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Games of corruption in preventing the overuse of common-pool resources

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Abstract

Maintaining human cooperation in the context of common-pool resource management is extremely important because otherwise we risk overuse and corruption. To analyse the interplay between economic and ecological factors leading to corruption, we couple the resource dynamics and the evolutionary dynamics of strategic decision making into a powerful analytical framework. The traits of this framework are: (i) an arbitrary number of harvesters share the responsibility to sustainably exploit a specific part of an ecosystem, (ii) harvesters face three strategic choices for exploiting the resource, (iii) a delegated enforcement system is available if called upon, (iv) enforcers are either honest or corrupt, and (v) the resource abundance reflects the choice of harvesting strategies. The resulting dynamical system is bistable; depending on the initial conditions, it evolves either to cooperative (sustainable exploitation) or defecting (overexploitation) equilibria. Using the domain of attraction to cooperative equilibria as an indicator of successful management, we find that the more resilient the resource (as implied by a high growth rate), the more likely the dominance of corruption which, in turn, suppresses the cooperative outcome. A qualitatively similar result arises when slow resource dynamics relative to the dynamics of decision making mask the benefit of cooperation. We discuss the implications of these results in the context of managing common-pool resources.

Keywords: resource management, illegal logging, overfishing, delegated enforcement, bribe

1. Introduction

The emergence of corruption in parallel with the exploitation of common-pool resources should hardly come as a surprise. The reason is that common-pool resources are subject to the tragedy of the commons [1] which occurs when agents exploit a resource at an unsustainable rate by acting rationally from the perspective of one's own self-interest. To protect the resource from overuse and thus avoid the tragedy, curbing behaviours that threaten sustainability by means of punishment may, at least in principle, seem as a straightforward solution. Field studies and laboratory game experiments alike [2, 3] suggest that it is essential to define a scale of graduated sanctions for those individuals who overuse the resource [4, 5, 6]. However, who is to administer punishment? Oftentimes the need for a dedicated enforcement agency arises because the access to common-pool

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resources is by definition difficult and costly to control [7]. Delegating the duty of enforcement to specialists in spotting and fining unsustainable behaviour (e.g. inspectors, rangers, police etc.) may in fact bring considerable savings to resource users [8, 9, 10, 11, 12, 13]. Unfortunately, enforcement agencies are prone to corruption [14, 15, 16, 17, 18, 19].

Although the study of corruption has traditionally been in the domain of economics, when it comes to the relationship between corruption and the management of common-pool resources, evolutionary game theory may offer certain advantages. By including the selection process, evolutionary game theory explicitly accounts for the temporal dynamics of the investigated system. This inclusion of the selection process permits the coupling of evolutionary and resource dynamics to create a more general and powerful analytical framework for the management of common-pool resources wherein both human behaviour and the resource coevolve [20, 21]. Within such a framework, on the one hand, it is possible to study the influence of ecological parameters (e.g. the resource growth rate) on the prospects that a resource will be overused. On the other hand, it is also possible to examine the efficiency of decision making in situations when the resource is still in a transient state due to the slow convergence of the resource dynamics.

Ours is not the first study on the sustainable use of common-pool resources with coupled social and resource dynamics. For example, Sethi and Somanathan [22, 23], Noailly et al. [24], and Tavoni et al. [25] aim at analysing community-based management, yet they employ different mechanisms to suppress the resource overuse (i.e. norm violators). These studies rely either on the existence of social capital, where some harvesters bear a cost and work as enforcers, and/or on the conformity to social norm(s). Instead of a norm-guided sanctioning system, our model introduces a new institution by building an enforcement system of paid enforcers who are voluntarily used by harvesters. Moreover, our focus is on the relation between resource and evolutionary dynamics (which take place at the different time scales) and the effects of ecological factors (such as the resource growth rate) as they pertain to the evolution of cooperative outcome. This is in contrast with the focus of other authors on social dynamics (i.e. cooperation enhancement mechanisms) and the analysis of equilibrium states despite having used the evolutionary game theory framework [22, 25].

While no explicit resource dynamics was incorporated, there were theoretical studies exploring how the change in incentive system influences cooperative outcome of public goods games among agents [26, 27, 28]. With various incentive distributions diversified by means of rewarding, punishing, or assigning endowment, these studies investigated optimal institutions to suppress defection. Ref. [27] introduced a feedback between contributions of cooperators and common resource availability by setting resource endowment linked to the resource level. The level of resource was determined only by the level of cooperation whilst here we treat the resource dynamics by including ecological features.

The paper is organised to first describe the basic characteristics of the coupled evolutionary-resource dynamical system, leaving the specifics of the corresponding mathematical representation for Appendix A. This dynamical system is analysed by means of numerical simulations, where the choice of using computational methods was largely determined by the system's complexity. The results of numerical analyses are then explained in great detail with particular focus on the underlying mechanisms. Interestingly, the more resilient the resource (as implied by a high growth rate), the more likely the dominance of corruption. This result indicates that in addition to the common

socio-economic factors, ecological factors such as the resource growth rate may provide incentives for illegal logging and overfishing observed in productive terrestrial and marine ecosystems, respectively [29, 30, 31, 32, 33, 34, 35, 36, 37, 38]. We also find that relatively slow resource dynamics mask the benefit of cooperation, thus making the emergence of cooperative behaviour more difficult. Finally, we discuss the implications of these results, including the importance of future developments, whereby the current framework could be extended by incorporating a currently missing spatial dimension.

2. Model

To develop our modelling framework, we build on the work of Lee et al. [39] who studied a simplistic evolutionary game model of corruption in the context of illegal logging. In particular, we devise a coupled evolutionary–resource dynamical system with the following characteristics:

1. any number of resource users (hereafter harvesters) share the responsibility of managing a specific part of the exploited ecosystem,
2. harvesters choose between three strategies for exploiting the resource,
3. an enforcement system may or may not be employed by harvesters depending on their choice of strategies,
4. enforcers may be honest or corrupt, and
5. the resource dynamically responds to the choice of harvesting strategies.

A schematic representation of the dynamical system with listed characteristics is shown in Figure 1. The corresponding mathematical developments are detailed in Appendix A.

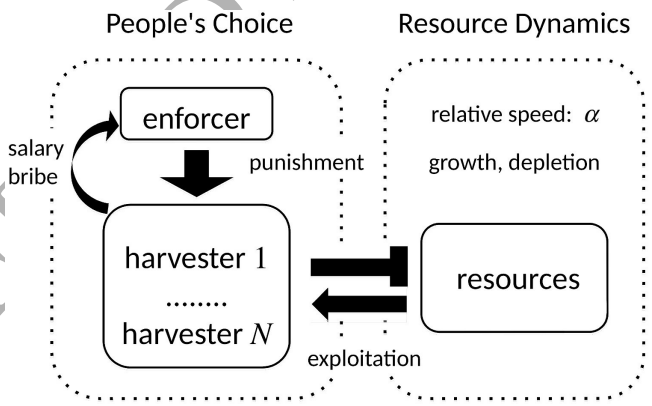

Figure 1: **A schematic representation of the coupled evolutionary–resource dynamics.** People's choices decide the resource exploitation level, while the resource state affects the choices made. In this coupled setting, much like the institutional incentives that motivate people's choices, the resource growth rate and the relative speed of resource dynamics may be decisive for the success in reaching the cooperative state.

