Contagious cooperation, temptation and ecosystem collapse*

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Abstract

Real world observations suggest that social norms of cooperation can be effective in overcoming social dilemmas such as the joint management of a common pool resource – but also that they can be subject to slow erosion and even to sudden collapse. We show that these patterns of erosion and collapse emerge endogenously in a model of a closed community harvesting a renewable natural resource in which the diffusion of social extraction norms takes place via interpersonal relations, and where individual agents also face the temptation of higher profits by overexploiting the resource. We explore the underlying mechanisms by analyzing under what circumstances small changes in key parameters (including the size of the community, and the rate of technological progress) trigger catastrophic transitions from relatively high levels of cooperation to widespread norm violation – causing the demise of the resource.

Keywords: social norms, common pool resource, co–evolution, resilience, alternative stable states.

JEL codes: C73, D62, D64, Q20.

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1 Introduction

The history of mankind is one of gradual change in environmental quality and natural resource abundance, punctuated with sudden collapses of populations, species, ecosystems, and sometimes even of entire civilizations (Diamond, 2005; Scheffer, 2009; Taylor, 2009). Examples include the fall of the Maya empire and the collapse of the human population on Easter Island following the depletion of forest resources (Bahn and Flenley, 1992; Brander and Taylor, 1998; Diamond, 2005; Lentz and Hockaday, 2009; Scheffer, 2009). System collapse is typically the result of the interplay between natural resource regeneration and the socio–economic system driving resource use. Most extant studies, however, have focused on the existence of non–linear relationships in the dynamics of renewable natural resources. Examples of natural systems characterized by non–linear dynamics are those which feature a minimum population size below which extinction is inevitable (because of genetic degeneration, or because of increased difficulties to find a potential mate; see for example Gould, 1972; Berck, 1979; van Kooten and Bulte, 2000, Ch. 7), but also those with complex interactions between the various components of the ecological system as is the case in, for example, shallow lakes and grazing systems in semi–arid ecosystems (Anderies et al., 2002; Janssen et al., 2004; Kefi et al., 2007). The non–linearities in the regeneration functions typically give rise to the prediction that continued overharvesting of the resource results in a gradual demise of the resource until a threshold – or tipping point – is reached, beyond which collapse is inevitable and where subsequent system restoration is very costly – if not impossible; cf. Scheffer et al. (2001).

In this paper we contribute to the literature on tipping points in socio–ecological systems by analyzing how social interactions between resource users affect a system's resilience.

Following the literature on economic cooperation in social dilemmas (Bischi et al., 2004; Bulte and Horan, 2010; Noailly et al., 2003; Osés–Eraso and Viladrich–Grau, 2007; Sethi and Somanathan, 1996) we develop a model in which a finite number of community members have access to a commonly owned renewable resource. As is the case in the real world, we assume that the common property regime is such that community members are allowed to harvest the resource, but that they are not allowed to hire non–community members to engage in resource harvesting too if their own time constraint is binding (McCarthy et al., 2001). Next, the natural regeneration function of the resource is modeled as a standard logistic growth function (Verhulst, 1838), and community members can decide to act cooperatively in harvesting the resource by limiting extraction, or not. Agents are tempted to act non–cooperatively (also referred to as defecting) because of the higher associated profits, but we also allow for the possibility that whenever a cooperator and a defector meet, the cooperator may convince the defector of the social desirability of acting cooperatively. The diffusion of social norms regarding harvesting is thus assumed to take place via interpersonal relations, with cooperation being "contagious" with a certain probability: when an encounter takes place, the cooperator makes a moral appeal to the defector to start acting in the community's interest, and the appeal may or may not be successful. This modeling approach is consistent with the effectiveness of verbal expressions of discontent in inducing and sustaining cooperation in social dilemma situations as observed in laboratory experiments (see for example Masclet, 2003), but the mechanism can also reflect the use of self–regulatory instruments like peer–to–peer sanctions or rewards (Fehr and Gächter, 2000 and 2002; Gächter et al., 2008; Janssen et al., 2010; Rand et al., 2009). Our model thus combines the literature on the evolution of social norms for resource harvesting (Ostrom, 2000; Richerson et al., 2003) with insights from that on contagious behavior (Cavalli–Sforza and Feldman, 1981; Dodds and Watts, 2005; Heal and Kunreuther, 2010; Lopez–Pintado and Watts, 2008; Young, 2009).

To the best of our knowledge, our paper is the first to generate tipping points without explicitly introducing any non–linearities in the dynamics of the ecological system or the socio–economic system that, by themselves, give rise to multiple equilibria. The regeneration function we use is the logistic growth function, where the percentage rate of growth decreases linearly with resource abundance, and the socio-economic system is self-stabilizing as well. If, for whatever reason, the number of cooperators increases, the social pressure on defectors to become cooperators increases. But the temptation to defect increases as well because the benefits of defecting are larger too. And the opposite holds if there is a sudden, exogenous decrease in the number of cooperators. The social pressure on non–cooperators decreases, but the rents from defecting are dissipated quickly too.

However, our system can still generate positive feedbacks between the two systems, giving rise to multiple equilibria. For some range of parameter values the "good equilibrium" can be very resilient to exogenous shocks or external developments (such as, say, exogenous technological progress in harvesting), while the same small shocks or developments cause the socio–ecological system to collapse if the parameters are close enough to a critical threshold. The positive feedbacks (giving rise to tipping points) emerge because the property rights regime implies that the community's harvesting time endowment is finite. If the resource stock declines due to an exogenous development, cooperators reduce their harvesting effort while defectors still harvest as much as they can. This increases the wedge between profits of defectors and cooperators, raising the temptation to defect. As a result, more cooperators decide to defect, putting even more pressure on the resource stock. This leads to a spiral of depletion and defection, and eventually, the system flips to the "bad" equilibrium. The societal consequences of such a flip can be substantial because the system exhibits hysteresis. Upon system collapse, moving back to the "good equilibrium" can be difficult and costly – if it is feasible at all.

To our knowledge, this paper is the first to show that collapse can be caused by interpersonal interactions and economic constraints, rather than by the presence of non–linear functions describing either resource growth or social pressure through user interaction. Our focus on the socio–economic subsystem is especially relevant because of the important role social capital and community governance play in managing common pool resources like fish, forests, or grazing lands (Baland and Platteau, 1996; Ostrom, 1990, 2008, 2009; Ostrom and Nagendra, 2006). Our paper is, however, not the first in noting that coupled socio–ecological systems can be inherently complex (Barkley Rosser, 2001; Liu et al., 2007; Rammel et al., 2007). Research on tipping points in the socio–economic system includes Schelling's model of segregation (Schelling, 1969; see also Card et al., 2008), and social reinforcement models (Ball, 2004; Bikhchandani et al., 1992; Gladwell, 2000; Granovetter, 1978; Noelle–Neumann, 1974; Scheffer et al., 2003). Regarding work about social interaction and renewable resource use, Iwasa et al. (2007) analyze a system in which agents are more inclined to undertake pollution–mitigating activities when the environment is in a poor state, and also when social pressure is high. In their model, alternative stable states occur when social pressure increases strongly with the fraction of cooperators in the community. This framework has been extended to incorporate non–linear resource dynamics as well, leading to even richer dynamics (Suzuki and Iwasa, 2009b). Finally, Taylor (2009) developed a model in which a resource has a certain minimum viable size and resource extraction has a negative effect on the profitability of a competing sector, making resource exploitation even more attractive. Taylor finds that this positive feedback leads to alternative stable states. The resource is either in relatively good shape, or fully depleted. Our paper is complementary to this research in that we do not use any functional forms that, by themselves, give rise to tipping points; in our model collapse can occur because individuals' time endowments are not infinite.

