (Kaya and Yokobori 1997). In our model, these emissions contribute to a global public bad. Said differently, emissions reductions by any nation reduce the damages cause by climate change for all nations. We are interested in exploring if an institution that combines emissions reduction policies with trade sanctions for non-compliance may be able to motivate globally meaningful action on climate change.

4.2.2 Trade and tariffs

Trade is an essential component of our model. We use a simplified “gravity model” of trade to estimate the trade flows that occur among nations (Bergstrand 1985). Within this framework, trade flows between nations $i$ and $j$ scale with the product of the size of their economies and are given by

$$T_{ij} = \gamma P_i W_i P_j W_j \quad (4.2)$$

where $T_{ij}$ is the value of goods traded and $\gamma$ is a parameter that modulates the overall volume of trade flows between their economies. We do not consider the effects of geography on trade, normally accounted for with a distance parameter in the
denominator that modulates total trade between two nations based on the cost of transportation between them. We ignore this complexity because we are primarily interested in how the general structure of trade can be used to generate incentives for action on climate change, rather than the exact spatial and geographic patterns of global trade. Also, we assume that the scale of trade is linear with the size of each economy; this makes analytical results feasible but may overvalue the importance of trade between large nations. With this model, trade flows are symmetric between any pair of nations and scale with the sizes of the economies. This symmetry is broken when tariffs are imposed, because as the price of the traded goods increases, the demand declines according to the price elasticity of demand, \( e \). We define \( e \) as the fractional decrease in trade volume that results from a fractional increase in the price of traded goods, here caused by the tariff, \( t \). The tariff, \( t \), is the fractional, so \( t = .1 \) implies a 10% tariff. As an example, if the traded goods from nation \( i \) to nation \( j \) are tariffed, the new level of exports from nation \( i \) to \( j \) will be \( (1 - et) \) times the baseline level because baseline trade is reduced by the tariff, according to the elasticity \( e \). The consequences on GDP of imposing a tariff are highlighted in figure 4.1. We model changes from the status quo, and the highlighted regions represent these changes. Derivations of the areas of these regions can be found in appendix 4.A. For nations imposing a tariff, GDP increases as a result of tariff revenue, but only to the degree that the revenue exceeds the status quo level of surplus from trade. In this case, the increase is given by \( et(1 - et)T_{ij} \) because this is the portion of tariff revenue that increases GDP beyond the status quo. Imposing a tariff also leads to a deadweight loss. A deadweight loss results from tariffs, and is a market inefficiency that corresponds to surpluses lost by exporters or importers that are not recouped with tariff revenue. The deadweight loss can be approximated as \( \frac{1}{2}(1 - e - et)et^2T_{ij} \). This approximation assumes that the demand curve is linear, which holds for small \( et \). Figure 4.1 highlights the increase in GDP from tariff revenue in blue,
Figure 4.1: Changes to GDP resulting from a tariff on imports. The yellow and green highlighted regions are deadweight losses for exporters and importers, respectively. The blue region is a surplus from trade that is transferred from the exporter to the importer via the tariff.

and the deadweight loss burden on the nation imposing a tariff in green. Nations that have their exports tarifed have GDP losses of $et(1 - et)T_{ij}$ due to tariffs decreasing benefits from trade and a deadweight loss of $\frac{1}{2}e^2t^2T_{ij}$. These impacts on tarifed exports are shown in figure 4.1 in blue and yellow, respectively.

### 4.2.3 Actions and costs

We assume that if nations choose to act, they invest a fraction of their GDP in emission reduction, resulting in a decrease of emissions per unit GDP, $I_i$. This reduction leads to lower global emissions, generating a public good. We assume that the net-present public benefit per unit of reduced emissions is $b$, as a fraction of GDP. Since $b$ is the net-present benefit of reduced emissions, its magnitude will depend on each
nation’s discount rate. In this model, we do not consider heterogeneity in the value of \( b \) that will result from each nation’s propensity to value the future, but this is an important future direction.

### 4.3 Performance standard model

In this section, we explore a simple model where a climate action policy is introduced in which nations make the binary choice of whether to adhere to the policy or not. In this model, we model a policy that imposes a carbon intensity target, \( I_A \). This is akin to setting a global performance standard. This policy is distinct from imposing a limit on per capita emissions, as will be explored later. If nations follow the policy, they decrease the carbon intensity (here defined as emissions per unit GDP) of their economy from \( I_B \), the business-as-usual, to \( I_A \), the level called for under action. Here, we assume that the intensity of all nations at the outset is \( I_B \). We assume that shifting from \( I_A \) to \( I_B \) will cost \( c \), as a fraction of GDP. In addition to agreeing to action, signatories of the plan also agree to impose a tariff, \( t \), on imports from non-signatories as punishment for non-action. Tariffs are revenue generating, so nations will have an incentive to follow along with this second component of the policy. However, there are potential regulatory hurdles limiting tariff increases by the WTO. Lastly, tariffs often lead to retaliatory action. We do not consider this retaliation in our model, but it could be an important future research direction.

We assume that each nation makes the decision of whether to act holding all else equal. Therefore, nations compare the direct costs and benefits of action with those of inaction, given the actions of other nations are fixed. For nation \( i \) we can write the
per capita wealth that results from action as

\[ W_{i,A} = \bar{W}_i \left( 1 - c + b \sum_{\substack{j \in m \\text{or} \ j = i}} (F_j - F_j) \right) + \sum_{\substack{j \notin m \\text{or} \ j \neq i}} \left( T_{ji}(1 - et)/P_i - \frac{1}{2}T_{ij}(et + t - et^2)/P_i \right) \]  

(4.3)

where \( \bar{W}_i \) is the initial per capita wealth of nation \( i \), \( c \) is the cost of action as a fraction of GDP, \( e \) is the price elasticity of demand for trade, \( t \) is the percent tariff, \( m \) is the set of nations that are mitigating their emissions excluding the focal nation \( i \). This is a crucial distinction because the cost:benefit ratio of action depends on the size of the focal nation that is weighing their alternatives. Not only does their decision depend on the costs of being tariffed compared to action, it also depends on the magnitude of the public goods benefit of action, which they influence. The public benefit of reduced emissions is \( b \) and thus relates to the social cost of carbon. Lastly, the terms in the second sum correspond to the impacts of imposing a tariff on imports from a non-compliant nation, thus the sum over all non-compliant nations is the net effect of the tariff policy. This expression can be simplified to

\[ W_{i,A} = \bar{W}_i \left( 1 - c + b(I_B - I_A) \sum_{\substack{j \in m \\text{or} \ j = i}} P_j \bar{W}_j + \frac{\gamma et}{2} (2 - et - t + et^2) \sum_{\substack{j \notin m \\text{or} \ j \neq i}} P_j \bar{W}_j \right) \]  

(4.4)

where \( \gamma \) is a parameter of the gravity model of trade, and the term for tariff income is simplified.

