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Summary

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Keywords: Common Pool Resource, Conditional Cooperators, Social-Ecological Complexity, Social Capital, Social Norms

JEL Classification: C73, D70, D64, Q20

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The transmission of sustainable harvesting norms when agents are conditionally cooperative

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Abstract

Experimental and observational studies have highlighted the importance of agents being conditionally cooperative when facing a social dilemma. We formalize this mechanism in a theoretical model that portrays a small community having joint access to a common pool resource. The diffusion of norms of cooperation takes place via interpersonal relations, while individual agents face the temptation of higher profits by overexploiting the resource. Agents remain conditionally cooperative, unless other individuals are misbehaving already. We can observe a bubble of conditional cooperators slowly building up followed by a sudden burst, which means that a transition from a cooperative social norm to non-cooperation occurs. Interestingly, in some parameter regions alternative stable states and limit cycles arise. The latter implies that the same community goes through such a transition repeatedly over long time spans – history thus repeats itself in the form of the creation and erosion of social capital.

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1. Introduction

By now, it is well established that self-regulation of communities can be effective in reducing overextraction of natural renewable resources, such as fish, forests, or grazing lands (Baland and Platteau, 1996; Ostrom, 1990). Obviously, self-regulation is no panacea and there are also examples in which community governance fails with devastating ecological and economic consequences (Ballet et al., 2007; Ostrom et al., 2007). In those cases, resources are either consistently overexploited, or the community switches suddenly from a sustainable harvesting regime to an unsustainable one. Typically, social capital – or its erosion – is highlighted as the pivotal element of successful community governance (Bowles and Gintis, 2002). In spite of this, it remains difficult to disentangle different aspects of social capital in order to understand the underlying mechanisms and processes (Durlauf, 2002; Sobel, 2002). Empirical studies have made substantial progress in unraveling social capital and have identified factors that determine under which conditions community governance thrives (Ostrom, 2009). In particular, community cohesion (Gutierrez et al., 2011), or individuals being conditionally cooperative (Rustagi et al., 2010) have been highlighted in that respect. Additionally, economic experiments have helped understanding the behavior of individuals facing a social dilemma (Fehr and Gächter, 2000; Janssen et al., 2010; Ostrom et al., 1994). Again, conditional cooperation has been identified as one of the most pronounced regularities; see Gächter (2007) for an overview. The importance of conditional cooperation has been highlighted both in a laboratory setting (Fischbacher et al., 2001; Keser and Van Winden, 2000), and in the field (Frey and Meier, 2004). One of the main challenges remains to integrate these findings into formal economic theory. By now it is well established that economic models based on the presumption of purely rational and self-interested agents generally perform poorly in explaining human decisions in social dilemma situations

(Jager et al., 2000; Ostrom, 1998). Clearly, the social context is essential to understand individuals' tendency to conform or violate a social norm (Ostrom, 2010). Strictly speaking, conditional cooperation is a form of context-dependent behavior, where the context refers to the number of other people's inclination to act cooperatively (Grujić et al., 2010; Traxler and Winter, 2012; Tyran and Feld, 2006). We formalize this context-dependency by developing a model to investigate the dynamics of social norms of cooperation for renewable resource harvesting. We take into account that individuals may be conditionally cooperative and our analysis distinguishes i) how social norms of cooperation may spread in the first place, and ii) when conditional cooperators decide to stop obeying them. Hence, we decompose conditional cooperation into a combination of social norm compliance, and context-dependent behavior (i.e. the tendency to violate a social norm if other individuals are also violating the norm). This distinction has been made verbally, cf. Kahan (1997) and Keizer et al. (2008), but we are not aware of a formal model that takes these two processes into account.

The notion of context-dependent behavior is in fact quite old, and many have suggested that individuals make their choices in a decision frame or an environmental context (Granovetter, 1985; Simon, 1956). This is especially the case when time for information acquisition is scarce, information is costly, and individuals can benefit from group knowledge by imitating others (Simon, 1959). If the overall uncertainty is high, herd behavior may be observed, because agents imitate each other's behavior directly. These informational cascades (Bikhchandani et al., 1992) are particularly visible in extreme situations such as riots, escape panics, or financial crashes, but also in fashions or fads (Gladwell, 2000; Noelle-Neumann, 1974; Scheffer et al., 2003).

Context-dependent behavior differs from following a social norm, which is a customary rule of behavior that is self-reinforcing (Young, 2008). When following a norm leads to a strictly higher payoff than not doing so, there is no need for enforcement. When this is not the case, social norms are enforced through two mechanisms. The first mechanism can be summarized as social sanctions. Instruments that have been explored in the literature include peer–to–peer punishments (Fehr and Gächter, 2000; Gächter et al., 2008), peer–to–peer rewards (Vyrastekova and van Soest, 2008), verbal expressions of disagreement and discontent (Masclet et al., 2003), but also excluding individuals from profitable economic exchange (Milinski et al., 2002), and direct ostracism (Vyrastekova and van Soest, 2007). In many cases these mechanisms are combined, and the mere threat of using them is often sufficient to induce cooperative behavior (Andreoni et al., 2003; Ostrom et al., 1994). The second enforcement mechanism can be best described by a process of norm internalization (Young, 2008). A social norm is internalized when an individual feels obliged to obey it, even when not monitored. In many cases, it is the combination of sanctions and norm internalization that works hand in hand: an individual who has internalized a norm may be willing to bear significant costs to punish norm violators (Manski, 2000; Scott, 1971) This happens because an agent who has internalized a social norm does not only feel obliged to act in a certain way herself, but she expects others to follow that strategy as well (Bicchieri, 2006). Once a certain norm is established in a population, individuals that do not have internalized the norm tend to conform in order to avoid punishment or disapproval that may lead to a loss of social status (Bernheim, 1994). Thus, norm compliance helps explaining why social norms of cooperation are followed even if non-cooperation seems the more profitable choice.