The setup of the paper is as follows. In section 2 we present the model, focusing on the mechanisms driving changes in the size of the resource stock and on those affecting the number of cooperating individuals in the community. To provide a benchmark against which to evaluate the outcome of the co–evolution of the ecological and socio–economic systems, we derive the standard non–cooperative equilibrium as well as the socially optimal allocation of effort. In sections 3 and 4 we analyze how the socio–economic and ecological systems co–evolve in response to changes in key drivers of change including population growth and technological progress in harvesting. The analysis is complicated but we are able to analytically identify the system's tipping points if (i) there are no sources of income other than resource harvesting and (ii) the driver of system change is an increase in community members' effective time endowments (for example because of technological progress in domestic activities). Having identified the mechanisms giving rise to tipping points in this simple (and probably not most realistic) case in section 3, we resort to a numerical analysis in section 4 in which we relax the assumption of no alternative sources of income and where we analyze the system's resilience in the face of more important drivers of change such as population growth, technological progress in harvesting, or changes in the strength of moral persuasion. Section 5 concludes.

2 The model

We take the Gordon–Schaefer renewable resource model as a starting point (Clark, 1990), and assume that there are $N > 1$ agents in a community who have access to a commonly–owned natural resource. The right to extract is exclusively associated with community membership; community members are not allowed to employ outsiders to assist in harvesting. The size of the resource stock at time t is denoted by $X(t)$. Each agent is endowed with a fixed effort rate $\hat{e}$ which she can allocate to harvesting the common pool resource, or to an alternative economic activity. The amount of effort agent i ($i = 1 \ldots N$) allocates to resource harvesting at time t is denoted by $e_i(t)$, and hence $\hat{e} - e_i(t)$ is the amount of effort she allocates to the alternative activity at time t. We assume that the return to effort in the alternative economic activity is constant and equal to w, so that the income agent i derives from this activity at time t is equal to $w\left(\hat{e} - e_i(t)\right)$.

The relationship between harvesting effort and the quantity of resource goods harvested is given by the Schaefer production function, $h_i(t) = qX(t)e_i(t),$ where $h_i(t)$ denotes the quantity harvested by individual i at time t and q is a technology parameter reflecting what share of the resource stock can be harvested per unit of effort employed (the so–called catchability coefficient). That means that the total quantity harvested by the N agents at time t equals $\sum_{i=1}^{N} h_i(t) = qX(t)\sum_{i=1}^{N} e_i(t)$.

Regarding the resource dynamics, harvesting reduces the remaining stock, but there is also natural regeneration. The change in the size of the resource stock at time t, $dX(t)/dt$, is equal to the net natural growth resulting from reproduction and mortality, $G\big(X(t)\big)$, minus the aggregate amount harvested by the N agents having access to the resource, $\sum_{i=1}^{N} h_i(t)$. We assume that resource regenerates according to the standard logistic growth function (Verhulst, 1838), $G\big(X(t)\big) = rX(t)\big(1 - X(t)/K\big)$, where $r > 0$ is the intrinsic growth rate and $K > 0$ is the carrying capacity – the maximum stock size the resource would eventually reach if no harvesting took place. Without loss of generality we rescale the resource stock with the carrying capacity by setting $K = 1$. The variable $X(t)$ can now be thought of as the size of the natural resource stock as a fraction of its maximum value, and hence the size of the resource stock changes over time as follows:

(1) $dX(t)/dt = rX(t)\big(1 - X(t)\big) - qX(t)\sum_{i=1}^{N} e_i(t).$

Regarding the returns to harvesting effort, we assume that resource goods can be sold at a time–invariant unit price P (so that sales revenues are equal to $Ph_i(t) = PqX(t)e_i(t)$), but we also assume that resource harvesting gives rise to an instantaneous negative externality: the returns any agent receives on her effort negatively depends on the total effort put in by the $N - 1$ agents. More specifically, we assume that the net income generated by resource harvesting at time t is equal to $\big(PqX(t) - vE(t)\big)e_i(t)$, where $E(t) = \sum_{j=1}^{N} e_j(t)$ denotes the community's aggregate effort in resource harvesting, and v reflects the extent to which the net marginal benefits of resource harvesting of an individual agent are reduced if the community's aggregate effort increases by one unit. Here, v can be thought of as the costs of congestion (for example because agents interfere with each other or have to compete for the bests spots), but also as any other negative interaction between contemporaneous harvesting activities (Cárdenas et al., 2000; Clark, 1990, p.223; Iwasa et al., 2007; Satake et al., 2007; Scheffer et al., 2000; Suzuki and Iwasa, 2009a; Wilson, 1982). Adding up the net revenues of harvesting and those of the alternative economic activity, total income earned by agent i at time t is:

(2) $\pi_i(t) = PqX(t)e_i(t) + w\left(\hat{e} - e_i(t)\right) - vE(t)e_i(t),$ where $0 \le e_i(t) \le \hat{e}.$[1]

Note that this setup implies that there are two negative externalities, an instantaneous one and an intertemporal one. The intertemporal externality arises because current resource extraction reduces the amount of resources available in the future – thus reducing the marginal productivity of harvesting effort (cf. (1) and (2)). The instantaneous externality, vE, arises because of, for example, crowding or congestion. These intertemporal and instantaneous externalities give rise to so–called Class I and Class II problems, respectively (Munro and Scott, 1985), and we assume that community members are concerned about the instantaneous crowding externality (the Class II problem) but not about the intertemporal externality (the Class I problem) – because they are not fully informed about the dynamics of resource regeneration, or simply because they are myopic. This setup is consistent with the real–world observation that many communities are able to reach a consensus on how to overcome the direct externality of the Class II problem (e.g. taking turns in getting the best fishing spots rather than competing for them), but not on the

[1] From here onwards we omit time indicators, unless omitting them may cause confusion.

amount of resource to be extracted, which corresponds to the Class I problem; see for instance Taylor (1987).

2.1 Privately and socially optimal resource use

Before analyzing the interaction of agents when some (but not necessarily all) adhere to a social norm, we first determine the socially optimal and privately optimal use of the renewable resource to obtain benchmarks for the more complex interactions between cooperators and defectors as presented in sections 3 and 4.

Because agents do not take the intertemporal Class I problem into account, the relevant benchmark for cooperation is the aggregate effort that maximizes the community's instantaneous aggregate income to overcome the Class II problem. We refer to this benchmark as the social optimum.[2] Using superscript SO to denote socially optimal values and taking into account that $0 \leq e_i(t) \leq \hat{e}$ for all t, the aggregate effort that maximizes instantaneous social welfare $E^{\mathrm{SO}}(X)$ is defined as follows:

$$(3) \quad E^{\mathrm{SO}}(X) = \max_{E} \left\{ PXqE + w\left(N\hat{e} - E\right) - vE^2 \,\middle|\, 0 \leq E \leq N\hat{e} \right\}.$$

Solving (3), the symmetric individual socially optimal extraction effort $(e^{\mathrm{SO}} = E^{\mathrm{SO}} / N)$ is equal to:

[2] The socially optimal level of the resource stock as defined here is below the "true" socially optimal level as it only solves the instantaneous Class II problem whereas the true social optimum would require agents taking into account the intertemporal (= Class I) problem as well.

