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# The survival of the conformist: social pressure and renewable resource management

ALESSANDRO TAVONI\*, MAJA SCHLÜTER†, SIMON LEVIN‡

## Abstract

This paper examines the role of other-regarding behavior as a mechanism for the establishment and maintenance of cooperation in resource use under variable social and environmental conditions. By coupling resource stock dynamics with social dynamics concerning compliance to a social norm prescribing non-excessive resource extraction in a common pool resource, we show that when reputational considerations matter and a sufficient level of social stigma affects the violators of a norm, sustainable outcomes are achieved. We find large parameter regions where norm-observing and norm-violating types coexist, and analyze to what extent such coexistence depends on the environment.

Keywords: cooperation, social norm, ostracism, common pool resource, evolutionary game theory, replicator equation, agent-based simulation, coupled socio-resource dynamics

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# 1 Introduction

Local and global ecosystems are under growing pressure worldwide, and their sustainable management indisputably calls for the stakeholders' cooperative efforts [18]. History has taught us that the livelihood of our species is inextricably related to our ability to cooperate, in the sense of restraining use of natural resources to sustainable levels, rather than giving in to excessive resource appropriation. However, depending on the characteristics of the system at hand, tensions between individual and collective good may undermine such norms of restraint. Common-pool resources (CPRs) where beneficiaries of the resource have open access to it are a notable case of appropriation externality paving the way for short-sighted resource utilization: all agents would be better off if they collectively restrained extraction but if the impact of one's action on the resource stock is ignored, it is individually rational not to do it. Thus, maintaining cooperation against the myopic self-interest of a potentially large fraction of individual users unwilling to restrict their behavior for the collective good, and despite growing environmental pressure, is a challenging task that often depends on a multitude of factors, as both successful and unsuccessful environmental management has shown [25]. Nevertheless, field work [26], controlled experiments involving participants playing stylized games aimed at reflecting the trade-offs inherent in these social dilemmas (e.g., public good [17] and CPR [16] games), as well as casual observation, suggest that human beings are able to overcome the obstacles to cooperation in a variety of settings.

Many explanations have been proposed to account for the widely-observed departures from the rational-agent models' predictions [12] of collectively inefficient resource management in the absence of regulatory institutions. Established mechanisms that have been advanced to account for the evolution of cooperation are [23]: kin selection (the inclination of related individuals to engage in cooperative behavior), direct reciprocity (the "I will scratch your back if you scratch mine" attitude towards reciprocating), indirect reciprocity (I will scratch your back because someone else scratched mine), network reciprocity (spatial structure is assumed to allow for unevenly mixed populations where some individuals interact more frequently than others) and multilevel selection (where the population is divided into groups whose members are allowed to enact different strategies depending on whether they are matched with own-group members or with members of other groups). More recently the term of assortment, indicating the "degree of segregation of different types of individuals into different groups" as Pepper [28] puts it, has gained consensus among scholars for its generality. See [37] and [10] for recent contributions to the group selection debate. It should be noted that many other mechanisms with a certain degree

of overlapping characteristics have been employed in various disciplines to highlight the tension between in-group and outsiders; among others, parochialism [5] and homophily [7]. Lastly, in an experimental setting involving the repeated public goods game, reward is shown to be conducive to cooperation [34].

These mechanisms have been shown to suffice for the evolution of cooperation in Prisoner's Dilemma games whenever the payoffs are such that the benefit-to-cost ratio of the cooperative action exceeds a certain mechanism-specific threshold. While the above mechanisms incorporate some of the empirically observed factors that influence the success of collective action, such as the topology of interactions and group size, we postulate that the link to other important drivers of cooperation needs to be made explicit if one wants to attempt to bridge the gap between the empirical findings on commons management and the theory.

In the present paper we aim to analyze a simple model that departs from the full-rationality paradigm by placing emphasis on two such drivers: the presence of individuals with other-regarding preferences and the conformist pressure in the direction of norm compliance arising from fear of community disapproval. Laboratory experiments, such as [9] and [20], respectively suggest that both are relevant, while contributions from social psychology [6] and the empirical literature on the commons [27] stress the importance of the second driver. For what concerns the empirical findings, the work of Ostrom [25, 26] has suggested that many CPRs have escaped the trap of the tragedy of the commons by being managed in a self-organizing manner with mechanisms such as rules, norms and graduated sanctions favoring cooperation among users. Such mechanisms may result from the repeated interactions of the resource users: given suitable conditions, for example in terms of knowledge of the ecosystem by the community members, they could develop a sense of what behavior is acceptable with respect to resource use.

The enforcement of the proper behavior or sanctioning thereof will take different forms depending on the features of the social and resource system at hand. One increasingly studied class concerns social norms. Following the work of Sethi and Somanathan [31], much attention has been given to the role of costly punishment of defectors in promoting cooperation; recent contributions aimed at extending their setup have been proposed by Noailly et al. [22] and Sethi and Somanathan [32]. While both retain the three agent types format, with defectors, cooperators and enforcers bearing the costs of punishment, the former allow for spatial structure in the interactions, and the latter introduce a concern for reciprocity among the agents. Yet, the empirical literature on the commons argues that a variety of sanctioning mechanisms against norm violators are utilized to promote successful management of irrigation systems, fisheries, pastures and forests ([25], ch. 8 and 11 of [2]). Moreover, as sug-

gested by the literature on social capital [3], [24], [15]), resource appropriators embedded in a social context can often rely on a wider set of tools than the traditionally considered costly sanctioning of free-riding behavior. When the result of one’s actions is observable, be it the resource extraction itself or the outcome of a productive activity that is dependent on the latter, field and experimental evidence suggests that individuals belonging to a community act more cooperatively than when in isolation, as a result of their exposure to social reprobation. With regards to water management institutions, norms of social consensus are often deemed as important as technical rationality [29]. Moreover, according to [11]: “Experimental results from behavioral economics, evolutionary game theory and neuroscience have firmly established that human choice is a social, not self-regarding, phenomenon. [...] Human decision-making cannot be accurately predicted without reference to social context”. Recent evidence on the importance of the social context in guiding individual behavior is found in [9] and [1].

In the present paper we focus on one such mechanism, which we term equity-driven ostracism, by which we refer to the exclusion of norm-violators from community privileges or social acceptance.<sup>1</sup> The underlying idea is that appropriators’ decisions about how much effort to exert in the extraction of a natural resource are based on the prevailing norms that have emerged in the community, in addition to the usual efficiency considerations. As a result of the compliance decision with respect to the norm, those who deviate (the defectors) may be refused resources and support by those who comply. As an example, the ostracism costs considered here could be thought of as originating from destruction of defector’s crop by the cooperators, or simply from refusal of help by the community towards a defector in the form of denial of loan of machinery or means of transportation needed to take the harvest to the market. The rationale for this behavior is that, in a community of individuals who share access to a natural resource, those who restrain their extraction level to the socially acceptable level will not show the same level of support they have for fellow cooperators, when it comes to defectors. In Tarui et al.’s words [35]: ‘The typical successful management regime has some means of limiting access to the commons and some means of punishment for over-harvesting. Access may be restricted to members of a particular community or group. Community members are responsible for monitoring and enforcement. Punishment can involve some type of loss of privilege, either temporary or permanent, or, for major offenses, banishment from the group’. We assume that, while the resource stock level is not directly observable, the extractive efforts of individual players can be inferred

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<sup>1</sup>The term ostracism is to be read here as a refusal of help towards norm violators rather than a physical displacement of the latter, as will be clarified in the following discussion.

by means of yield comparisons, as detailed in Section 2.2. The inherent tradeoff between unrestricted profit seeking and norm adherence can be visualized in Figure 1.