Very little is known about how context-dependency and herd behavior interacts with well-established social norms. The strongest evidence in this respect comes probably from studies that have looked at maritime disasters. Frey et al. (2010) compare the sinking of the *Titanic* and the

Lusitania in terms of survival probability. The authors conclude that the social norm “women and children first” is only followed on the *Titanic*, but not on the *Lusitania*, perhaps because the *Lusitania* sunk much quicker, leading to herd behavior overruling social norms. This finding has been challenged by Elinder and Erixson (2012) who analyzed 18 different maritime disasters and concluded that the enforcement of social norms typically breaks down in such situations irrespective of the duration of the catastrophe, the *Titanic* being an exception.

In our model, a common pool resource is harvested by community members that are either cooperatively minded or selfish (referred to as defectors). Following the literature on economic cooperation in social dilemma situations (Bischi et al., 2004; Bulte and Horan, 2010; Sethi and Somanathan, 1996) we assume that individuals are more inclined to defect if the profits of doing so are particularly high. Social pressure arises as a result of defectors being surrounded by cooperative agents (Iwasa et al., 2007; Tavoni et al., 2012). Following Richter et al. (forthcoming), we assume that cooperators are intrinsically motivated to obey the social norm and try to persuade defectors to cooperate as well.

The new element in this study is that a distinction is made between intrinsic cooperators, who have fully internalized the norm and conditional cooperators, who have not. An individual of the latter group is acting cooperatively but tempted by the higher profit he considers to join the group of defectors. We assume that the tendency to become a defector depends on the number of agents that are already defecting (Granovetter, 1978; Macy, 1991). By incorporating conditional cooperation, it is shown that the socioeconomic system may suddenly collapse, even if it is stable from the outside. This happens, because unnoticed the group of conditional cooperators – indistinguishable from intrinsic cooperators – slowly increases in size and a bubble of conditional cooperators builds up. The decision to defect has a stochastic component, and if defection happens to increase (by chance), the bubble suddenly bursts. Then, herd behavior can be observed, as conditional cooperators cascadingly turn into defectors. In contrast to earlier work by Richter et al. (forthcoming), the collapse is not caused by alternative stable states but even materializes if the system has only one equilibrium. In addition, the model also generates sudden changes due to alternative stable states or limit cycles.

In Section 2 we develop the social-ecological model, derive optimal harvesting strategies and formulate the dynamical model. The model is based on three coupled differential equations describing the evolution of the resource stock, as well as the social norms. Section 3 analyzes the model and presents results, while section 4 concludes and sketches further avenues of research.

2. The social-ecological model

We start from the model of contagious cooperation studied by Richter et al. (forthcoming), and extend this model by incorporating conditional cooperation. We assume that there are N agents in a small community who have access to a commonly-owned natural resource. The common property regime is such that outsiders are not allowed to access the harvest grounds to extract the resource (Schlager and Ostrom, 1992). Resource regeneration is described by the generic logistic equation, which assumes a spatially fully diffused resource with a uniform density and a natural growth function that is specified as

$$G(X) = rX\left(1 - \frac{X}{K}\right), \qquad (1)$$

where X denotes the biomass of the natural resource, r is the intrinsic growth rate and K the carrying capacity.[1] Furthermore, we assume that the community faces a complex social dilemma caused by two externalities. First, harvesting gives rise to an intertemporal negative externality as excessive extraction today reduces the size of the available resource stock tomorrow. While the benefits of harvesting are individual, the subsequent effect on the development of the stock is borne by all community members. Second, resource exploitation is getting increasingly costly if aggregate effort increases. An example for such a static externality are congested resource grounds, forcing individuals to spend more time and fuel to find a good spot, and replacing material that interferes and tears (Boyce, 2000; Schlager, 2002). While it is in the community's best interest to collectively take these externalities into account, each individual has the incentive to only care about her own payoff. Our approach is similar to the one of Bischi et al. (2004), who assume that cooperators maximize joint profits, while selfish individuals, referred to as defectors, only maximize their individual profits.

2.1 Resource harvesting decisions

Each agent can either decide to engage in resource harvesting or has the outside option to work on an alternative economic activity. Time is limited, and each individual is endowed with a fixed effort rate $\hat{e}$ which can be divided between these two activities. The rate at which agent i allocates effort to resource harvesting at time t is denoted by $e_i(t)$, $i = 1,\ldots, N$. The return to effort in the alternative economic activity is constant and equal to w per unit of effort, which is

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[1] Throughout the paper time arguments are omitted, unless confusion may arise.

consequently the opportunity cost of engaging in resource harvesting. The income agent *i* derives from this activity per unit of time at time *t* is consequently $w\left(\hat{e}-e_i(t)\right),$ where $0 \leq e_i(t) \leq \hat{e}.$ The relationship between an individual agent's harvesting effort $e_i(t)$ and the quantity of resource goods harvested is given by the Schaefer production function

$$h_i(t) = qX(t)e_i(t), \tag{2}$$

where *q* is the catchability coefficient. The development of the resource stock is then given by

$$\frac{dX}{dt} = rX\left(1-\frac{X}{K}\right) - qEX, \tag{3}$$

where $E = \sum_{i=1}^{N} e_i.$ Regarding harvesting revenues, we assume that resource goods can be sold at a constant price *P* so that agent *i*'s sales revenues are $Ph_i(t).$ We follow Clark (1980) by modeling the instantaneous negative externality as a cost component in the profit function that depends on the aggregate effort *E*(*t*) the community puts into resource harvesting.[2] We thus assume that if an agent employs effort $e_i(t)$, she incurs congestion costs equal to $Z(e_i,...e_N) = vE(t)e_i(t)$, where *v* reflects the marginal costs of congestion associated with one unit increase in aggregate effort.[3] Individual profits π_i are then given by

$$\pi_i(X, e_1, ..., e_N) = PqXe_i + w(\hat{e}-e_i) - vEe_i\,. \tag{4}$$

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[2] Alternatively, one could assume that crowding does not increase costs, but decreases productivity, which would give similar results. Indeed, both specifications have similar consequences as they cause harvesting effort and profits to be smaller, and effort rates chosen by cooperators to be (weakly) lower than those by defectors.