$$(4) \quad e^{\mathrm{SO}}(X)=\begin{cases} \hat{e} & \text{if} \quad X \geq (w+2vN\hat{e})/(Pq), \\ \dfrac{PqX-w}{2vN} & \text{if} \quad w/(Pq) \leq X < (w+2vN\hat{e})/(Pq), \\ 0 & \text{if} \quad 0 \leq X < w/(Pq). \end{cases}$$

We can determine the socially optimal steady state resource stock as follows. Substituting $\sum_{i=1}^{N} e_i = N\hat{e}$ and $\sum_{i=1}^{N} e_i = (PqX-w)/2vN$ – cf. (4) – into equation (1) and setting $dX/dt = 0$, we find that the socially optimal steady state resource stock is equal to:

$$(5) \quad X^{\mathrm{SO}}=\begin{cases} (r-\hat{e}Nq)/r & \text{if} \quad \hat{e} \leq \dfrac{r(Pq-w)/N}{2rv+Pq^2}, \\ \dfrac{2vr+wq}{2vr+Pq^2} & \text{if} \quad \hat{e} > \dfrac{r(Pq-w)/N}{2rv+Pq^2}. \end{cases}$$

Next, let us analyze what happens if all agents try to maximize their own private welfare without taking into account the negative consequences of their extraction effort on the welfare of all other agents in the community. We refer to this outcome as the non–cooperative equilibrium (using superscript NC). The effort that maximizes instantaneous private welfare is given by

$$(6) \quad e(X,E_{-i}) = \max_{e_i}\left\{PXqe_i + w(\hat{e}-e_i) - v(E_{-i}+e_i)e_i \,\middle|\, 0<e_i \leq \hat{e}\right\},$$

where $E_{-i} \equiv \sum_{j\neq i} e_j$. The best response function for selfish agents to the aggregate effort of the $N-1$ other agents in the community is given by

$$(7) \quad e^{\mathrm{BR}}(X,E_{-i}) = \min\left\{\frac{PXq-w}{2v} - \frac{1}{2}E_{-i}, \hat{e}\right\},$$

where superscript BR stands for best response. In the symmetric non–cooperative equilibrium we have $E_{-i} = (N-1)e^{\mathrm{BR}}$, and hence the symmetric non–cooperative equilibrium effort equals

$$
(8) \quad e^{\mathrm{NC}}(X)=\begin{cases} \hat{e} & \text{if} \quad X \geq \left(w+v\left(N+1\right)\hat{e}\right)/\left(Pq\right), \\ \dfrac{PqX-w}{v\left(N+1\right)} & \text{if} \quad w/\left(Pq\right) \leq X < \left(w+v\left(N+1\right)\hat{e}\right)/\left(Pq\right), \\ 0 & \text{if} \quad 0 \leq X < w/\left(Pq\right). \end{cases}
$$

Next, we determine the non–cooperative equilibrium steady state resource stock. Substituting $\sum_{i=1}^{N} e_i = N\hat{e}$ and $\sum_{i=1}^{N} e_i = N\left(PqX-w\right)/v\left(N+1\right)$ – cf. (8) – into equation (1) and setting $dX/dt = 0$, we find that the non–cooperative steady state resource stock is equal to

$$
(9) \quad X^{\mathrm{NC}}=\begin{cases} \left(r-\hat{e}Nq\right)/r & \text{if} \quad \hat{e} \leq \dfrac{r\left(Pq-w\right)/N}{2rv+Pq^2}, \\ \dfrac{\left(N+1\right)vr+Nwq}{\left(N+1\right)vr+NPq^2} & \text{if} \quad \hat{e} > \dfrac{r\left(Pq-w\right)/N}{2rv+Pq^2}. \end{cases}
$$

Comparing (4) to (8) and (5) to (9), we find that $X^{NC} \leq X^{SO}$ and $e^{\mathrm{NC}}(X) \geq e^{\mathrm{SO}}(X)$, and the social optimum and non–cooperative equilibrium coincide only if either N = 1, or $\hat{e} \leq \dfrac{r\left(Pq-w\right)/N}{2rv+Pq^2}$. The latter result occurs because if the total amount of effort in the community $(N\hat{e})$ is too small to draw down the resource stock to a level below $X=\left(w+2vN\hat{e}\right)/Pq$, it is both socially and privately optimal for all community members to put in $\hat{e}$ effort into resource harvesting. Therefore, a social dilemma only materializes if $\hat{e} > \dfrac{rPq/N}{2rv+Pq^2} \equiv \hat{e}_0$. Furthermore, if $\hat{e} > \hat{e}_0$ the larger the community (N), the more resource rents are dissipated absent any cooperation. If N is sufficiently large such that $N/\left(N+1\right) \approx 1$, all resource rents are dissipated as soon as the time constraint ceases to be binding in harvesting:

$$(10)\quad \pi_i^{\mathrm{NC}} = \left(PqX - w - vN\left(\frac{PqX - w}{v(N+1)}\right)\right) e_i^{\mathrm{NC}} + w\hat{e} \approx w\hat{e} \;\text{ if }\; w/(Pq) < X < \left(w + v(N+1)\hat{e}\right)/Pq.$$

2.2 Modeling cooperation, defection and the dynamics of social interaction

We assume that agents choose between two modes of behavior, acting cooperatively or non–cooperatively (also referred to as defection). We assume that cooperating agents take the instantaneous Class II problem into account, while agents acting non–cooperatively just try to maximize their own instantaneous income, taking the effort of all other agents as given. In this subsection, we first derive the effort rates chosen by the cooperators and defectors, and then discuss the mechanisms inducing cooperators to defect, and those inducing defectors to start cooperating.

Following Bischi et al. (2004), we assume that cooperators always put in their fair share of the aggregate effort that would maximize instantaneous social welfare given the current size of the resource stock, $E^{\mathrm{SO}}(X)$. In other words, cooperators choose $e^C = E^{\mathrm{SO}}(X)/N = e^{\mathrm{SO}}(X)$ for all *X*, where $e^{\mathrm{SO}}(X)$ is given by (4).

Next, we derive what harvesting effort defectors choose to maximize their private welfare, taking into account both the size of the resource stock *X* and the number of cooperators and defectors in the community – as the numbers of cooperators and defectors influence the aggregate extraction effort invested by the defectors. We use $C(t)$ and $D(t)$ to respectively denote the number of cooperators and defectors in the community at time *t*, where $D(t) \equiv N - C(t)$. A defector then maximizes his instantaneous profits, facing an aggregate effort rate of the $N-1$ other agents equal to $E_{-i} = Ce^{\mathrm{SO}} + \left(D-1\right)e^{\mathrm{BR}}$. Substituting this expression into (7) and using (4), we find that the equilibrium effort defectors allocate to harvesting is equal to:

$$(11)\quad e^{D}(X,C) = \begin{cases} \hat{e} & \text{if} \quad X \geq \dfrac{w}{Pq} + \dfrac{2vN\hat{e}(N-C+1)}{Pq\left(2N-C\right)}, \\ \dfrac{\left(PXq-w\right)\left(2N-C\right)}{2vN(N-C+1)} & \text{if} \quad \dfrac{w}{Pq} \leq X < \dfrac{w}{Pq} + \dfrac{2vN\hat{e}(N-C+1)}{Pq\left(2N-C\right)}, \\ 0 & \text{if} \quad 0 \leq X < \dfrac{w}{Pq}. \end{cases}$$

Note that the harvesting effort of defectors does not only depend on the size of the resource *X*, but also on the number of agents acting cooperatively *C* at every instant in time. Furthermore, consistent with intuition, $e^{D}(X,C) = e^{\mathrm{NC}}(X)$ if $C = 0$; cf. (8) and (11).