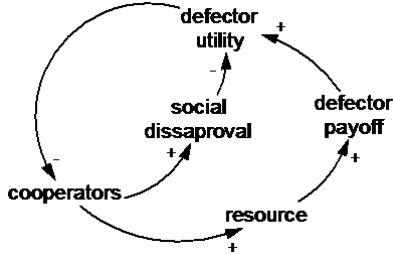


Figure 1: Interactions between the composition of the population, resource abundance and norm enforcement

This schematization allows us to highlight the ever-changing conditions faced by appropriators choosing among extraction patterns. If the number of cooperators increases, so will the resource stock, favoring the defectors the most (due to their behavior being unrestricted by the norm) and rendering opportunistic behavior more profitable, thus posing unfavorable selective pressure on the cooperators’ population. These trends are captured by the outer arrows originating from the cooperators in Figure 1, where a “+” sign indicates that both variables change in the same direction (e.g. more cooperators will lead to more resource) while a “-” sign indicates an inverse relationship (e.g. more social disapproval leads to less defector payoff). However, as shown by the inner arrows, an increase in the number of cooperators also leads to greater social disapproval towards norm violators, as fewer defectors will face ostracism by a larger community of norm followers, denying them the benefits of cooperation. We implement this simple mechanism in an evolutionary framework in order to allow for departures from optimizing behavior as prescribed by Nash equilibrium and to account for the dynamic nature of common property resources. Namely, rather than assuming that the resource appropriators instantaneously maximize their material well-being in a repeated-interaction model with discounted future, we let evolution gradually shape the proportion of agents playing a given strategy by favoring the more successful one. The advantage of this bounded rationality approach (imitate the successful behavior with inertia) is that it avoids the downfalls of the multiplicity of equilibria and lack of robustness to noise, while retaining the behavioral tendency to move in the direction of a more profitable strategy.<sup>2</sup>

The results of the analysis, presented in Section 2, suggest that both monomor-

<sup>2</sup>For an example of a standard game theoretic approach, see [21]; for a critique of the commonly used approaches in the economic analysis of common property, see [32].

phic and dimorphic populations emerge: that is we find stable full compliance and full defection equilibria as in Sethi and Somanathan [31], but also mixed equilibria where both types coexist. In Section 3 we investigate the impact of variation in environmental conditions, by allowing for variability in the rate of resource regeneration as well for a multiplicity of extraction strategies subject to evolutionary pressure. Section 4 provides concluding remarks.

## 2 A model of coupled socio and resource dynamics

We examine the role of other-regarding behavior as a mechanism for the establishment and maintenance of cooperation in resource use under variable social and environmental conditions. This is done by modeling the evolution of compliance to a social norm prescribing conformity to an agreed extraction level, and its coevolution with a CPR stock dynamic [27]. The coupled dynamics allow us to investigate the stability of cooperation in a population of resource users who have symmetrical access to it and are not only concerned with their own yield from productive use of the resource, but also with their status with respect to other community members, as acceptance to the community is at stake. Pay-off comparisons (e.g. with respect to crop size) lead to ostracism of the norm violators by the cooperating community, which denies defectors the benefits of resource and knowledge support, imposing losses on them that may offset those incurred by cooperators when restricting resource extraction practices to more sustainable ones. That is, individuals face a trade-off: on the one hand they can extract resource at individually optimal (but socially detrimental, [35]) levels without restricting usage, or on the other hand they can constrain themselves to a socially agreed upon acceptable level. By doing so, their conventional materialistic pay-off is necessarily below that of the non-cooperating agents, because of the above mentioned lower extraction and consequently reduced yield (which is increasing in the extraction effort). However, violators of the social norm are penalized by being excluded from the help of the cooperating community (e.g. in bringing the yield to the market): such defectors-specific ostracism costs have a variable magnitude that depends on the relative size of the cooperating community, since at low frequencies of cooperative agent types, the defectors will incur only mild consequences, but at high enough frequencies of cooperators, the former may incur high enough ostracism costs that it will be advantageous to be part of the sustainable community. Lindbeck [19] suggests the following property of norms: “a social norm is felt more strongly, the greater the number of individuals who obey it. Thus, the adherence to a social norm is a choice con-



ditioned on other individuals' adherence to the same norm. The psychological explanation for this type of behavior may be either that disapproval from others is more troubling if expressed by many people than by few or that other people's behavior is assumed to signal information about what is proper or potentially successful behavior."

Agents are considered as productive units (one can think of an agent as an individual or a family), whose share of the total production (e.g. the size of their crop) is proportional to the share of their appropriation effort with respect to the aggregate effort. Their source of revenue is assumed to positively depend on two factors: the availability of an indispensable resource for both productivity and livelihood, such as water broadly conceived, and the amount of effort agents put in their productive (income-generating) actions. That is, both the resource and the appropriation effort enter in the agents' (twice-continuously differentiable) production function  $f(E, R)$ , where  $E$  represents the community effort (e.g. the aggregate water usage) resulting from the actions of the  $n$  agents comprising it, and  $R$  is the resource available to the community (which may either be entirely consumed in a given time period, or saved in part for future consumption). Formally, letting  $e_i$  be the individual effort (i.e. his/her resource uptake), which can either take value  $e_c$  for a cooperator or  $e_d$  for a defector, with  $e_c < e_d$  due to the more sustainable practices of the former, the following inequalities are therefore assumed to hold<sup>3</sup>:

$$\frac{\partial f(E, R)}{\partial E} > 0, \frac{\partial f(E, R)}{\partial R} > 0, \frac{\partial^2 f(E, R)}{\partial E^2} \leq 0, \frac{\partial^2 f(E, R)}{\partial E \partial R} \geq 0, \frac{\partial(f(E, R)/E)}{\partial R} \geq 0$$