To weigh the decision of whether to act, a nation must compare the economic effects of action to inaction. We can write the payoff under business-as-usual as

\[ W_{i,B} = \bar{W}_i \left( 1 + b \sum_{j \in m} (F_j - F_j) \right) - \sum_{j \in m} \left( T_{ji}(1 - et)/P_i + \frac{1}{2}T_{ij}(et)^2/P_i \right) \]  

(4.5)
so that even those who do not act still receive the benefits of the mitigation of other nations, making climate action in our model a global public good. Further, tariffs reduce exports from non-acting nations, lowering their GDP directly though taxation as well as via a deadweight loss. This can be simplified in terms of per capita GDP as
\[ W_{i,B} = W_i \left( 1 + b(I_B - I_A) \sum_{j \in m} P_j \bar{W}_j - \frac{\gamma et}{2} (2 - et) \sum_{j \in m} P_j \bar{W}_j \right). \] (4.6)

Within this framework, we can analyze the conditions under which a focal nation will be better off acting to address climate change, or staying on the BAU pathway. We expect nation \( i \) to act when
\[ W_{i,A} - W_{i,B} > 0 \] (4.7)

implying that per capita GDP is expected to be greater under action than under BAU. Condition (4.7) will hold when
\[ b(I_B - I_A)P_i \bar{W}_i - c + \frac{\gamma et}{2} \left( (2 - et - t + et^2) \sum_{j \in m, j \neq i} P_j \bar{W}_j + (2 - et) \sum_{j \in m} P_j \bar{W}_j \right) > 0. \] (4.8)

To elucidate further what shapes the incentives for action, note that all \( P_j \)'s and \( \bar{W}_j \)'s are fixed. Further, we can rewrite the formula for when action is beneficial for a nation in terms of the fraction of the rest of the world economy that is acting. We have \( \sum_{j \in m, j \neq i} P_j \bar{W}_j + \sum_{j \in m} P_j \bar{W}_j + P_i \bar{W}_i = G \), where \( G \) is a constant, equal to global GDP. Now, we define \( f_A \) as the fraction of the global economy (in terms of GDP) that is following the performance standard, excluding nation \( i \), and \( f_B \) as the fraction of the global economy that is following BAU, excluding nation \( i \). Finally, let \( f_i = P_i \bar{W}_i/G \) This allows us to rewrite our condition under which action is favored
as

\[ b(I_B - I_A)Gf_i + \frac{\gamma et}{2} ((2 - et - t + et^2)Gf_B + (2 - et)Gf_A) > c. \] (4.9)

Note that \( f_i + f_B + f_A = 1 \) and therefore we can simplify this condition to

\[ b(I_B - I_A)f_i + \frac{\gamma et}{2} [(2 - et)(1 - f_i) - (t - et^2)f_B] > \frac{c}{G}. \] (4.10)

Note that since \( 1 - et \) portion of trade that remains after a tariff is imposed, we constrain \( 1 - et > 0 \) so that there are not negative trade flows. This implies that the term \( t - et^2 \) will be positive. As a result, the incentives for action increase as \( f_B \) decreases. Thus, increased rates of action will increase the incentives for other nations to act as well. This important result means that, once initiated, a small coalition of climate-tariff-imposing nations should attract an increasing number of additional nations into the coalition.

We can consider the conditions under which a single nation will want to act unilaterally. In this case \( f_A = 0 \), and we can simplify action criterion solving for the critical level of \( f_i \) that will lead unilateral action being favored. This requires

\[ b(I_B - I_A)f_i + \frac{\gamma et}{2} (2 - et - t + et^2)(1 - f_i) > \frac{c}{G}. \] (4.11)

Also, since equation (4.9) is linear in \( f_i, f_B, \) and \( f_A \) we know that the boundary that separates regions favoring action from ones that favor inaction will be linear. Also, since \( f_i + f_B + f_A = 1 \) the decision of a focal nation can be shown on a simplex.

4.4 Per capita emissions standard

Although a policy that requires each nation to attain a fixed level of carbon intensity is simple and tractable, an alternative approach is to limit per capita emissions. These policy approaches differ because in the former, wealthier nations can have higher
emissions per capita than poorer nations. A global per-capita emissions limit may be more appealing to some nations because it is a policy that achieves a fair outcome, in the sense that each nation’s people are held to the same level of emissions. However, with this setup, high-emission nations will be required to make greater reductions in $I_i$, their energy intensity, to reduce per capita emissions, $W_i I_i$, to meet the threshold.

We model a policy that maintains the tariffs from the previous section, but in lieu of a technology standard sets a limit on per capita emissions. Therefore, an upper bound on per capita emissions will be set. Nations that choose to act will pay a fraction of GDP, $c$, for each unit of reduction of $I_i$ until per capita emissions, $W_i I_i$, are not greater than $E$. If a nation’s emissions are already below this level, no mitigation investment is necessary. Tariffs will be imposed on trade originating in nations whose per capita emissions exceed $E$.

With this framework, each nation will have a different cost-benefit balance for action that will depend on the wealth of the nation, as well as its energy use and emissions patterns. This will allow us to consider how a policy could be set in place among developed nations, and expand to successive waves of nations as their level of development advances. A policy that sets an upper bound on per capita emissions is beneficial from an ethical perspective as it promotes fairness among nations, and people. However, the wealthiest nations will have to pay the highest price to meet the targets set, potentially limiting their incentive to act.

A key change made in this section is that the magnitude of action required by each nation depends on its baseline per-capita emissions. For nation $i$, with per-capita emissions $W_i I_i$, the amount of mitigation needed to reach the per capita emissions limit, $E$ will be given by the new level of energy intensity $I_i = \frac{E}{W_i}$. The cost of action to the nation $i$, as a fraction of GDP is $c \left( I_i - \frac{E}{W_i} \right)$. Therefore, the total cost, all else being equal, scales linearly with population size, and the magnitude of mitigation required. In practice, there is likely increasing marginal costs for increasing levels of
mitigation, because the cheapest methods of increasing the performance of the energy system will be taken first. We however, do not consider this effect.

As in the previous section, we incorporate the impact of tariffs on both nations that impose and nations that face tariffs on trade. These effects remain the same before. Only the degree of action each nation is called upon to contribute differs.