Next, we model social interaction by taking into account two countervailing forces. One is that agents are tempted to act non–cooperatively because of the higher profits associated with acting selfishly. The other is that agents see the need of solving the instantaneous Class II problem, and hence cooperators have an incentive to try to convince defectors of the social desirability of reducing their harvesting effort to the cooperative level. We explain the two countervailing forces one by one.

Regarding the temptation to start acting selfishly, we assume that agents are more likely to defect the larger is the income associated with acting non–cooperatively as compared to that of acting cooperatively. This assumption is consistent with the observation that individuals tend to consider relative payoff differences rather than absolute ones (Azar, 2007). More specifically we assume that the fraction of cooperators that decide to defect at time *t* because of the temptation of higher income is equal to $\frac{dC/dt}{C} = -\beta\left(1 - \frac{\pi^C(X)}{\pi^D(X,C)}\right)$, where β is a parameter capturing the extent to which cooperators are tempted to become defectors for a given payoff ratio π^C/π^D. Clearly, $dC/dt \le 0$ because, by definition, $\pi^D \ge \pi^C$; cf. (2), (4) and (11).

Next, we assume that whenever a cooperator meets a defector, there is a probability μ that the former succeeds in convincing the latter to act cooperatively. While we do not specifically rule out that cooperators turn into defectors after an encounter, we do assume that the net effect favors cooperation. This is plausible because in our setup defectors have no incentive to convince cooperative individuals to defect. The occurrence of discrete encounters can be modeled as a Poisson process. The probability of an encounter taking place in the time interval $(t,\ t+\Delta t)$ is proportional with Δt and with the number of cooperators $C(t)$ and defectors $D(t)$. For Δt sufficiently small, the possibility of a community member having more than one encounter is negligible. Using λ to denote the Poisson parameter, the probability of a cooperator meeting a defector in the time interval $(t,\ t+\Delta t)$ is then equal to $\lambda C(t)D(t)\Delta t/N$. Taking into account the fixed size of the community and defining $\alpha \equiv \lambda\mu$, the expected value of the change in $C(t)$ is equal to $C(t+\Delta t) - C(t) = \alpha C(t)D(t)\Delta t/N$, and hence $dC/dt = \alpha C(N-C)/N$. Combining the effects of moral persuasion and temptation, the number of cooperators develops over time according to the following differential equation:

(12) $$dC/dt = \frac{\alpha}{N}C(N-C) - \beta C\left(1 - \frac{\pi_C(X)}{\pi_D(X,C)}\right).$$

We can now analyze how the behavioral composition of resource users in the population affects the size of the resource stock, and vice versa.[3] Suppose there are $C(t)$ cooperators at time t (and hence $N - C(t)$ defectors). In equilibrium, we have (i) $dX/dt = 0$, and (ii) $dC/dt = 0$; see equations (1) and (12), respectively. The number of cooperators does not change over time ($dC/dt = 0$) if the number of cooperators defecting equals the number of defectors being persuaded to act cooperatively:

$$(13) \quad \frac{\alpha}{N} C(N-C) = \beta C\left(1 - \frac{\pi^C(X)}{\pi^D(X,C)}\right)$$

and $dX/dt = 0$ requires that

$$(14) \quad rX(1-X) = qX\left(Ce^C + (N-C)e^D\right).$$

We proceed as follows. In section 3 we analyze the case where there is no alternative economic activity (w = 0) so that the resource good is the only source of income for the community. This assumption allows us to derive analytical results because $\pi^C / \pi^D = e^C / e^D$ (cf. (2)), thus considerably facilitating the analysis of (12) and (13). With w > 0 analytical results cannot be obtained, and hence we resort to a numerical analysis presented in section 4.

[3] If the success rate of convincing defectors is too low (more specifically, if $\alpha \leq \beta(N-1)/2N$), cooperators will completely disappear from the population – as shown in section 4.2. Inserting C = 0 in equation (12) it is easy to see that the disappearance of cooperators results in dC/dt = 0 independent of whatever policy intervention a regulator may want to undertake. This is neither plausible nor very interesting, and hence we assume that $\alpha > \beta(N-1)/2N$.

3 The co–evolution of cooperation and the resource stock absent alternative employment options

Suppose the community is self–sufficient and there is no alternative economic activity. The absence of an alternative economic activity can be captured by setting w = 0, which can be inserted directly into equations (1)–(14).

3.1 The steady states of the socio–ecological system

Combining (4) and (11) and setting $w = 0$, we can identify three regimes (R1–R3).

(15.R1) If $X \geq \frac{2vN\hat{e}}{Pq}$, we have $e^C = e^D = \hat{e}$.

(15.R2) If $\frac{2vN\left(N-C+1\right)\hat{e}}{Pq\left(2N-C\right)} \leq X < \frac{2vN\hat{e}}{Pq}$, we have $e^C = \frac{PqX}{2vN}$ and $e^D = \hat{e}$.

(15.R3) If $0 \leq X < \frac{2vN\left(N-C+1\right)\hat{e}}{Pq\left(2N-C\right)}$, we have $e^C = \frac{PqX}{2vN}$ and $e^D = \frac{PqX\left(2N-C\right)}{2vN\left(N-C+1\right)}$.

Before analyzing the three regimes, let us first have a closer look at the two boundaries separating the three regimes. As is evident from (4), the boundary between regimes 1 and 2 is

(16) $X(C)\big|_{R1/R2} = 2vN\hat{e}/Pq$,

and this is a horizontal line in (C,X) space. For all $X \geq X(C)\big|_{R1/R2}$ every agent in the community chooses the maximum effort rate $\hat{e}$, while the cooperative agents always choose interior harvesting effort rates when $X < X(C)\big|_{R1/R2}$. As implied by equation (11), the boundary separating regimes 2 and 3 is given by

$$(17)\quad X(C)\big|_{R2/R3} = \frac{2vN\left(N-C+1\right)\hat{e}}{Pq\left(2N-C\right)},$$

and this boundary is downward–sloping and concave in the (*C*,*X*) space. For any number of cooperators *C*, defectors continue harvesting at the maximum effort rate $\hat{e}$ for all $X \geq X(C)\big|_{R2/R3}$, whereas every community member chooses an interior harvesting effort rate when $X < X(C)\big|_{R2/R3}$.

Let us now turn to analyzing the dynamics of the size of the resource stock and of the number of cooperators in the three regimes. All results are summarized in Table 1. Row A of this table contains the regime boundaries (16) and (17), while rows B, C and D represent $e^C(X)$, $e^D(X,C)$ and $E(X,C)$, respectively, in each of the three regimes; cf. (15.R1)–(15.R3). It is then straightforward to calculate both the percentage change in the size of the resource stock $\left(\frac{1}{X}\frac{dX}{dt}\right)$ and the percentage change of the number of cooperators $\left(\frac{1}{C}\frac{dC}{dt}\right)$ in each of the three regimes by inserting $E(X,C)$ into the associated differential equations (1) and (12) – see rows E and G. Then, we calculate the combinations of *X* and *C* that give the isoclines $dC/dt = 0$ and $dX/dt = 0$ (see equations (13) and (14)) – the so–called nullclines for the two state variables *X* and C; see rows F and H, respectively.

