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Robustness of norm-driven cooperation in the commons to environmental variability

Maja Schlüter[1], Alessandro Tavoni[2] & Simon Levin[3,4,5]

[1]Stockholm Resilience Centre, Stockholm University, 10691 Stockholm, Sweden, maja.schlueter@stockholmresilience.su.se

[2] Grantham Research Institute, London School of Economics, London WC2A2AZ, England,

[3] Department of Ecology and Evolutionary Biology at Princeton University, Princeton, NJ 08544, US

[4]University Fellow, Resources for the Future, Washington, DC 20036, USA

[5] Fellow, Beijer Institute of Ecological Economics, P.O. Box 50005, SE-104 05 Stockholm, Sweden

Abstract

Growing empirical evidence points to the importance of social norms for achieving sustainable use of common pool resources (CPR). Social norms can facilitate the cooperation and collective action needed to sustainably share a common resource. With global change, however, the social and environmental conditions under which cooperation has evolved and been maintained in the past may vary dramatically. Higher variability of resource availability and more frequent extreme events, for instance, will put additional pressure on cooperation, possibly triggering its collapse, with detrimental effects on the environment. In light of this, the potential impact of climate change on conflict has recently received considerable attention. Here we assess the robustness of norm-driven cooperation to changing resource availability in a stylised model of community harvesting from a shared resource. The model is a generalised representation of CPR extraction, which allows for social disapproval towards norm-violators. We use an agent-based model to assess the robustness of cooperative outcomes to variable resource flows. Our results indicate that both resource abundance and low resource variability can lead to its unsustainable use, while either scarcity or high variability in the resource have the potential to stabilize cooperation. These findings provide insights into possible effects of global change on self-governance of the commons. They also indicate that there is no simple answer to the question whether global change has the potential to destabilize cooperation in natural resource use, and lead to environmental degradation and possibly conflict.

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. Hardin, 1968, Dawes, 1980). While early research emphasized the need for government control or privatisation (Hardin 1968), recent empirical work has highlighted that communities are often capable of overcoming the dilemma and achieve sustainable resource use through self-governance (Ostrom, 1990). Different mechanisms have been proposed for successful self-governance, such as communication, monitoring and sanctioning (Ostrom 1990, Gibson et al., 2005, Dixit et al., 2012) or reciprocity (Dixit et al., 2012). Ostrom (1990) and others (Janssen et al., 2010) have found that successful communities often establish social norms, i.e. "a rule or standard of behaviour shared by members of a social group" (*Encyclopedia Britannica*, 2005), to discourage individual overharvesting. Norms have proven to be invaluable to create and reinforce the behaviours needed to exploit a common pool resource sustainably, or to provide a public good (Kinzig, 2013). Often, norms are enforced through non-monetary sanctions, rather than through coercion (Schlüter and Theesfeld, 2010). Theoretical research has shown that norms can facilitate the evolution of cooperation, but do not guarantee it (e.g. Tavoni et al., 2012).

Much research on cooperation in CPRs has so far focussed on the social aspects of the dilemma while assuming strongly simplified and constant resource conditions. However, social interactions, such as the enforcement of norms that promote cooperation, do not take place in a void or in a static environment. CPRs are part of interlinked systems of humans and nature (Berkes and Folke, 1998), so called social-ecological systems (SES). SES develop over time through interactions of individual agents that spread to higher levels due to agents' collective behaviour (Levin et al., 2012). 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 (Ostrom 2009). Recent research on collective action for sustainable resource use hence tries to take attributes of the resource system into account, alongside with those of resource users and governance systems (e.g. Ostrom, 2007, Ostrom, 2009, Hagedorn, 2008). Taking the two-way interactions between social and biophysical or ecological processes into account can provide new insights for addressing issues of environmental change (Agrawal and Chhatre, 2011).

The impact of resource dynamics on local collective action becomes even more relevant in the face of large scale environmental or social change. Climate change, for instance, has the potential to drastically alter the environmental conditions under which collective action for sustainable resource use is achieved today. It is likely to change the quantity and variability of resource flows, exacerbating existing resource scarcity and leading to more extreme events (see e.g. Bates et al., 2008 and IPCC Intergovernmental Panel on Climate Change, 2007, 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 for communities that share joint resources. This might lead to increased pressure and 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, but it may be reasonable to expect an increased likelihood of cooperation breakdown when resource variability and uncertainty increase.

This question has recently been the subject of increased attention in the climate change debate, particularly with respect to whether climate change will lead to an increase in political instability and intra-state armed conflict (see e.g. Hsiang et al., 2013). Results so far are inconclusive, showing that scarcity and variability can lead to an increase in conflict, but also foster cooperation. Burke et al. (2009) link conflict incidences in Sub-Saharan Africa to variation in temperature and argue that warmer years lead to increased likelihood of armed conflict in Africa. They explain this by a decrease in agricultural productivity and hence economic performance. Hsiang et al. (2011) have found that the risk of civil conflicts doubles during El Nino years in countries that are affected by ENSO. The abrupt change in climate happening during an El Nino event seems to play an important part in the outbreak of conflict; however, it is too early to say whether climate change will have the same effect.