The net effect of imposing a tariff can be computed from the sum of each bi-lateral interaction of between pairs of nations. From this we can write the national wealth resulting from action as

$$W_{i,A} = W_i \left( 1 - c \left( T_i - \frac{E}{W_i} \right) + b \sum_{\substack{j \in m \lor j = i \hfill \atop k \notin m \lor k \neq i}} \left( F_j - F_j \right) P_j W_j + \frac{T_k}{2P_i} e^t (2 - et - t + e^t) \right)$$

(4.12)

where $m$ is the set of other nations acting, excluding nation $i$. This can be simplified to

$$W_{i,A} = W_i \left( 1 - c \left( T_i - \frac{E}{W_i} \right) + b \sum_{\substack{j \in m \lor j = i \hfill \atop k \notin m \lor k \neq i}} \left( I_j - E W_j \right) P_j W_j + \frac{\gamma e^t}{2} (2 - et - t + e^t) \sum_{k \in m} P_k W_k \right)$$

(4.13)

The nations following BAU have resulting wealth

$$W_{i,B} = W_i \left( 1 + b \sum_{j \in m} \left( F_j - F_j \right) P_j W_j - \frac{T_k}{2P_i} e^t (2 - et) \right)$$

(4.14)

which considers all the interactions between BAU and acting nations. This expression can be simplified to

$$W_{i,B} = W_i \left( 1 + b \sum_{j \in m} \left( I_j - \frac{E}{W_j} \right) P_j W_j - \frac{\gamma e^t}{2} (2 - et) \sum_{k \in m} P_k W_k \right)$$

(4.15)
To determine whether a focal nation has an incentive to act, we calculate the conditions under which $W_{i,A} > W_{i,B}$. For a focal nation, this will depend on the actions of all other nations. However, in this model the result depends only on total size of the world’s economies that follow BAU or act on climate change. We have:

$$(c - bP_i W_i) \left( I_i - \frac{E}{W_i} \right) < \frac{\gamma et}{2} \left[ (2 - et - t + et^2) \sum_{j \in m, j \neq i} P_j W_j + (2 - et) \sum_{k \in m} P_k W_k \right]$$

as our condition under which a focal nation is better off acting on climate change. Note that the left-hand side terms are the net domestic cost-benefit ratio of action, and the right-hand side is the influence of other nations’ tariff actions on the incentives for action of the focal nation. We can simplify this expression and write it in terms of $G_A$ and $G_B$. We have

$$(c - bP_i W_i) \left( I_i - \frac{E}{W_i} \right) < \frac{\gamma et}{2} \left[ (2 - et)(G_B + G_A) - (t - et^2)G_B \right]$$

As before, $t - et^2 > 0$, indicating that the incentives for action increase in the fraction of the economy that acts. This is because as the size of the acting coalition grows, the gains from imposing tariffs decrease more slowly than the cost of being sanctioned with tariffs increases. This is critical for a policy that seeks to be self-enforcing.

### 4.5 Further directions

We have shown that the incentive structure created by imposing tariff on non-compliant nations will, in general, make the incentives for action increase in the size of the acting coalition. However, we have not computed the Nash equilibrium strategy profiles under our two models, nor directly analyzed the impact of heterogeneity.
in the size of economies on the propensity for action a stable equilibrium. In order to
directly assess the impact of heterogeneity of GDP across nations, we will generate
sets of nations with log-normal GDP distributions. By varying the variance of the
distribution, we can analyze sets of nations with different Gini coefficients. Then we
will assess the effect of inequality on the ability of a coalition to form and persist, by
analyzing the Nash equilibria under these different conditions.

4.6 Discussion

Our analyses reveal three major findings. First, a small coalition of nations that
imposes climate-harm-dependent tariffs on imports from nations with which they
trade can switch the cost-benefit analyses of climate change reduction policies in
other nations such that the trading partners would receive net economic benefits from
policies that reduced their climate change impacts. This will be especially strong if
the coalition is composed of the world’s major economies because the magnitude of
the shift in the incentives depends on the amount of the global economy following the
policy, not the number of nations following it. Second, the impact of trade sanctions
occurs both when a policy is based on a performance standard for each nation and
when based on a more equitable metric, per capita emissions of each nation. Third,
under both scenarios, a climate-change coalition, once formed, will tend to attract
more nations, and the growth in the size of the coalition makes it beneficial for even
more nations to join the coalition. This positive feedback means that an appropriately
structured climate change coalition has the potential to overcome the tragedy of the
commons that otherwise occurs with atmospheric emissions of greenhouse gasses.

There are many important additional directions and issues that merit further
analyses. First, some of the least developed nations currently receive few financial
benefits from exports, and thus may be much less likely to join a climate-change-
reduction coalition. However, per capita GHG emissions scale with per capita GDP, and thus the lack of participation by such nations would have only minor impacts of global GHG emissions. As the economies of the least developed nations grow, and their emissions become greater, a point would be reached at which joining the coalition would be beneficial. In section 4.3 we assumed that when nations decide whether to act on climate change, they compare the relative benefits of action and inaction without considering feedback effects on wealth of all nations, and how this impacts their own decision. These feedbacks could be important, but incorporating them will make analytical findings difficult. To overcome this, I propose to use the results of section 4.3 as a baseline to compare to computational results using parameters taken from the literature and incorporating these important wealth feedbacks. This will allow us to analyze the minimum size of a coalition that makes it a Nash equilibrium for all other nations to act and allow for analysis of the factors that determine this minimum coalition size.

The analysis of the feasibility of the approach in section 4.3 will also benefit from parameter ranges and estimates taken from the literature. This will make it clear whether the action of one nation, as proposed by Baker et al. (2017) will have any chance of leading to global action.

Heterogeneity across nations in parameters hitherto assumed to be constant could also be important. Differences in vulnerability may lead some nations to act and others to drag their feet.