For completeness, it is necessary to define the three harvesting strategies. The most straightforward strategy is that of *Defector*s who refuse to employ enforcers and selfishly overexploit

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the resource. Cooperators would exhibit exactly the opposite behaviour, but because their strategy is under all circumstances inferior to that of *Defector*s, we need a more sophisticated type of cooperative harvesters. We refer to such harvesters as *CondC*s to indicate that their cooperation is conditioned on whether everybody agrees to employ an enforcer. The strategy of *CondC*s would offer an effective protection against defection, if it were not for bribe. Namely, defecting harvesters—labelled *ComD*s—may commit to hiring an enforcer, but subsequently pay a bribe to avoid being punished for overexploiting the resource. The effectiveness of *ComD* strategy critically depends on the degree to which enforcers are honest. For further details and a mathematical representation of the described setup, readers are referred to Appendix A.

While it may appear that players in evolutionary games religiously stick to prescribed strategies, this is not the case. The dynamics in evolutionary game theory resemble trial and error, whereby players eventually reach an equilibrium through the selection process that weeds out suboptimal strategies. However, unlike in the case of perfectly rational players, selection takes time and in transient states some fraction of players will be making bad choices. In our model, harvesters and enforcers alike search for better options under the given incentives from the environment. Strategies are updated in every step of the game according to the relative payoffs obtained through the previously made choices (see Appendix A for details). Far from sticking to the same strategy, harvesters and enforcers respond to the state of the resource and learn new behaviour as the time passes by.

The dynamical system arising from our assumptions transcends the limitations of more traditional approaches in two major ways. First, the incentives for cooperation and defection depend on the state of the resource and consequently the ecological parameters determining this state. Second, defecting harvesters may experience the negative effects of their own overuse of the resource with a considerable time delay. A novelty is that the propensity for corruption to prevail becomes a function of factors other than the usual socio-economic ones; for example, these new factors include the resource recovery rate and the difference in timescales between evolutionary and resource dynamics.

3. Results

3.1. Evolutionary bistability

We first illustrate the basic evolutionary outcomes of the dynamical system at hand. Because there are three types of harvesters (*CondC*, *ComD*, and *Defector*) and two types of enforcers (honest and corrupt), their fractions can be plotted inside a prism-shaped region. Figure 2 illustrates evolutionary trajectories generated by the model. If the initial condition is such that honest enforcers are abundant, trajectories converge to a point with 100% *CondC*s and thus the vanishing fractions of other player types. By contrast, if the initial fraction of corrupt enforcers is sufficiently high, trajectories converge to a point dominated by *Defector*s.

We maintain inequality among parameters ($A > b > c > s \geq B$) because we focus on the situation in which penalty should cancel/absorb benefit, which in turn is larger than the cost of cooperation. Salary and bribe are set lower than the cooperation cost which guarantees the advantage of defection. The same inequality was used in the previous model [39]. However, we increased the penalty to consider the situation in which the resource dynamics may make cooperation difficult.

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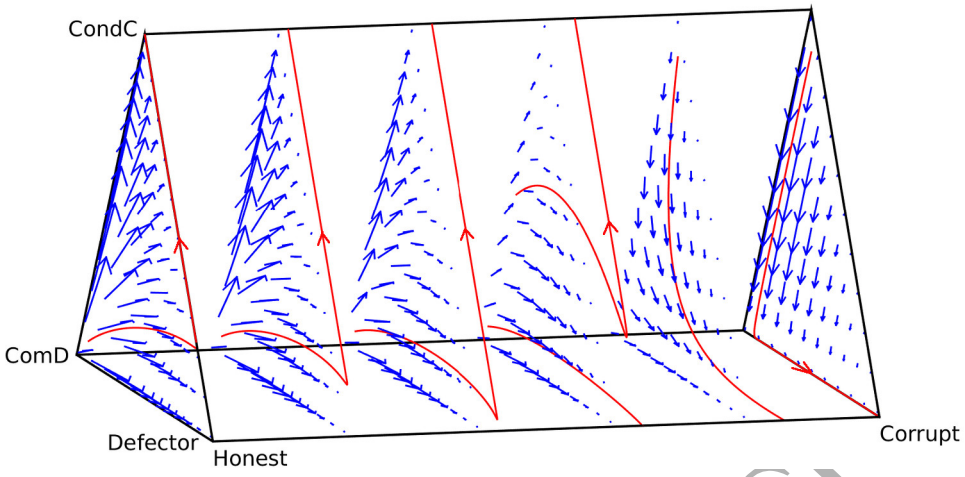

Figure 2: **Evolutionary bistability.** If honest enforcers abound initially, then the trajectories of the dynamical system converge to a monomorphic equilibrium in which only *CondC* harvesters remain. If, by contrast, corrupt enforcers abound initially, trajectories converge to a monomorphic equilibrium in which all harvesters are *Defector*s. The parameter values are $M = 100$, $p = 1$, $A = 10p$, $c_h = 0.5p$, $\lambda = 0.5$, $s = c_h h^*/10$, $B = s$, $\alpha = 1$, and $g = 0.1$. Unless stated otherwise, the same values were used to generate all other figures in the present paper.

Furthermore, enforcer salary and bribe depend on the harvesting rate, h^*, while remaining lower than the cooperation cost.

We examine the described evolutionary bistability more closely using the extreme cases with (i) all honest and (ii) all corrupt enforcers (see also Appendix B). Figures 3a and b, respectively, illustrate the replicator dynamics in these cases. When honest enforcers are abundant (Fig. 3a), the replicator dynamics of harvesters converge to an all-*CondC* equilibrium ($x_1 = 1$, $x_3 = x_5 = 0$). An important characteristic of such dynamics is that honest enforcers are particularly harmful for *ComD*s, who end up paying the cost of hiring an enforcer as well as the fine imposed by enforcers. The system, therefore, quickly moves away from any state in which *ComD*s are abundant. The struggle between *CondC* and *Defector* strategies is more difficult to resolve especially because a *CondC* harvester surrounded by *Defector*s responds to circumstances precisely by defecting. However, if a *CondC* harvester meets others of its kind, it reaps the benefit of cooperation which eventually (very slowly) leads to the dominance of *CondC* harvesters. By contrast (Fig. 3b), abundant corrupt enforcers in the same situation turn the tide in favour of *Defector*s, but only with the help from *ComD*s. Namely, the latter type of defectors undermine the effort of *CondC*s, yet do not get punished, thus reducing the benefit of cooperation. Such a reduction drives the system away from states with abundant *CondC*s, leading to a struggle between the two types of defecting strategies in which true *Defector*s always win ($x_5 = 1$, $x_1 = x_3 = 0$).

Next, we turn the attention to the evolutionary dynamics of enforcers (see also Appendix B). The states with 100% *CondC*s constitute a line of equilibria for enforcers, differing in the ratio of honest to corrupt ones. The reason for having a line of equilibria is that, if most harvesters are *CondC*s, honest and corrupt enforces achieve exactly the same fitness because the bribe is not paid. Similarly, the states with 100% *Defector*s also constitute a line of equilibria for enforcers

