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Robustness of norm-driven cooperation in the commons

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Summary

Sustainable use of common-pool resources such as fish, water or forests depends on the cooperation of resource users that restrain their individual extraction to socially optimal levels. Empirical evidence has shown that under certain social and bio-physical conditions self-organized cooperation in the commons can evolve. Global change, however, may drastically alter these conditions. We assess the robustness of cooperation to environmental variability in a stylised model of a community that harvests a shared resource. Community members follow a norm of socially optimal resource extraction, which is enforced through social sanctioning. Our results indicate that both resource abundance and a small increase in resource variability can lead to collapse of cooperation observed in the no-variability case, while either scarcity or large variability have the potential to stabilize it. The combined effects of changes in amount and variability can reinforce or counteract each other depending on their size and the initial level of cooperation in the community. If two socially separate groups are ecologically connected through resource leakage, cooperation in one can destabilize the other. These findings provide insights into possible effects of global change and spatial connectivity, indicating that there is no simple answer as to their effects on cooperation and sustainable resource use.

Keywords: social-ecological system; cooperation; norms; global change; collapse; common-pool resource

1. Introduction

Theoretical and empirical research has long been concerned with finding ways to overcome social dilemmas in natural resource use that arise when the individual short-term benefits from resource exploitation lead users to collectively overharvest (e.g. [1],[2]). While early research emphasized the need for government control or privatisation [1], recent empirical work has highlighted that communities are often capable of overcoming the dilemma and achieve sustainable resource use through cooperative self-governance [3]. Different mechanisms have been proposed for successful self-governance, such as communication, monitoring and sanctioning ([3], [4]) or reciprocity [5]. Ostrom [3] and others [6] have found that successful communities often establish social norms, i.e. "rule(s) or standard(s) of behaviour shared by members of a social group" [7], to discourage individual overharvesting.

The social interactions that enable cooperation and the development of social norms in common-pool resources (CPRs), however, do not take place in a void or a static environment. CPRs are part of interlinked systems of humans and nature [8], so called social-ecological systems (SES). SES develop over time through micro-scale interactions of individual agents that spread to higher levels due to agents' collective behaviour [9]. These include agent-agent interactions, e.g. when a norm-follower observes a norm-violation by another agent, and interactions between agents and resources in the form of extraction, monitoring or maintenance activities. Therefore, characteristics of the ecological system that affect agent-resource interactions also shape individual and collective behaviour in SES. Properties of the resource system that have proven relevant in explaining successful self-governance in social-ecological systems are, among others, the productivity of a resource, the mobility of the resource and its reproductive rate [10]. Recent empirical research on collective action for sustainable resource use hence tries to take attributes of the resource system into account, along with those of resource users and governance systems (e.g. [10], [11]).

The role of bio-physical conditions for the evolution of cooperation and hence sustainable resource use becomes even more relevant in view of increasing pressures on resource systems by climate and other global change processes [12]. Their impact has the potential to drastically alter the environmental conditions under which collective action for sustainable resource use has been achieved in the past. Climate change, for instance, is likely to change the quantity and variability of resource flows, exacerbating existing resource scarcity and leading to more extreme events (see e.g. [13] and [14] p. 8 for the impact of climate change on water scarcity in arid regions). Socio-political developments and human migration have the potential to alter the needs for natural resources such as land, water and marine resources, with potentially major impacts on today's resource use patterns. With increased demand or variability comes increased uncertainty, which can put additional pressure on individual and collective action. This might lead to more incentives for opportunistic behaviour in situations where cooperative collective action was well-established before. The consequences of these changes for CPR management are to a large extent unknown.

The impact of climate change on political stability and intra-state armed conflict has recently been the subject of increased attention in the climate change debate (see e.g. [15]). Results so far are inconclusive, showing that resource scarcity and variability can lead to an increase in conflict (see e.g. [16] , [17]), but also foster cooperation. Similarly, there is an on-going debate about an increase in the potential of war over water with an increase in water stress. While some argue that the likelihood of conflicts will increase (e.g. [18], [19], [20]) others point out that history has shown that countries do not go to war over water but rather solve their water issues through trade (e.g. import of food) and international agreements ([21], [22],

[23]). Gizelis and Wooden [24] caution against deterministic direct links between resource state and conflict, highlighting the importance of domestic institutions in determining how a community or nation will react to a rapid or slow change in resources.

The robustness of collective action to the impacts of global change thus remains an open question. The aim of this paper is to investigate the robustness of norm-driven cooperation in a CPR to changing resource availability. To this end we developed an agent-based model, henceforth termed *CP-norm,* of a community of norm-following and norm-violating harvesters that share a common resource. The model is inspired by the game-theoretic model presented by Tavoni et al. [25], henceforth *TSL,* but takes an agent-based approach that models community-level outcomes as they emerge from micro-level interactions. This allows us to test the approximations of the evolutionary game-theoretic TSL model and, given a good fit between the two, provides us with a theoretically sound basis on which we gradually build to add more realism to the model, such as stochastic resource flows, with-in group social dynamics and between group ecological dynamics. In the following we establish the base simulation model and test its validity by comparing the ensuing conclusions with the TSL model. We then explore different scenarios of resource scarcity and variability as well as cooperation within two socially separate groups that are ecologically linked. We conclude with a discussion of our findings in light of other empirical and experimental evidence, and discuss policy implications.