[3] The partial derivatives are given by $\partial Z / \partial e_i = vE$ and $\partial Z / \partial E = ve_i,$ while the cross partial derivate is given by $\partial^2 Z / \partial e_i \partial E = v.$ This implies that the marginal costs of increasing own effort are higher if the resource grounds are particularly crowded, but also that the users who are particularly active suffer more from an increase in effort by others – the economic intuition is that in both cases it is very difficult to avoid contact with other individuals.

Intrinsic cooperators (C_{I}) and conditional cooperators (C_{C}) try to manage the resource optimally by employing their fair share of the aggregate optimal effort rate that gives the maximum economic yield (MEY), as given by $e_C^{\mathrm{MEY}} = E^{\mathrm{MEY}} / N$ with $C = C_{\mathrm{I}}, C_{\mathrm{C}}$. Cooperators invest e_C^{MEY} only when the resource is at the equilibrium level that supports the MEY. If this is not the case, cooperators use an adaptive effort rule in order to approach the MEY. This implies that if defectors overexploit, cooperators will reduce their effort rates as an attempt to rebuild the resource stock. In order to determine e_C^{MEY}, we solve the maximization problem of cooperators, which depends on the discount rate δ and can be given as

$$\max_E \int_0^\infty \left(PqXE - vE^2 + w(N\hat{e} - E) \right) \mathrm{e}^{-\delta t} dt \qquad (5)$$

subject to the dynamics of the resource stock (3) and taking into account each agent's effort endowment. Writing down the current value Hamiltonian $\mathcal{H}(t)$ (Kamien and Schwartz, 1981) gives

$$\mathcal{H}(t) = PqXE - vE^2 + w(N\hat{e} - E) + \lambda \left(rX \left(1 - \frac{X}{K} \right) - qEX \right), \qquad (6)$$

where λ is the co-state variable. Taking the appropriate first derivatives, the first-order conditions for the cooperators' maximization problem are

$$PqX - w - 2vE - \lambda qX = 0, \qquad (7a)$$

$$PqE + \lambda r - 2\lambda r \frac{X}{K} - \lambda qE + \dot{\lambda} = \delta\lambda. \qquad (7b)$$

Using the dynamics of the resource stock (3) with (7) and setting all time derivatives equal to zero we obtain

$$E^{\mathrm{MEY}} = r\left(1 - X^{\mathrm{MEY}} / K \right) / q \qquad (8)$$

and ultimately

$$X^{\text{MEY}} = \frac{K}{4rA}\left(\sqrt{\delta^2 A^2 - 2\delta r(K^2P^2q^4 - KPq^2(3B+4rv) - 2rv(B+2rv) + r^2F^2} - \delta A + rF\right) \quad (9)$$

with $A = KPq^2 + 2rv$, $B = qw$ and $F = A + B$.

In order to approach these optimal steady state values, a simple stock-size dependent effort rule is employed of the type $e = a + bX$ with $a < 0$ and $b > 0$, see Hilborn and Walters (1992). The parameter a is set at a given value reflecting a precautionary reference point that determines a minimum biomass level, below which effort is chosen to be zero. The parameter b is set such that each cooperator invests the socially optimal effort level when the resource stock is at its socially optimal level, i.e. the one delivering the MEY. Taking further into account that effort cannot be negative, the effort rate for cooperators is given by

$$e_C = \max\left(a + bX, 0\right) \text{ with } b = \left(e^{\text{MEY}} - a\right) / X^{\text{opt}}. \quad (10)$$

Defectors (D) do neither make an attempt to engage in sustainable harvesting, nor do they consider the consequences of their actions on the payoff of fellow community members. Instead, they take advantage of cooperative efforts by other agents and appropriate all remaining rents. Therefore, they maximize the profit function (4) for individual effort taking into account the number of cooperators, which gives the best response function (BR)

$$e_{\text{BR}} = \left(PXq - w - vE_{-i}\right) / \left(2v\right) \quad (11)$$

with $E_{-i} = E - e_i$. For a single defector, the effort of all other agents can be given by $E_{-i} = \left(D-1\right)e_D + \left(N - D\right)e_C$, which gives, together with (11), the optimal effort of a defector as

$$e_D = \frac{(PXq - w) - ve_C(N-D)}{v(D+1)}. \quad (12)$$

Furthermore, it is assumed that at any time all agents rapidly choose the optimal effort that corresponds with their group. We suppose that in the subsequent sections the system resides beyond this transient state.