It is useful to consider again the joint level of effort  $E$  resulting from the actions of the  $n$  agents choosing their level of effort  $e_i$ ; letting  $f_c \in [0, 1]$  be the proportion of cooperators, we have  $E = n[f_c e_c + (1 - f_c)e_d]$ . We assume that  $n$  is fixed, so that entry is ruled out, while  $f_c$  is continuous and non-negative, and see that for positive levels of  $e_c$  and  $e_d$ , the total level of effort is a decreasing function of the frequency of cooperators. The two effort levels, which are here assumed to sum up the behavioral inclinations of all agents in the community, are bounded below by the collectively efficient resource use level and above by the static Nash equilibrium level. This amounts to requiring that both agent types follow practices that are above those that would maximize collective utility, but to a different extent: the defectors ignore the emergent social norm prescribing the socially agreed-upon acceptable individual effort  $e_c$  by choosing a greater level  $e_d$  (we consider a range of values up to the individually rational

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<sup>3</sup>These assumptions are generally employed in the literature concerning resource exploitation in a common pool resource, such as, for example, a fishery where a community of fishermen have access to it and each can decide on the individual level of exploitation (jointly affecting the sustainability of the resource utilization). Cf. [31, 38, 24].

but inefficient Nash equilibrium level resulting in excessive resource use), while cooperators stick to  $e_c$ , which, as a special case, may coincide with the level that efficiently trades off the individual incentive towards high or uncoordinated resource utilization with the social need to impose constraints to guarantee a sustainable use (which ultimately benefits all individuals). Letting  $E_{eff}$  be the community efficient level,  $e_{eff} = E_{eff}/n$  the corresponding individual efficient level under symmetry, and  $e_{nash}$  be the Nash equilibrium individual level of effort, we formalize what is stated above as:  $e_{eff} \leq e_c < e_d \leq e_{nash}$ . A direct implication of such constraints is that  $E_{eff} \leq E \leq E_{nash}$ . See Dasgupta and Heal ([8], 55-60) for a comprehensive treatment of exhaustible resources, and Oses-Eraso, Viladrich-Grau ([24], 398) for the description of a process leading to the prevalence of one representative strategy for each type of behavior. In §2.3 we restrict attention to  $e_{eff} = e_c$ , i.e. we hypothesize that the emergent norm prescribes collectively optimal extraction levels, but, differently from the cited literature, we consider what happens for different magnitudes of defection (allowing  $e_d$  to range from slightly above  $e_{eff}$  to Nash effort levels).

These conditions guarantee that, at the aggregate level, positive rents from productive use of the resource can be maintained. That is, the average product of labor is assured to be above the opportunity cost of labor independently from the share of defectors, providing the incentive for agents to increase their resource use (as they can earn positive profits for positive levels of effort; see Figure A.1 for a graphical representation). It is further assumed that  $f(0, R) = 0 = f(E, 0)$  for the obvious reason that strictly positive levels of effort and resource are required to generate income via the function  $f(E, R)$ . The individual payoff given resource  $R$  and the behaviour of all community members is:

$$\pi_i(e_1, e_2, \dots, e_n, R) = \frac{e_i}{E} f(E, R) - we_i \quad (1)$$

Letting  $R^*$  be the equilibrium resource level (to be defined more precisely below) and  $\Pi(e_1, e_2, \dots, e_n, R) = \sum_{i=1}^n \pi_i = f(E, R) - wE$ , the optimal solution to the aggregate payoff maximization problem is given by  $E_{eff} = \arg \max_E (\Pi)$ , and satisfies  $f'(E_{eff}, R^*) = w$ , where  $w$  is the opportunity cost of labor  $w$ . An example of a function guaranteeing the existence of an optimal solution, at each point in time, to the aggregate payoff maximization problem, is the Cobb-Douglas formulation with decreasing returns to scale:  $f(E, R) = \gamma E_t^\alpha * R_t^\beta$ ,  $\forall E \geq 0, R > 0$  and  $\alpha + \beta < 1$ . For the sake of compactness and to stress that the payoff to  $i$  is only indirectly affected by the others' choice of effort (through  $f(E, R)$ ), we will use the notation  $\pi_i(e_i, R)$  below. We know that, due to the negative appropriation externality arising from the disconnect between individual extraction and knowledge of its effect on the resource stock,

the aggregate level of effort in equilibrium if all agents play according to the Nash equilibrium will be above  $E_{eff}$  as each individual will treat the resource stock as fixed and therefore extract more resource than is efficient.

## 2.1 Resource dynamics

Let's turn to the resource dynamics and the interaction with the social dynamics occurring as a result of human action. Focusing on the ecological features governing the resource first, in the absence of human appropriation we are left with the constant resource inflow ( $c$ ) and a term dependent on the resource level ( $R$ ) as well as on three parameters ( $d$ ,  $k$  and  $R_{max}$  governing the discharge, curvature and maximum storage capacity) to account for a positive rate of growth up to the  $R_{max}$  (e.g. the upper limit in a groundwater aquifer's intake), which becomes negative beyond that level. We follow [14] for what concerns the above mentioned ecological variables, and include the aggregate resource use by the individuals ( $ER$ ), which appear as the last term of the equation:

$$\dot{R} = c - d\left(\frac{R}{R_{max}}\right)^k - ER \quad (2)$$

$\dot{R}$  indicates the time derivative of the resource stock, i.e. its overall rate of change resulting from the interaction of replenishment, discharge and utilization. Note that the resource replenishment rate, which is captured by the first term in the right-hand side of (2), is exogenous with respect to the frequency of cooperators (and consequently the resource extraction), which affects instead the second and last terms, respectively representing the limits to resource accumulation (due to stock effects) and the resource utilized by the community for productive tasks such as irrigation.

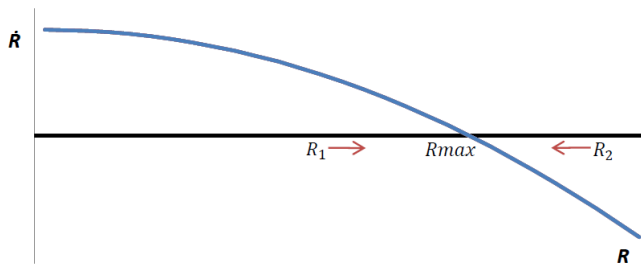


Figure 2: The rate of change of the resource as a function of its stock, in the absence of appropriation ( $E=0$ ). The discharge rate  $d$  is set equal to the inflow  $c$  to maintain a carrying capacity equal to  $R_{max}$ .

For the sake of concreteness, one can think of agents extracting water for irrigation purposes from an underground reservoir subject to replenishment due

to snowmelt or rain, whose ability to store water has a natural upper bound ( $R_{max}$ ). Beyond it, discharge occurs at a rate that is increasing in the deviation from the maximum storage capacity. Two facts are worth noting at this point. First, in the absence of extraction, the equilibrium resource level will settle on  $R_{max}$ . This is true since, if the stock at one point in time is to its left ( $R_1$  in Figure 2), the resource will continue to accumulate ( $\dot{R} > 0$ ) until  $R_{max}$  is reached; if instead the stock at a given time is to its right ( $R_2$ ), discharge will bring it back to  $R_{max}$ . Secondly, due to human extraction, the equilibrium resource level  $R^*$  will actually be below the maximum storage capacity.<sup>4</sup> With these notions in mind, we are now ready to shift attention to the strategies and tradeoffs faced by the two types of agents.