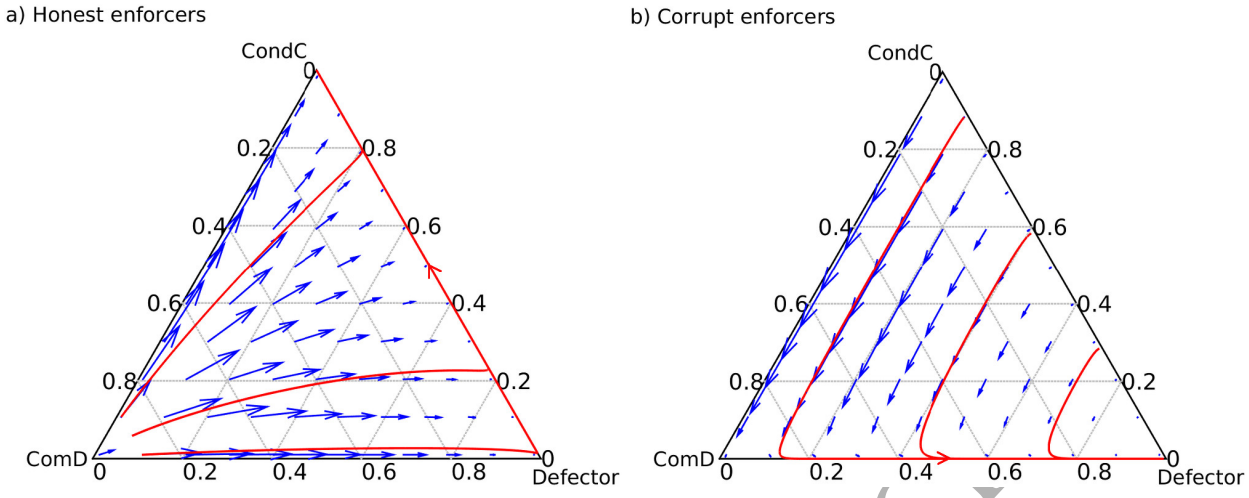

Figure 3: **The evolutionary dynamics of extremes.** a) If all enforcers are honest, *ComD*s are effectively fined and disappear from the system. In the remaining struggle between *CondC* and *Defector* strategies, the former eventually prevails (see Appendix A). b) If all enforcers are corrupt, *ComD*s get away with undermining the benefit of cooperation by paying a bribe. Corruption ultimately causes the elimination of *CondC*s from the system. In the remaining struggle between *ComD* and *Defector* strategies, the latter always wins (see Appendix A).

simply because the latter are not even hired by the former. As a result, the fitness of both types of enforcers is zero.

An interesting aspect of the replicator dynamics of enforcers is an apparent disadvantage of honest enforcers relative to their corrupt counterparts (Appendix B). This disadvantage is reflected in the fact that the abundance of honest enforcers decreases in favour of corrupt ones inside the prism-shaped region. One might think that the fraction of corrupt enforcers reaches 100% as the evolutionary end result, yet this does not happen. Instead, starting from any initial condition within the prism-shaped region, trajectories for enforcers reach an equilibrium with a mixture of the two enforcer types. The reason can be understood by considering that, if the fraction of *CondC*s is high, the rate of change of the relative abundance of the two enforcer types becomes very low; in fact, an order of magnitude lower than the rate of the decrease of *Defector*s, thus yielding the coexistence of honest and corrupt enforcers as the end result.

To summarise, the system is bistable. Depending on the initial conditions, the evolutionary end result is either 100% cooperation or 100% defection. To characterise the propensity of the model to generate a fully cooperative outcome, we consider the fraction of initial states that yield 100% cooperation—a quantity called the index of cooperation (*IC*).

In simulations, we opted for a practical (as opposed to a theoretical) definition of *IC*. Namely, calculating the relative area of the domain of attraction for cooperative outcomes is hampered by the mentioned property of the model, whereby the behaviour of *CondC*s is almost indistinguishable from the behaviour of *Defector*s if the system is in a state in which the latter type of harvesters dominates. Such a property makes the evolutionary dynamics extremely slow, and thus—in some cases—the convergence towards a fully cooperative state rather "platonic" (i.e. the benefits of cooperation cannot be enjoyed over any remotely practical time period). To circumvent the described

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difficulty in calculating *IC*, we take into account only the number of initial states that after 2000 generations result in an evolutionary trajectory converging to a fully cooperative state. An implication is that our practical definition of *IC* always yields a lower value than the one that would be obtained using a theoretical definition (i.e. the one with a cutoff point at infinite time). For the case illustrated in Figure 2, *IC* is slightly below 45%. In the next section, we proceed to examine how *IC* depends on the model parameters.

3.2. Parameter dependence of the index of cooperation

Compared to the payoffs that depend solely on socio-economic parameters, e.g. the number of cooperators in a focal group (N) or the cost of hiring enforcers (s), in the present work the payoffs are also proportional to the amount of harvest; that is, the payoffs are influenced by ecological parameters such as the resource growth rate (g) or the relative speed of resource dynamics (α). In what follows, we examine the effect of each parameter on the fraction of the initial conditions that result in perfect cooperation.

We investigated the effect of group size (N), and found that it is crucial for maintaining cooperation. We increased N from 2 to 18, beyond which the system always resulted in defection. Resilience of resource denoted by growth rate g varied from 0.1 to 0.9, still showing diverse Index of cooperation (*IC*) values from low to high. Relative speed of resource dynamics (α) was located in the range of 0.2 to 0.4. We stopped increasing over 0.4 because the critical change in IC appeared near the value of 0.32.

Dependence on the group size, N. The influence of the newly introduced social factor (group size, N) on the index of cooperation (*IC*) is best seen in Figure 4. In general, as the group size increases, it becomes more difficult to establish a fully cooperative state. The reason is that having more members in a group gives *ComD*s more space to exploit *CondC*s. Namely, even if a group consists of $N-1$ *CondC*s, the remaining one harvester could be *ComD* who exploits the others and thus flourishes in the long term. A consequence is that with increasing N, the fraction of purely cooperative groups—wherein *CondC*s enjoy the highest benefit of cooperation—decreases sharply. *CondC*s are therefore destined to fare worse at higher N unless there is more help from honest enforcers. Another aspect of the system revealed by Figure 4 is that cooperation seems harder to establish as the resource growth rate (g) becomes higher. Because this result indicates that ecological factors may provide incentives for the resource overuse in addition to usual socio-economic factors, we devote further attention to the underlying mechanism.

Dependence on the growth rate, g. A higher resource growth rate creates a defector-friendly environment (Fig. 5). To explain this result, we refer to an analytical expression in Lee et al. [39], where it was shown that the fraction of honest enforcers needed to establish cooperation is given by $(c-B)/(A-B)$, with c being the opportunity cost of cooperation, and A and B the same fine and bribe, respectively, as defined in Appendix A. Here, we connect c to ecological parameters and find that the opportunity cost of cooperation (i.e. the amount of harvesting forgone by cooperators relative to defectors) is proportional to the optimal harvesting rate of the form $h^* \propto g/N$ (see Eq. A.2). Accordingly, with an increasing resource growth rate, g, the fraction of honest enforcers needed to nullify the advantage of defection gets higher and the evolution of cooperation becomes

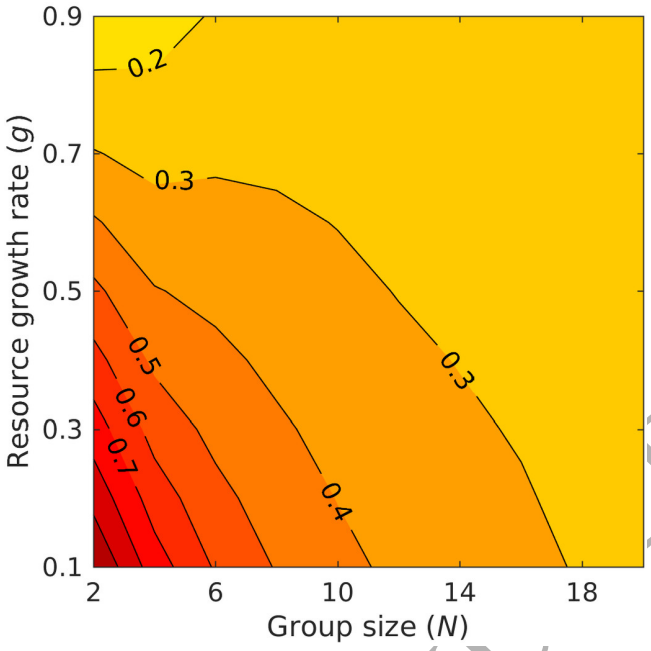

Figure 4: **Cooperation is harder to establish as the group size (N) increases.** A larger group size provides more opportunities for *ComD*s to mix with *CondC*s and exploit the benefit of cooperative effort. The same qualitative (i.e. negative) effect on cooperation is seen as the resource growth rate (g) increases.

less likely. Note that the index of cooperation is less sensitive to the resource growth rate for larger groups because an increasing N counters the described effect of an increasing g.