Similarly, there is an on-going debate about an increase in the potential of war over water with an increase in water stress due to climate change. While some argue that the likelihood of conflicts will increase (World Water Assessment Programme, 2009, Kundzewicz and Kowalczak, 2009, Serageldin, 2009, Zeitoun, 2009), 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 (Barnaby, 2009, Shamir, 2009, Dinar et al., 2010). A study of cross-country waterways revealed that cooperation by far outweighed conflict (Barnaby 2009). Gizelis and Wooden (2010) point out that governance, i.e. the ability of the government to address problems of resource scarcity, can play a crucial role in whether scarcity is likely to give rise to violent conflict. They 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. Social norms are one form of domestic institution that potentially influences a response to environmental change.

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 of a community of norm-following and norm-violating harvesters that share a common resource, henceforth termed *CP-norm*. CP-norm allows us to model cooperation as it emerges from individual interactions of resource users, and to introduce features such as resource variability. The model closely follows the analytical model presented by Tavoni et al. (2012), henceforth TSL, but differs in its approach to modelling community-level outcomes and allows for the introduction of more realistic features. Analyses of scenarios using CP-norm reveal that the impact of resource variability on cooperation can be twofold: leading to a collapse of cooperation and resource levels or enhancing cooperation, depending on the magnitude of the fluctuations. Interestingly, we find that low resource variability can lead to higher chances of overexploitation, relative to the case of certainty. The degree to which norm-violators benefit from resource fluctuations through occasional high resource availability decreases the willingness of co-operators to engage collectively in sanctioning the norm-violators. As the capacity for collective action slowly erodes, the community passes a threshold that leads to a rapid collapse of cooperation and overexploitation of the resource base.

The remainder of the paper is organized as follows. First, we describe the main features of the TSL and CP-norm models and compare the ensuing conclusions from the two models. Second, we explore different scenarios of resource variability and mean resource supply. 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

We model a community of harvesters that collectively exploit a shared resource such as a groundwater reservoir, a fish population or a common pasture. The community is composed of norm-followers (or co-operators, C) that adhere to a norm of sustainable resource extraction, and norm violators (or defectors, D) that extract more than is socially optimal. Cooperation in the community is facilitated, but not guaranteed, by social disapproval directed from co-operators towards norm violators. We use an agent-based modelling approach to be explicit about the local interactions between users and resources that create observed community level patterns. By implementing the game-theoretic model as an agent-based model we thus test the approximations of the TSL model. At the same time, an agent-based model that corresponds well with the analytical model provides us with a theoretically sound basis on which we gradually build to add more realism to the model that cannot be captured in the game- theoretic approach.

TSL investigate conditions under which community disapproval of norm violators enables sustainable resource use. Social disapproval is expressed as ostracism, e.g. a refusal of help or access to social capital towards norm violators, which decreases the utility they receive from resource use (see Tavoni et al. 2012 and Table A1 in the appendix for details on the ostracism function). 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. The effectiveness and severity of the disapproval increase with the number of norm followers in the community and the degree of the norm violation. However, sanctioning only becomes effective if the number of norm followers, and hence the social capital in the community, is sufficiently large (see Oses-Eraso and Viladrich-Grau, 2007 for an example of the role of social capital for social approval).

Norm followers pay a fixed cost for financing the sanctions associated with social disapproval that is independent of the number of norm violators in the community. Such cost can be interpreted as an investment in the cooperating community's social capital, as reflected by the decreased payoff that norm followers receive from resource extraction compared to norm violators, and by the increased effectiveness of sanctioning as the number of cooperators increases. For a treatment where punishment costs are directly linked to the number of defectors, see Sethi and Somanathan (1996). Norm violations are observable through the higher payoffs that violators receive from high resource extraction. In the above example of groundwater extraction, the violation is visible through increased crop production. Sanctioning takes place on the basis of equity considerations, leading norm followers to act more strongly against individuals extracting well above the accepted norm (Fehr and Fischbacher, 2002, Maier-Rigaud et al., 2010). By modelling sanctioning by norm followers as a function of the difference in payoffs, we allow for graduated sanctioning, which has proven to be an important feature of successful self-governing systems (Cox et al., 2010, Ostrom 1990, Ostrom, 2000, Sigmund et al., 2010). Graduated sanctioning implies that the severity of sanctioning is adjusted according to the severity of the offence and its frequency.

The results of the TSL model indicate that the norm enforced through ostracism can promote cooperation and hence sustainable resource use when the community of co-operators is not too small and the norm violation is not excessive. In cases where the norm violation and the community of co-operators 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 rather high resource productivity in the presence of a large share of co-operators). When the community of norm followers is small the norm of sustainable resource use succumbs and all members over-extract, leading to resource degradation.