## 2.2 Equity-driven ostracism

Recall that equation (1) represents the amount an individual appropriator can make based on his/her effort and the yield, abstracting from costs originating from social stigma (and the consequential ostracism imposed by the community on defectors). This amount is proportional to the aggregate payoff (itself a function of the production function  $f$ ), in relation to the individual's resource uptake  $e_i$ , which positively enters in the first term in the right hand side of (1) and negatively in the second term representing the work-related costs. To account for the costs accruing to norm violators when identified by the community as such, we incorporate them as shown:

$$\begin{aligned}
 U_i &= \pi_i - \omega(f_c) \max \left\{ \frac{\pi_i - \pi_c}{\pi_d}, 0 \right\} \\
 &= e_i \left( \frac{f(E, R)}{E} - w \right) - \omega(f_c) \max \left\{ \frac{e_i - e_c}{e_d} \left( \frac{f(E, R)}{E} - w \right), 0 \right\} \quad (3)
 \end{aligned}$$

This translates to a payoff to a norm complier (cooperator) that is simply given by

$$U_c = \pi_c \quad (4)$$

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<sup>4</sup>In fact, due to the boundary conditions on the effort levels and (1), the equilibrium resource level will satisfy the condition  $0 < R_{nash} \leq R^* \leq R_{eff} < R_{max}$ , where  $R_{nash}$  is the resource level corresponding to monomorphic Nash behavior (a population comprised solely of individuals maximizing profits taking  $R$  as exogenous), and  $R_{eff}$  is the socially optimal level that would obtain if all individuals jointly maximized collective welfare (effectively internalizing the appropriation externality). Therefore, depending on the population composition, and consequently on the aggregate extraction, the equilibrium level  $R^*$  will be closer to one of the above two boundaries: in a dimorphic population comprised of a majority of defectors,  $R^*$  will be close to  $R_{nash}$ , while its distance from  $R_{eff}$  will be shorter the more the number of cooperators. Note that according to the above inequality, even under full defection there is a positive resource value ( $0 < R_{nash}$ ) guaranteeing the assumed positive rents.

while a norm violator will be subject to:

$$U_d = \pi_d - \omega(fc) \frac{\pi_d - \pi_c}{\pi_d} \quad (5)$$

Raakjær and Mathiesen [33] found, among the five more relevant factors affecting compliance in Danish fisheries: the economic gains to be obtained from noncompliance, deterrence and sanctioning costs, and the presence of “norms (behaviour of other fishers) and morals”. In (5), the gains appear in  $\pi_d$ , while the losses due to the sanctions and the comparison with others are captured by the product  $\omega(fc)((\pi_d - \pi_c)/\pi_d)$ . Notice that the strongest action against defectors will be taken when the number of cooperators is largest (i.e.  $\pi_d - \pi_c$  and  $\omega(fc)$  are highest), while when defection is spread all over it will go almost unnoticed (i.e.  $\pi_d \approx \pi_c$  and  $\omega(fc)$  is low).

Recalling the tradeoffs highlighted in Figure 1, one sees from the comparison of (4) and (5) that, for what concerns the productivity, defectors have an advantage ( $\pi_d > \pi_c$ ) as a consequence of their higher appropriation; due to stock effects, such productivity advantage positively depends on the relative abundance of cooperators. On the other hand, defectors are deprived of the communitarian social capital and experience a reduction to the income generated with resource-intensive productive activities, while cooperators can also tap in the community for help and thus enjoy the entire yield  $\pi_c$ . As compliance to the social norm is voluntary and observable (via differences in the yield of the production, since the latter depends on the amount of resource extraction), these benefits are denied to non-members; further, in light of [19], it is assumed that the community ostracism function  $\omega(fc)$  is positive and increasing in the number of participants (abiding to the social norm), once a critical mass  $\bar{f}_c$  has been established. As  $f_c$  further rises, the group’s sanctioning ability increases less than proportionally (growth is slowest at the start and end of a time period

Lastly, we note that in (5)  $\omega(fc)$  multiplies the ratio between the payoff difference and the defector’s payoff, to model a reaction by the cooperators which is stronger the larger the relative intensity of the defection (leading to a larger negative productivity gap of norm followers with respect to defectors).

### 2.3 Evolution of ostracism

The analysis of the behavioral evolution of agents facing decisions on their resource practices is conducted by means of replicator dynamics [36]. By so doing, we avoid the complete rationality requirements typical of models of optimization, while retaining (myopic and lagged) convergence towards better outcomes due to the imitation of successful behavior. Such an approach is particularly well-

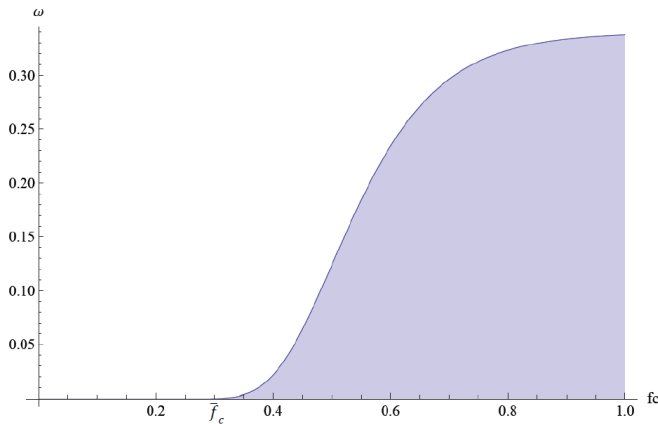


Figure 3: Ostracism function according to the Gompertz growth function  $\omega(f_c) = he^{te^{gf_c}}$ , where  $h, t, g$  are parameters governing, respectively, the maximum sanctioning (asymptote), the sanctioning effectiveness threshold (displacement) and the growth rate of the function.  $e$  is the Euler's number,  $h = 0.34$ ,  $t = -150$ ,  $g = -10$ .

suiting to the analysis of the evolution of norm adoptions as it allows us to focus on emergent phenomena without being confined, as is the case for neoclassical analysis, to equilibrium outcomes and representative agents solely described by their optimizing behavior. Here, rather than rationally best responding to the actions of others as in Nash equilibrium, individuals update their strategies when given the option, and switch to the strategy of the agent with which they are randomly matched if the utility of the latter is above the individual's. It can be shown that such strategy revision takes place with a probability that is proportional to the payoff difference with respect to the average: if, for example, the average is well above the payoff of a cooperator, he or she is more likely to notice the benefits from switching than if the average were only slightly above the agent's payoff. Formally, this leads to the 2-strategy replicator dynamics, which combined with (3) yields, after rearranging terms:

$$\dot{f}_c = f_c(U_c - \bar{U}) = f_c(1 - f_c)(U_c - U_d) = f_c(1 - f_c) \frac{\pi_d - \pi_c}{\pi_d} (\omega(f_c) - \pi_d) \quad (6)$$