2. A model of norm-driven cooperation in the commons

Social dynamics

We model a community of harvesters that collectively exploit a shared resource such as a groundwater reservoir, a fish population or a common pasture. Over time the community has identified the socially optimal extraction level. Restraining one's resource extraction to this level has become a social norm, i.e. a shared rule of behaviour [26]. Harvesters can either follow the norm (norm followers or cooperators) or extract more for their own benefit (norm violators or defectors). Violation of the norm is sanctioned through social disapproval by norm followers. Social disapproval has been shown to be an important mechanism to promote compliance with social norms ([27], [3]). Fehr and Gächter [28] have showed in an experimental setting that cooperators experience strong emotions when observing free-riders. Such reactions are often manifested through disapproval towards the defectors, even when it is costly and it does not imply monetary gains for the cooperators (see also [29] for social disapproval in field experiments in Southeast Asia). In the presence of such behavioural drivers, second-order freeriding, i.e. when a subject cooperates but abstains from costly punishment, is rarely observed empirically [28]. For the purpose of this investigation we thus focus on first-order freeriding only, and assume that all norm followers sanction norm violators, provided that the proportion of cooperators is large enough.[1]

Social sanctioning reduces the utility that norm violators receive from resource use. Conceptually, this is due to refusal of help by the cooperators' community, for instance in the form of denial of access to community benefits directed towards defectors. For example,

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[1] See Sasaki and Uchida [30] for a model of social exclusion as a successful mechanism for cooperation in the presence of second-order free riding. Social exclusion in their model implies that norm violators are fully excluded from the benefits of the common good. This is contrary to the model presented here where social disapproval only leads to a reduction in utility as detailed below.

Japanese villagers or Irish fishermen disapprove of community members who overuse the resource by depriving them of the benefits provided by cooperation in other economic activities ([31], [32]). Sanctioning is modelled as a behavioural response of individual norm followers to inequality, hinging on feelings of disapproval towards norm violators. To fix ideas, one can think of this setup as one where community members that extract more groundwater to irrigate their crops than socially accepted will be refused necessary harvesting machinery, or access to a market stand to sell their goods. In its most extreme version, inequality aversion may trigger spiteful reactions by norm followers, with material consequences such as crop destruction. This non-costly social disapproval does not involve any prior payment into a punishment pool. Furthermore, while sanctioning is carried out in peer-to-peer interactions it requires a large enough pool of cooperators in the community to be effective. It is thus neither pool- nor peer-punishment as distinguished by Sigmund et al. [33], but contains elements of both.

The severity of the social sanction increases with the number of norm followers, as more harvesters disapprove of the free-riders (Figure S1). The larger the proportions of cooperators the more difficult it will be for a norm violator to find support to process or commercialize her harvest. The more the cooperative strategy is chosen, the larger the social capital in the community, which in turn enhances the strength of the sanctions towards norm violators. On the other hand, when cooperation and hence social capital is low, sanctioning is ineffective (i.e. disapproval by a minority of norm followers does not have much effect on the majority of norm violators, if at all). This is expressed in the relationship $\omega(f_c) = he^{te^{gf_c}}$ where f_c is the proportion of cooperators in the community at a given time ($f_c = \frac{n_c}{n}$), h, t, g are parameters governing, respectively, the maximum sanctioning (asymptote), the sanctioning effectiveness threshold (displacement) and the growth rate of the function (see [34] for an example of the role of social capital for social approval).

In addition to depending on the number of norm followers in the community, the severity of social sanctioning is also influenced by equity considerations, leading norm followers to act more strongly against individuals extracting well above the accepted norm (and thus receiving much higher payoffs [35], [36]). Experimental research has shown that the degree to which individuals resent free riders increases with the ensuing income gap [28]. By modelling social sanctioning by norm followers as a function of the difference in payoffs, $H = \frac{\pi_D - \pi_C}{\pi_D}$, we allow for graduated sanctioning. Graduated sanctioning consists in adjusting the sanctions to the severity and frequency of the offence, and it has proven to be an important feature of successful self-organizing systems ([37], [38], [33]).

Resource Dynamics and Production

The shared resource is modelled by the following equation:

$$R_{t+1} = R_t + c - d\left(\frac{R_t}{R_{max}}\right)^2 - q * E * R_t \qquad (2.1)$$

where R_t is the resource at time t, c is the inflow, d is the natural discharge rate, R_{max} is the carrying capacity, q is the efficiency of extraction and $E = n[f_c e_c + (1 - f_c)e_d]$ is the total extraction effort of the n-member community. e_c and e_d are the extractive effort levels of the norm followers (cooperators) and norm violators (defectors), respectively.

The TSL model assumes that resource inflow is constant. In reality, however, resource dynamics are rarely constant, but fluctuate intra- and inter-annually. We thus extend the model to feature a variable resource inflow $\hat{c}$, a random Gaussian variable with mean c and standard deviation σ. The outflow rate $\hat{d}$ varies according to the inflow.

$$R_{t+1} = R_t + \hat{c} - \hat{d}\left(\frac{R_t}{R_{max}}\right)^2 - q * E * R_t \qquad (2.2)$$

Agents earn the following payoff from resource exploitation:

$$\pi_i = \frac{e_i}{E} F(E, R_t) - we_i \qquad (2.3)$$

Gross π_i increases with extraction level e_i and resource abundance R_t, according to $F(E, R_t)$. The production function $F(E, R_t)$ is modelled using the widely adopted Cobb-Douglas form with decreasing returns to scale (see Table S1 for details and Figure S2 for a sensitivity analysis of the coefficients of the Cobb-Douglas function). The harvesting costs are proportional to the effort e_i, with the coefficient w representing costs per unit effort. Figure 1 shows the equilibrium resource levels for different levels of total effort (Fig 1a), the total production for different levels of total effort (Fig 1b), and total production for different resource levels (Fig 1c).