4.A Derivation of tariff consequences

The area of the blue rectangle in figure 4.1 is the amount of GDP gain that imposers of a tariff receive due to direct tariff income, and the amount of GDP lost by exporters due to tariffs. The area of the blue rectangle is $Q_1(P_0 - P_1)$. While these variables do
not appear in the rest of the papers analyses, we can transform this expression into a
term that depends only on the parameters of the model from our assumptions. By our
definition of elasticity, we know that imposing a tariff of $t$ percent will lead $et$ percent
reduction in the quantity of traded goods. Therefore, we can the resulting level of
trade as $Q_1 = Q_0(1 - et)$. Also, assuming that the supply function is linear we know
that $\frac{P_0}{Q_0} = \frac{P_1}{Q_1}$. Thus, we can write the resulting trade price as $P_1 = \frac{Q_1P_0}{Q_0} = (1 - et)P_0$
by substituting our expression for $Q_1$ into the formula. With these two expressions,
we can rewrite our expression for the rectangle as

$$Q_1(P_0 - P_1) = Q_0(1 - et)(P_0 - (1 - et)P_0)\quad (4.18)$$

which can be simplified to

$$Q_1(P_0 - P_1) = Q_0P_0(1 - et).et.\quad (4.19)$$

We have modeled the value of traded goods, which is the product of the quantity of
traded goods and their price, therefore we can write $Q_0P_0 = T_{ij}$ for ex-ante levels of
trade between a pair of nations. From this, we can write our final expression for the
impact of the tariff as

$$T_{ij}(1 - et).\quad (4.20)$$

Next, we consider the deadweight loss imposed upon exporters by a tariff. In fig-
ure 4.1 this is the yellow shaded triangle, given by $\frac{1}{2}(Q_0 - Q_1)(P_0 - P_1)$. Following the
similar steps as above we can re-write this in terms of our parameters by substituting
in the computed values for $Q_1$ and $P_1$. This gives us $(P_0 - (1 - et)P_0)(Q_0 - (1 - et)Q_0)$
which can be written as $\frac{1}{2}P_0Q_0(et)^2$ and simplified to

$$\frac{T_{ij}(et)^2}{2}.\quad (4.21)$$
Lastly, we consider the deadweight loss incident upon imposers of a tariff. This is given by the green shaded area in figure 4.1. We approximate this as a triangle with area

\[ \frac{1}{2}(Q_0 - Q_1)(P_1 - P_0). \]

We can write \( P_1 \) in terms of \( P_0 \) because due to our assumptions about the tariff, we know that

\[ P_1 = P_0(1 + t) = (1 - et)(1 + t)P_0. \]

With this we can make substitutions and simplifications finding that the deadweight loss the tariff imposes on nations that tariff imports is

\[ \frac{1}{2}(1 - e - et)et^2T_{ij}. \quad (4.22) \]
### 4.B Parameters and variables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Number of nations</td>
</tr>
<tr>
<td>$W_i$</td>
<td>Per capita GDP of nation i</td>
</tr>
<tr>
<td>$F_i$</td>
<td>Emissions of nation i</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Population of Nation i</td>
</tr>
<tr>
<td>$I_i$</td>
<td>Emission per unit GDP of nation i</td>
</tr>
<tr>
<td>$T_{ij}$</td>
<td>Value of trade between nation i and j</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Trade parameter with units 1/GDP</td>
</tr>
<tr>
<td>$t$</td>
<td>Fractional tariff on trade</td>
</tr>
<tr>
<td>$b$</td>
<td>Marginal social benefit of reduced emissions as a fraction of GDP</td>
</tr>
<tr>
<td>$c$</td>
<td>Cost of action as a fraction of GDP</td>
</tr>
<tr>
<td>$m$</td>
<td>The set of nations that are acting on climate change excluding the focal nation</td>
</tr>
<tr>
<td>$G$</td>
<td>Global GDP</td>
</tr>
<tr>
<td>$f_A$</td>
<td>Fraction of global economy acting</td>
</tr>
<tr>
<td>$E$</td>
<td>Limit on per capita emissions</td>
</tr>
<tr>
<td>$G_B$</td>
<td>Size of global BAU economy excluding the focal nation</td>
</tr>
<tr>
<td>$G_A$</td>
<td>Size of global action economy excluding focal nation</td>
</tr>
</tbody>
</table>
Chapter 5

Localized pro-social preferences, public goods and common-pool resources

Avinash Dixit, Simon Levin and Andrew Tilman

Abstract

Pro-social preferences are thought to play a significant role in solving society’s collective action problems of providing public goods and reducing public bads. However, pro-sociality is often limited to members of an in-group. We construct a theoretical model where society is split into subgroups and each person cares only about the welfare of others within this subgroup. We examine the consequences of such localization for the economic outcomes of the whole society. We then extend that model to more general topologies, where individuals exhibit some cross-group pro-sociality.

5.1 Introduction and motivation

As the world becomes more interconnected, we increasingly are faced with problems of the Commons and their governance (Hardin 1968; Ostrom 1990; Levin 1999). Individuals and nations withdraw water, fish and other resources from a finite pool;
overuse of antibiotics erodes their effectiveness (Smith et al., 2005); and the emission of pollutants and greenhouse gases fouls the atmosphere. In most such situations, individual incentives are insufficient to restrain usage and sustain the Commons; governments must find ways to change the incentive structure to overcome the tendency to overexploit. The task may be easier in smaller societies, where pro-social preferences may play a greater role. In this paper, we examine how pro-sociality may make action in the collective good easier, and how incentives can reinforce pro-sociality to achieve collective benefits.

Pro-social preferences and other-regarding behaviors more generally are a fact of life, though it is often puzzling how they are sustained (Henrich et al., 2001; Gintis, 2003; Fehr and Gintis, 2007; Akçay et al., 2009; Henrich et al., 2010). In a related paper we examine one pathway, where each generation educates the next to instill pro-social preferences (Dixit and Levin, 2017). In this paper, we beg the question of why pro-sociality exists, but rather ask what its consequences are for achieving cooperation.

The main issue on which we focus in this paper is particularly relevant to public goods or bads that affect large and widespread populations; maintenance of order and regulation in trade, commerce and financial markets (goods), ocean fisheries, emissions of greenhouse gases and some other pollutants (bads), are examples with worldwide reach. However, it is evident from public policy debates that pro-sociality does not extend worldwide. Individuals care more about their immediate circles of family and friends than they do for the general public in their region or state, more for their local population than for the national citizenry at large, and more for their fellow-citizens than for foreigners. We ask how far such localized pro-sociality can help solve collective action problems that have wider global scope. We construct some simple theoretical models that give some answers, and more guidance on how
to think about such problems and ideas for future research. In this paper, we assume given patterns of pro-sociality and examine the consequences for individual actions.