The dotted superscript stands for time derivative: equation (6) models the evolution of cooperating types. We are interested in the nullclines satisfying  $\dot{f}_c = 0$ : in addition to the monomorphic outcomes characterized by one type of agent only, we look for solutions in which positive amount of both types coexist (with  $f_c \neq 0$  and  $f_c \neq 1$ ). That is,

$$(f_c^*, R^*) : \theta(f_c^*, R^*) = \frac{\pi_d(e_d, R^*) - \pi_c(e_c, R^*)}{\pi_d(e_d, R^*)} (\omega(f_c^*) - \pi_d(e_d, R^*)) = 0 \quad (7)$$

The system described in (2)-(6) can be represented in the  $(\mu, f_c)$  parameter space, where  $\mu$  is the effort multiplier between a cooperator and a defector; for instance, in Figure 4,  $\mu = 2$  signifies that the defector's effort is twice the cooperator's effort, while  $\mu_{nash}$  signifies that  $e_d = e_{nash}$ . While only one type of defector is considered at a time (as well as one cooperator type satisfying  $\mu = 1$  and extracting at the collectively efficient level), Figure 4 allows one to investigate the prospects for cooperation for different levels of defection. We deem it useful to condense this information in the compact graphical tool below, since, depending on the social and ecological characteristics of the system under consideration, the concept of defection may vary greatly. For example, in a relatively well-established community (both in a temporal and spatial dimension), it may be reasonable to expect that a clear and shared notion of norm violation has taken shape over time, and therefore that defectors are somewhat cautious and refrain from extracting at a very high level (such as  $\mu_{nash}$ ). On the other hand, a relatively new community, or one which is more spatially fragmented, may be characterized by higher defection levels (e.g.  $\mu > 2$ ), due to the lack of clarity over what the acceptable behavior is. Figure 4 illustrates the fate of cooperation for different definitions of defection, i.e.  $\mu$  levels, in order to capture these different cases in a comprehensive manner. Given the positive value of the first three terms on the right hand side of (6), (with the exception of degenerate cases), it is straightforward that the proportion of cooperators will increase ( $\dot{f}_c > 0$ ) provided that  $\omega(f_c) > \pi_d(e_d, R)$ . Where the system ultimately stabilizes depends on the initial conditions: however, as we can readily observe from Figure 4, we have both areas characterized by the presence of one type of agent only and areas of coexistence. Note that with an increase in cooperators the ostracism  $\omega(f_c)$  increases, but so does the defector payoff  $\pi_d(e_d, R)$ , because productivity increases with an increase in  $f_c$  due to the higher resource level; such interaction causes non-trivial dynamics that are analyzed here under the evolutionary lens provided by the replicator equation. In the Appendix we derive results from the stability analysis based on the linearization matrix  $J$  of the system (2)-(6), which shows that:

- a)** the Defector equilibrium is a stable attracting fixed point;
- b)** the Cooperator equilibrium is stable so long as the defector's payoff is bounded above by the full compliance ostracism costs, i.e.  $\omega(1) > \pi_d$ .

What happens for intermediate frequencies of cooperators? From (7) we know that, if it exists, the coexistence equilibrium must satisfy  $\omega(f_c^*) = \pi_d(e_d, R^*)$ . Inspection of the curves in Figure 4 allows one to assess the qualitative features of the system resulting from the above condition: to the left of locus  $a$ , i.e. for low initial  $f_c$ ,  $\omega(f_c) < \pi_d(e_d, R)$ , so the system will evolve towards the stable

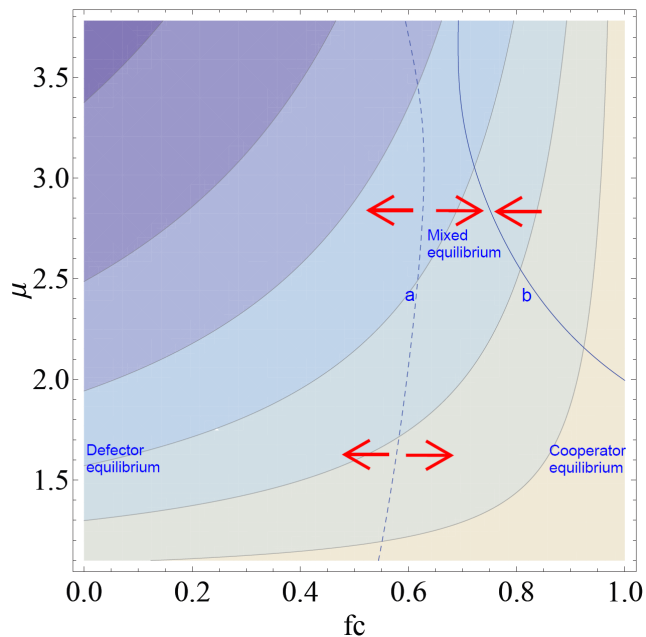


Figure 4: The  $\omega(f_c^*) = \pi_d(e_d, R^*)$  loci guaranteeing coexistence of types (given the ostracism function in Fig. 3), superimposed on the contours of the resource function at equilibrium (brighter shades indicate higher resource levels). The cooperators extract at the social optimum, while defectors above it, according to their type as given by the effort multiplier  $\mu$ : given the latter (e.g.  $\mu = 2.5$ ) one can determine which equilibrium arises for a given initial  $f_c$  (e.g. a Mixed equilibrium on locus  $b$  with relatively high  $R^*$  for  $f_c = 0.8$ ). The highest level of  $\mu$  on the y-axis corresponds to  $\mu_{nash}$ , and yields, depending on the initial  $f_c$ , either a Mixed or a Defector equilibrium (both with the minimal  $R^*$  in their category).

defector equilibrium independently of  $\mu$ . If, for instance, we consider defectors who extract resource according to the Nash rule ( $\mu_{nash} : e_d = e_{nash}$ ), the equilibrium will be characterized by  $\omega(0) = 0 < \pi_d(e_d, R_{nash})$  (see footnote 4). To the right of locus  $a$ ,  $\omega(f_c) > \pi_d(e_d, R)$ , so the community of appropriators following the restrictive norm will grow larger. The system will transition towards the cooperator equilibrium when the effort difference between cooperators and defectors is not too large (low  $\mu$ ), as the above inequality will continue to hold until stable monomorphic cooperation obtains, with  $\omega(1) > \pi_d(e_d, R_{eff})$  (see Figure 4 and footnote 4). When instead effort differences are large, the proportion of cooperators will keep increasing up to a point where  $\omega(f_c^*) = \pi_d(e_d, R^*)$ : at this point population composition does not change any longer and the mixed equilibrium persists. The same obtains when starting to the right of locus  $b$ ; in other words,  $b$  is a stable locus of mixed equilibria. Note that this is not true for locus  $a$ , which is unstable.