Figure1

Strategy updating

Agents are either norm followers with a socially optimal extraction effort or norm violators with a higher effort. The magnitude of resource over-extraction by the norm violators, henceforth called the *degree of cheating*, is captured by the multiplier μ in $e_d = \mu * e_c$. The maximum degree of cheating considered in our analysis corresponds to the resource extraction that maximises individual benefits (the Nash equilibrium – see Tavoni et al. [25] for the calculations of socially optimal and private extraction levels).

The utility U that agents receive from their payoff depends on the level of social disapproval they are exposed to, which is a function of the level of cooperation in the community and the payoff differences. C enjoy the entire (lower) payoff $U_C = \pi_C \geq 0$, while D may see their higher payoff reduced due to social disapproval: $U_D = \pi_D - \omega H \geq 0$ (where the intensity of defection is measured by $H = \frac{\pi_D - \pi_C}{\pi_D}$).

The agent-based model differs from TSL in that it explicitly models players as individual agents that interact locally and update their effort levels by imitating better performing strategies of other agents. Pairs of players meet randomly to compare utilities $U_{i,j}$. When the utility of agent *i* is below that of the opponent, it updates its extraction effort by imitating agent *j*'s with a probability equal to the normalized utility difference (cf. [39]).

$$\text{if } \Delta_i = U_i - U_j < 0 \Rightarrow \; e_i \to e_j \qquad \text{with probability} = \frac{\Delta_i}{|U_i| + |U_j|} \text{ and } i, j \in \{C, D\} \qquad (2.4)$$

We use a pairwise updating rate (one random agent updates each time step) as is common in simulations of evolutionary games, however we also explored higher updating rates, i.e. settings where more than one agent updates its effort within a single time step (Figure S3). The parameters and variables for the simulations as well as an overview of the functions are given in Table S1.A detailed model description using the ODD+D protocol [40] can be found in Table S2.

3. Impact of variable or increasing resource inflows

Under constant resource conditions cooperation and hence sustainable resource use are stable when the community of cooperators is not too small and the norm violation is not excessive (see Figure 2a and [25]). In cases where the norm violation and the community of cooperators are both large, norm followers and norm violators coexist. Here, the reduction in utility resulting from social disapproval is balanced by the gains that few norm violators obtain from higher extraction of a resource that is only slightly overharvested (due to the high resource abundance in the presence of a large share of cooperators). The region of coexistence is sensitive to the maximum amount of sanctioning a community with high levels of cooperation can exert on norm violators (Figure S4). A decrease of the maximum sanctioning amount at high levels of norm violation decreases the area of coexistence in favour of larger areas of full defection. Similarly, when the community of norm followers is small the norm of sustainable resource use collapses and all members over-extract, leading to resource degradation.

The results of the game-theoretic analysis and the agent-based simulations agree well (Figure S5), which suggests that we can deploy the potential of CP-norm for greater complexity to go beyond validation of the analytical model and introduce more realistic features. The robustness of the TSL model to assumptions about the specific functional forms of the social disapproval or resource functions has additionally been confirmed by [41]. They show that the qualitative behaviour of the model remains the same even when the social disapproval and the resource outflow functions are linear in the proportion of cooperators or resource level, respectively.

3.1. Impact of variable resource inflow

Under constant resource inflow and a maximum sanctioning level (h) that is slightly lower than in the TSL model defectors dominate the whole parameter space for cheating levels of approximately 300 to 365% (red area extending across the whole range of initial proportion of fc in Figure 2a). When resource inflow is subject to small fluctuations ($\sigma = 1$) the coexistence equilibrium at the boundaries to this all-D area is destabilized leading to an expansion of the area of full defection ($f_c = 0$) into regions where cheating levels are higher or lower (increase of the red area in Figure 2b). High levels of resource variability, on the contrary, destabilize the defector equilibrium for values of initial proportion of fc >0.6 leading to a dominance of coexistence outcomes (disappearance of the red area and increase in light blue area in Figure 2c). Hence, the norm can be maintained with high resource variability even when norm violations are large (given that the initial level of social capital in the community is large enough). The percentage of cooperators in the coexistence is slightly higher than with no fluctuations.

Figure 2

The transition from resource variability enhancing defection to its enhancing cooperation happens around a resource variability of $\sigma = 10$ where about 50% of simulation runs converge to coexistence (Figure 3a). Beyond this level of variability coexistence also expands to areas with lower initial proportions of C and the proportion of cooperators in the coexistence state increases. The increase in size of the coexistence region as well as the increase of cooperation in the coexistence state under conditions of high resource variability are consistent with the results of Tavoni et al. [25]. Under conditions of high resource variability, average resource availability is reduced because of the concavity of the resource function. This leads to reduced payoffs for both norm violators and norm followers. At the same time the costs of social disapproval that affect only norm violators remain constant because they are independent of resource variability. As a consequence a few norm violators switch strategy until the gains from overexploitation and the costs of social disapproval balance out, thus increasing the frequency of cooperation in the mixed equilibrium.

The sudden collapse of cooperation under conditions of low resource variability was not predicted by TSL. Under conditions of low resource variability norm violators benefit occasionally from high inflow events while average resource availability remains almost the same. A random local encounter of a norm violator with a norm follower during such a high inflow event can cause the norm follower to change strategy. This initiates a slow process of changing proportions of cooperators in the mixed equilibrium until the resource is degraded up to a point where a situation of high resource inflow and subsequent increase in defection can tip the system into the defector equilibrium. This is accelerated by the decrease in social capital and hence sanctioning capacity of the community, which further destabilizes coexistence and results in the collapse of cooperation.