The agent-based model differs from TSL in that it explicitly models players as individual agents that harvest the resource and update their strategies through learning about other agent's strategies when they meet each other. The resource, which again can be thought of as water from an aquifer used for irrigation, is modelled as a discrete-time version of the resource dynamics of the TSL model:

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

(Equ. 1)

where R_t is the resource at time t, c the inflow, d the natural discharge rate, R_{max} the carrying capacity, q the efficiency of extraction and E the total extraction effort of the community.

Agents are either norm-followers with a socially optimal extraction strategy or norm-violators with a higher extraction level. The magnitude of resource over-extraction by the norm violators, henceforth called the degree of cheating, is represented through the multiplier μ in $e_d = \mu * e_c$, where e_d and e_c are the extractive effort levels of the defectors and co-operators, respectively. The maximum degree of cheating considered in our analysis corresponds to the resource extraction that maximises individual benefits (Nash equilibrium – see Tavoni et al. (2012) for the calculations). Agents receive a payoff Π from exploiting the resource, which increases with extraction level and productivity of the resource. The productivity of the resource is modelled using the widely used Cobb-Douglas production function with decreasing returns to scale (see Table A1 for details). The utility U agents receive from their payoff depends on the level of ostracism 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 ostracism: $U_D = \pi_D - \omega H \geq 0$ (where the ostracism function determining the sanctioning effectiveness ω is described in Table A1, and the intensity of defection is measured by $H = \frac{\pi_D - \pi_C}{\pi_D}$).

A pair of players meets randomly to compare utilities $U_{i,j}$ and update their strategies. When the utility of agent *i* is below that of the opponent, it updates its strategy by imitating the strategy of agent *j* with a probability equal to the normalized utility difference (cf. Morgan, 2003).

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

(Equ. 2)

We use a pairwise updating rate (one random agent updates each time step) as it is common in simulations of evolutionary games, however we also explored higher updating rates, i.e. settings where more than one agent updates its strategy within a single time step (see Figure A1 in Appendix). A detailed model description using the ODD+D protocol (Müller et al., 2013) can be found in Table A2 in the Appendix. The parameters and variables for the simulations are given in Table A1.

3. Results

3.1. Comparison of the two models

The discrete agent-based model largely reproduces the results of the TSL model as described above, where cooperation or coexistence of co-operators with a few defectors prevails when the initial number of co-operators in the community is large enough (see Figure A2 for a comparison with the TSL model). Differences between the two models occur when conditions are such that the random encounter of two agents can occasionally lead to a collapse of cooperation where in most instances coexistence prevails. Coexistence of both strategies is created by two opposing feedback loops (Figure 1): an increase in the relative proportion of C and hence a decrease in total extraction effort leads to increasing returns per effort, which increases payoffs for C and D. At the same time an increase in the frequency of C and an increase in the payoff difference increases the social pressure D individuals are exposed to, which reduces their utility. Finally, if the community social capital is low, sustainable resource extraction cannot be maintained and defectors prevail (left side of figure A2a and b). In this state the resource is heavily overexploited and payoffs are much lower (Figure A3a). The community composition has significant effects on resource levels as figure A3b shows.

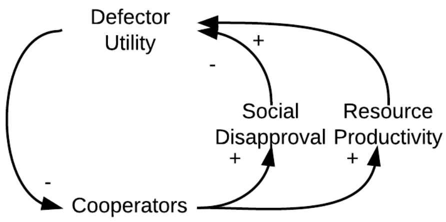


Figure 1: The two main feedbacks driving the dynamics of the coupled system. When cooperators increase, then the inner positive social feedback loop leads to a further increase in co-operators, while the outer negative ecological feedback loop leads to an increase in defectors. The relative strengths of the two feedback loops determine the evolution of the system to all-D, all-C or a mixed equilibrium. Note that a “+” indicates a positive relationship between the two variables (e.g. when a increases, b also increases), while a “-” indicates a negative relationship (e.g. when a increases, b decreases).

(a) .. (b) (c)