Dependence on the relative speed of resource dynamics, α. Parameter α controls the speed of resource dynamics relative to a rate at which the human decision-making process takes place. Thus, when the value of α is low, decisions are made while the resource level is still far from its equilibrium. Figure 6 suggests that decision making in such conditions is less effective in establishing cooperation. The reason for this is that insufficient time passes for the optimal harvesting rate to reveal the full benefit of cooperation before the next decision on an appropriate harvesting strategy is made. For the benefit of cooperation to fully reveal itself, the resource has to be in its equilibrium state.

We note that equations (A.1) and (A.2) show that a larger α enhances both the speed of resource recovery and harvest rate simultaneously, but it does not alter equilibrium resource level or the optimal harvesting rate. In contrast, a larger speed of resource recovery, g, increases the harvesting rate and promotes opportunistic behaviour.

A closer look at the dependence of *IC* on α (Fig. 7), while confirming that cooperation evolves more easily with a higher value of this parameter, also reveals that above a certain threshold ($\alpha \approx 0.35$) there is no further improvement in the level of cooperation. This threshold appears to be independent of the group size, N, which can be understood as follows. The strategy of *CondC*s is by definition superior if the resource level at the time of decision making (i.e. generational time τ) is close to the optimal level. To reach the optimal level, the resource in a patch occupied by *CondC*s

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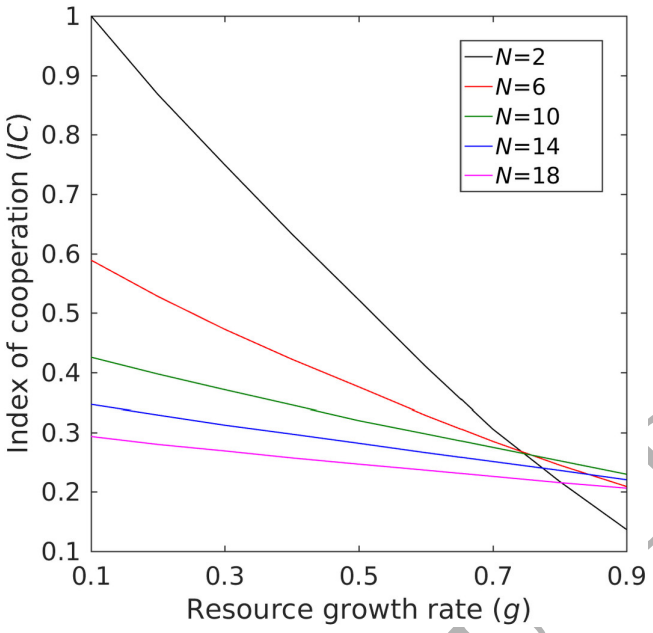

Figure 5: **Cooperation is harder to establish as the resource growth rate (g) increases.** A faster growing resource creates a defector-friendly environment by increasing the opportunity cost of cooperation (i.e. the amount of harvesting forgone by cooperators relative to defectors). Note that the index of cooperation is less sensitive to the resource growth rate for larger groups because increasing N and g cancel each other.

alone must equilibrate. How quickly the equilibrium is approached is determined by the resource change rate (i.e. dR/dt; Eq. A.3 in Appendix A). It can be shown by inserting Eq. (A.2) and $k = N$ into Eq. (A.3) that in a fully cooperative patch the dependence of dR/dt on N is eliminated. Accordingly, the convergence of the resource dynamics to the equilibrium is determined solely by parameter α, meaning that the full benefit of cooperation becomes apparent at the same threshold value of this parameter irrespective of the group size.

Dependence on the cost of harvesting, c_h. Of the four main model parameters analysed here in some detail (N, g, α, and c_h), the cost of harvesting is the only one that influences the dynamical system in two opposite ways. Specifically, the cost of harvesting decreases the optimal harvesting rate, $h^*(= Cg/N$, where C is a constant), but at the same time the resource level becomes higher due to reduced exploitation. This relates in a relatively complex manner to the potential advantage of *ComD*s over *CondC*s. Therefore, it is *a priori* unclear how the increasing cost of harvesting affects the success of reaching a cooperative state. With the parameter set that we analysed numerically, the effect of increasing c_h is such that the advantage of *ComD*s decreases only marginally (Fig. 8), making the evolution of cooperation a bit easier.

Another interesting aspect of the dynamics in this context is that the reduced advantage of *ComD*s makes their payoff more similar to the payoff of *CondC*s, thus allowing the former to exploit the latter for a longer period of time. A consequent effect is that corrupt enforcers receive more bribe and reach higher abundance in the population by the end of the evolutionary dynamics. This effect is stronger as the group size, N, gets larger because in this case it is more likely that a

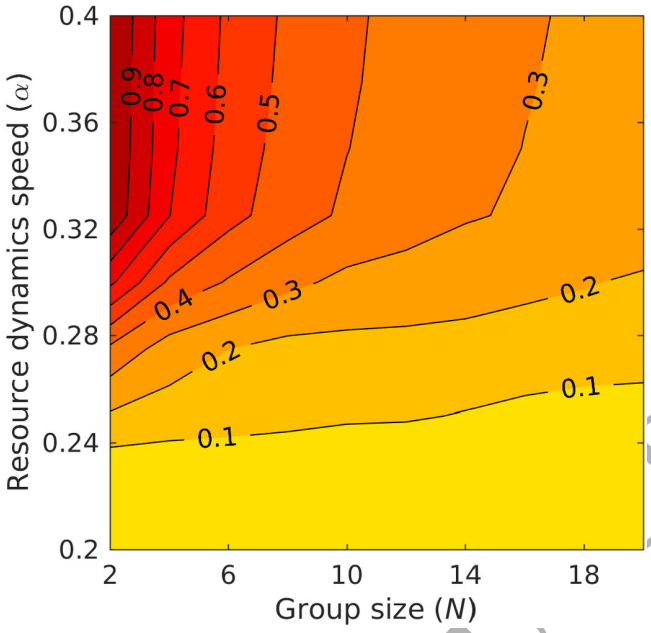

Figure 6: **Cooperation is harder to establish as the relative speed of resource dynamics (α) decreases.** A low value of α means that strategic decision making happens at a much faster time scale than the resource replenishment. In such conditions, the resource is still far from its equilibrium at the time each decision is made. Consequently, the full benefit of cooperation cannot be seen and establishing cooperation becomes more difficult.

ComD will "sneak" into a group of *CondC*s. In the end, the index of cooperation, *IC*, may even decrease under certain conditions as seen in the right bottom corner of the phase plane shown in Figure 8 (for $N > 10$).

Dependence on other parameters. On top of the parameters mentioned so far, there are five remaining parameters that affect the system's dynamics in expected or, at least, less surprising ways. These are (i) salary s and (ii) bribe B for enforcers, (iii) fine A paid by *ComD*s, (iv) the extent of defection, λ, and (v) the number of patches comprising the ecosystem, M (Appendix A). For simplicity, we make all parameters that are measured in monetary terms (s, B, A, and c_h) proportional to resource price p. In addition, we choose salary small enough to allow *CondC* to outweigh *Defector* when there are only few *ComD*s left in the system. We set the bribe to be the same as the salary. The two expected results are that, as the fine and/or the bribe increases, *ComD*s get more suppressed. Resource price p and forest size M always appear combined in the formulas for payoffs, including the opportunity cost of cooperation which, as mentioned before, is critical in determining the fraction of honest enforcers needed to reduce the advantage of *ComD*s over *CondC*s. It is intuitively clear that such a cost should become higher when the resource is more expensive (p) or when there is more resource waiting to be exploited (M). Thus, increasing pM discourages the cooperative outcome.