2.2 Social dynamics

In the previous sub-section we have developed a model where agents can choose between two types of behavior when exploiting the resource: to act cooperatively, or to defect. The underlying social dynamics are more complex, as we assume that the community consists of the three types: Intrinsic cooperators (C_{I}), conditional operators (C_{C}), and defectors (*D*) with $C_{\mathrm{I}} + C_{\mathrm{C}} + D = N$. The main mechanisms of our social dynamics are developed below and can be summarized as i) moral persuasion, ii) temptation, and iii) each agent having a social threshold for defection, giving rise to herd behavior. Verbally, the essence of our models relies essentially on the following assumptions that are all empirically well-founded. First, some agents are willing to uphold a social extraction norm (doing what is optimal for the group as a whole), and try to impose social pressure on non-cooperators to also start adhering to the norm (Bicchieri, 2006; Manski, 2000; Scott, 1971). Second, the propensity to (dis)obey a cooperative norm depends on the temptation to defect, but also on whether individuals have recently been exposed to cooperatively minded agents (Janssen and Mendys-Kamphorst, 2004; Keizer et al., 2008). Third, agents make their propensity to defect conditional on the number of agents behaving accordingly (Granovetter, 1978; Noelle-Neumann, 1974). In Fig. 1 the dynamics of the social-ecological system are presented in a scheme showing the mechanism of each component of the system. All agents have access to the common pool resource, and defectors harvest more than cooperators (indicated by the thicker arrow). Moral persuasion turns defectors into intrinsic cooperators, while the temptation to pursue higher harvests triggers agents to lose their intrinsic motivation and to become conditionally cooperative. But only if sufficiently many agents defect already, conditional cooperators are prepared to do so as well, potentially resulting in herd behavior.

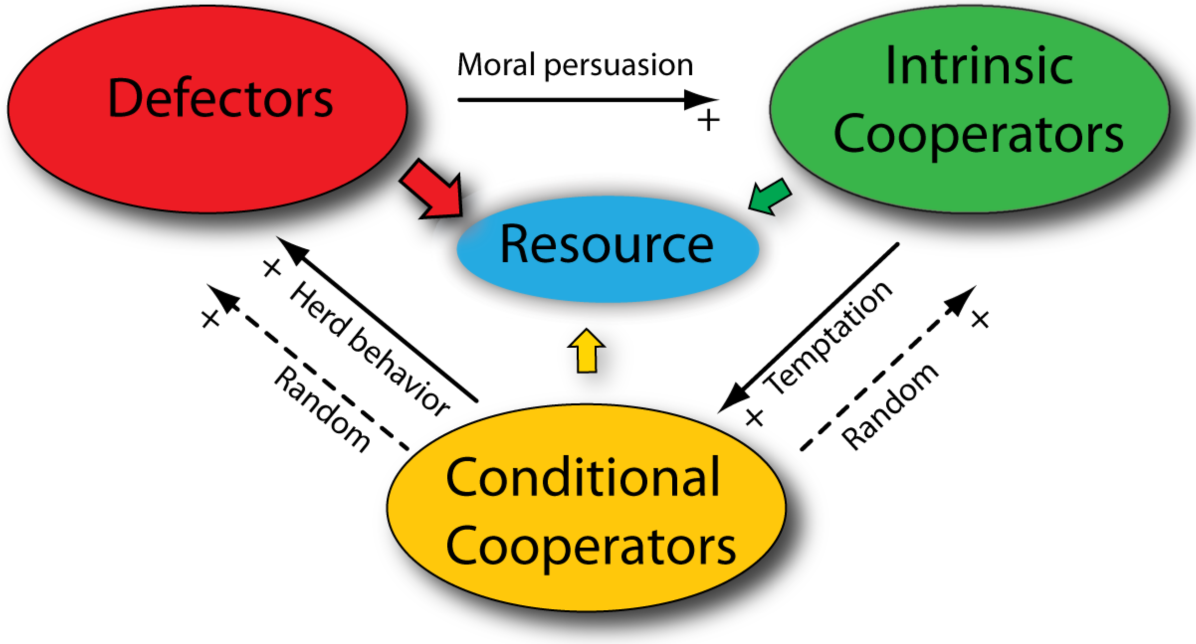

Fig. 1. The socio-economic dynamics of the system. Directed changes are driven by moral persuasion, temptation and the inclination to defect once a social threshold is passed and herd behavior may occur. Conditional cooperators may also change behavior randomly, which reflects a certain degree of uncertainty in their decision-making process.

Building upon Richter et al. (forthcoming), we assume that intrinsic cooperators are intrinsically motivated to keep up the social norm and make an effort in persuading defectors to act cooperatively. Whenever an intrinsic cooperator meets a defector, there is a probability υ that the former succeeds in convincing the latter to act cooperatively. Assuming that social encounters occur randomly, the probability of an intrinsic cooperator meeting a defector can be modeled as a Poisson process. The probability of an encounter taking place in a short time interval $(t, t+\Delta t)$ is equal to $\lambda C_{\mathrm{I}}(t)D(t)\Delta t / N,$ where λ is the Poisson parameter. Moral persuasion thus increases the number of intrinsic cooperators by $C_{\mathrm{I}}(t+\Delta t) - C_{\mathrm{I}}(t) = \alpha C_{\mathrm{I}}(t)D(t)\Delta t / N$, where $\alpha \equiv \lambda \upsilon$.[4]

Obviously, intrinsic cooperators take notice of the higher profits associated with defection. While intrinsically motivated to act cooperatively, the prospect of having higher payoffs tempts agents to start acting selfishly, and we assume that agents are more likely to consider defection the larger π_D is compared to $\pi_C,$ see (4), (10) and (12). In our model, intrinsic cooperators do not start defecting immediately even if temptation is sufficiently high. Instead, they lose the intrinsic motivation to adhere to the social norm and become conditionally cooperative. More specifically, we assume that the transfer rate due to temptation from intrinsic cooperator to conditional operator takes the form $\beta C_{\mathrm{I}}\left(1 - \pi_C / \pi_D\right)$.