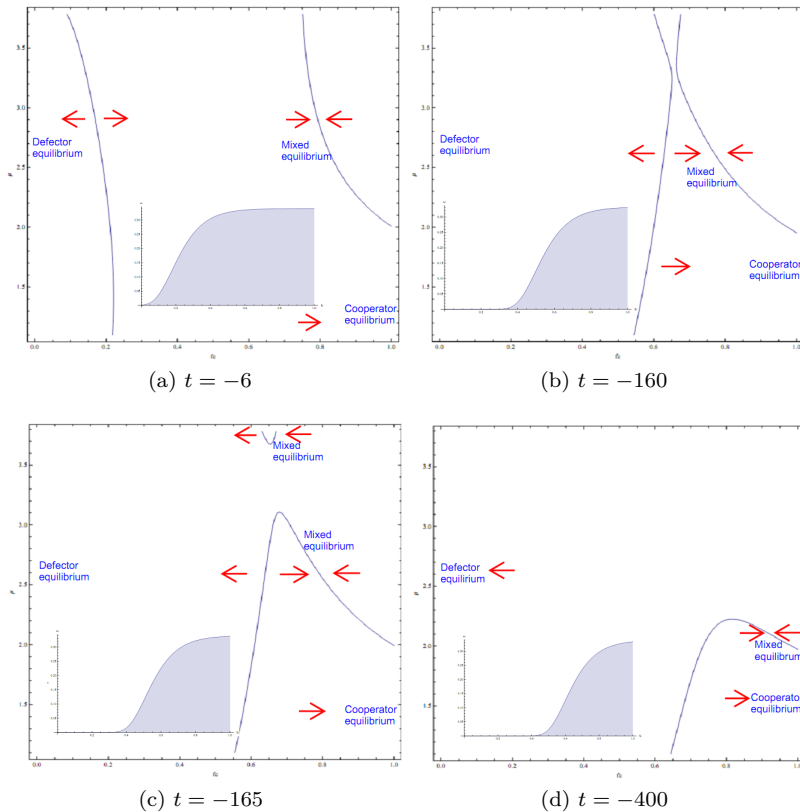


Figure 5: The  $\omega(f_c^*) = \pi_d(e_d, R^*)$  coexistence nullclines with increasingly ineffective sanctioning at low  $f_c$ . The insets represent ostracism functions according to the Gompertz growth function  $\omega(f_c) = he^{te^{gf_c}}$ , parametrized to deprive the ostracism of efficacy below a varying  $f_c$  threshold.  $h$  and  $g$  are fixed at 0.34 and  $-10$  and  $t$  is varied so that the threshold is increasingly larger.

### 3 Social and resource variation

#### 3.1 Varying the effectiveness of ostracism

To investigate the impact of the threshold  $\overline{f_c}$  (i.e. the minimum level beyond which the community of norm followers becomes effective in ostracising the violators) on the evolution of cooperation, we vary the parameter  $t$  of the ostracism function (Figure 3). Figure 5 depicts the nullclines corresponding to alternative ostracism functions (in the insets).

As  $t$  increases in (absolute) magnitude, so does the minimum percentage of the population that is required for the community sanctions to be effective. In the inset of Figure 5a, at low  $f_c$  a small amount of ostracism is already in place, while the effectiveness threshold is  $\overline{f_c} > 30\%$  in Fig. 5b and Fig. 5c, and

$\overline{f_c} > 40\%$  in Fig.5d. While the sanctioning ability of the cooperating community is quite similar in Fig. 5b and Fig.5c, they are used to illustrate how a further (albeit small) rightward shift of the threshold leads to a qualitative shift in the landscape of the equilibria. The basin of attraction of the Defector equilibrium now comprises the entire  $f_c$  space for values of  $\mu$  that are roughly between 3.1 and 3.7, while for even higher values of  $\mu$ , a small coexistence area is again present (right hand side of the top nullcline). At such high level of extraction on the defectors' part, violating the norm and extracting above the optimal level pays off both when the cooperating community is very large (and free riding on its restraint outweighs the ostracism costs) and when it is smaller ( $f_c \lesssim 0.6$ , due to its limited sanctioning ability). However, for a small neighborhood around 65% cooperation, norm followers fare better thanks to the increased ostracism costs they are able to impose on defectors. To the right of the coexistence ray, the situation is again reversed to  $\omega < \pi_d$ , since the high profits that can be made by deviating from the norm when the resource is close to the social optimum outweigh the ostracism costs.

The bottom nullcline in Fig. 5c also concerns polymorphic equilibria (to the right of the peak), while for  $\mu \lesssim 2$ , depending on the initial  $f_c$ , the system transitions to either a Cooperator equilibrium or a Defector equilibrium. Lastly, in Fig. 5d the top nullcline disappears and the bottom one shrinks, but both a (small) area of coexistence and the monomorphic equilibria are retained.

Similar analyses are conducted in the following two figures, which respectively show the disruptive effect of increasingly slower ostracism emergence and increasingly ineffective sanctioning on the evolution of cooperation.

Across all the variations presented in this section, commonalities are evident in terms of the types of the emergent equilibria. On one end of the spectrum, when conditions are extremely favorable for cooperators due to their high sanctioning ability (Fig. 7a), only monomorphic equilibria obtain, with the Cooperator equilibrium having the larger basin of attraction. In this case the amount of defection ( $\mu$ ) is almost irrelevant to the outcome, as the (initial) relative size of the cooperating community solely determines the evolutionary trajectory. For many intermediate specifications, areas of coexistence appear in the  $(f_c, \mu)$  space: while stable, these polymorphic equilibria take place for a range of  $\mu$ , outside of which the system eventually evolves to a monomorphic equilibrium (e.g. Fig. 6b). As the ostracism effectiveness is further reduced, the basin of attraction of the Defector equilibrium expands, at the expense of the Cooperator equilibrium which at a certain point disappears (e.g. for  $h < .2$ , c.f. Fig. 7d).