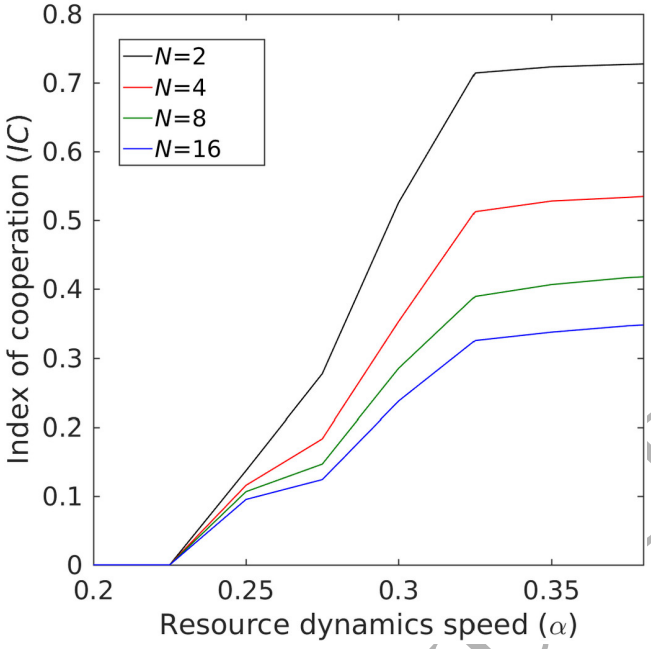

Figure 7: **Faster resource dynamics is beneficial for the cooperative outcome, but only up to a point.** The benefit of cooperation is more apparent if the resource level is close to its equilibrium value at the time of strategic decision making. Consequently, a faster convergence rate is supportive of cooperation up to a point at which the time needed for the resource to equilibrate is of the same scale as the time period between two consecutive strategic decisions. As argued in the text, the convergence rate is largely determined by parameter α, irrespective of group size N.

4. Discussion

Key to the sustainable exploitation of common pool resources is ensuring that resource users (i.e. harvesters) comply with set policy targets. In this context, it is helpful to understand the effectiveness of candidate enforcement mechanisms, including delegated punishment. As a candidate mechanism, delegated punishment suffers from bribery and corruption which represent two almost synonymous hindrances to cooperation. Despite the risk of corruption, without paid enforcer the system goes to defection such that harvesters may not choose long-term perspective but easily submit to the short-term temptation of the social dilemma structure.Lee et al. [39] studied the successfulness of a simplistic evolutionary system (with only two harvesters per patch who decide whether to hire an enforcer) in maintaining cooperation in the face of corruption, but fell short of exploring the connection between the resource state and harvesters' payoffs. The present work aims at filling this shortfall in at least two major ways. First, we account for the possibility that any number of harvesters can exploit a single patch of the resource which is important in social and economic systems wherein N-player interactions are fundamental (as opposed to physical systems with pairwise interactions; see Ref. [40]). Second, we incorporate the dynamics of resource depletion and recovery, thus allowing both human behaviour and the resource to coevolve [20]. By maintaining the same basic representation of the institutional framework and incentives, the contrast between the old and the new dynamical system allows us to discuss not only the strain

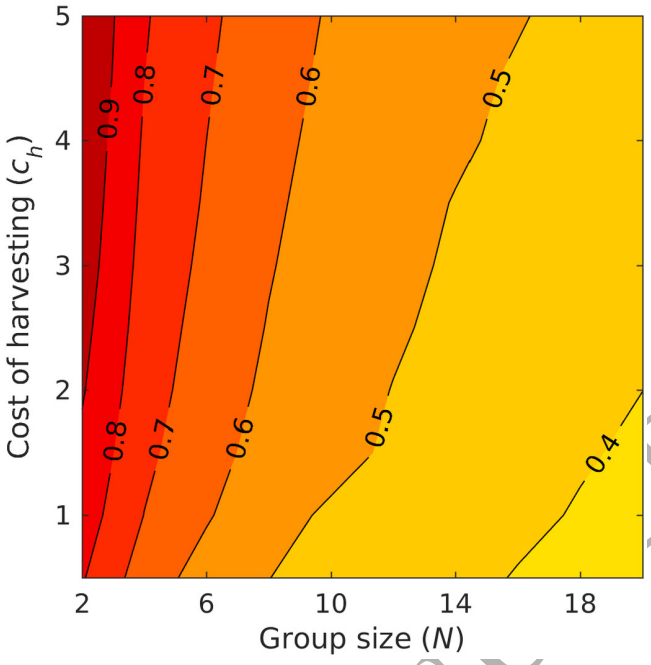

Figure 8: **The cost of harvesting (c_h) has a mixed effect on the emergence of cooperation.** The cost of harvesting (i) decreases the optimal harvesting rate, but (ii) increases the resource level due to reduced exploitation. It is *a priori* unclear which of the two effects will prevail. With the default parameter set, an increasing cost of harvesting is marginally in favour of the cooperative outcome.

on the resource brought about by more harvesters per patch, but also the role of ecological (as opposed to social) processes in establishing cooperation.

One of the defining characteristics exhibited by the introduced dynamical system is bistability, resulting either in the dominance of *CondC* harvesters (100% cooperation) or the dominance of *Defector* harvesters (100% defection), depending on the initial conditions. The outcome favourable to cooperation strongly hinges on the initial abundance of honest enforcers who prevent the opportunistic behaviour of *ComD* harvesters. For the cooperative outcome to emerge, the increasing temptation (in the form of e.g. timber price) for *ComD*s and the increasing opportunity cost of cooperation both require that the initial fraction of honest enforcers turns higher. The importance of the initial fraction of honest enforcer was fully emphasized in Ref. [39], where the threshold for the collapse of cooperative system was $(c - B)/(A - B)$. The role of opportunity cost is particularly interesting because of the dependence on (i) the number of harvesters per patch and (ii) the ecological parameters. This is in sharp contrast with the model of Lee et al. [39] in which the opportunity cost of cooperation is a mere constant.

Considering the number of harvesters per patch (N), increasing N suppresses the desirable evolutionary outcome. The reason why establishing cooperation becomes more difficult as N increases is that having more harvesters per patch improves the chances for *ComD*s to be mixed with *CondC*s and thus exploit the effort of cooperators. As a consequence, the advantage of having more cooperators in the same group becomes jeopardized and, remembering that the model

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exhibits bistability, defection surfaces as the dominant mode of action. This echoes the result of several observations on successful community-based management with own rule sets for resource use, in which larger group size hindered establishment of cooperation [4].

Considering ecological processes, a faster resource growth (i.e. recovery) rate favours defection. The reason is that an increase in the resource growth rate increases the opportunity cost of cooperation rather than the level of the disposable resource which would benefit cooperators. A higher resource growth rate therefore creates an extra incentive for defection. Determining what is the contribution of this incentive to overexploitation is a task in the domain of econometrics, but one that may be exceedingly difficult to complete because of the complex interactions of many explanatory factors. For instance, the favourable climate of many (sub)tropical countries sustains productive forests that are heavily overexploited as a consequence of illegal logging [29, 30, 31, 32, 33]. Similarly, waters off the coast of West Africa, due to coastal upwelling, are nutrient rich and thus support large fish stocks that are fished with little regard for sustainability [34, 35, 36, 37, 38]. In these cases, however, weak enforcement systems are likely to blame for the current situation. The problem of West African fisheries is compounded by the excess fishing capacity of multiple foreign fleets, e.g. from the EU, Japan, China, and South Korea.