Conditional cooperators do not make an effort in persuading defectors, and make their own cooperation contingent on sufficiently many agents not defecting. The temporal dynamics of the conditional cooperators depends on the number of cooperators that start hesitating and on the ones of them that subsequently become defectors. Following the threshold model of cooperative behavior (Granovetter, 1978; Young, 2009), we assume that conditional cooperators are more inclined to defect if this is common behavior in the group. A functional form that satisfies these properties can be given by the sigmoid Hill function, which is a continuously increasing function with values close to zero for $D << \theta$ and close to unity for $D >> \theta$ with a rapid transition near

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[4] Note that in our model defectors do not change their behavior after an encounter with conditional cooperators, who are – unlike intrinsic cooperators – not making an effort to morally persuade defectors.

$D = \theta;$ see also Janssen and Scheffer (2004) and Scheffer (2009). The social threshold function $S(D;\theta,\gamma)$ is given by the form

$$S(D;\theta,\gamma) = \frac{D^{\gamma}}{\theta^{\gamma} + D^{\gamma}}, \tag{13}$$

where θ is the point at which $S(D;\theta,\gamma)$ equals ½ with slope $\gamma;$ see Fig. 2.

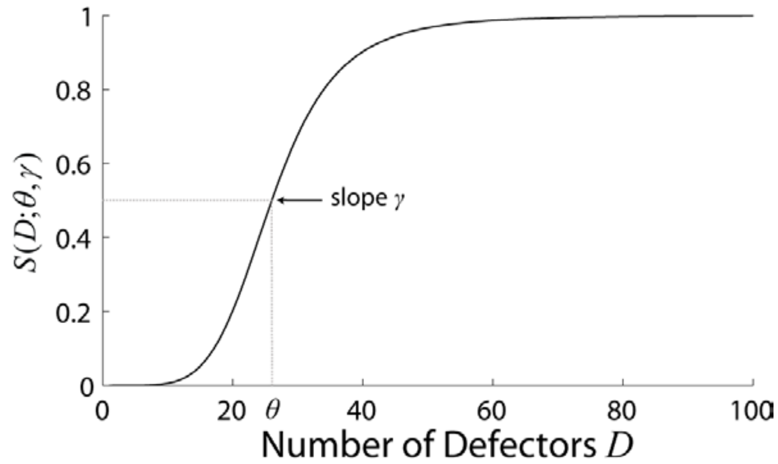

Fig. 2. The shape for the Hill with parameter values for θ and γ as given in Table 1.

Since hesitation is a rather uncertain and temporary state of indecision, we will assume that there is also a stochastic component in the decision making process. A small fraction η of the conditional cooperators will move stochastically to one of the other groups, no matter what happens around them. The rate at which the group of conditional cooperators changes over time can be described by

$$\frac{dC_C}{dt} = \beta C_{\mathrm{I}}\left(1 - \frac{\pi_C}{\pi_D}\right) - C_{\mathrm{C}}\left(\frac{\mu D^{\gamma}}{\theta^{\gamma} + D^{\gamma}} + \eta\right), \tag{14}$$

where the parameter μ scales the strength of the herd behavior.

Symbol	Description	Value
Model variables		
X	Resource stock	
C_I	Number of intrinsic cooperators	
C_C	Number of conditional cooperators	
D	Number of defectors	
Model parameters		
N	Number of agents	100
r	Intrinsic growth rate	0.4
K	Carrying capacity	100
$\hat{e}$	Effort endowment	0.6
q	Catchability coefficient	0.01
p	Resource sales price	500
v	Congestion cost	1
w	Opportunity cost of effort	2
δ	Discount rate	0.05
a	Precautionary reference point	–0.3
α	Strength of moral persuasion	0.5
β	Strength of temptation	0.2
θ	Hill function parameter	$N/4$
γ	Hill function parameter	5
μ	Strength of herd behavior	1
η	Stochastic decision parameter	0.1

Table 1. Key variables and default values of the parameters with their economic denotation

Having introduced all components of our system, the following equations fully describe the dynamics of our system:

$$\frac{dC_{\mathrm{I}}}{dt} = \frac{\alpha}{N} DC_{\mathrm{I}} - \beta\left(1 - \frac{\pi_C}{\pi_D}\right)C_{\mathrm{I}} + \frac{1}{2}\eta\left(N - D - C_{\mathrm{I}}\right), \tag{15a}$$

$$\frac{dD}{dt} = -\frac{\alpha}{N} C_{\mathrm{I}} D + \left(\frac{\mu D^{\gamma}}{\theta^{\gamma} + D^{\gamma}} + \frac{1}{2}\eta\right)\left(N - D - C_{\mathrm{I}}\right), \tag{15b}$$

$$\frac{dX}{dt} = rX\left(1 - \frac{X}{K}\right) - qX(N - D)e_C - qXDe_D. \tag{15c}$$

Note that the equation (14) can be omitted because $C_{\mathrm{C}} = N - D - C_{\mathrm{I}}$. The dynamics of the system (15) depends on the chosen values of the parameters. In Table 1 the set of parameters are presented with their economic denotation. Moreover, default values are given, which are used throughout this study unless it is specified differently in the text.

3. Results

The presence of conditional cooperators in combination with the finite effort endowment leads to very interesting dynamics of the system such as hysteresis and sudden changes in the time domain. Throughout the analysis, we will distinguish two cases: the effort endowment $\hat{e}$ is either relatively high or low. If $\hat{e}$ is high, the pressure on the resource is consequently also high. If $\hat{e}$ is low, the pressure on the resource is relatively low, for example because the household size is small or the available technology is limiting the maximum exploitation rate.