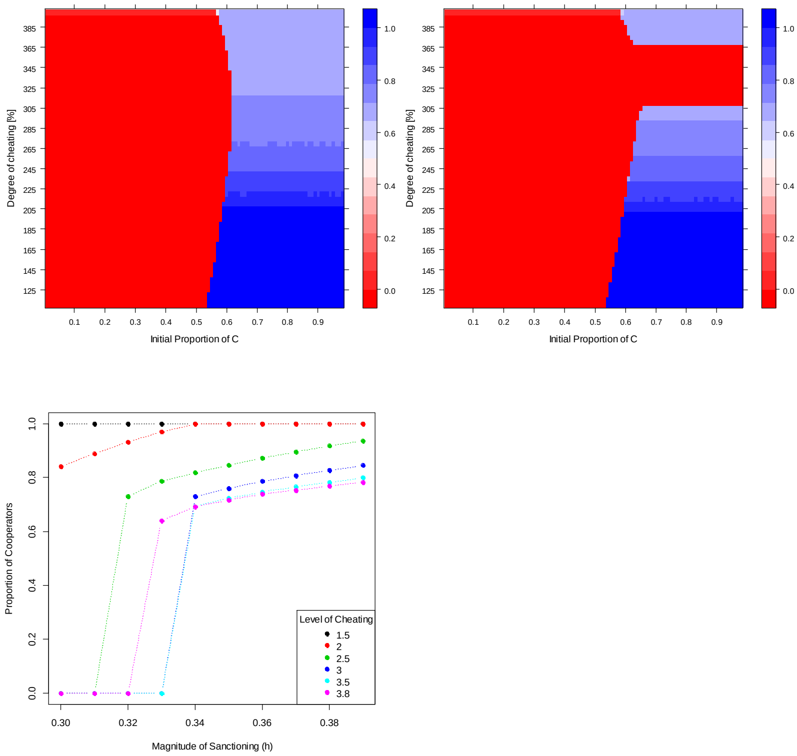


Figure 2: a) Level of cooperation in CP-norm corresponding to the TSL model with omega asymptote: h= 0.34 (ostracism function: $\omega(f_c) = he^{te^{gf_c}}$), values in cells represent average values at end of simulation, red cells indicate an all-D equilibrium, dark blue an all-C and light blue a mixed equilibrium; results are mean values of 50 simulation runs. In case where the system converges to either all-D or mixed equilibrium the results represent the mean of the value that the system converged to in >=50% of the runs; b) Maximum sanctioning h=0.33. C) Levels of cooperation with increasing levels of maximum sanctioning (h) for an initial fc= 0.7 and different degrees of cheating (μ).

The maximum amount of sanctioning the community can inflict on a norm violator when its social capital is high determines the region of coexistence of both strategies (Figure 2). If we slightly decrease the maximum sanctioning amount, D can thrive over the whole range of initial C for a region with relatively high degrees of cheating (Figure 2b) where there was coexistence before (Figure 2a). In this region the benefits from overharvesting are still high enough (i.e. resource productivity is not too low) to outweigh the costs of ostracism inflicted by a community with an initially large number of co-operators. A reduction in the amount of sanctioning co-operators can apply lowers their capacity to reduce the resource benefits of defectors, who therefore can thrive no matter how large the community of co-operators. Once over-harvesting becomes excessive (μ>3.6), however, the decrease in resource productivity reduces the advantage of the defectors and makes them more susceptible to the costs of social disapproval. In this region, coexistence with approximately 70% norm followers obtains over a range of initial proportion of co-operators. The results indicate the sensitivity of the coexistence of norm followers and violators to the strength of the community social pressure or the degree of resource over-exploitation. When the degree of cheating is too high resource productivity becomes too low, reducing the additional benefits defectors obtain from resource over-extraction. At the same time the sanctioning by co-operators is non-linear and increases with the degree of cheating, which also works against defectors and enables coexistence to thrive when cheating is very high. The sensitivity of the coexistence to the maximum amount of sanctioning increases with the degree of cheating (Figure 2c). The higher the degree of cheating the higher the maximum sanctioning needed to enable coexistence. However, as cheating increases resource productivity decreases, so that with very high levels of cheating (e.g. 380%) coexistence occurs at lower levels of sanctioning.

The agreement between the game-theoretic analysis and the agent-based simulations 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 ostracism or resource functions has additionally been confirmed by (Lade et al., 2013). They show that the qualitative behaviour of the model remains the same even when the ostracism and the resource outflow functions are linear in the proportion of co-operators or resource level, respectively.

3.2. Impact of variable resource inflow

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

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

(Equ. 3)

We first study the impact of resource fluctuations for the scenario with lower maximum sanctioning costs ($h = 0.333$). Low variability ($\sigma = 1$) destabilizes coexistence at the boundaries between coexistence and defector equilibrium in regions with high degrees of cheating (high μ) (Figure 3a). The region of coexistence shrinks, resulting in a larger range of cheating where cooperation cannot be achieved and the resource is severely overharvested. High variability at high degrees of cheating, on the contrary, destabilizes the defector equilibrium (Figure 3b). Here the region of defection that under constant conditions reaches over the whole range of initial C levels largely disappears, i.e. the majority of runs lead to coexistence. Hence, with high resource variability the norm can be maintained most of the times even when norm violations are large (given that the initial level of social capital in the community is large enough). Next to that the percentage of cooperators in the coexistence is slightly higher.