Tendency to cooperate is further impeded by a slowly converging resource dynamics relative to the rate at which the decision-making process takes place. The main reason for such a result is that bad decisions become apparent later than would be the case with a relatively fast resource, which masks overuse and causes depletion in the long run. An anecdotal example would be the water use in Jeju Island, South Korea. Groundwater reservoirs on the island are being heavily exploited by industrial mineral water plants and tourism-related infrastructure, especially golf courses [41]. The rationale for heavy exploitation is high precipitation (i.e. a seemingly fast "recovery" rate), yet the rate at which reservoirs actually fill up may be quite slow, which often causes the estimates of the current state to be questioned [42, 43]. This non-biological resource is actually in double jeopardy: (i) the recovery rate appears favourable due to high precipitation which, according to the model, should favour defection and (ii) the actual convergence of the resource dynamics may be taking decades which is slower even than a typical time scale for making strategic governmental decisions.

It is instructive to compare our delegated enforcement system with common alternatives. Peer punishment, for example, makes it possible to have cooperators who avoid punishing defectors. Because punishment is costly, such cooperators are called second-order free riders. Theoretical analyses [44, 45, 46, 47, 48, 49] suggest that second-order free-riding is advantageous over being a cooperator who punishes defectors. A pool punishment system tries to address this problem by punishing even second-order free riders. Our enforcement system, by comparison, avoids the problem of second-order free-riding altogether because hiring an enforcer is voluntary to begin with. Unfortunately, harvesters may have little regard for the health of a resource being exploited, in which case opting out of the enforcement system immediately undermines its usefulness, possibly leading to the loss of the freedom of choice—enforcement becomes compulsory [8, 9, 10, 11]. A more insidious problem is that there are circumstances under which corruption weakens delegated enforcement even if the system is used by harvesters. The present analysis singles out several factors conducive of corruption (e.g. a large number of harvesters per patch, high resource growth rate, slow resource dynamics relative to the decision-making process). If one or more of

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these factors dominate the evolutionary dynamics, giving up delegated enforcement and replacing it with an alternative system may be a better solution. This result implies that besides the ecological features of the system, decision-making process should be carefully designed for the success of management. Voluntary concern for the resource level by resource users and enforcers in initial stage could be more accurately estimated and in addition detailed decisions such as group size or the optimal harvesting amount could be easily shared among players, an option often neglected in centralized systems.

If a society or a community has established solid social capital, it may be worth considering some mechanisms of social pressure as rule-enforcing power. There exist theoretical studies that coupled resource dynamics and norm-following behaviour, applying social norms of cooperation as enhancement mechanism [50, 25, 51]. These studies found that good (bad) quality of common resource is accompanied with high (low) level of cooperation, but models still included non-linear behaviour caused by feedbacks in coupled dynamics [50]. Some models incorporated resource variability, introducing random variable to the resource dynamics and investigating its impact. In the model of Tavoni et al. [25], increased variability decreased the average resource level and then the payoffs of all strategies. Social pressure, however, is not influenced by the change, thus becoming more effective in suppressing defectors. Resource scarcity in Richter et al. [51] takes the opposite role by providing temptation for defectors to break the rules and cause cooperation breakdown. Resource variability may be important factor considering the possible environmental fluctuations such as climate change, and will be an interesting future research direction for our model.

Turning briefly to the potential for future development, an implicit assumption here is that voluntary monitoring activity by harvesters is ineffective. Such an assumption is plausible if a relatively small number of harvesters covers a large harvesting area, which *is* rather typical of common-pool resources. Furthermore, the model suggests that a delegated enforcing system also turns ineffective as the number of harvesters per patch becomes high. We, however, ignore the possibility that many harvesters working in the same area may actually be spotting each other on a regular basis. As the frequency of mutual encounters increases, voluntary monitoring and subsequent punishment at a harvester's own cost (i.e. pool punishment) should reach the effectiveness of a delegated punishment system. To analyse the conditions under which pool punishment might match the efficiency of delegated punishment, one way forward would be to formulate a spatially explicit model. This model could use the distribution of harvesters in space as a basis for determining how likely voluntary monitoring is to be effective. A conclusion is that, because all enforcement systems and accompanying punishments have some merits and demerits, a single universally valid solution does not exist. Studying the specifics of each common-pool resource is necessary before implementing enforcement.

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A. Model description

A.1. Resource dynamics and the two types of harvesters

We begin the model description with the resource dynamics. Let us consider an ecosystem composed of a large number of patches, where each patch is used by N harvesters. If the harvesting rate is too high, a patch gets depleted and all harvesters suffer the consequences of low resource availability. We can further imagine that any patch is composed of M units, where each unit is either in state 1 (filled) or state 0 (empty). Units are subject to Markovian transitions between these states. If we denote the amount of the resource by R, then R equals the total number of units in state 1. The transition rate from 1 to 0 is Nh, i.e. the product of the number of harvesters, N, and the per capita harvesting rate, h. The rate of recovery from 0 to 1 is the growth rate of the resource, g. In our simplified picture, a unit in state 1 is occupied by e.g. a single tall tree, whereas a unit in state 0 contains only small trees and shrubs unsuitable for harvesting. Under these circumstances, the dynamical equation for R is:

$$\frac{dR}{dt} = \alpha \left[g(M - R) - NhR \right]. \tag{A.1}$$

Here, α is the speed of the resource dynamics relative to the turnover rate of the people's opinion, where the latter follows the replicator dynamics, as explained below.

Having specified the resource dynamics, we are in a position to introduce two types of harvesters. Let us first note, however, that the equilibrium resource level is $R = Mg/(g + Nh)$. Furthermore, the payoff of each harvester is $pRh - c_h h$, where p is the price of the harvested resource. We assume that the cost of harvesting is proportional to the harvesting rate, which gives rise to the second term, $c_h h$. If R is kept at the equilibrium value, the payoff is maximised at

$$h^* = \frac{g}{N} \left[\sqrt{\frac{pM}{c_h}} - 1 \right]. \tag{A.2}$$

Quantity h^* is hereafter called the cooperative optimum harvesting rate. Of all the cases in which all harvesters adopt the same harvesting rate, h^* results in the maximum per capita payoff. At this point, there is a critical dilemma faced by each harvester that needs to be considered when devising a harvesting policy. If a single harvester adopts a harvesting rate faster than the optimum, h^*, then this particular harvester gains more at the expense of the other harvesters. A harvester who harvests at a higher than the optimal rate, $h^*(1 + \lambda)$, $\lambda > 0$, is called a defector. By contrast, an adopter of the cooperative optimal harvesting rate is called a cooperator.

Let us examine the effect that defectors have on the equilibrium value of the resource. If a patch includes k cooperators and $N - k$ defectors, the dynamics are specified by:

$$\frac{dR}{dt} = \alpha \left[g(M - R) - h^* kR - h^*(1 + \lambda)(N - k)R \right], \tag{A.3}$$

thus giving rise to equilibrium $R = gM/[g + h^*(N + \lambda(N - k))]$. The last expression is a decreasing function of the number of defectors, $N - k$, indicating the depletion by overuse and therefore the negative effect of defection. Note that if the generation time is short, the resource level may not be able to reach the equilibrium value.

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A.2. Rule enforcers and the corruption thereof

Because individually a harvester can benefit from harvesting more than the others, the setup described so far is typical of the tragedy of the commons [1]. Without additional structure, the evolution would favour defection. Lee et al. [39], to avoid the unfavourable evolutionary outcome, introduced rule enforcers who monitor harvesting rates, report their findings publicly, and punish defectors. In theory, if defectors are forced to pay a sufficiently high fine, denoted hereafter by A, all harvesters should find cooperation to be a better alternative.