3.2. Impact of changes in average resource flows

Environmental change might not only lead to higher variability but also to changes in the average quantity of a natural resource. Lade et al. [41] investigate collapses of cooperation in the TSL model that arise through increasing inflow or changes in other properties of the system such as the costs of effort. Their results show that decreasing resource availability increases cooperation while increasing resource availability can lead to a collapse of cooperation and resources. The former is similar to a situation of high inflow variability where the average resource availability is reduced, while the latter corresponds to the effects of small variation where short term high abundance of resources benefits defectors.

Our analysis confirms that the collapse of cooperation with increasing mean resource inflow occurs across the whole range of initial densities of cooperators (Figure 3b, red area for inflow values >50). Decrease of the mean inflow on the contrary leads to coexistence at lower initial densities of cooperation and an increase in the number of norm followers until for very low inflow values norm followers dominate (Figure 3b).

Figure 3

3.3. Combined effects of resource availability and variability

Most likely, however, environmental change will impact mean resource flows and variability simultaneously. We test the effect of a combination of both for robustness of cooperation at different levels of initial cooperation and hence social capital in the community (Figure 4). When initial social capital is high (fc_init = 0.8) the pattern of collapse with mean inflow ≥ 50 and enhanced cooperation with mean inflow < 50 remains (Figure 4a). The collapse of cooperation with increasing resource availability cannot be counteracted by large resource variability (which favours cooperation) except for a region of mean resource availability up to approximately 55. The collapse of cooperation that was observed for small resource variability at a mean inflow of 50 does not occur for average inflows < 50, indicating that the reduction of the average resource availability which favours cooperation has a stronger effect on outcomes.

When initial social capital is at intermediate levels (fc_init = 0.5) norm violators dominate for a constant inflow > 23. An increase in variability leads to coexistence and an increase of norm followers in the community at larger mean resource availability (Figure 4b). The higher the variability the higher average inflow levels at which coexistence can be found. Finally at very low values of initial social capital (fc_init = 0.3) where norm violators dominate under constant conditions changes in average inflow and resource fluctiations have only very limited effects. Once mean inflow drops very low (<11) norm followers dominate. A small region of co-existence with high numbers of norm violators exists at low levels of resource variability and mean inflows between c=10 and c= 20. Here increase of variabilty leads to increase of norm violators at the higher end (c = 20) and increase of norm followers at the lower end (c = 10). Coexistence disappears at higher variability where the community is either dominated by norm violators (at average inflows > 17) or norm followers.

In general decreasing initial social capital in the community counteracts the benefits of lower mean inflow and areas of coexistence at low average resource inflow decrease. The quality of the transition from a community dominated by norm violators to one dominated by norm followers changes when moving from a community with high initial social capital to one with low. While in the former decreasing average inflow and increasing resource variability lead to coexistence that is dominated by increasing numbers of norm followers, in the latter theses changes lead to coexistence dominated by decreasing numbers of norm violators until in both cases the community switches to dominance of norm followers.

Figure4

4. Evolution of cooperation in socially separated but ecologically connected groups

We now investigate a situation in which two socially independent communities of resource users are ecologically connected with each other, for instance through a shared aquifer. Each group (henceforth group 1 and group 2) has the same number of members (n) as the sole group in the above results and exploits its own resource R_j, $j \in \{1, -1\}$. R_j has identical characteristics to R, the unique resource modelled in (2.2), but is largely disconnected from R_{-j}, the resource that can be appropriated by the other group. However, there can be spill-overs such that resource from the least depleted resource of the more successful group leaks towards the other one. We investigate the establishment of norm-driven cooperation under different assumptions on the strength of the leakage between the two resources (δ). Social disapproval and imitation operate as before, but are restricted to interactions within each group.

The two resources and their connectivity are modelled by equation 3.1:

$$R_{j,t+1} = R_{j,t} + c - d\left(\frac{R_{j,t}}{R_{max}}\right)^2 - q * E_t * R_{j,t} + \delta\left(R_{-j,t} - R_{j,t}\right) \qquad (3.1)$$

For positive values of δ, a fraction of each groups' resources is available to the other group, with the difference $R_{-j,t} - R_{j,t}$ representing the net flow between the two.

Figure5

When the initial share of cooperators in group 1 is $f_c(0) \leq 0.65$, leakage from the more cooperative group 2 has no effect on group 1, which remains in a state of widespread defection (Figure 5, upper two panels). At the same time the level of cooperation in group 2 increases with δ: increasing leakage reduces resource availability in group 2, which favours cooperation. Once initial shares of cooperators within group 1 increase beyond about 65%, we are in a region where a mixed equilibrium prevails in the base model. Here, the leakage from the more cooperative group 2 can destabilize the mixed equilibrium as seen by an increase in all-D outcomes for $\delta = 0.1$. With leakage of $\delta \geq 0.2$ cooperation in Group 1 collapses (Figure 5, middle left panel). An increasingly strong leakage provides for an overabundance of resources in group 1 which can lead to the cascading collapse of cooperation that we have also observed earlier with increasing resource availability. When both groups have identical $f_c(0)$, increasing resource connectivity (δ) leads to collapse of cooperation in one of the two groups (Figure 5 bottom left panel). There is no clear pattern concerning which group's cooperative coexistence collapses, which is expected as the collapse is the result of stochastic events. For $f_c(0) = 1$ in group 1, the interaction reverses and leakage between the resources of group 1 and group 2 destabilizes the mixed equilibrium in group 2.