Let us first have a look at the nullcline of the resource stock in the three regimes; see row F in Table 1. If $\hat{e} \leq e_0$, the total amount of effort in the community $(N\hat{e})$ is too small to draw down the resource stock to the level where harvesting starts posing a social dilemma (that is, at $X = 2vN\hat{e}/Pq$; compare (4) and (8)). If $\hat{e} > e_0$, *X* is always reduced to a level equal to or below

$X = \left(w + 2vN\hat{e}\right) / Pq$ because it is both privately and socially optimal to do so. Hence, we only have *dX/dt* = 0 in regime 1 if the community's aggregate time endowment is sufficiently small.

< Insert Table 1 about here >

To have the system reach regimes 2 and 3, we need $\hat{e} > e_0$. If that is the case, the nullcline of *X* in regime 2 is equal to $X(C) = \frac{2vN\left[r - q\hat{e}\left(N - C\right)\right]}{2vNr + Pq^2C}$, which is an upward–sloping and concave function of the number of cooperators, *C*; see row F for regime 2. Finally, the nullcline of *X* is upward–sloping and concave in regime 3, as given by $X(C) = \frac{vr}{Pq^2Z(C) + vr}$, where $Z(C) = \frac{N - C + C/2N}{N - C + 1}$. Because $Z(C) \approx 1$ if *C* is small relative to *N*, the nullcline is almost horizontal in regime 3. Finally, there is a trivial nullcline at *X* = 0 (not shown): once the renewable natural resource is fully extinct, it will never recover.

The nullclines of the resource stock can also be depicted graphically; see Figure 1A. We present the case where $\hat{e} > e_0$ because we already know from Table 1 that if the individual effort endowment is below this level, there is just one non–trivial steady state (which is located in regime 1, with all community members being cooperators). Instead, Figure 1 depicts the more interesting case of $\hat{e} > e_0$. In this case, as indicated by row F of Table 1, the nullcline for *X* is an almost horizontal line in regime 3, it is concave and upward–sloping in regime 2, and in regime 1 we always have *dX/dt* < 0 for all $0 \le C \le N$. Finally, the dynamics of the resource stock are indicated in this figure by means of arrows; for all stocks above (below) the nullcline of *X*, the resource stock is declining (increasing) over time.

<Insert Figure 1 about here>

Next, let us analyze the location of the *dC/dt* = 0 isocline in the three regimes; see row H in Table 1. There is a trivial nullcline at $C = 0$ (not shown); if there are no cooperators, nobody is available to convince the defectors of the desirability of acting cooperatively. In addition, the nullcline of *C* is vertical at $C = N$ in regime 1: because $e^C(X) = e^D(X, C) = \hat{e}$, all agents are cooperators if $X \geq 2vN\hat{e}/Pq$. Next, in regime 2 the nullcline of *C* is a linear upward–sloping function of *X*: $C(X) = \left(2v(\alpha - \beta)N\hat{e} + \beta PqX\right)/2v\hat{e}\alpha$. Finally, the nullcline of *C* is vertical in the (*C*,*X*) space in regime 3: $C(X) = \frac{3}{2}N - \frac{1}{2}\sqrt{N^2 + \frac{4\beta N}{\alpha}(N-1)} > 0$.[4] As was the case with the resource stock in Figure 1A, we can graphically depict the dynamics of the number of cooperators in the community; see Figure 1B. For all numbers of cooperators left (right) of the non–trivial nullcline of *C* (as defined in row H of Table 1), the number of cooperators in the community increases (decreases) over time.

Let us now determine the steady states of the system in the three regimes, which requires calculating the intersection points of the *dX/dt* = 0 and *dC/dt* = 0 isoclines (see also Appendix

[4] Recall from footnote 3 that we assume $\alpha > \beta(N-1)/2N$. That means that indeed $C(X) > 0$ for all $X > 0$.

A). Both the number of equilibria as well as their location in the various regimes depend on the relative sizes of all parameters of both the socio–economic and ecological subsystems. If $\hat{e} \leq \hat{e}_0$, the system has one non–trivial steady state, $(C, X) = \left(N, \left(r - \hat{e}Nq\right)/r\right)$, and this steady state is located in regime 1; see row F in Table 1.

The case of $\hat{e} > \hat{e}_0$ can be represented graphically by superimposing Figures 1A and 1B; see Figure 2. From Figures 2A, 2B and 2C we see that there is no steady state in regime 1 if $\hat{e} > \hat{e}_0$, but there may be 0, 1 or 2 steady states in regime 2, and there is maximally one stable steady state in regime 3.[5] We proceed with analyzing the various cases.

<Insert Figure 2 about here>

Regarding the number of steady states in regime 2 if $\hat{e} > \hat{e}_0$, we have zero steady states in that regime if the *dC/dt* = 0 isocline is located strictly to the North–West of the *dX/dt* = 0 isocline for all values of *C*; see Figure 2A. In equation (A6) of Appendix A we show that this is the case if $\hat{e} > \hat{e}_1$, where $\hat{e}_1$ is defined by

$$(18) \quad \hat{e}_1 = \frac{4\beta r P^2 q^3}{N\left(4\beta P q^2\left(2rv + Pq^2\right) - \alpha\left(4rv\left(rv + Pq^2\right) + P^2 q^4\right)\right)}.$$

[5] All equilibria with either X = 0 or C = 0 are trivial, and all of them are unstable. Because of these reasons, we ignore them in the rest of the paper.

Here, $\hat{e}_1$ is defined as the effort endowment for which $dC/dt = 0$ and $dXdt = 0$ are tangent in regime 2. If $\hat{e} > \hat{e}_1$, there are zero equilibria in regimes 1 and 2, and there is exactly one equilibrium in regime 3; see E_3 in Figure 2A.[6]

If, however, $\hat{e}_0 < \hat{e} \leq \hat{e}_1$, there are either one or two equilibria in regime 2, and one or zero in regime 3; see Figures 2B and 2C. First, the nullclines of X and C are tangent if $\hat{e} = \hat{e}_1$, giving rise to just one equilibrium in regime 2, and also one in regime 3. Note that the nullcline of C in regime 2 is an upward–sloping straight line that intersects the top regime boundary at $C = N$.[7] Also note that the nullcline of X is upward–sloping and concave in regime 2, and that it hits the $C = N$ axis at resource stock level that is strictly below the top regime boundary.[8] That means that the two nullclines always intersect twice in regime 2 unless the intersection point of the C nullcline with the lower boundary is to the South–East of that of the X nullcline; see Figure 2C. Using the specifications of the nullclines of X and C from either regime 2 or regime 3, these nullclines intersect at the boundary between regimes 2 and 3 if $\hat{e}$ is equal to $\hat{e}_2$, where $\hat{e}_2$ is derived in equations (A7) and (A8) in Appendix A:

[6] This can easily be inferred from Figure 2A. The nullcline of C is vertical in regime 3 while the associated nullcline of X is upward sloping and concave (albeit near–horizontal); see rows F and H in Table 1. That means that the two nullclines always intersect in regime 3 as long as the nullcline of C intersects the boundary between regimes 2 and 3 to the North–West of the point where the nullcline of X intersects that boundary. This condition is always met if the nullcline of C is located strictly to the North–West of the nullcline of X in regime 2 – because the nullcline of C is an upward–sloping and straight line in regime 2 while the associated nullcline of X is upward–sloping and concave.

[7] This can be verified by inserting $X = 2vN\hat{e}/Pq$ into $C(X) = \left(2v\left(\alpha - \beta\right)N\hat{e} + \beta PqX\right)/2v\hat{e}\alpha$ in row H of Table 1.

[8] This can be verified by inserting $C = N$ into $X(C) = \dfrac{2vN\left[r - q\hat{e}(N-C)\right]}{2vNr + Pq^2C}$ in row F of Table 1.