There are two problems with any fine-based mechanism. First, a defector may escape punishment by paying a bribe, B ($B < A$), to the rule enforcer who consequently neglects the case. Second, someone must cover the cost, denoted by s, of hiring a rule enforcer. A rule enforcer cannot be hired unless all the harvesters in a group agree to do so. Assuming that harvesters are classified according to (i) whether they cooperate or defect and (ii) whether they are willing to hire an enforcer or not, we end up with four harvester types. The payoffs of these four types show that cooperators are always inferior to defectors, which prompted Lee et al. [39] to introduce a more sophisticated strategy named conditional cooperator. A conditional cooperator is a harvester who cooperates only if the other harvesters are willing to support the enforcer, but defects otherwise. Note that a harvester cannot tell if the other harvesters cooperate or not, but the information on who is willing to support the enforcing system is readily available. Therefore, the behaviour of a conditional cooperator is based on the opponents' attitudes towards the enforcement system. Conditional cooperators are, in fact, so sophisticated that they are superior to defectors, because when the former are surrounded by the latter, everyone's behaviour is the same, but when two or more conditional cooperators meet, they enjoy the benefit of cooperation. To undermine the dominance of conditional cooperators, at least some defectors must commit to the rule enforcement and only then exploit the others by defecting. In summary, three types of harvesters remain in the system: (i) conditional cooperators (hereafter *CondC*s), (ii) committing defectors (*ComD*s), and (iii) defectors (*Defector*s). Committing defectors are willing to support the enforcement system, but defect (i.e. engage in illegal logging), and use the bribe to get out of trouble if caught by an enforcer. Defectors, by contrast, simply refuse to commit to hiring an enforcer. Although we could envision two more types of harvesters (committing cooperators and unconditional cooperators), they disappear from the system because of having payoffs that are always lower than those of the three emphasised harvester types.

Next, we define two rather straightforward types of enforcers. An honest enforcer refuses to receive bribe and always reports the true state of affairs. A corrupt enforcer, by contrast, is ready to receive bribe and neglect the mischief of defectors. Hence our evolutionary game model is comprised of a combination of replicator equations: one set for harvesters and the other for enforcers. In the literature [52], the dynamics exhibited by such a model is called two population replicator dynamics.

A.3. Strategy updating

For the evolutionary dynamics to unfold, harvesters must be able to update their strategies. To that end, we adopt the discrete-time replicator equations with non-overlapping generations. At the beginning of a generation, N harvesters are randomly chosen from each of the three types and assigned to a patch until all patches are covered. Numbers k, l, and m of harvesters belonging to

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CondC, *ComD*, and *Defector*, respectively, who end up in the same patch, follow the multinomial distribution with averages equal to the fractions of each harvester type in the whole population. These fractions for *CondC*, *ComD*, and *Defector* are denoted by x_1, x_3, and x_5, respectively, where the notation used is consistent with Lee et al. [39]. Note that $x_1 + x_3 + x_5 = 1$ and $k + l + m = N$. The relative abundance of patches with k, l, and $m = N - k - l$ harvesters of type *CondC*, *ComD*, and *Defector*, respectively, is given by

$$q(k,l) = \frac{N\,!}{k\,!l\,!(N-k-l)\,!} x_1^k x_3^l (1 - x_1 - x_3)^{N-k-l}. \tag{A.4}$$

The total number of combinations, due to constraints $k = 0, 1, ..., N$, $l = 0, 1, ..., N$, and $k + l \leq N$, is $(N + 1)(N + 2)/2$.

Strategy updating is dependent on the payoff realised by each type of harvesters during generational time τ. The payoff is, in turn, dependent on the state of the resource, $R(\tau)$, at time τ, which is given by Eq. (A.3). Finally, the resource dynamics obeying Eq. (A.3) depends on number k of *CondC*s in a patch. We therefore calculate the trajectories of the resource for all $(N + 1)(N + 2)/2$ possible compositions of the three harvester types. Given the above information, a basic expression for the per capita return from harvesting is $[pR(\tau) - c_h] \times h$. This expression, for completeness, must be appended with terms reflecting management costs, e.g. the cost of hiring an enforcer, fines charged to defectors, and the bribe.

By combining harvesting returns and management costs, we obtain the equations for the per capita payoff of each harvester type. If k and l are the number of *CondC*s and *ComD*s in a patch, then it is convenient to denote the per capita payoff of type i harvesters by $w(i|k,l)$. In the case $k + l = N$, we have

$$\begin{aligned} w(1|k,l) &= w(1|k+l=N) \\ &= (pR(\tau|k) - c_h)\, h^* - s, \end{aligned} \tag{A.5}$$

$$\begin{aligned} w(3|k,l) &= w(3|k+l=N) \\ &= (pR(\tau|k) - c_h)\, h^*(1+\lambda) \\ &\quad - (s + Ay_1 + B(1-y_1)). \end{aligned} \tag{A.6}$$

If, however, $k + l < N$, then for all i

$$\begin{aligned} w(i|k,l) &= w(i|k+l<N) \\ &= (pR(\tau|0) - c_h)\, h^*(1+\lambda). \end{aligned} \tag{A.7}$$

Here, $R(\tau|k)$ is used to denote the state of the resource at time τ in a patch harvested by a group that contains k *CondC*s without any *Defector*s. Note that k is set to zero in Eq. (A.7) because, if one or more *Defector*s are present in the group, enforcers are not hired, prompting all *CondC*s to defect. The presence of an enforcer (Eqs. A.5 and A.6) implies a hiring cost, s. If the enforcer is honest (with probability y_1; Eq. A.6), the overuse of the resource is prevented by charging fine A to *ComD*s. By contrast, a corrupt enforcer (with probability $1 - y_1$) is ineffective because of accepting bribe B.

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The evolutionary dynamics arising from the above considerations is given by the replicator equations. These are:

$$x_i^{n+1} = \frac{W(i)}{\sum_j W(j)x_j^n} x_i^n, \ (i = 1, 3, 5) \tag{A.8}$$

where $W(i)$ is the average per capita fitness of type i harvesters ($i = 1, 3, 5$) in generation n. The most direct way to obtain an expression for $W(i)$ is to calculate the average per patch payoff of type i harvesters and then divide the result by the average number of type i harvesters in a patch. Taking *CondC*s as an example, the average per patch payoff is $\langle kw(1|k,l)\rangle = \sum_{k,l} kw(1|k,l)q(k,l)$, whereas the average number of *CondC* harvesters in a patch is $\langle k\rangle = \sum_{k,l} kq(k,l)$. Here, $\langle\cdot\rangle$ indicates averaging using the multinomial distribution in Eq. (A.4). Consequently,

$$W(1) = \frac{\langle kw(1|k,l)\rangle}{\langle k\rangle} = \frac{\sum_{k,l} kw(1|k,l)q(k,l)}{\sum_{k,l} kq(k,l)}. \tag{A.9}$$

Analogous reasoning yields the fitness functions of *ComD*s and *Defector*s, where the relative magnitudes of these functions inform us about the system's dynamics (Eq. A.8; Appendix B).

In the last step of the model construction for the purpose of strategy updating, we make an important simplifying assumption. Namely, at the beginning of generation $n + 1$, the resource level in all patches, $R_{n+1}(0|k)$, is set equal to the average per patch resource level at the end of generation n, i.e. $R_{n+1}(0|k) = \langle R_n(\tau|k)\rangle$. The benefit from such an assumption is that we maintain a deterministic description of the system.