5. Discussion and Conclusions

The focus of this study is on the robustness of cooperation, as measured by the rate of adoption of a strategy prescribing sustainable resource use. Specifically, we investigate the robustness to changes in resource availability caused by environmental change, as well as to the spatial connectivity of biophysical systems. Little research so far has investigated the impacts of complex structural and temporal characteristics of the social and ecological systems on the performance of coupled social-ecological systems. Ecological studies of resource or ecosystem collapse often neglect changes in agent behaviour arising from social or social-ecological interactions. At the same time, the finiteness, structure and dynamics of resources and the ecosystems they are part of are often neglected in studies of common pool resource use. This can lead to misleading results if the system is truly coupled, as demonstrated here and in [41].

In our model a community of harvesters exploits a shared resource such as water from a groundwater aquifer. A norm of sustainable resource extraction is maintained through social sanctioning of norm violators. Norm followers disapprove of freeriding by excluding norm violators from the social capital needed to realize the full benefits of resource extraction. The interaction of this social mechanism with the resource dynamics determines the ensuing level of cooperation and state of the resource. Under constant resource inflow full cooperation obtains when the community social capital is large enough to be able to sanction norm violators, provided that the extent of the violation is not too large. Otherwise, a minority of norm violators coexists with a majority of cooperators, thanks to the large benefits of overharvesting a well maintained resource.

These findings echo those of Sethi and Somanathan [42], who, in a setting involving three strategies (defection, cooperation without punishment, and cooperation with punishment), find that, in addition to a full defection equilibrium that is always stable, an equilibrium where defectors are wiped out can also be stable. Noailly et al. [43][44] extend Sethi and Somanathan's model by embedding it on a network. They find coexistence of all three strategies when sanctions are imposed locally on neighbours. Note that coexistence and cooperative equilibria in these models always include cooperators and enforcers, thus issues of second order freeriding prevail. Sasaki and Uchida [30] showed in a three-strategy model that social exclusion can overcome second-order freeriding even when it is costly and stochastic. Our model and results depart from these studies in important ways. The first difference is that here we focus on non-costly social sanctioning through disapproval rather than costly punishment; second, there are only two strategies as all cooperators engage in social disapproval; lastly, our mixed equilibrium involves the coexistence of cooperative and selfish types. This coexistence is consistent with the widely observed persistence of both behaviours in small groups, as shown by numerous studies in the laboratory and in the field [35].

Our study complements the above-mentioned studies and previous work with the TSL model, by providing a systematic assessment of the consequences of temporal variability and spatial complexity for cooperation and by using a disaggregated modelling approach. The latter allows us to address macro-level dynamics as they arise from micro-level interactions of harvesters with a dynamic resource. One example is the collapse of cooperation with small resource fluctuations, a feature of the agent-based model that was not observed in the mean-field TSL model. The break-down of cooperation is the result of a random local interaction between a norm follower and a norm violator at a moment when short-term high resource abundance provides an advantage to the norm violator. The decrease of cooperation and social capital slowly erodes the social norm, ultimately leading to a cascading collapse of cooperation and the ensuing tragedy of the commons. Such a situation qualifies as one that has the three preconditions for a crisis, according to Taylor [45]: weak governance, as the social disapproval does not guarantee eradication of defection; a threshold beyond which the system can tip into a different regime; and positive feedbacks that magnify the impacts of a shock. It also highlights the need to carefully consider the level of aggregation at which interactions are modelled.

Similarly, cooperation breaks down when the average resource availability increases. Higher resource levels provide higher benefits to norm violators, which outweigh the losses they suffer due to exclusion from the social capital of the community. Resource scarcity, or an increase in resource variability, on the other hand can enhance cooperation and lead to an increase in the proportion of norm followers. Contrary to our findings, Richter et al. [46] have shown that resource scarcity can lead to a breakdown of cooperation in harvesting a common pool resource. In their model, cooperators adapt their effort to changing resource levels which increases the temptation to defect when resource become scarce. Empirical studies of cooperation in river basin management confirm the increase in cooperation with resource variability. Dinar et al. [23] and Ansink and Ruijs [47] found that the existence and stability of treaties for transboundary water sharing increased with resource fluctuations. In both cases the stability of an agreement was strongly dependent on the characteristic of the agreement, the benefit functions of the actors and the distribution of political power [47], or on the existence of other cooperation-enhancing mechanisms such as trade [23].

Lastly we extended the agent-based model to include more realism with respect to the spatial characteristics of the ecosystem that provides the shared resource. Our results indicate that an ecological spill-over from a more cooperative group does not necessarily enhance cooperation in the less cooperative group. On the contrary, resource leakage can destabilize cooperation due to the positive feedbacks that arise when resources become more abundant. Fragmentation of the governance of a common pool resource can thus make cooperation more difficult, as random events can lead to a collapse of cooperation in one of the groups, under conditions where stable coexistence would prevail in a single group. Other research, however, indicates that cooperation is more difficult to achieve in larger groups [3], thus potentially counteracting the benefits of less fragmentation. An interesting extension to our work would be to investigate the social-ecological dynamics of two or more groups that are connected ecologically and socially, for example through an institution or migration. We plan to include more social structure and adaptive responses to changes in resource availability in future extensions of the model.