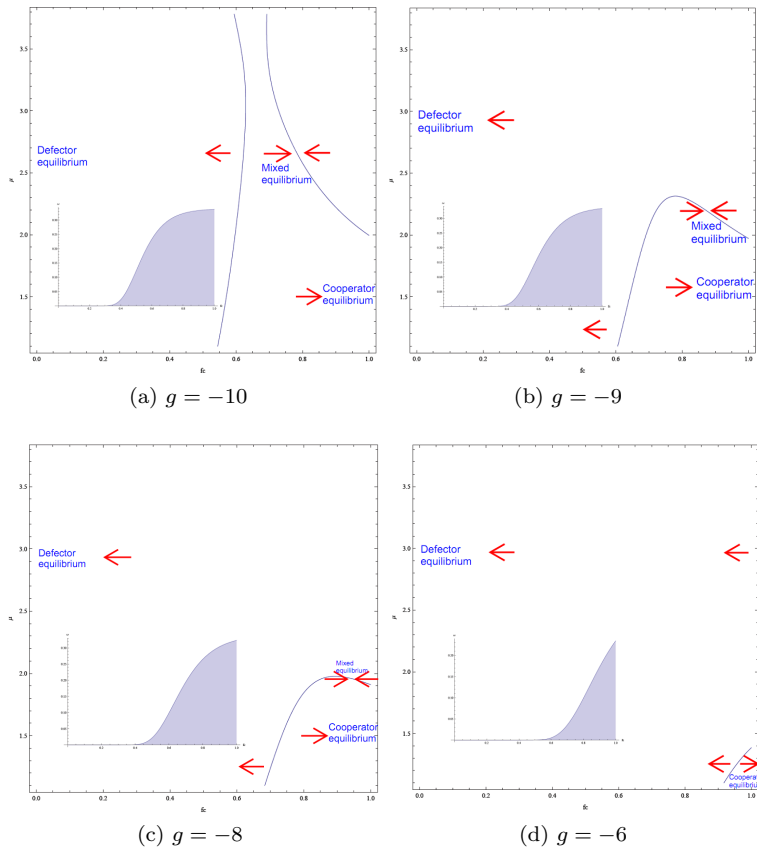


Figure 6: The  $\omega(f_c^*) = \pi_d(e_d, R^*)$  coexistence nullclines with increasingly slower ostracism emergence. The insets represent ostracism functions according to the Gompertz growth function  $\omega(f_c) = he^{te^{gf_c}}$ ;  $h$  and  $t$  are fixed at 0.34 and  $-150$  here, and the growth rate  $g$  is progressively diminished.

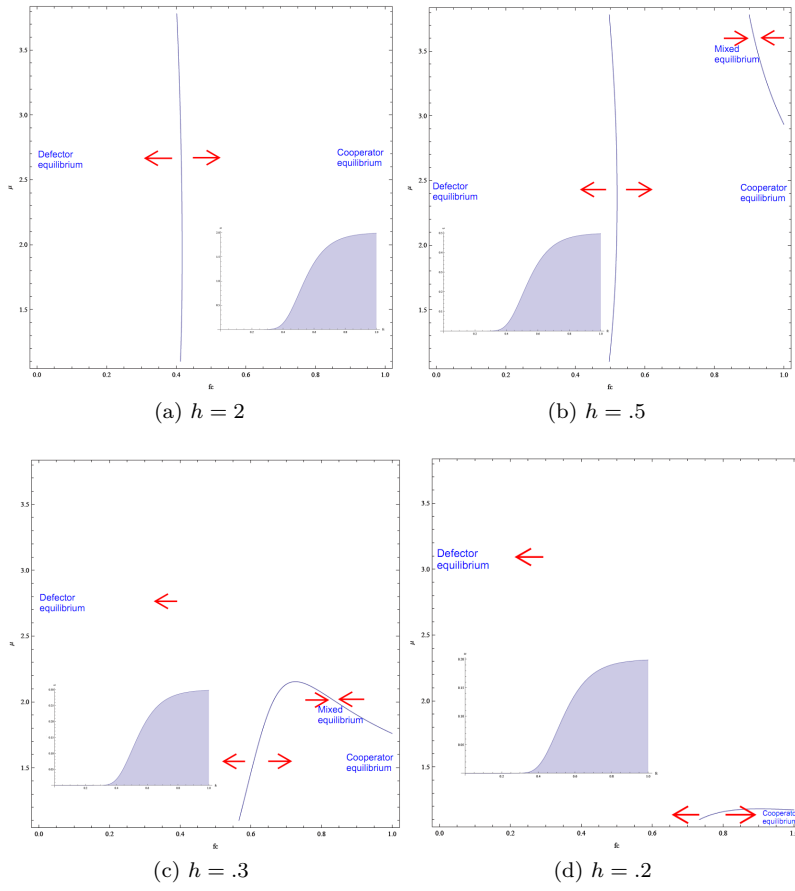


Figure 7: The  $\omega(f_c^*) = \pi_d(e_d, R^*)$  coexistence nullclines with increasingly ineffective sanctioning. The insets represent ostracism functions according to the Gompertz growth function  $\omega(f_c) = h e^{t e^{g f_c}}$ ;  $t$  and  $g$  are fixed at  $-150$  and  $-10$  here and the maximum sanctioning  $h$  is progressively diminished.

### 3.2 Variable resource inflow

In reality resource flows are subject to variation. If one considers for instance water availability, particularly in semi-arid regions it can vary drastically within and between years. Climate change is likely to increase this variability and lead to more frequent extreme events. This puts additional pressure on water users that have to cope and adapt to changing resource conditions. To assess the effect of inflow variability on the stability of cooperation we consider the impact of introducing a perturbed variable inflow to the resource pool. The modified resource dynamics becomes:

$$\dot{R} = \tilde{c} - d\left(\frac{R}{R_{max}}\right)^k - ER \quad (8)$$

where  $\tilde{c}$  is a random variable with mean  $c$ , following a symmetric unimodal distribution. The following reasoning shows that with an increase in the variability of inflow to the common resource pool, the percentage of cooperators in the mixed equilibrium increases, thus indicating an advantage for cooperators. This is due to the concavity of the resource function at  $\dot{R} = 0$  (see Figure 2), which leads to a decrease in the average resource volume with inflow variability. Recalling the analysis of Section 2, letting  $\tilde{R} < R$  be the perturbed resource volume at time  $t$ , we note that the corresponding payoff  $\tilde{\pi}_i(e_i, \tilde{R}) < \pi_i(e_i, R)$ , which implies that  $\tilde{\pi}_d(e_d, \tilde{R}) < \pi_d(e_d, R)$ . However, the ostracism function is independent of  $R$ , so the basin of attraction of the Cooperator equilibrium expands at the expense of that of the Defector Equilibrium. Put differently, a lower average resource volume leads to reduced payoffs for both defectors and cooperators. Defectors, however, are also subject to ostracism which is only a function of the frequency of cooperators and thus is not affected by inflow variability. Therefore, the decrease in defector payoff with unchanged ostracism costs decreases the frequency of defectors in the ensuing equilibria.