(a) Low variability ($\sigma = 1$) b) High variability ($\sigma = 10$)

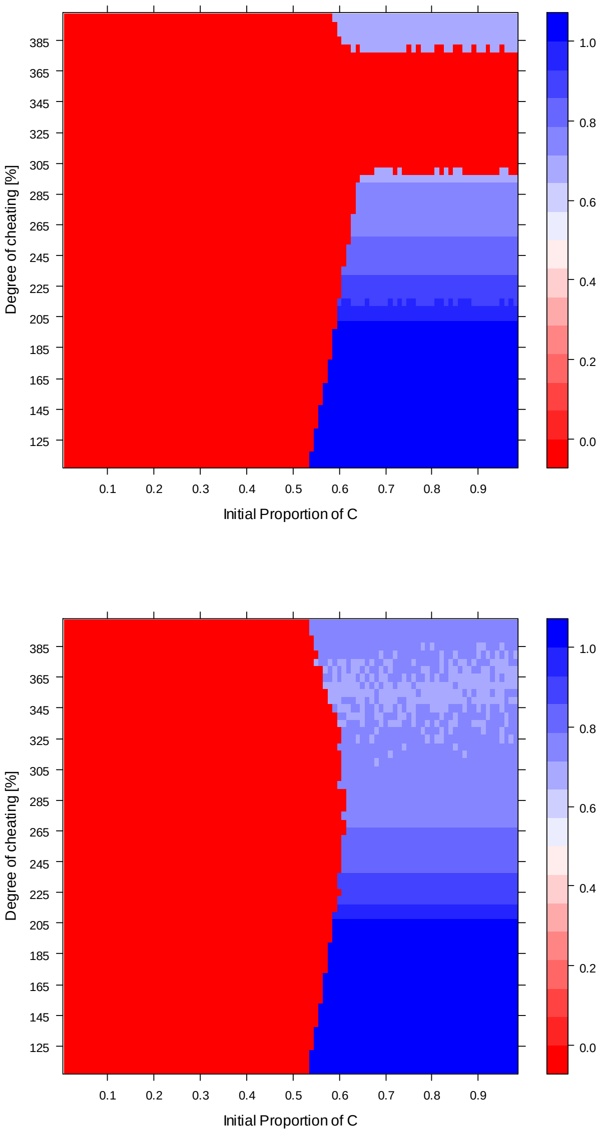


Figure 3: Results of simulations for maximum sanctioning parameter (omega asymptote): h=0.333; a) low resource variability ($\sigma = 1$); b) high resource variability ($\sigma = 10$); average of 50 simulation runs, results are counted as cooperative when at least 50% of the runs converge to a mixed equilibrium

The transition from the variability enhancing defection to its enhancing cooperation for different levels of maximum sanctioning can be seen in Figure 4, which depicts the percentage of runs that converge to cooperation or coexistence with increasing inflow variability. For the scenario with lower maximum sanctioning levels, the transition happens around $\sigma = 10$ where about 50% of the runs converge to coexistence (Figure 4b). Beyond this level of variability the coexistence region also expands to areas with lower initial proportions of C (Figure 4a and 4b) and the proportion of co-operators in the coexistence state increases (not shown).

(a) (b)

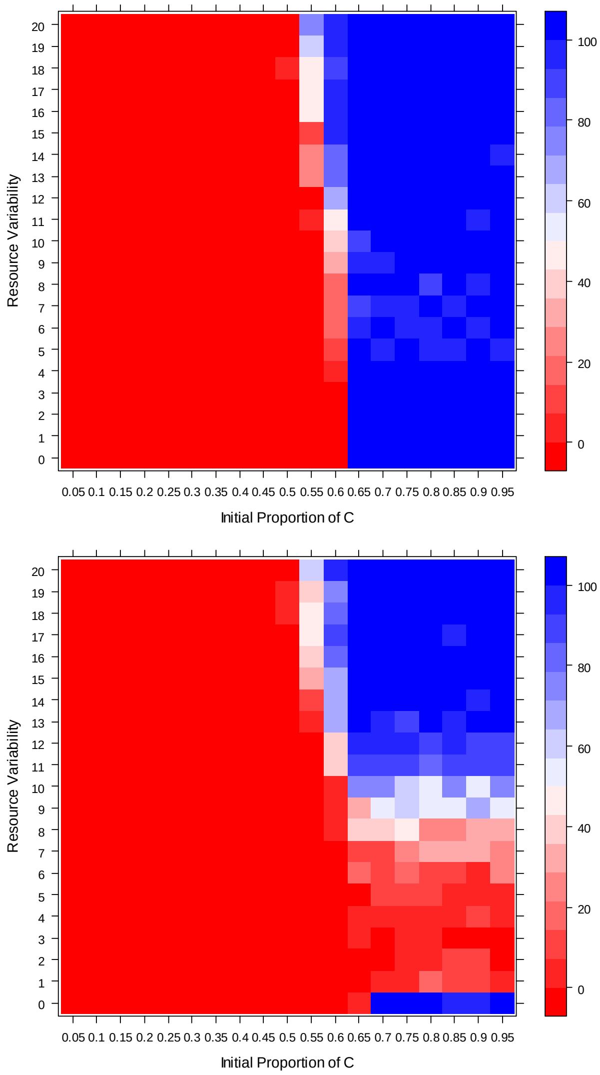


Figure 4: Percentage of cooperative solutions with increasing resource variability (measured in terms of standard deviations from c) at a fixed degree of cheating $\mu = 3$. a) Maximum sanctioning parameter (omega asymptote): h=0.34, b) Maximum sanctioning parameter (omega asymptote): h=0.333; red colour indicates that 0% of runs result in a cooperative solution.