3.1 *Equilibria and limit cycles*

First we analyze the case where the pressure on the resource is high; see Fig. 3. For any starting value $(C_{\mathrm{I},0}, D_0, X_0)$ the system will tend to either an equilibrium $(C_{\mathrm{I}}^*, D^*, X^*)$ or a limit cycle.[5] Two trivial equilibria are easily traced from the equations (15). First, if no intrinsic cooperators are present in the community, moral persuasion is absent and ultimately all community members will be defecting, as given by $C_{\mathrm{I}}^* = 0$ and $D^* = N$. This equilibrium is globally stable for small

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[5] Unless specifically stated, all results are insensitive to starting values.

values of the moral persuasion parameter α; see Fig. 3a. Second, if temptation is absent $(\beta = 0)$, all individuals will become intrinsic cooperators, as given by $C_{\mathrm{I}}^* = N$ and $D^* = 0$. For increasing values of β we find a continuation in the form of an internal equilibrium, see Fig. 3b. This equilibrium state is stable except for a small interval of β where it is unstable: through a Hopf bifurcation a small amplitude stable limit cycle arises at one end of the interval and disappears at the other end. Stable periodic solutions with larger amplitudes are found for various parameter values. Fig. 3c shows an example of a limit cycle unfolding over time.

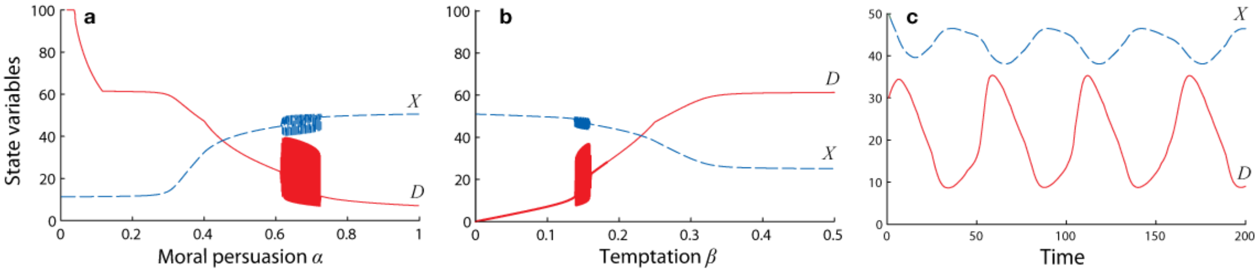

Fig. 3. The equilibrium number of defectors *D* (solid) and the level of the resource *X* (dashed) for different parameter values of the moral persuasion parameter *α* (a) and temptation *β* (b) for the case where pressure on the resource is high and $\hat{e}$ = 0.6. Over time, oscillatory dynamics may occur, *β* = 0.15 (c).

The results are qualitatively similar for the case where pressure on the resource is relatively weak ($\hat{e}$ is low), except for some important differences; see Fig. 4. First, if the effort endowment $\hat{e}$ is low, exploitation is less severe, which implies a larger equilibrium resource stock. Second, full defection occurs even if moral persuasion is relatively high; compare Fig. 3a with 4a. Full defection also occurs if temptation is relatively weak, ceteris paribus; compare Fig. 3b with 4b. It is perhaps surprising that *higher* defection occurs if $\hat{e}$ is smaller and the pressure on the resource is *weaker*. This finding is explained by the fact that a smaller $\hat{e}$ implies that X is larger for a given number of defectors, which means that profits for defectors are also larger. Therefore, the higher $\hat{e}$, the fewer defectors are needed to have all rents dissipated. Third, and largely unexpected, we find that alternative stable states may coexist if $\hat{e}$ is low. For example if temptation increases (a shift along the horizontal axis in Fig. 4b), defection gradually increases, but suddenly the system flips to a stable equilibrium of full defection. Fig. 4c shows such an example of hysteresis with two simulations for the same set of parameters and different initial conditions. While the upper panel portrays a situation where full defection occurs rapidly, in the lower panel initial conditions are such that the system stabilizes with only half the agents defecting. This shows that the steady state may be situated at either of the two branches depending on the history of the system.

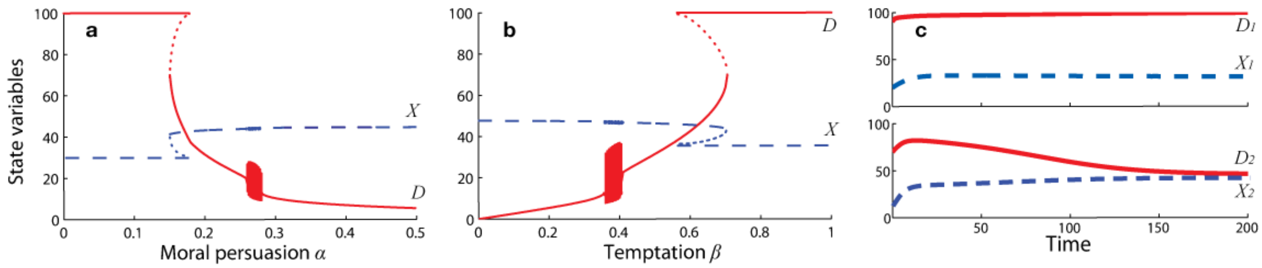

Fig. 4. The equilibrium number of defectors D (solid) and the level of the resource X (dashed) for different parameter values of α (a) and β (b) for $\hat{e}$ = 0.275. Panel c shows that alternative stable may occur, depending on different initial values, α = 0.16. Initial values are $(C_{G,0}, D_0, X_0) = (5, 90, 20)$ in the upper panel and $(C_{G,0}, D_0, X_0) = (25, 70, 20)$ in the lower one.

3.2 *Bubbles and hidden transitions*

We next consider the community facing a situation without a temptation to defect (β = 0). Then, at t = 0, a change takes place, which brings about a strong temptation (β = 0.3); see Fig. 5a.