5.2 A general pro-sociality framework

Here we lay out a model of public good provision with prosocial preferences, building on Dixit (2009). There are \( n \) individuals, labeled \( i = 1, 2, ..., n \). Each can exert two types of effort: private \( x_i \), and public \( z_i \). The public good may consist of the effort itself, for example volunteered time, or it may be a good or service produced one-for-one using aggregate public effort; either interpretation works equally well. We assume the public good increases the productivity of private effort; for example, better roads make private transport more efficient, and better education increases private skills and therefore raises the productivity of individual labor\(^1\). We assume this effect is channeled through a function

\[
Z = g(z_1, z_2, ..., z_n)
\]

so that the relationship between each individual’s investment in the public good and the resulting level of the public good can be adjusted to account for varying degrees of congestion. At one extreme, \( Z \) is simply the sum of the \( z_i \)’s and there is no congestion. Alternatively, complete congestion would imply that \( Z \) is the mean of the \( z_i \)’s. Our general framework allows for us to consider intermediate cases as well. The degree of congestion of public goods makes them more closely resemble common-pool resources, where the use by one person precludes it’s use by others. With our framework, individual \( i \)’s income is given by

\[
y_i = f(x_i, Z) \tag{5.1}
\]

\(^1\)Conversely, public bads such as pollution and congestion lower private productivity; this is a mirror-image case of our model and can be analyzed similarly.
where \( f \) is a function of private input, \( x_i \) and the level of the public good, \( Z \), with levels of the public good impact the productivity of private investment. This income is transformed into utility via a function that incorporates pro-sociality, and the cost of investment in public and private goods. This can be expressed generally as

\[
U_i = h(y_1, ..., y_n, x_i, z_i, Z)
\]

where \( h \) is non-decreasing in \( y_1, ..., y_n \) and \( Z \). This framework allows for the study of public goods provision under pro-sociality because we can calculate the Nash equilibrium level of contribution to the public good relative to the socially optimal contribution as pro-sociality varies. We will explore a specific case of this general framework in the rest of the paper. We examine the case where there is a cost to investment in public and private goods, and examine the social benefits of pro-sociality under different degrees of public-goods spillovers.

### 5.3 Model

First, consider a group of \( n \) individuals contributing \( z_i \) to the public good. (Public bads can be handled by change of sign with a little care to ensure positive solutions.) The public good that goes into the production function, to raise the productivity of private inputs, is

\[
Z = \eta \frac{\sum_i z_i}{n} + (1 - \eta) \sum_i z_i = \left( \frac{\eta}{n} + (1 - \eta) \right) \sum_i z_i \equiv \mu \sum_i z_i
\]

where \( \eta \in [0, 1] \), so \( \eta = 1, \mu = 1/n \) gives the full congestion case and \( \eta = 0, \mu = 1 \) the no-congestion case. Intermediate values of \( \eta \) cover the cases where the public good in question has some level of congestion (as is nearly always the case).
Now consider two groups, 1 and 2, and introduce these subscripts on the relevant variables. (Many groups can be included with more notation.) Group 1’s public good $Z_1$ has effectiveness $\lambda_{11}$ on its own production and $\lambda_{12}$ on group 2’s production, and similarly for group 2. These are spillovers of the public good from one group to another. In general, we expect $\lambda_{11} > \lambda_{12}$, but this need not be true. In the case of air pollution, for example, the direction of the wind implies that pollution may primarily affect populations. This effect is especially strong in riverine systems, where fertilizer runoff generates a public bad that primarily causes damages (eutrophication) downstream.

We model the income of individual $i$ in group 1 as

$$y_{i1} = x_{i1} \left( 1 + \lambda_{11} Z_1 + \lambda_{21} Z_2 \right) = x_{i1} \left( 1 + \lambda_{11} \mu_1 \sum_j z_{j1} + \lambda_{21} \mu_2 \sum_k z_{k2} \right)$$

so that the income of each individual depends on the local levels of public goods, accounting for spillovers, as well as their own private investment, $x_{i1}$. Income of members of group 2 can be similarly expressed.

To model the Nash equilibrium and socially optimal investments in the public good, we let each individual in group 1 have a pro-sociality level $\gamma_{11}$ for others within her or his group, and $\gamma_{12}$ for people in group 2. These pro-sociality parameters determine the impact of the income of all other individuals on the utility of each person. Here, we do expect $1 \geq \gamma_{11} \geq \gamma_{12} \geq 0$, so that all individuals care at least as much about members of their own group as other groups. Also, we assume that there are costs to both public and private effort. We define the utility of a individual $i$ in group 1 as

$$u_{i1} = y_{i1} + \gamma_{11} \sum_{j \neq i} y_{j1} + \gamma_{12} \sum_k y_{k2} - \frac{1}{2} c_1 (x_{i1} + z_{i1})^2$$

(5.4)
so that the marginal cost of effort (both public and private) is increasing. This will make a positive equilibrium likely. With this framework, we can analyze both the Nash equilibrium strategies of individuals in each group as well as the socially optimal strategies of every individual. This will allow us to assess the conditions under which pro-sociality alone is able to support optimal provision of public goods, and examine relative public good provision under limited pro-sociality.

5.4 Results

5.4.1 First-order conditions

To solve for the Nash equilibrium harvesting strategies, we compute the first-order conditions for maximizing $u_{i1}$ with respect to the strategy choice, $(x_{i1}, z_{i1})$. The first-order conditions are

\[
\begin{align*}
\frac{\partial u_{i1}}{\partial x_{i1}} &= 1 + \lambda_{11} Z_1 + \lambda_{21} Z_2 - c_1 (x_{i1} + z_{i1}) = 0 \\
\frac{\partial u_{i1}}{\partial z_{i1}} &= \left( x_{i1} + \gamma_{11} \sum_{j \neq i} x_{j1} \right) \lambda_{11} \mu_1 + \gamma_{12} \sum_k x_{k2} \lambda_{12} \mu_1 - c_1 (x_{i1} + z_{i1}) = 0
\end{align*}
\]

Notice that the second condition has a sum over all individual except individual $i$. This is because while the level of pro-sociality is $\gamma_{11}$ for other individuals in group 1, it it always 1 for yourself. Define

$$\phi_1 = \left[ 1 + (n_1 - 1) \gamma_{11} \right] / n_1$$

as the effective level of pro-sociality within group 1. Notice that $1 \geq \phi_1 \geq \gamma_{11} \geq \gamma_{12} \geq 0$. Since within a group each individual faces the same incentives, the equilibrium strategy will be the same for all members of group 1. As a result, we can substitute $x_1$ as the common value of $x_{i1}$ for all $i$, and similarly $z_{i1} = z_1$ for all $i$. Then the
conditions become

\[ c_1(x_1 + z_1) = 1 + \lambda_{11} \mu_1 n_1 z_1 + \lambda_{21} \mu_2 n_2 z_2 \]
\[ c_1(x_1 + z_1) = n_1 \phi_1 \lambda_{11} \mu_1 x_1 + n_2 \gamma_{12} \lambda_{12} \mu_1 x_2 \]

once \( \phi_1 \) is substituted into the expression. Similarly, from the first-order conditions for an individual in group 2 we have

\[ c_2(x_2 + z_2) = 1 + \lambda_{12} \mu_1 n_1 z_1 + \lambda_{22} \mu_2 n_2 z_2 \]
\[ c_2(x_2 + z_2) = n_1 \gamma_{21} \lambda_{21} \mu_2 x_1 + n_2 \phi_2 \lambda_{22} \mu_2 x_2. \]

These four equations can be solved for \( x^*_1, z^*_1, x^*_2, z^*_2 \), which are the Nash equilibrium strategies for members of each group.