(19) $$\hat{e}_2 = \frac{\beta r P q}{\alpha N\left(rv + Pq^2\right) + \beta\left(2rNv + Pq^2\left(2N-1\right)\right) - \sqrt{\alpha}\sqrt{N}\sqrt{\alpha N + 4\beta\left(N-1\right)}\left(rv + Pq^2\right)}.$$

If $\hat{e} < (>)\ \hat{e}_2$ the nullcline of C intersects the lower regime boundary to the South–East (North–West) of the point where the nullcline of X hits the lower boundary. Hence, a necessary condition for having two equilibria in regime 2 and one in regime 3 is that $\hat{e}_1 > \hat{e} > \hat{e}_2$, while a necessary condition for having just one equilibrium in total is that $\hat{e} < \hat{e}_2$ (where the equilibrium is located in regime 1 if $\hat{e} < \hat{e}_0$, and where it is located in regime 2 if $\hat{e}_0 < \hat{e} < \hat{e}_2$).

So we can now fully describe all possible equilibrium constellations for all possible levels of effort endowments. First, if $\hat{e} \le \hat{e}_0$, there is one stable equilibrium in regime 1 (not shown in Figure 2). Next, if $\hat{e}_0 < \hat{e} < \hat{e}_2$, the system still has just one stable equilibrium, E_1, and this equilibrium is located in regime 2; see Figure 2C. If $\hat{e}_2 < \hat{e} < \hat{e}_1$, we have three equilibria in total; a stable and an unstable one in regime 2 (E_1 and E_2, respectively), and a stable one (E_3) in regime 3 – as depicted by Figure 2B. Finally, if $\hat{e} > \hat{e}_1$, there is just one stable equilibrium (E_3) in regime 3, as depicted in Figure 2A.

The stability properties of the situations depicted for $\hat{e} > \hat{e}_1$ (Figure 2A) and $\hat{e}_0 < \hat{e} < \hat{e}_2$ (Figure 2C) are straightforward, but they are slightly more complicated in case of $\hat{e}_2 < \hat{e} < \hat{e}_1$ (Figure 2B). The phase diagram associated with the latter case is presented more clearly in Figure 3. Figure 3A shows that equilibria E_1 and E_3 are locally stable nodes, while they are separated by an unstable saddle–point E_2. And Figure 3B shows that if the system is in the "good" equilibrium E_1 ("bad" equilibrium E_3), a shock that reduces (increases) the number of cooperators can move the system to the "bad" equilibrium E_3 ("good" equilibrium E_1), but only if the shock is sufficiently large to make the system jump into the basin of attraction of E_3 (E_1) beyond the separatrix going through the unstable intermediate equilibrium E_2.

<Insert Figure 3 about here>

So, our socio–ecological system can be in a variety of steady states, and the number of steady states depends on the parameters of the system. Figure 4 shows a conceptual figure of the feedback structure of the system and explains which mechanisms cause these multiple equilibria. Moral persuasion is stronger if there are more cooperators, but so is the temptation to defect – because the best–response function of a defector is a decreasing function of the aggregate effort put in by the other community members; cf. (7). The two effects stabilize each other, and the interaction of cooperators and defectors alone does not cause multiple equilibria. Rather, it is the fact that individual harvesting effort can never be larger than $\hat{e}$ that produces these alternative stable states. Because individual labor is in limited supply, a positive feedback arises between the size of the resource stock and the number of defectors. The smaller the resource stock, the larger the payoffs of defectors relative to those of cooperators (see the dotted line between the resource stock and the number of defectors in Figure 4). And the more defectors there are, the smaller is the resource stock (see the uninterrupted line between the resource stock and the number of defectors in Figure 4). This positive feedback produces alternative stable states and may lead to catastrophic transitions. Without the effort constraint, the relative change in harvesting effort of cooperators and defectors would be the same, keeping the payoff ratio, and hence the temptation to defect, constant. Hence, if harvesting effort were unbounded, we would only have one steady state, the "bad" equilibrium E_3.

<Insert Figure 4 about here>

3.2 The availability of effective labor time and system collapse

In section 3.1 we have shown that the socio–ecological system exhibits alternative stable states. In principle, the system can move from one stable equilibrium to another because of exogenous changes in the harvesting technology (q), the size of the community (N), the agents' time endowment ($\hat{e}$), or in any other parameter in either the ecological or the socio–economic system. In this subsection we analyze how the system is affected when exogenous developments increase the community's aggregate time endowment available for resource harvesting. Here, $\hat{e}$ may change because of efficiency improvements in household chores. Admittedly, from the list of potential drivers of system collapse this is the least plausible one, but analytically it is the easiest one. Therefore, we focus on the impact of changes in $\hat{e}$ in this subsection, but we present the full analysis of the consequences of, among others, population growth and technological progress in section 4.2.

The typical pattern for the equilibrium values of C and X as a function of $\hat{e}$ (keeping all other parameters constant) are presented in Figures 5A and 5B, respectively.

<Insert Figure 5 about here>

Starting from the point where agents have time endowments less than $\hat{e}_0$, the aggregate effort available $N\hat{e}$ is insufficient for the community to reduce the resource stock below $X = 2vN\hat{e} / Pq$ (cf. (16)) even if all community members spend all their effort on resource harvesting (see also rows B and C in regime 1 of Table 1). Because defectors and cooperators all harvest at the maximum rate, temptation to defect is absent and hence $C = N$ for all values of $\hat{e}$ below $\hat{e}_0$; see Figure 5A. The equilibrium resource stock is equal to $X = \left(r - Nq\hat{e}\right) / r$, and hence the size of the resource stock decreases linearly with $\hat{e}$; see Figure 5B. This is the case as long as $\hat{e} < \hat{e}_0$ and the steady states associated with each effort endowment are all located in regime 1.

So, for $\hat{e} < \hat{e}_0$, the system displays a gradual decline of the resource stock X if $\hat{e}$ increases. However, changes in $\hat{e}$ affect the system in multiple respects; all proofs are presented in Appendix B. First, any increase in $\hat{e}$ results in the boundary between regimes 1 and 2 shifting up (the cooperators switch to interior harvesting effort rates at larger remaining stock sizes if $\hat{e}$ increases), while the boundary between regimes 2 and 3 rotates to the North–East (see (16) and (17), but also equations (B1) and (B2) in Appendix B). Second, the locations of the $dX/dt = 0$ and $dC/dt = 0$ isoclines are also affected by changes in $\hat{e}$. From row F in Table 1 we see that the nullcline of X shifts down in regime 2 if the agents' time endowment increases, while the nullcline of C shifts to the left in that regime – as shown in row H in Table 1 (see also equations (B3) and (B4) in Appendix B). When $\hat{e}$ becomes larger than $\hat{e}_0$ and continues to increase, the system moves through the phase diagrams and equilibria as presented in Figure 2A, 2B and 2C – but in reverse order. So, for $\hat{e}_0 \le \hat{e} < \hat{e}_2$, the two nullclines intersect zero times in regimes 1 and 3 and just once in regime 2, and the associated equilibrium, E_1, is globally stable; see Figure 2C. If

$\hat{e}$ continues to increase, the *dX/dt* = 0 isocline shifts further down while the *dC/dt* = 0 isocline continues to rotate upward, and hence E_1 moves to the South–West. That means that *C* and *X* continue to gradually decline if $\hat{e}$ continues to increase in the range $\hat{e}_0 \leq \hat{e} < \hat{e}_2$; see Figure 5. In regime 2 the cooperators reduce their effort below $\hat{e}$, and the more so the smaller is *X*; see row B in Table 1. The defectors, however, keep on harvesting at the maximum rate, and hence the difference in profits between cooperators and defectors increases with $\hat{e}$. As a result *C* falls, but the fall in *X* is less pronounced because the cooperators reduce their harvesting effort.