With high inflow fluctuations, agents benefit from random high flow events; however, in the longer term they receive less payoff because the average resource productivity is lower. This is a consequence of the concavity of the resource productivity function, and hence the utilities (see also Tavoni et al. 2012 for the same effect in the analytical model). Norm violators at the same time are still subject to the same costs of social disapproval, which are not affected by resource dynamics. This leads to a disadvantage for the norm violators and allows the co-operators to thrive and the mixed equilibrium to become increasingly stable. A few norm violators switch strategy until the gains from overexploitation and the costs of social disapproval balance out. The increase in the coexistence region as well as the increase of cooperation in the coexistence state is consistent with the results of Tavoni et al. (2012).

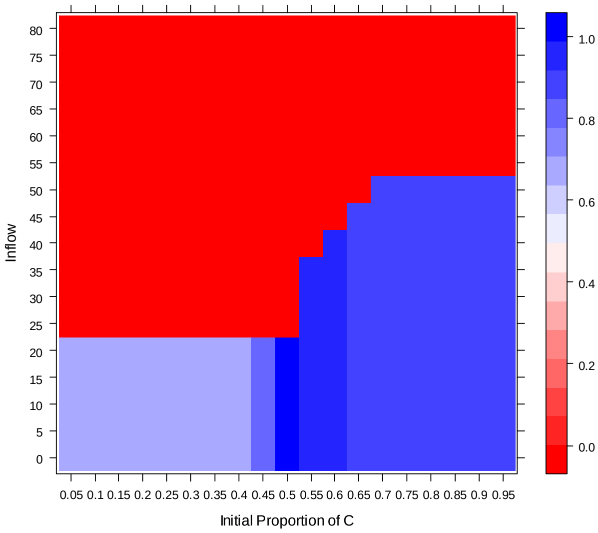
Low levels of variability on the contrary can lead to a sudden collapse of cooperation. While D and C benefit from occasional high flow events here as well, the longer term reduction in payoff is not as pronounced as with higher resource variability. A high flow event thus provides an advantage for the norm violator, increasing the probability of a norm follower switching strategy. This initiates a slow process of changing proportions of co-operators in the mixed equilibrium as co-operators increasingly switch to the defector strategy. Increasing defection slowly degrades the resource 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.

3.3. 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. (2013) investigates 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 co-operators (Figure 5a, results for inflow values >50). Decreases in the mean inflow on the contrary lead to coexistence at lower initial densities of cooperation and an increase in the number of co-operators (Figure 5a). This is contrary to the scenarios with high resource variability where the probability of coexistence increases but the proportion of co-operators remains largely constant around 70% (Figure 5b). At resource inflows of 20 or lower the state of all defection disappears and coexistence with approximately 60% co-operators prevails independent of the initial proportion of cooperation as overharvesting does not pay off any longer.

(a) (b)



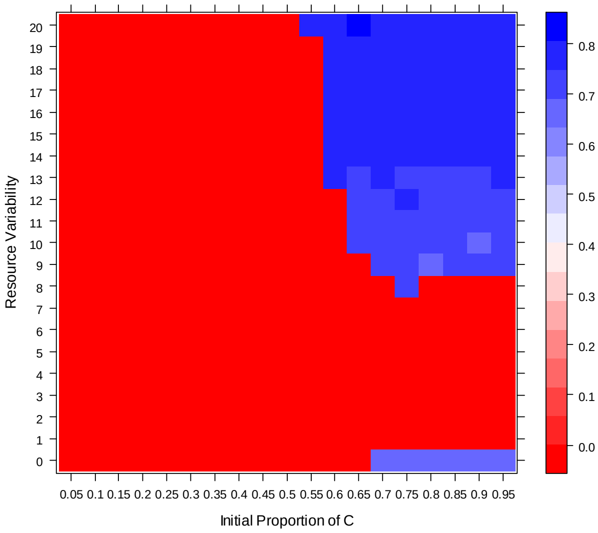


Figure 5: Level of cooperation with a) increases in mean inflow (c) and b) increases in standard deviation of c=50; $h = 0.333$, $\mu = 3.0$; average of 30 simulation runs, results are counted as cooperative when at least 50% of the runs converge to a mixed equilibrium. Note that figure 5b represents the same simulation as Figure 4b, however, it depicts the average level of cooperation in runs that converge to coexistence, not the percentage of runs that converge to coexistence.