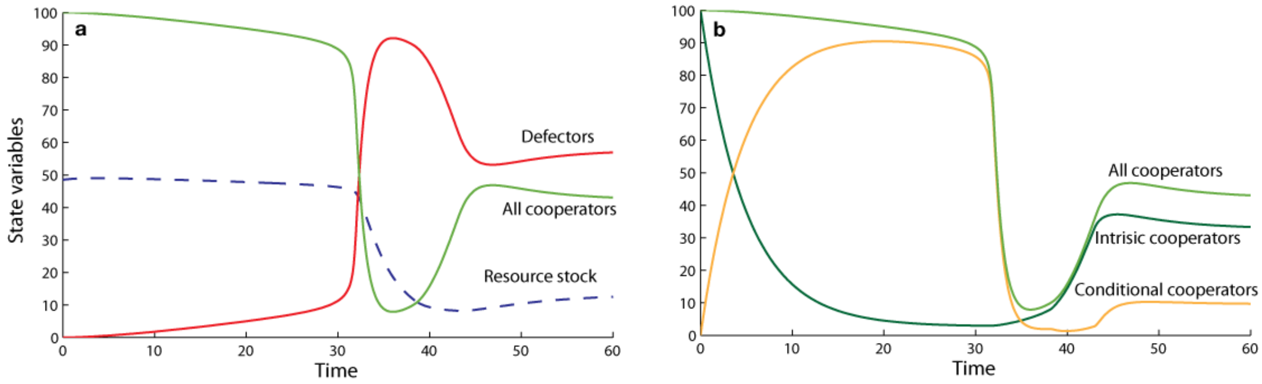

Fig. 5. Sudden change from a state in which cooperation is the norm to a state in which defection is widespread. The number of cooperatively working agents $C_\mathrm{I} + C_\mathrm{C}$ (green solid) slowly decreases up to the moment of collapse (a). The resource *X* (blue dotted) also remains at a high level. The number of defectors *D* (red solid) stays low until the collapse. The sudden collapse of cooperation (light green) can only be understood when one observes the sudden transition of intrinsic cooperators C_I (dark green) into conditional cooperators C_C (yellow) (b).

In the beginning, no alarming changes can be observed, as the number of cooperatively working agents $C_\mathrm{I} + C_\mathrm{C}$ decreases only very slowly and the resource *X* remains at a high level. Suddenly, a drastic collapse of cooperation occurs and defection overshoots to a level involving 95% of all community members, before defection equilibrates at about 60% of all agents. From the outside, the underlying process cannot be explained without understanding the role of conditional cooperators; see Fig. 5b. Unnoticed from the outside, a steady transition of intrinsic cooperators C_I into conditional cooperators C_C has occurred, resulting in a bubble of conditional cooperators and ultimately in a collapse of the social-ecological system. An important element in this process is the threshold mechanism that is incorporated in the model through the Hill function and the stochastic component ($\eta > 0$) in the decision making process. This implies that if the number of defectors is small, a conditional cooperator chooses with equal chance either to return to the group of intrinsic cooperators C_I or to become a defector *D*; see also (15). When the number of defectors increases, a spiral of defection materializes and agents defect cascadingly, which is typical for herd behavior. Note that this process materializes in spite of no apparent complexities, such as alternative stable states. This phenomenon is simply caused by the adjustment transition towards one stable equilibrium. So even if the system is outside the domain of limit cycles or alternative stable states, surprises may occur as a result of the internal dynamics.

3.3 *Dependence upon exogenous factors*

While social complexity in the form of conditional cooperation is the main mechanism behind the results, external driving forces may affect the resilience of the system and may induce a shift between different qualitative states (limit cycle, single equilibrium, alternative stable states). Fig. 6 shows how ecological, economic or demographic changes can alter the state of the social-ecological system. A change in the intrinsic growth rate, for example due to climate change, has a profound effect on the number of defectors (Fig. 6a). For very small and intermediate intrinsic growth rates, a limit cycle can be observed, while in-between a stable equilibrium materializes. Surprisingly, defection rises with a higher intrinsic growth rate, and then gradually falls again. This dome shaped defection pattern translates into a sigmoid shape of the resource stock (see dashed line in Fig. 6d). While a higher intrinsic growth rate does not immediately results into a higher resource stock (as defection increases as well), there is a point where enough rents are created to make cooperation viable, which results in decreasing defection and increasing resource stock, which ultimately approaches the resource stock delivering the maximum economic yield (X_{MEY}).

Economic change, for example an increase in the return of the outside opportunity *w*, has a negative effect on defection, because it makes working elsewhere more profitable and overexploitation less tempting (Fig. 6b). Consequently, an increase in *w* brings the system closer to the X_{MEY}, even though not substantially (Fig. 6e). Again, a transition from a stable equilibrium to a limit cycle can be observed.