The socially optimal outcome requires full pro-sociality because when individuals are fully pro-social they act to maximize the total income of the whole population. Thus, when \( \phi_1 = \gamma_{11} = 1, \gamma_{12} = 1 \) and \( \phi_2 = \gamma_{22} = 1, \gamma_{21} = 1 \) we have socially optimal investment in public goods. By comparing the solution with these values and the solution for the smaller values that seem more reasonable in reality, we can compare the optimum and the outcome with only partial pro-sociality.

Almost arbitrary asymmetry across the groups is allowed, so the groups can have unequal populations, asymmetric spillovers of the public goods, or asymmetric pro-sociality levels for insiders and for each other. This given this flexibility, our results will be general, but we also examine special cases of interest.
5.4.2 Second-order conditions

To assure that the solutions from the first order conditions are valid, we have to consider the second-order conditions. These conditions will place constraints on parameter values under which our analysis applies.

Begin with individual $i$ in group 1. The matrix of the second-order derivatives, derived from expression (5.4.1) is

$$
\begin{pmatrix}
\frac{\partial^2 u_{i1}}{\partial x_{i1}^2} & \frac{\partial^2 u_{i1}}{\partial x_{i1} \partial z_{i1}} \\
\frac{\partial^2 u_{i1}}{\partial z_{i1} \partial x_{i1}} & \frac{\partial^2 u_{i1}}{\partial z_{i1}^2}
\end{pmatrix}
= \begin{pmatrix}
-c & \lambda_{11} \mu_1 - c \\
\lambda_{11} \mu_1 - c & -c
\end{pmatrix}.
$$

If this matrix is negative definite, then our first order condition yield a maximum, as desired. This holds when

$$c^2 - (c - \lambda_{11} \mu_1)^2 > 0,$$

which can be simplified to

$$2c > \lambda_{11} \mu_1. \tag{5.6}$$

This implies that if the costs of effort are sufficiently high, the Nash equilibrium that we calculate from the first order conditions will hold.

Assuring that our calculations for the social optimum hold may require additional constraints on the parameters. The objective function for the global optimum is

$$V = \left[ \sum_{i1} y_{i1} - \frac{1}{2} c_1 (x_{i1} + z_{i1})^2 \right] + \left[ \sum_{k2} y_{k2} - \frac{1}{2} c_2 (x_{k2} + z_{k2})^2 \right] \tag{5.7}$$

where the $y$'s are given by equation (5.3). The choice variables are all the $(x_{ig}, z_{ig})$.

Then the second-order conditions bring in all the cross-partials

$$\frac{\partial^2 u_{i1}}{\partial x_{i1} \partial z_{j1}} \text{ for } j \neq i, \quad \frac{\partial^2 u_{i1}}{\partial x_{i1} \partial z_{k2}}$$

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that were irrelevant to individual choice. These conditions will involve an intratible $2(n_1 + n_2)$ by $2(n_1 + n_2)$ matrix. To simplify this, we seek an optimum in a 4-dimensional subspace, using the fact that all the within-group choices equal, so we write $x_1$ for all $x_i$’s. This yields

$$V = n_1 \left[ y_1 - \frac{1}{2} c_1 (x_1 + z_1)^2 \right] + n_2 \left[ y_2 - \frac{1}{2} c_2 (x_2 + z_2)^2 \right]$$ \hspace{1cm} (5.8)$$

with first-order conditions

$$y_1 = x_1 (1 + \lambda_{11} \mu_1 n_1 z_1 + \lambda_{21} \mu_2 n_2 z_2)$$
$$y_2 = x_2 (1 + \lambda_{12} \mu_1 n_1 z_1 + \lambda_{22} \mu_2 n_2 z_2)$$ \hspace{1cm} (5.9)$$

and the matrix of second-order cross-partialis of $V$ with respect to $(x_1, z_1, x_2, z_2)$ is

$$A = \begin{pmatrix}
-n_1 c_1 & -n_1 c_1 + n_1^2 \lambda_{11} \mu_1 & 0 & n_1 n_2 \lambda_{21} \mu_2 \\
-n_1 c_1 + n_1^2 \lambda_{11} \mu_1 & -n_1 c_1 & n_1 n_2 \lambda_{12} \mu_1 & 0 \\
0 & n_1 n_2 \lambda_{12} \mu_1 & -n_2 c_2 & -n_2 c_2 + n_2^2 \lambda_{22} \mu_2 \\
n_1 n_2 \lambda_{21} \mu_2 & 0 & -n_2 c_2 + n_2^2 \lambda_{22} \mu_2 & -n_2 c_2
\end{pmatrix}$$ \hspace{1cm} (5.10)$$

and if the $k$ leading principal minors, $A_k$, satisfy

$$(1)^k \text{Det}[A_k] > 0$$

for all $k \leq 4$, then $A$ is negative definite, and our solution of the global optimum from the first-order conditions will hold. The diagonals are all negative so our condition holds for $k = 1$. Turning to the leading 2-by-2 principal minor gives

$$(n_1 c_1)^2 - (-n_1 c_1 + n_1^2 \lambda_{11} \mu_1)^2 > 0$$
or

\[ 2c_1 > n_1 \lambda_{11} \mu_1 \]  

(5.11)

The determinant of the leading 3x3 principal minor is negative when

\[ n_1 n_2 \left( n_1^2 n_2 \lambda_{12}^2 \mu_1^2 c_1 - 2n_1^2 c_1 c_2 \lambda_{11} \mu_1 + n_1^3 c_2 \lambda_{11} \mu_1^2 \right) < 0 \]

and can be simplified to

\[ 2\lambda_{11} c_1 c_2 > \mu_1 \left( n_1 c_2 \lambda_{11}^2 + n_2 c_1 \lambda_{12}^2 \right). \]  

(5.12)