Overall, our results indicate that there is no simple answer to the question whether connectivity and environmental change has the potential to destabilize cooperation in natural resource use, leading to environmental degradation (and possibly conflict). In situations where communities have the social capital to maintain cooperation through social disapproval of norm violators, as may be the case here for appropriate initial conditions, reinforcing feedbacks between increase in returns from resource exploitation and decrease in effectiveness of sanctioning can cause collapse. But the opposite obtains, i.e. higher levels of cooperation fixate in the population, when decreasing returns strengthen the social norm. Whether one or the other feedback dominates depends on the magnitude of the resource variability and the direction of change in average flows. When both effects occur in combination they can either reinforce or counteract each other. In situations where environmental change leads to a strong increase in resource variability and a decrease in average resource availability, we would expect an increase in cooperation (under the conditions of our model settings). In situations where the two factors operate in opposite directions the picture is not as clear and outcomes will depend on the initial conditions, as well as on the degree of the impacts.

The differences in the effect of changes in resource availability and ecological connectivity on cooperation highlight the important role of structural factors such as the characteristics of the actors, the institutional and governance settings, and the ecological conditions for determining the consequences of environmental change. Several recent studies emphasize that the role of institutions in mitigating the effect of climate-induced resource scarcity should not be underestimated ([23],[24],[47]). Informal rules such as the social norm modelled here can play an important role for the establishment of cooperation and may also be relevant for maintaining cooperation under resource scarcity. Policies to enhance the adaptive capacity of natural resource use, particularly of CPRs, may thus benefit from taking social norms and their role in stabilizing cooperation into account. Ultimately, however, it is the complex and non-linear interplay of social and ecological dynamics that determine the success of the cooperative strategy. It is thus important to take the coupling between the social and ecological subsystems into account when analysing cooperation on natural resource use.

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Competing Interests:

We have no competing interests.

Authors contributions

MS, AT and SAL jointly designed the study, developed the model and analysed and interpreted the model results. MS drafted the manuscript; AT and SAL revised it critically. All authors gave final approval for publication.

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Figure Legends:

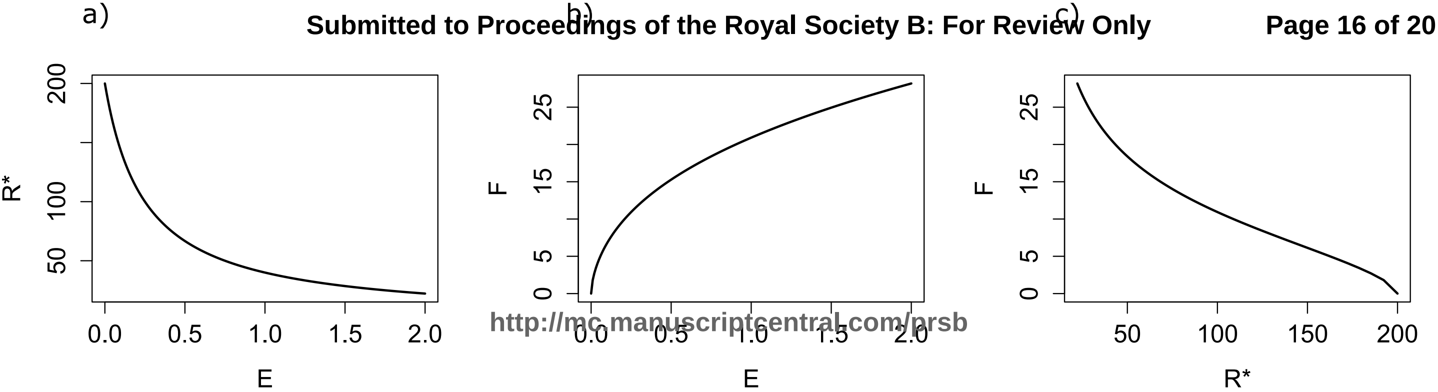
Figure 1: a) Equilibrium resource level $R^*$and b) total production F for different levels of total effort E, c) total production F for different levels of equilibrium resource level R^* (corresponding to different total effort levels)

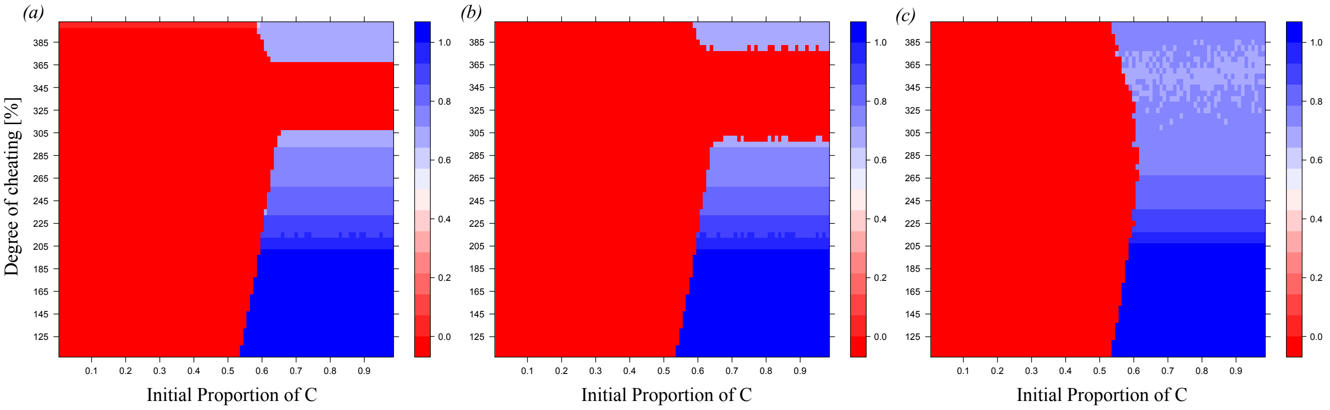
Figure 2: Level of cooperation with increasing resource variability; (a) no resource variability ($\sigma = 0$); (b) low resource variability ($\sigma = 1$); (c) high resource variability ($\sigma = 10$); dark blue indicates 100% cooperation, red indicates 0% cooperation. Maximum sanctioning $h = 0.333$, for all other parameter values see Table S1.