A comparison of both effects (Figure 6) reveals that an increase in mean inflow will always lead to dominance of defectors and hence resource collapse no matter how strong resource fluctuations are, except for a very small region where the increase in mean inflow is low (c=55) and fluctuations are high ($\sigma > 15$). Similarly a decrease in mean resource inflow always promotes cooperation, even at low resource fluctuations. Here, high levels of fluctuations merely lead to an increase in the density of co-operators in the coexistence. Hence the effect of changes in the mean inflow is stronger than the effect of inflow variation, but they act synergistically as an increase in fluctuations decreases mean resource availability. Collapse of cooperation as observed with low inflow fluctuations does not occur any longer because of the stronger effect of the increase in cooperation with decreasing mean inflow. Hence, the benefits that defectors experience from resource variability are not as pronounced as when mean inflow is constant.

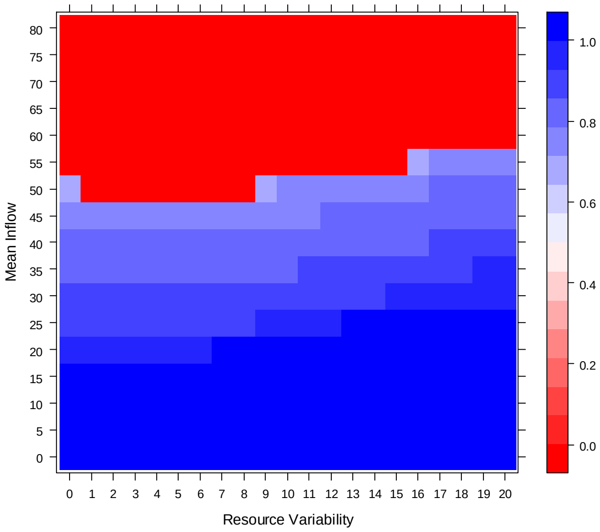


Figure 6: Level of cooperation for a comparison of effect of resource variability versus changes in mean inflow. $h = 0.333$, $\mu = 3.0$, $f_{c,init} = 0.8$; average of 30 simulation runs, results are counted as cooperative when at least 50% of the runs converge to a mixed equilibrium.

4. Discussion and Conclusions

We have investigated the robustness of cooperation in a community of harvesters exploiting a resource where a norm of sustainable resource extraction is maintained through social disapproval of norm violators. Under constant resource inflow conditions the community engages in full cooperation and sustainable resource use when the community social capital is large enough to disapprove effectively of norm violators and the violation is not too high. If norm violations are high, the community cannot sustain full cooperation but a few norm violators coexist because of the benefits of overharvesting when resource conditions are good. If the social capital of the community is low, cooperation cannot establish and resources are heavily overexploited. Social disapproval is thus a necessary but not sufficient condition for cooperation and hence collective action for sustainable resource use to emerge.

Our results also indicate that under certain conditions the maximum level of sanctioning a community with high social capital can administer to a norm-violator can be critical for the persistence of cooperation. Here, a slight decrease of the utility loss norm-violators experience through social disapproval can lead to a collapse of cooperation. This confirms theoretical and experimental studies that indicate that the severity of sanctioning plays an important role in the evolution of cooperation (see e.g. Jiang et al., 2013, Shimao and Nakamaru, 2013, Iwasa and Lee, 2013) and its stability (Ansink and Ruijs, 2008). The sensitivity of cooperation to the details of the sanctioning mechanism also raises the question of how the strength of sanctioning, i.e. the degree of social disapproval, emerges and how results may differ if different community members are more or less vulnerable to the social disapproval exerted on them by the norm followers. Future work may profitably investigate these issues in an agent-based model, or experimental or field settings. Another important aspect is the consideration of direct costs for the community members that engage in sanctioning that is dependent on the number of defectors. Testing these results in the presence of other models of costly sanctioning would represent an important extension.

Collective action that tolerates a few norm-violators and thus achieves resource use that is close to socially optimal under constant resource conditions can abruptly collapse when resource flows are subject to small fluctuations. The collapse is accompanied by the loss of the social norm and collapse of the resource. A small increase in resource variability as a consequence of climate change, change in resource use patterns or internal dynamics of a biological resource such as a fish population thus increases the probability of a breakdown of cooperation in a previously well-functioning community. It does so by providing short term advantages for norm violators in situations when resources are more abundant than usually. Our own field observations of water withdrawal for irrigation in Uzbekistan have shown that uncertainty of water availability can lead to opportunistic behaviour where actors take out as much water as possible in order to insure against future low water availability. Similarly, Brockhurst et al. (2007) found that cooperation amongst bacteria breaks down at low levels of disturbance because of an accumulation of cheaters. In their model cooperative traits most readily evolve under an intermediate level of disturbance. Under a high disturbance regime cooperation cannot evolve, because the threshold density above which cooperation provides a group benefit is never reached as their growth is continuously interrupted. In our case cooperation cannot evolve independent of the magnitude of the disturbance when there is low initial levels of cooperation, and hence a lack of social capital to effectively disapprove of norm-violators