If $\hat{e}$ continues to increase so that it moves into the range $\hat{e}_2 \leq \hat{e} < \hat{e}_1$, the nullclines have shifted such that they intersect twice in regime 2; see Figure 2B. Now two new equilibria emerge, in addition to the initial (and locally stable) equilibrium E_1: the unstable equilibrium E_2, located in regime 2, and the locally stable equilibrium E_3, located in regime 3. The three equilibria are represented in Figure 5 – with the stable equilibria being connected by continuous lines and the unstable equilibria being connected by the dotted line. As long as $\hat{e} < \hat{e}_1$, the system remains in the good equilibrium E_1, and further exogenous increases in $\hat{e}$ just move the nullcline of *C* more to the left while the nullcline of *X* continues to shift down. That means that E_1 continues to gradually move to the South–West. This implies that the basin of attraction of the "good" equilibrium shrinks, and hence the system's resilience decreases.

While the decline in resource conservation and cooperation is thus gradual for increases in $\hat{e}$ as long as $\hat{e} < \hat{e}_1$, the system collapses at $\hat{e} = \hat{e}_1$. At this critical threshold (or tipping point), equilibria E_1 and E_2 coincide in regime 2, and even an infinitesimally small increase in $\hat{e}$ beyond $\hat{e}_1$ causes the equilibrium in regime 2 to vanish, moving the system to the one remaining equilibrium, E_3, in regime 3; see Figure 2A. The system collapses, and in Figure 5 the equilibrium values of C and X drop to the lower branches. During the transition from the good equilibrium E_1 to the bad equilibrium E_3, the profits of cooperators fall with an increase in $\hat{e}$ because (i) they reduce their effort and (ii) the return on whatever effort they decide to put in, falls too – because of the fall in X. Profits of the defectors fall too, but less so because they do not reduce their effort yet – and hence only suffer from the lower returns to effort. That means that the temptation to defect continues to increase, the more X falls. Eventually, the system comes to a halt at the bad (but stable) equilibrium, E_3. Because of the fact that the $dX/dt = 0$ isocline is almost horizontal in regime 3, the equilibrium size of the resource is very close to the steady state resource stock absent any cooperation, as defined in equation (9). In regime 3, all agents harvest at interior effort rates, and hence subsequent increases in the effort endowment beyond $\hat{e}_1$ neither affects the number of cooperators, nor the size of the resource – as is also shown in Figure 5.

This analysis has important implications for policy makers as it makes clear that choosing the moment to intervene is of crucial importance to prevent the collapse of the socio–ecological system. As shown in Figure 5B, we find that increases in the time endowment result in intermediately fast decreases in the size of the resource stock if it is sufficiently plentiful (if $\hat{e}$ increases in the range $0 < \hat{e} < \hat{e}_0$). If $\hat{e}$ continues to increase in the range $\hat{e}_0 \leq \hat{e} < \hat{e}_1$ resource depletion seems to stabilize until $\hat{e}$ reaches $\hat{e}_1$, at which point the resource suddenly collapses. This pattern makes it hard for a potential manager of the resource (the regulator, or the government) to decide *when* to intervene. When observing a decline in the rate of resource depletion (when $\hat{e}$ increases beyond $\hat{e}_0$), the manager may falsely conclude that the system is stabilizing so that it becomes less urgent to intervene, while in fact the system is getting closer to collapse.

So what can the manager do once the system has collapsed? In this model the system collapse is reversible, but at substantial cost. Reducing effort back to $\hat{e}_1$ is not enough to restore the system to the good equilibrium E_1. The equilibria E_1 and E_2 in regime 2 re–emerge when $\hat{e}$ falls below $\hat{e}_1$ (see Figure 2B) but the system does not jump from E_3 to E_1 because the community is "trapped" in the basin of attraction of the "bad" equilibrium E_3; see also Figure 3. The system only flips back to E_1 if $\hat{e}$ is decreased below $\hat{e}_2$, so that E_3 disappears again. Hence, $\hat{e}_2$ is the second tipping point of the system.

4 Model extensions

The analysis in section 3 focused on the impact of changing the effective time endowment, $\hat{e}$, on the socio–ecological system, when resource harvesting is the community's only source of income. The assumption of $w = 0$ was introduced to obtain analytical results, not because it is more plausible than the case of $w > 0$. Also, exogenous changes in $\hat{e}$ are not likely to be the most important driver of change in the use of renewable resource systems. We remedy these two shortcomings by presenting a numerical analysis of the impact of changes in $\hat{e}$ when $w > 0$ in subsection 4.1, and by subsequently analyzing (in subsection 4.2) whether the same patterns of gradual change and sudden collapse can emerge if other parameters in the socio–ecological system are subject to exogenous change, such as technological progress and population growth.

4.1 The role of outside labor market in the resilience of the socio–ecological system

If labor markets are present and $w > 0$, analytical solutions can no longer be obtained. The main reason for this is that with $w > 0$ we no longer have $\pi^C / \pi^D = e^C / e^D$ (cf. (2)), which proved to be very convenient in working with equations (12) and (13). For the case of $w > 0$ we resort to a numerical analysis, showing that the presence of labor markets leads to results that are qualitatively very similar to those obtained in section 3; see Figure 6.

<Insert Figure 6 about here>

Figure 6 shows the internal equilibria of the two state variables C and X for different values of the effort endowment $\hat{e}$. As before, for sufficiently small time endowments there is no social dilemma, and hence the temptation for cooperators to defect is absent; $C = N$ in Figure 6A. Larger time endowments do imply, however, that more can be harvested at every time t, and hence the resource stock decreases linearly; see Figure 6B. If the time endowment of individual agents continues to increase, the socio–ecological system moves into regime 2 where cooperators start using less effort for harvesting than is available, while the defectors continue to harvest at the maximum rate. If the time endowment increases even more, the socio–ecological system collapses in exactly the same way as described in section 3. A positive feedback emerges because a reduction in the size of the resource stock results in cooperators reducing their effort rates while defectors do not, and the subsequent relative increase in defection payoffs reduces the number of cooperators, which, in turn, reduces the moral pressure to act cooperatively, and hence the resource stock falls even more. That means that all qualitative results obtained analytically assuming $w = 0$ carry over to the case of $w > 0$, and also the policy implications remain unchanged. If the resource stock seems to stabilize at an intermediately high level this is no guarantee that the system is resilient against shocks. And if the system has collapsed, restoring the system to the good equilibrium requires a reduction in the individual time endowments to a level that is (much) lower than the level at which the system was observed to collapse.

The only novel insight obtained from this analysis using $w > 0$ is that cooperation increases if the time endowment continues to increase after collapse; see Figure 6A. This increase in cooperation materializes because $\lim_{\hat{e}\to\infty} \pi^C / \pi^D \uparrow 1$ if $w > 0$. If $\hat{e} > \hat{e}_1$, the socio–ecological system is in equilibrium E_3 located in regime 3 (where all agents choose interior harvesting effort rates), and hence increases in w only increase the amount of money earned at the external labor markets, where the same wage rate applies to cooperators and defectors alike. Hence, the larger $\hat{e}$, the larger the income share of wages earned at the external labor market, and hence the closer the payoff ratio is to 1 (cf. equation 2). That means that the increase in cooperation following environmental collapse should not be interpreted as a sign that the system is moving back to a better equilibrium; it is purely the result of a decreasing difference in payoffs between acting cooperatively and non–cooperatively, resulting in less temptation to defect. Similarly, if the system has collapsed, the regulator should not be concerned about the fact that policies aimed at reducing the agents' time endowment actually results in a *decrease* in cooperation– reducing the time endowment of all agents reduces the wage share in total income and hence the payoff ratio between cooperators and defectors falls, so that it becomes more tempting to defect. As was the case in section 3, the system only flips back to the good equilibrium if the time endowment is reduced to a level well below the one that triggered collapse in the first place.