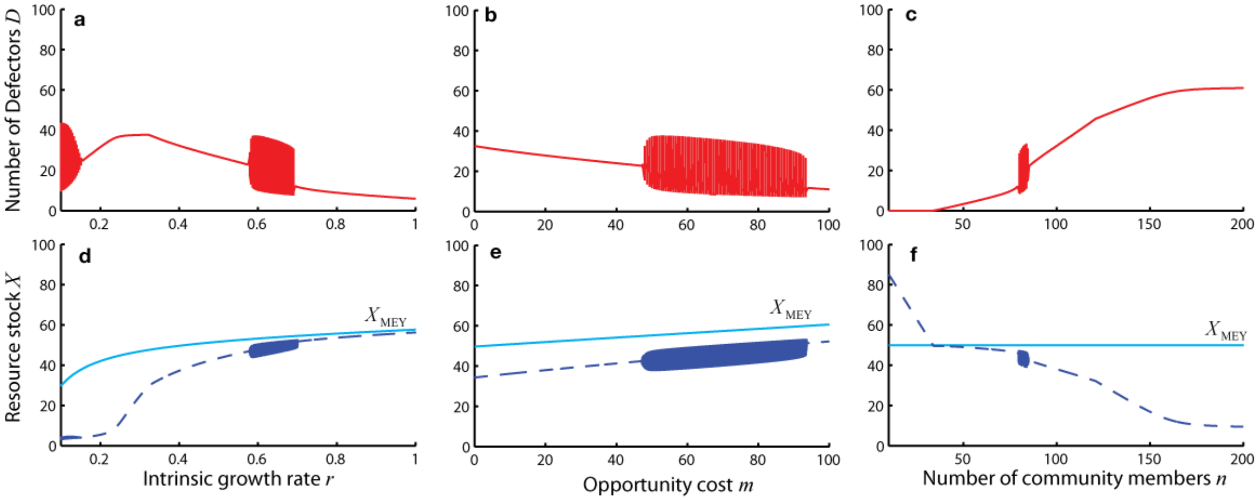

Fig. 6. Depicted are the equilibrium number of defectors D (a-c) and the level of the resource X (d-f) for different parameter values for ecological change (r), economic change (w), demographic change (n) for $\hat{e}$ = 0.6.

Demographic change, such as an increase in the number of community member due to population growth, has a strong effect on defection. For very low levels of N, all community members cooperate (Fig. 6c), and the resource stock X is well above the X_{MEY} (Fig. 6f). When the community size increases above a certain level, the social dilemma materializes, defection occurs, and the resource stock drops below the X_{MEY}. Once the resource stock drops below the X_{MEY}, cooperators start restraining themselves, defection is still rare, and the resource stock decreases only marginally. Once the system reaches a limit cycle, defection increases substantially and also the resource gets depleted severely. For high levels of N, defection keeps increasing, but at a rate less than the population increases (which would be given by the 45 degree line). As a result, the resource stock equilibrates at a low level of X.

4. Conclusions

We have shown that the presence of conditional cooperators has profound effects on the evolution and the robustness of community governance systems. Combining the effects of moral persuasion, temptation, as well as conditional cooperation gives consistent patterns, as well as surprising dynamics. The model corroborates earlier findings that not only the resource dynamics, but also the evolution of cooperation depends markedly on the time available for working that is constraining effort (Richter et al., forthcoming). Perhaps surprisingly, defection can be much more pronounced if less time is available for working in the resource sector and the aggregate pressure on the resource is only modest. This shows that social norms of cooperation may be more difficult to establish if defectors are still able to enjoy high profits because the resource is still in a decent shape. This sheds interesting light on the question whether a crisis facilitates or impedes institutional change (North, 2005). In that respect, the interaction of conditional cooperation and deteriorating external conditions may explain why social norms – once established – may suddenly collapse. An important insight from our model is that incorporating conditional cooperators may lead to surprising dynamics, even if the system is apparently stable and features a single equilibrium. This happens because the shift from agents being intrinsically cooperative towards being conditionally cooperative occurs largely unnoticed. Thus, we may observe a collapse of the sustainable exploitation of a resource due to a massive defection of agents previously cooperating because of herd behavior.

Furthermore, we find that the qualitative dynamics of the resource system may suddenly change. Depending on exogenous shocks, the social-ecological system may either have a single stable equilibrium, alternative stable states, or even a limit cycle. In particular, a change in the intrinsic growth rate (r) leads to surprising patterns, as it has a limit cycle at low and intermediate values for r and a stable equilibrium in-between. Equally important is the dome-shaped relationship between defection and the intrinsic growth rate. This result may have strong implications for the governance of complex ecosystems, because a reduced stock productivity has not only a direct effect on the steady state resource biomass, but also an indirect effect, transmitted through higher defection. This seems especially relevant for cases where the population is under stress by a reduced intrinsic growth rate (Hutchings, 2005), for example due to climatic changes (Walther et al., 2002), loss of habitat (Armstrong and Falk-Petersen, 2008), trophic interactions (Terborgh and Estes, 2010), or evolutionary change (Enberg et al., 2012).

In our model, we assume that defectors can be easily identified upon social encounter, which may be more realistic for small communities, where defectors are unable to form their own social clusters or “gangs” to avoid social pressure (Acheson, 1988). Also, we rule out the possibility to hide harvests – an assumption that seems more plausible if the resource grounds are either small, or resources have to be landed at a central place. If monitoring is more difficult, this may impede the evolution of cooperative harvesting norms (Coleman and Steed, 2009; Rustagi et al., 2010). If defectors can hide some of their harvests, this may also imply that cooperators fail to perceive the correct resource stock levels and do not take the required efforts to rebuild the stock. This seems especially relevant for resource systems where the resource stock is not directly visible, as is the case for most fisheries (Gutierrez et al., 2011). In our model, a systemic collapse is entirely due to the institutional setting and the underlying biological processes are rather simple. We assume that the renewable resource grows logistically, which has the advantage that any emerging social phenomena arise from a very generic non-spatial model. Allowing for a spatial dimension favors usually cooperation, because cooperative clusters can emerge that defectors cannot invade (Noailly et al., 2007), while cooperation in non-spatial models requires additional mechanisms. For a similar reason we omitted more specific resource characteristics, such as an Allee effect that may occur in biological populations. It is well known that many resource systems are inherently non-linear and may fully collapse if the resource abundance is too low (Kramer et al., 2009). In this study we have chosen to model the dynamics of the resource by using the relatively simple logistic growth model. In this way it has become clear that collapse does not occur as the result of a complicated entanglement of resource dynamics and behavior of the agents exploiting the resource, but solely because of social complexity. Therefore, it remains to be investigated to what extent adding ecological complexity will affect the evolution of social norms of cooperation.

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