Perhaps surprisingly, cooperation is stabilized and sudden breakdowns no longer occur once the size of the variability crosses a certain threshold (and the initial proportion of cooperation is large enough). Under conditions of high resource variability, norm violators are at a disadvantage because they experience much larger fluctuations in payoffs than norm followers, while still experiencing the same amount of social disapproval. This reduction of utility decreases the probability that a norm follower changes strategy allowing the social norm to persist. Ansink and Ruijs (2008), using a game-theoretic model, have found that increased variability can have both positive and negative effects on the stability of treaties for transboundary water sharing. They point out that the characteristic of the agreement, the benefit functions of the actors and the distribution of political power play an important role in determining the stability of an agreement. Similarly, in an empirical investigation of transboundary river basin management Dinar et al. (2010) found that river basins with high precipitation and runoff variability show higher levels of cooperation than those with low variability. However, when variability becomes too large, voluntary cooperation (expressed in terms of likelihood of treaty formation and number of treaties) becomes less likely. They explain the non-linear relationship between water supply variability and cooperation by the fact that cooperation enhancing mechanisms such as trade may not be effective at all levels of variability.

Furthermore, in our study the robustness of cooperation in situations where norm followers and norm violators coexist is very sensitive to an increase in the mean level of the resource, as a small increase in the replenishment rate can cause a breakdown of cooperation. With an increase in resource supply the additional benefits that a norm violator receives from overharvesting outweigh the negative effects of social disapproval. With every additional community member using more resource the norm quickly erodes, similarly to what happens with low resource variability. A decrease in resource availability, on the other hand, promotes cooperation as the risk of income loss through community disapproval is high and outweighs the benefits of overharvesting. Under conditions of resource scarcity, cooperation is thus a viable strategy that most community members adhere to. The decrease in resource availability also leads to coexistence of norm-followers with a few norm-violators at lower levels of initial social capital in the community. While this provides some hope for sustainable CPR use under conditions of environmental change, it remains to be tested empirically whether strong community norms can enhance the robustness of cooperation to decreasing resource availability.

Importantly, changes in average resource availability and variance can have positive and negative effects on cooperation and hence sustainable resource use depending on the direction and degree of environmental change. Both empirical and other theoretical research has come to similar conclusions. Additionally, several studies highlight that the role of institutions in mitigating the effect of climate-induced resource scarcity (Gizelis et al. 2010) or the types of institutions and possibilities for renegotiation (Ansink and Ruijs 2008) should not be underestimated. Dinar et al. (2010) also highlight the role of the institutional settings and capacity within nation states for facilitating environmental cooperation. Informal rules such as the social norm modelled here play an important role for the establishment of cooperation and may also be relevant for maintaining cooperation under resource scarcity, as we can see in our theoretical modelling. The complex and non-linear interplay of social dynamics through disapproval of norm violators with the ecological dynamics through the rewards actors get from resource use determine the success or failure of cooperative strategies. It is thus important to take the coupling between the social and ecological subsystems into account when analysing and governing social-ecological systems towards sustainable resource use.

Overall, our results indicate that there is not a simple answer to the question whether environmental change and its impact on natural resources has the potential to destabilize cooperation in natural resource use and lead to environmental degradation (and possibly conflict). In situations where communities have the social capital to maintain cooperation through social disapproval of norm violators, as we model here, the magnitude of the variability determines whether cooperation is destabilized or enhanced. Reinforcing feedbacks between increase in returns from resource exploitation and decrease in effectiveness of sanctioning can cause collapse, or lead to higher cooperation when increasing resource scarcity strengthens social norms. The effect strongly depends on the magnitude of the resource variability. Policies to enhance the adaptive capacity of natural resource use, particularly of CPRs, should thus take social norms and their role in (informally) stabilizing cooperation and hence collective action in a community into account. Enhancing the social norms and their effect on benefits of norm violators can potentially increase the adaptive capacity of the community to future increase in resource scarcity.

The modelling approach presented here allowed us address the dynamics arising from the coupling of social and ecological processes by explicitly taking into account changes in community structure and agent behaviour caused by changes in resource conditions and vice versa. Particularly the former are often neglected in studies of regime shifts that focus solely on the ecological system and treat the social system as a driver. This can lead to misleading results if the system studied is truly coupled as we demonstrate here and in Lade et al. (2013). These are theoretical results based on specific assumptions about the behaviour of resource users (e.g. imitation of better-performing strategies), resource dynamics and mechanisms of cooperation. A next step in further exploring the role of environmental variability in coupled SES will be to test these results in the laboratory and the field in order to get more realistic insights into the effect of resource scarcity and variability on the robustness of cooperation.

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