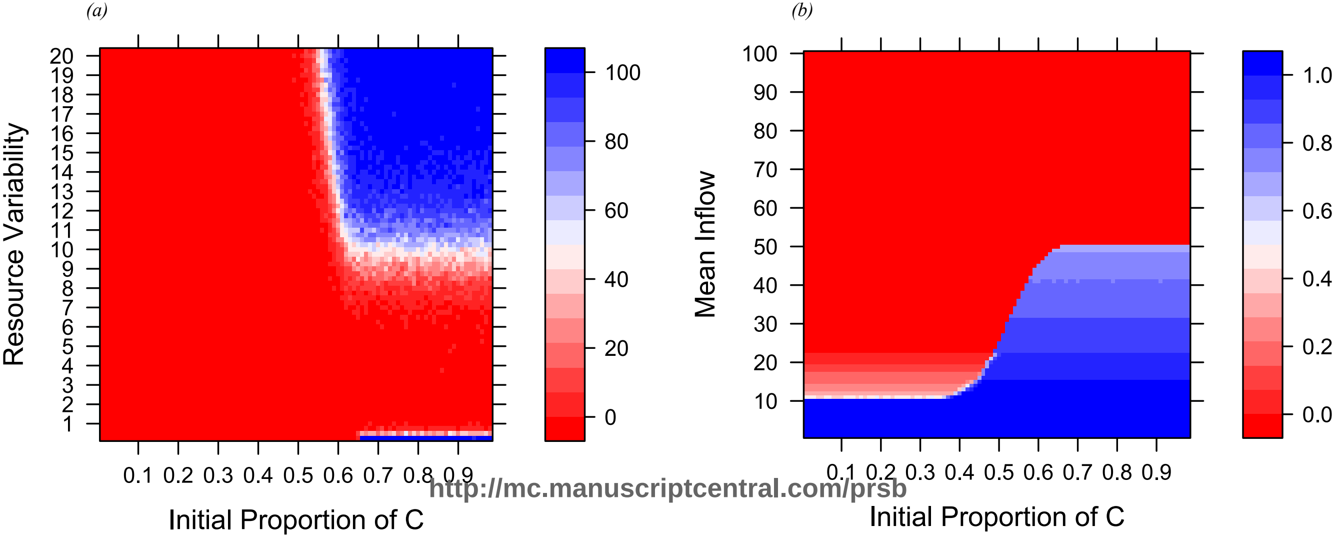
Figure 3: (a) Percentage of cooperative outcomes with increasing resource variability at a fixed degree of cheating $\mu = 3$. Red colour indicates that 0% of runs result in a cooperative outcome. (b) Level of cooperation with increases in mean inflow c. $\mu = 3.0$, initial $f_c = 0.8$. For parameter values see Table S1.

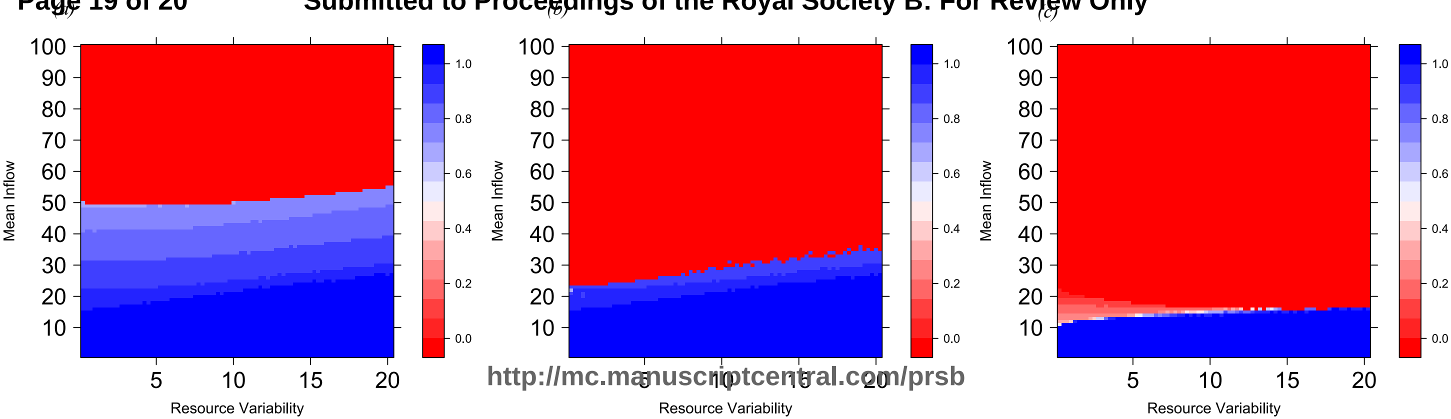
Figure 4: Level of cooperation for a combination of changes in mean and variance of resource flows, (a) initial $f_c = 0.8$, (b) initial $f_c = 0.5$, (c) initial $f_c = 0.3$; $\mu = 3.0$. For parameter values see Table S1.