## 4 Summary

In this paper we have developed a model of community-based appropriation of a common pool resource in the presence of a norm allowing discrimination of resource use behavior. Burton [4] suggests that a ‘possible method to encourage collective action is the use of some form of sanctions on those who deviate from the group. Sanctions may take the form of a “loss of respect” [13], “social pressures aimed at creating personal shame” [30], or “social excommunication” [30]’. In the context developed here, individuals departing from what the community considers as acceptable behavior (in terms of non-excessive resource

extraction), are therefore subject to what we call equity-driven ostracism: a denial of support by the cooperating community which has tangible consequences on the wealth of the norm violators. Such retaliation, which may be thought of as consisting of spiteful actions (e.g. denied machinery lending and crop destruction) or social reprobation (e.g. negative gossiping and refusal to share information), depends on two factors. On the one hand the relative strength of the community of norm followers, since a larger community is assumed to be more effective at ostracizing defectors. Secondly, the intensity of the response by the community is assumed to be higher the larger the entity of the defection, which is revealed by the differences in the yield of the production, as the latter depends on the amount of resource extraction. Another noteworthy feature is that we model the coupled socio-economic and ecological dynamics of a common pool resource, such as water, that provides benefits indirectly by being utilized as an input of production rather than for its intrinsic value (as is the case for fish in fisheries). Sections 2 and 3 considered cooperation as the outcome of an evolutionary process, with successful strategies spreading in the population as a result of a process of imitation. We find that:

- a)** A Defector equilibrium, unregulated by the norm, is achieved when the community of cooperators is unable to engage in effective ostracism, either because of its small size relative to the population, or because of its ineffectiveness. Otherwise, the system evolves to either (b) or (c).
- b)** A Cooperator equilibrium, where all abide to the norm, arises so long as the defector's payoff is bounded above by the full compliance ostracism costs:  $\omega(1) > \pi_d(e_d, R_{eff})$ . This is the case when the effort differences between cooperators and defectors are not too large.
- c)** Stable coexistence obtains for a range of intermediate specifications, in situations that are not particularly favorable for either type, sparing both from being eradicated:  $\omega(f_c^*) = \pi_d(e_d, R^*)$ .
- d)** Under variable resource replenishment rates, cooperators thrive better, because they can still benefit from the social capital provided by other cooperators despite a reduction in average resource volumes, while the defectors experience a decrease in payoffs to  $\tilde{\pi}_d(e_d, \tilde{R})$ .

The model presented here focuses on agents harvesting from a renewable resource while facing a social norm discerning between acceptable and excessive behavior. Notwithstanding its simplicity, it allows to identify three regimes for the stationary state of the evolutionary dynamics, depending on the initial

number of norm followers, the effort gap between types and the community effectiveness in enforcing the norm. In (a) the resource is severely over-harvested, a situation reminiscent of the tragedy of the commons; in (b) the resource is efficiently shared by a homogeneous population restricting use to the collectively optimal level; in (c) both type coexist and manage to partially internalize the externality. Where the system ultimately converges depends on the path followed.

## Appendix

### Stability analysis

In this section we shed light on the monomorphic equilibria found in §2.3 by means of the stability analysis based on the linearization matrix  $J$  of the system (2)-(6):

$$J = \begin{bmatrix} \frac{\partial \dot{f}_c}{\partial f_c} & \frac{\partial \dot{f}_c}{\partial R} \\ \frac{\partial \dot{R}}{\partial f_c} & \frac{\partial \dot{R}}{\partial R} \end{bmatrix} = \begin{bmatrix} \varphi[\omega'(f_c)(f - f_c^2) + \omega(f_c)(1 - 2f_c) + (2f_c - 1)\pi_d] & 0 \\ nR(e_d - e_c) & \frac{-dkR^{k-1}}{R_{max}^k} - E \end{bmatrix}$$

$$\text{where } \varphi = \frac{\pi_d(e_d, R) - \pi_c(e_c, R)}{\pi_d(e_d, R)}$$

The diagonal terms of  $J$  are the eigenvalues, and since  $\frac{\partial \dot{R}}{\partial R} < 0$ , whether an equilibrium is asymptotically stable depends on the sign of  $\partial \dot{f}_c / f_c$ . When  $f_c = 0$ , both eigenvalues of  $J$  are negative real numbers and the Defector equilibrium is a stable attracting fixed point. When  $f_c = 1$ ,  $\partial \dot{f}_c / f_c = \varphi(\pi_d - \omega(1))$ , which is negative provided that  $\omega(1) > \pi_d$ . Thus, the Cooperator equilibrium is stable so long as the defector's payoff is bounded above by the full compliance ostracism costs.

### Calculation of effort

Consider the production function  $F(E, R) = \gamma E^\alpha R^\beta$ . Recalling the equilibrium condition for the resource,  $\dot{R} = c - d(\frac{R}{R_{max}})^k - ER = 0$ , for  $k = 2$  its dependence on the aggregate effort level (and consequently on  $f_c$ ) can be expressed as follows:

$$R^* = (-E + \sqrt{E^2 + 4c \frac{d}{R_{max}^2}}) \frac{R_{max}^2}{2d} \quad (\text{A.1})$$

Alternatively, at resource equilibrium,  $E(R^*) = \frac{c}{R^*} - \frac{d}{R_{max}^2} R^*$ .

Following [8], the static efficient effort  $E_{eff}$  is the solution of the collective welfare maximization problem where individuals act cooperatively assuming all

remaining  $(n - 1)$  agents extract  $e_c$  as well, which yields the following condition:

$$F'(E_{eff}, R^*) = w \quad (\text{A.2})$$

At the opposite end of the spectrum, a community comprised of all defectors following the Nash rule (with  $\mu = \mu_{nash}$  as described in Section 2.3), will collectively exert  $E_{nash}$  solving:

$$\frac{F(E_{nash}, R^*)}{E_{nash}} - \frac{1}{n} \left( \frac{F(E_{nash}, R^*)}{E_{nash}} - F'(E_{nash}, R^*) \right) = w \quad (\text{A.3})$$

For the parameters utilized in Fig. 2 and Figures 4-A.1 ( $w = 15$ ,  $c = d = 50$ ,  $R_{max} = 200$ ,  $n = 50$ ,  $\gamma = 10$ ,  $\alpha = .6$  and  $\beta = .2$ ), the solutions to (A.2) and A.3 are  $E_{eff}(R^* = 84.91) = 0.483$  and  $E_{nash}(R^* = 26.89) = 1.826$ , respectively (the latter occurs at  $\mu$ 's upper bound for,  $\mu_{nash} = 3.781$ ). Then the individual appropriation efforts are simply calculated as  $e_{eff} = E_{eff}/n$  and  $e_{nash} = E_{nash}/n$ .

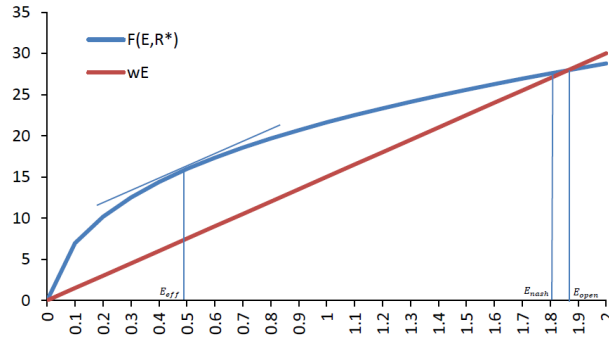


Figure A.1: Aggregate production resulting from different levels of resource appropriation. At  $E_{eff}$  all agents abide to the norm, while at  $E_{Nash}$  they all ignore the appropriation externality (while still making positive rents, since the open access effort  $E_{open} > E_{Nash}$ ).

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