A.4. Evolutionary dynamics of enforcers

The evolutionary dynamics of enforcers unfolds in parallel with the evolution of harvesters. A mathematical description of this dynamics is again based on the replicator equations. Hence, for the abundance of honest enforcers, y_1, we have:

$$y_1^{n+1} = \frac{\hat{W}(1)}{\hat{W}(1)y_1^n + \hat{W}(2)(1 - y_1^n)} y_1^n. \tag{A.10}$$

Because the only alternative to being an honest enforcer is to be corrupt, for the abundance of the latter type, y_2, it immediately follows that $y_2 = 1 - y_1$. In Eq. (A.10), $\hat{W}(i)$ indicates the fitness of type i enforcer ($i = 1$ for an honest and $i = 2$ for a corrupt enforcer).

As in the case of harvesters, expressions for the fitness of enforcers follow from the corresponding per capita payoffs. Let $\hat{w}(i|k,l)$ be the per capita payoff of an enforcer of type i. We distinguish two cases. If $k + l = N$, the per capita payoff of honest enforcers is $\hat{w}(1|k,l) = Ns$, whereas that of corrupt enforcers is $\hat{w}(2|k,l) = \hat{w}(1|k,l) + lB$. These expressions state that all N harvesters in a patch pay cost s of hiring an enforcer, but a corrupt enforcer additionally receives bribe B from each of the l *ComD*s. The fact that $\hat{w}(1|k,l) < \hat{w}(2|k,l)$ implies that being a corrupt enforcer is always advantageous. In the alternative case of $k+l < N$, we have $\hat{w}(1|k,l) = \hat{w}(2|k,l) = 0$ because no enforcer is hired in patches with one or more *Defector*s. Fitness functions are obtained by averaging the per capita payoff:

$$\hat{W}(1) = \langle\hat{w}(1|k,l)\rangle = (x_1 + x_3)^N Ns, \tag{A.11}$$

$$\hat{W}(3) = (x_1 + x_3)^N N(s + x_3 B). \tag{A.12}$$

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To summarise, the evolutionary dynamics are given by a discrete-time autonomous set of variables x_1, x_3, and y_1, as well as the average resource level at the end of a generation, $\langle R(\tau|k)\rangle$. Within each generation, a differential equation describes the resource dynamics, thus yielding a hybrid model. The most important aspects in which the present mathematical framework differs from that of Lee et al. [39] is that (i) a group of harvesters on a single patch can be of any size which makes it impossible to construct a simple payoff representation in terms of matrices and (ii) we adopted a discrete-time formalism for evolutionary dynamics in order to, at each time step, describe the resource dynamics using a differential equation.

B. Analytical results

To examine the relative strength of the three types of harvesting strategies (*CondC*, *ComD*, and *Defector*), we calculate the differences between their respective fitness functions. Particularly instructive in this context is the behaviour of the dynamical system at the sides of ternary domains in Figures 3a and b.

First, we look at the relative strength of *ComD*s (x_3) and *Defector*s (x_5) when a negligible fraction of *CondC*s ($x_1 = 0$) is present in the system. The fitness difference is

$$W(3) - W(5) = -x_3^{N-1}\left(s + B(1 - y_1) + Ay_1\right) < 0, \tag{B.1}$$

which follows from the definition of fitness in Eq. (A.9) and equality $\langle R(\tau|k)\rangle = R(\tau|0)$ reflecting the fact that all harvesters are defectors. Eq. (B.1) shows that $W(3) < W(5)$, meaning that *Defector*s dominate over *ComD*s when the fraction of *CondC*s approaches zero. Intuitive reasoning behind this result is that *ComD*s thrive by exploiting *CondC*s, but here we are looking at the case in which the latter type of harvesters is disappearing.

Second, we compare the relative strength of *CondC*s (x_1) and *Defector*s (x_5) when the presence of *ComD*s is negligible ($x_3 = 0$). The corresponding fitness difference becomes

$$\begin{aligned} W(1) - W(5) = x_1^{N-1}\big[p\left(\langle R(t|k+1)\rangle - R(t|0)\right)h^* \\ - \left(pR(t|0) - c_h\right)h_2 - s\big], \end{aligned} \tag{B.2}$$

where we denoted the excess harvesting rate of *Defector*s with h_2, i.e. $h_2 = (1 + \lambda)h^*$. The three terms within square brackets have the following interpretation: (i) the benefit of cooperation, quantifying the improvement in resource abundance due to the presence of cooperators, (ii) the opportunity cost of cooperation, measuring the additional payoff forgone by cooperators, but taken by *Defector*s, and (iii) the cost of maintaining the delegated enforcement system. The standard parameter set in the present work is chosen such that the benefit of cooperation outweighs the sum of the other two terms. Therefore, if the fraction of *ComD*s is diminishing over time, then *CondC*s eventually start to overcome *Defector*s and in the end dominate the population. However, the rate of convergence can be painfully slow, especially when *Defector*s are abundant, because in that case *CondC*s most of the time behave the same as *Defector*s making it very hard to distinguish the two types of harvesters.

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Finally, we compare the relative strength of *CondC*s (x_1) and *ComD*s (x_3) when the fraction of *Defector*s is negligible ($x_5 = 0$). The fitness difference amounts to

$$\begin{aligned} W(3) - W(1) = \\ (x_1 + x_3)^{N-1} \left[-p \left(\langle R(t|k+1) \rangle - \langle R(t|k) \rangle \right) h^* \right. \\ \left. + \left(p \langle R(t|k) \rangle - c_h \right) h_2 - \left(B(1 - y_1) + A y_1 \right) \right], \end{aligned} \tag{B.3}$$

where the first term in square brackets is the marginal fitness improvement from introducing one more cooperator. The second and the third term have exactly the same meaning as the corresponding terms in Eq. (B.2) although the form is a little different. The parameter values, in particular bribe B and fine A, are chosen such that both options, $W(3) > W(1)$ and $W(3) < W(1)$, are possible depending on the fraction of honest enforcers, y_1.

Inequality $W(3) > W(1)$ may hold even in the presence of *Defector*s. In fact, it holds globally (i.e. at all points of the ternary domain in Figure 3b) in the extreme case when all enforcers are corrupt ($y_1 = 0$). An implication is that evolutionary trajectories always cross contour lines defined by $x_3/x_1 = \text{const.}$ because the replicator equations guarantee $(x_3/x_1)_{\text{next}} = (W(3)/W(1))(x_3/x_1) > x_3/x_1$, the effect of which is seen in Figure 3b. As a consequence, *CondC*s eventually disappear ($x_1 = 0$). In a struggle between *ComD* and *Defector* strategies, the latter prevails as already explained. If most enforcers are corrupt, the system ends up in state $x_1 = x_3 = 0$, $x_5 = 1$. *ComD*s cannot be the ultimate winners, but they thrive by exploiting *CondC*s, thus undermining the prospects of reaching a cooperative outcome.

The reverse inequality, $W(3) < W(1)$, holds if most enforcers are honest ($y_1 = 1$). In this case it is interesting to look at the relative strength of the two type of enforcers which follows immediately from Eqs. (A.11) and (A.12)

$$\hat{W}(1) - \hat{W}(2) = -(x_1 + x_3)^N x_3 B < 0. \tag{B.4}$$

The abundance of honest enforcers monotonically decreases with the generational time. One might be tempted to conclude that eventually the whole population of enforcers turns corrupt. What happens, however, is that factor x_3 in Eq. (B.4), representing the fraction of *ComD* harvesters, becomes very small and erases the advantage of receiving bribe way before corrupt enforcers take over the population. Depending on the initial conditions, the evolutionary end result is some spontaneous mix of honest and corrupt enforcers.

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