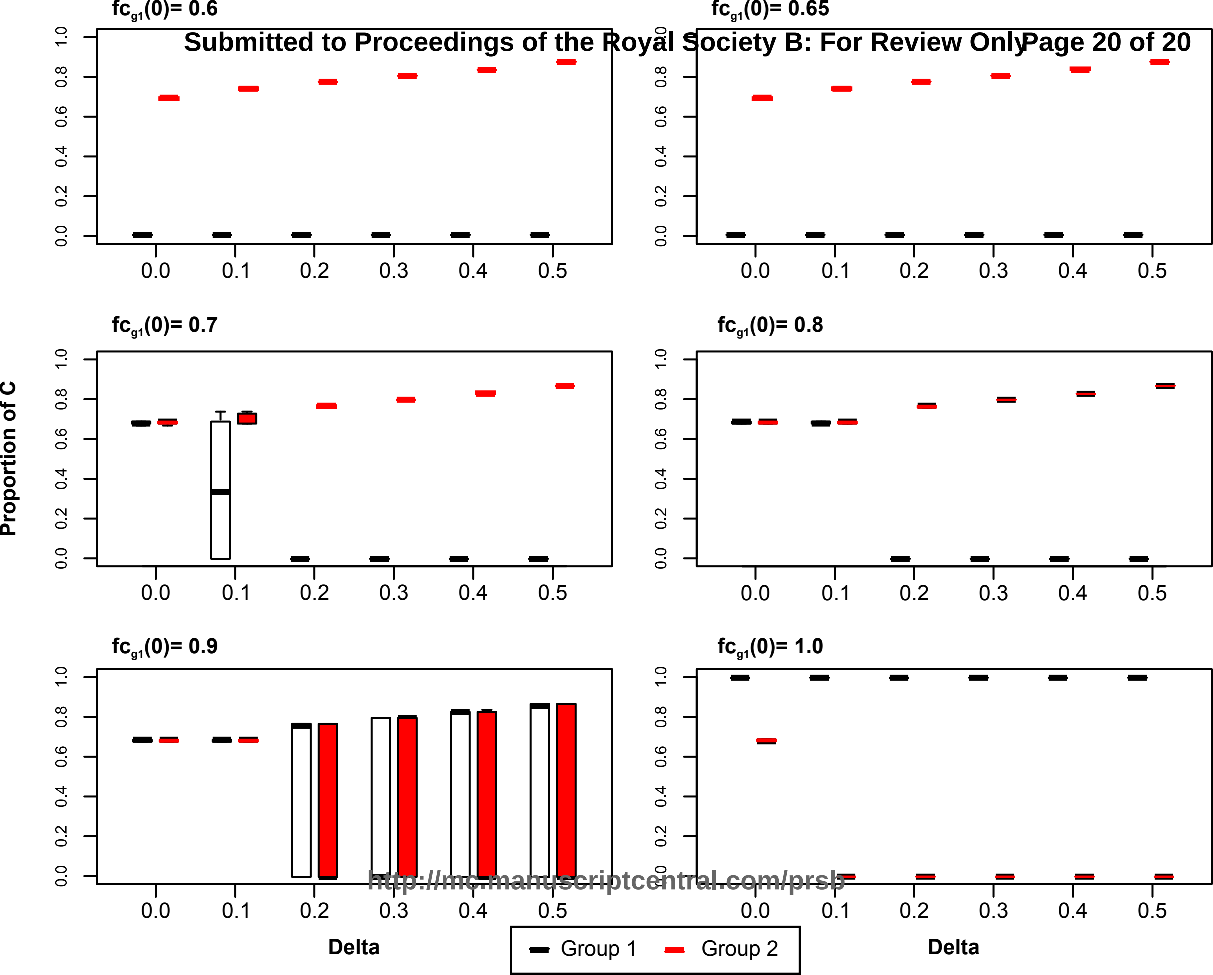
Figure 5: Level of cooperation in Group 1 (black) and Group 2 (red) with increasing strength of leakage δ and increasing levels of initial cooperation in group 1 ($f_{c,g1}(0)$ in title of panel) with $f_{c,g2}(0)$ of group 2 fixed at 0.9. The lines indicate the median, the box below and above the 1st and 3rd quartiles respectively. $\delta \in [0,0.5]$.


a)
R*
200
100
50
0.0
0.5
1.0
1.5
2.0
E
b)
F
0
5
15
25
0.0
0.5
1.0
1.5
2.0
E
c)
F
0
5
15
25
50
100
150
200
R*


(a)
(b)
(c)
Degree of cheating [%]
385
365
345
325
305
285
265
245
225
205
185
165
145
125
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Initial Proportion of C
1.0
0.8
0.6
0.4
0.2
0.0


(a)
Resource Variability
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Initial Proportion of C
100
80
60
40
20
0
(b)
Mean Inflow
100
90
80
70
60
50
40
30
20
10
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Initial Proportion of C
1.0
0.8
0.6
0.4
0.2
0.0


(a)
(b)
(c)
Mean Inflow
100
90
80
70
60
50
40
30
20
10
Resource Variability
5
10
15
20
1.0
0.8
0.6
0.4
0.2
0.0


$fc_{g1}(0)$= 0.6
$fc_{g1}(0)$= 0.65
$fc_{g1}(0)$= 0.7
$fc_{g1}(0)$= 0.8
$fc_{g1}(0)$= 0.9
$fc_{g1}(0)$= 1.0
Proportion of C
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
0.5
Delta
Delta
Group 1
Group 2