The determinant of the entire matrix will be positive, as required, when

\[
\begin{align*}
\mu_1^2 \mu_2 n_1 [c_2 \lambda_{11} (\lambda_{12}^2 + \lambda_{12} \lambda_{21} - 2\lambda_{11} \lambda_{22}) + \\
\mu_2 n_2 (\lambda_{12}^2 - \lambda_{11} \lambda_{22})(\lambda_{12} \lambda_{21} - \lambda_{11} \lambda_{22}) + \\
> c_1 [c_2 (\lambda_{12} \lambda_{21} \mu_2 (\mu_1 + \mu_2) + \lambda_{12} \mu_1 (\mu_1 + \mu_2) - 4\lambda_{11} \lambda_{22} \mu_1 \mu_2) + \\
\lambda_{22} \mu_1 \mu_2 n_2 (2\lambda_{11} \lambda_{22} - \lambda_{21} \lambda_{12} - \lambda_{12}^2)]
\end{align*}
\]

which cannot be easily simplified to a clear expression. The general idea of these criteria is that spillovers \((\lambda_{ij})\) and non-congestion \((\mu_i)\) should be sufficiently small in relation to the effort cost coefficients \(c_i\). To see the intuition behind this, note that both the benefit gain of the calculation (coming from the \(y_i\)) and the loss side (the costs of efforts or contributions) are of the same order of magnitude (quadratic): the former because of the products of \(x's\) and \(z's\), and the latter because of the square of \(x's\) and \(z's\). To get a finite optimum, the coefficients on the cost side should be large in relation to those on the gain side, otherwise net gain can be increased indefinitely by proportionate increases in all the \(x's\) and \(z's\). Unfortunately, the implied limits on spillovers and non-congestion are quite strict. Roughly, each should be no bigger than

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inversely proportional to the square root of the relevant population size. That also makes sense, because the spillovers of each person’s contribution affect many people, and without sufficient congestion the sum of contributions will have a big effect on productivity of lots of people.

5.4.3 Closed-form solution

When the second-order conditions hold, we can proceed from the first-order conditions for investments in public and private goods,

\[
\begin{align*}
    c_1(x_1 + z_1) &= 1 + \lambda_{11} \mu_1 n_1 z_1 + \lambda_{21} \mu_2 n_2 z_2 \\
    c_1(x_1 + z_1) &= n_1 \phi_1 \lambda_{11} \mu_1 x_1 + n_2 \gamma_{12} \lambda_{12} \mu_1 x_2
\end{align*}
\]

and

\[
\begin{align*}
    c_2(x_2 + z_2) &= 1 + \lambda_{12} \mu_1 n_1 z_1 + \lambda_{22} \mu_2 n_2 z_2 \\
    c_2(x_2 + z_2) &= n_1 \gamma_{21} \lambda_{21} \mu_2 x_1 + n_2 \phi_2 \lambda_{22} \mu_2 x_2
\end{align*}
\]

and solve for the equilibrium levels of effort, \((x_1^*, z_1^*, x_2^*, z_2^*)\).

There are two terms that arise throughout the solutions. First, consider the matrix of public-good spillovers given by the lambda’s,

\[
\Lambda = \begin{bmatrix}
    \lambda_{11} & \lambda_{12} \\
    \lambda_{21} & \lambda_{22}
\end{bmatrix}
\] (5.13)

and the matrix of public-good spillovers element-wise multiplied by the pro-sociality values,

\[
\Gamma \Lambda = \begin{bmatrix}
    \lambda_{11} \phi_1 & \lambda_{12} \gamma_{12} \\
    \lambda_{21} \gamma_{21} & \lambda_{22} \phi_2
\end{bmatrix}
\] (5.14)
Let $|\Lambda| = \text{det}(\Lambda)$ and $|\Gamma\Lambda| = \text{det}(\Gamma\Lambda)$. These quantities appear repeatedly in the solution of the first-order conditions. As the structure of the model is symmetric, I have shown below only the equilibrium values for individuals in group 1. The solutions for individuals of group 2 will be the same but with subscripts reversed. Below is the equilibrium value for investment private effort.

$$x^*_1 = \frac{-(\lambda_{22} - \lambda_{21})c_1 n_2 \lambda_{22} \phi_1 \mu_2^2 + (\lambda_{11} - \lambda_{12})c_2 n_1 \lambda_{12} \gamma_{12} \mu_1^2 - (\lambda_{12} \gamma_{12} \mu_1 - \lambda_{22} \phi_1 \mu_2)c_1 c_2}{|\Gamma\Lambda||\Lambda| \left(n_2^2 n_2^2 \mu_1^2 \mu_2^2\right)}$$

(5.15)

Investment in the public good is given by the following:

$$z^*_1 = \frac{(\lambda_{22} - \lambda_{21}) \mu_2 (n_1 c_1 \mu_1 \lambda_{11} + n_2 c_1 \mu_2 \phi_2 \lambda_{22} - n_1 n_2 \mu_1 \mu_2 |\Gamma\Lambda| - c_2)c_2 + (n_2 \mu_1 \mu_2 |\Gamma\Lambda| + c_1 \mu_1 \gamma_{12} \lambda_{12} - c_1 \mu_2 \phi_2 \lambda_{22})c_2}{|\Gamma\Lambda||\Lambda| \left(n_1^2 n_2^2 \mu_1^2 \mu_2^2\right)}$$

(5.16)

Using this solution, we can numerically compare outcomes under limited prosociality to the social optimum (which occurs at full prosociality). Furthermore, we will explore special cases that lead to simplification of the expressions for the equilibrium strategies.
5.4.4 Symmetric groups

In this section, we explore the simplest possible case, where the two groups are identical. All spillovers of the public good are the same, so $\lambda = \lambda_{11} = \lambda_{12} = \lambda_{21} = \lambda_{22}$. This is best thought of as the case where the public good is global. Further, we have defined the in-group pro-sociality value as $\phi = \phi_1 = \phi_2$ and cross-group pro-sociality value as $\gamma = \gamma_{12} = \gamma_{21}$. Lastly, we assume that both populations are of equal size, $n = n_1 = n_2$. This results in the groups being fully symmetric.

By making these substitutions into the closed form solutions from equation 5.15 and equation 5.16 we get the equilibrium investment in the public and private good. The equilibrium becomes

$$x^* = \frac{c}{n \mu \lambda (c (2 + \phi + \gamma) - 2n \lambda \mu (\phi + \gamma))} \quad (5.17)$$

for investment in the private good, and

$$z^* = \frac{n \lambda \mu (\phi + \gamma) - c}{n \mu \lambda (c (2 + \phi + \gamma) - 2n \lambda \mu (\phi + \gamma))} \quad (5.18)$$

for investment in the public good. We know that the social optimum will be achieved when there is full pro-sociality, $\phi = \gamma = 1$. Using this, the realized level of public good investment to the socially optimal level of public good investment can be compared. This allows for measurement of how close to the optimum the groups are under limited pro-sociality.

First, it is important to consider the second-order conditions for the above equilibria to hold. These require $c > n \mu \lambda$. Furthermore, for $z^* > 0$, $2 \geq \phi + \gamma \geq \frac{c}{n \mu \lambda} \geq 1$. 

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Given these restrictions on parameters we can examine the ratio of public-good investment under limited pro-sociality to the optimal level. This ratio is

\[ \frac{z^*}{z_{opt}} = \frac{4(c - \lambda \mu n)(c - \lambda \mu n(\gamma + \phi))}{(c - 2\lambda \mu n)(c(\gamma + \phi + 2) - 2\lambda \mu n(\gamma + \phi))} \] (5.19)

which, due to the global nature of the spillovers and symmetric restrictions, depends only on the sum of the pro-sociality terms, \((\phi + \gamma)\), not on the relationship between the in-group and out-group pro-sociality. To meet the second-order conditions, and have positive investment in the public good, the sum of the pro-sociality terms cannot be less than 1. This is an unrealistically high level of pro-sociality, especially for large groups. Highlighted in figure 5.1, \(z^*/z_{opt}\) is convex, so getting close to the optimum requires nearly full pro-sociality.

In order to gain insight into cases where cross group spillovers of public goods are different from within group spillovers, we will relax our restrictions on \(\lambda\) in the following section. This will allow us to examine the case of loosely connected local public goods.

### 5.4.5 Local public-good case

In this section, we have similar symmetry conditions as above, however, now we let \(\lambda_o = \lambda_{11} = \lambda_{22}\) and \(\lambda_c = \lambda_{21} = \lambda_{12}\) for ‘own’ group and ‘cross’ group spillovers. As in the previous section, we calculate the relative investment in the public good compared to the optimum as a function of the level of pro-sociality. We have

\[ \frac{z^*}{z_{opt}} = \frac{(\lambda_c + \lambda_o)(\mu n(\lambda_c + \lambda_o) - 2c)(\mu n(\gamma \lambda_c + \phi \lambda_o) - c)}{(c - \mu n(\lambda_c + \lambda_o))(c(\lambda_c(\gamma + 1) + \lambda_o(\phi + 1))) - \mu n(\lambda_c + \lambda_o)(\gamma \lambda_c + \phi \lambda_o))} \] (5.20)

for the ratio of public goods investment to the optimum. As cross group spillovers decrease, the importance of out-group pro-sociality diminishes. However, even if \(\lambda_c\) is small, in group pro-sociality, \(\phi\), must still be quite large to get near the social
Figure 5.1: The ratio of investment in the public good to the optimal public good investment is shown as a function of total pro-sociality, which can range from $1/n$ to 2 because it is $\phi + \gamma$. The shape of the curve is convex, so it takes nearly complete pro-sociality to come close to the social optimum. $n = 1200$, $\mu = .2$, $\lambda = .8$, $c = 200$.

optimum. In the limiting case, suppose that $\lambda_c = 0$. Then we have

$$
\frac{z^*}{z_{opt}} = \frac{\lambda_o \left( \mu n \lambda_o - 2c \right) \left( \mu n \phi \lambda_o - c \right)}{(c - \mu n \lambda_o) \left( c (\phi \lambda_o + \lambda_o) - \mu n \phi \lambda_o^2 \right)}
$$

(5.21)

### 5.4.6 Further directions

Thus far, we have analyzed a model where there is a cost to increasing investment in both public and private effort. As a further direction, we will analyze the outcomes when there is a fixed budget. These two approaches may yield different predictions about the ability of pro-sociality to generate substantial public goods investment. In addition to expanding the scope of the theory, we will also consider case studies that span a spectrum of congestibility and spillover structure. Here we list possible case studies for the models developed. A key feature of the modeling is its focus on
<table>
<thead>
<tr>
<th>Public Goods</th>
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</thead>
<tbody>
<tr>
<td>Spillovers or Congestibility</td>
</tr>
<tr>
<td>Congestible</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Non-congestible</td>
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</tbody>
</table>

Figure 5.2: Possible applications for our model across the degrees of congestibility and degree of spillovers

the relationship between pro-sociality, public good spillovers and the possibility for nearing an optimal outcome.

Air quality is a public good that can have high spillovers from one jurisdiction to another, however particulate matter (PM) pollution is often quite local. The nature of the pollutant, and its propensity to disperse will impact the likelihood of pro-sociality being sufficient to mitigate the damages from the pollution.

Also, cities, states and countries use local funds to invest in infrastructure and services, many of which are available not only to residents, but visitors as well. Investment in such public goods may depend on the amount of use they receive by residents, versus visitors.

5.5 Discussion

We modeled the provision of public goods resulting from pro-social preferences within and across groups. We incorporated spillovers of the public good across groups and allowed for varying degrees of congestion of the public good. This flexible framework allows for the analysis of many public good and common-pool resource problems. We find that the level of contribution to public goods is convex in the level of total pro-sociality for global public goods, and therefore nearly total pro-sociality is needed for
optimal provision of public goods to occur. To extend this work, we will compare this result to ones generated for local public goods to determine the circumstances under which pro-sociality is most effective. Further, we will analyze a related model the assumes a fixed budget investment, and finally unite the two approaches in a general model that has the flexibility to apply across all the cases in figure 5.2.

5.A Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{ij}$</td>
<td>individual $i$ in group $j$’s investment in private good</td>
</tr>
<tr>
<td>$z_{ij}$</td>
<td>individual $i$ in group $j$’s investment in public good</td>
</tr>
<tr>
<td>$Z_j$</td>
<td>Aggregate public good level in group $j$</td>
</tr>
<tr>
<td>$n_j$</td>
<td>Population size of group $j$</td>
</tr>
<tr>
<td>$\eta, \mu$</td>
<td>congestion in production of the public good</td>
</tr>
<tr>
<td>$\rho$</td>
<td>a measure of the elasticity of substitution</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Returns to scale</td>
</tr>
<tr>
<td>$\lambda_{ij}$</td>
<td>Public Goods spillovers from group $i$ to group $j$</td>
</tr>
<tr>
<td>$a$</td>
<td>Share parameter</td>
</tr>
<tr>
<td>$C_{ij}$</td>
<td>Cost of investment for individual $i$ in group $j$</td>
</tr>
<tr>
<td>$B_j$</td>
<td>Budget of individuals in group $j$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>cost scaling parameter, $\phi = 1$ leads to linear costs, $\phi \to \infty$ leads to fixed budget $B$</td>
</tr>
<tr>
<td>$\gamma_{ij}$</td>
<td>Degree of pro-sociality of individuals in group $i$ toward individuals in group $j$</td>
</tr>
<tr>
<td>$y_{ij}$</td>
<td>Income of individual $i$ in group $j$</td>
</tr>
<tr>
<td>$U_{ij}$</td>
<td>Utility of individual $i$ in group $j$</td>
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</tbody>
</table>
Bibliography