4.2 The role of other drivers in ecosystem collapse

Changes in the agents' time endowment is not the most plausible development driving the socio–ecological system; population growth (an increase in N) and technological progress regarding the effectiveness of harvesting effort (q) are likely to be more relevant in practice. In addition, it is interesting to see how the system is affected by increases in the crowding externality (v) and in the strength of moral persuasion (α). Let us discuss each of these four in turn (while maintaining the assumption of $w > 0$); see Figure 7.

<Insert Figure 7 about here>

In Figures 7A and 7B we show the impact of increases in the harvesting technology parameter, q, on the steady–state levels of C and X, respectively. The patterns are very similar to those presented in Figure 6, including the observation that cooperation increases if q continues to increase after collapse. The only difference is that in this case the steady–state resource stock continues to fall with increases in q. Higher levels of q increase the marginal productivity of resource harvesting and hence agents allocate more labor to resource harvesting, and the resulting fall in X then restores the equilibrium between the net marginal productivity of resource harvesting and its opportunity cost, the outside wage rate w.

In Figures 7C and 7D we show the impact of increases in population size (*N*) on *C* and *D*. The consequences of increases in *N* (for given $\hat{e}$) are qualitatively identical to the ones observed in Figure 6 (resulting from an increase in $\hat{e}$ for a given *N*). Indeed, increases in *N* affect resource exploitation in essentially the same way as increases in $\hat{e}$: both result in the increase in the community's available harvesting time while leaving the marginal productivities unaffected.

Next, let us analyze how the system responds to increases in *v*, the external crowding parameter. Not surprisingly, the size of the resource stock increases with *v* (see Figure 7F) – if the crowding externality is not very severe. The reason is that a higher *v* reduces the returns from resource harvesting, and hence agents spend more time at the external labor market the larger is *v*. The consequences for cooperation, however, are surprising: the higher *v*, the higher the need for cooperation, but Figure 7E shows that this does not generally translate into larger numbers of cooperators. The reason is that the cooperators tend to attach much larger weight to the crowding externality than do the defectors, and hence the profit ratio π^C / π^D is decreasing in *v*. If the crowding externality becomes really large, the temptation to defect becomes very large too, and the socio–ecological system collapses. In this case, however, continued increases in the crowding externality beyond the tipping point now result in higher levels of resource conservation, even though cooperation remains at a very low level – because the higher crowding costs continue to decrease profitability of resource harvesting, inducing defectors to allocate an increasingly large share of their labor time to working at the external labor market.

Finally, we analyze the impact of increases in the strength of the moral persuasion parameter, *α*, in Figures 7G and 7H. These figures show that for low initial levels of *α*, increases in the strength of persuasion does not have much impact on either cooperation or the size of the resource stock – until α reaches a critical threshold. After crossing this threshold the system jumps to a much higher level of both cooperation and resource conservation, and the system is also quite robust against possible weakening of moral persuasion: if α has increased sufficiently for the system to flip to the good equilibrium, α can fall substantially before the system flips back to the bad equilibrium. Again, this is a direct result of the properties of systems exhibiting alternative stable states.

So, exogenous developments in population size, state of the technology, the severity of the harvesting externality all give rise to the same dynamics as do changes in the time endowment itself – as analyzed analytically in section 3.2. Note that while the drivers analyzed in section 4.2 do not directly affect the agents' nominal time endowment, they do affect the effective time endowment. Better technologies or less severe harvesting externalities increase the marginal productivity of resource harvesting, and hence increase the relative scarcity of time. This shows that not the change, but the mere presence of constraints on economic activity is sufficient to produce multiple equilbria. Technological development, influx of agents from outside the community, small changes in the defectors' susceptibility to moral persuasion, all these changes can give rise to a sudden collapse. A gradual change in key parameters may reduce the resilience of the system, thus paving the way to a catastrophic transition.

5 Conclusions

We developed a model of renewable resource use in which agents can decide to act cooperatively with respect to resource harvesting, or not. Social harvesting norms can spread through the community because of interpersonal relationships between cooperators and defectors (because the former try to convince the latter of the social desirability of acting cooperatively), but community members also always face the temptation to act non–cooperatively – because of the higher profits. The resulting socio–ecological system is characterized by multiple equilibria, so that small changes in key parameters (including the size of the community, and the rate of technological progress) can trigger catastrophic transitions from relatively high levels of cooperation to widespread norm violation – causing the demise of the resource. Our setup is unique in that (i) it does not need to assume the ecological system to be highly non–linear to generate multiple equilibria, and (ii) tipping points emerge even though both the ecological and the socio–economic systems, by themselves, are inherently stable.

In our socio–ecological system, tipping points arise not because we introduce them explicitly in the differential equations, but because of the interaction between the ecological and socio–economic subsystems. Here, positive feedback relationships occur because of the fact that, in closed communities, the amount of labor a community member can allocate to resource harvesting is necessarily finite because the property right system usually does not allow members to hire external labor. If, for whatever reason, the resource becomes scarcer, the cooperators in the community decrease their harvesting effort while defectors continue to allocate all their available time to harvesting – if the net private marginal benefits of harvesting are strictly positive. A decrease in the size of the resource thus increases the relative profitability of defecting, and cooperation starts to decrease. Reduced cooperation further reduces the resource stock, thus reinforcing the temptation to defect, and also reduces the moral pressure on the non-cooperators. Thus, a positive feedback between the resource stock and the number of cooperators emerges endogenously in our system – possibly resulting in the collapse of the socio–ecological system. And if the exogenous development is reversed (possibly because of government intervention), the system may flip back to the good equilibrium because of an opposite positive feedback loop. A larger resource stock induces cooperators to increase their harvesting effort, while defectors are still harvesting at the maximum rate. As a result, the relative profit difference falls, and so does the temptation to defect. Reduced temptation increases the number of cooperators, which increases the resource stock, and lowers temptation even more. However, while a small change in the driver may cause the system to collapse, a non–marginal change in the driver is needed to restore the system to its good state. Hence, the system is characterized by hysteresis.

Our model thus shows that even if the system looks smooth on the outside because there are no non–linearities in the resource dynamics, the regulator must be aware of potential collapses of cooperation in communities having access to renewable common pool resources. In that sense, our paper is complementary to the literature analyzing inherently non–linear natural resource systems (such as shallow lakes and grazing lands) as including non–linear resource dynamics in our model would render the system even more complex.

While our model is purely theoretical in nature, it does give rise to one important policy implication. A regulator monitoring the ecological system should not be led to believe that any decrease in the rate of depletion of a natural resource is evidence of the system stabilizing. The decrease in depletion rates may be caused by some agents reducing their effort rates while others do not. If so, the subsequent relative increase in the returns to defection may trigger a positive feedback between increased defecting and ever lower resource stocks, ultimately resulting in a sudden collapse of the resource stock.

Table 1: Overview of the equilibrium effort rates of the cooperators and defectors in the three regimes, and the dynamics of the resource stock and of the number of cooperators and defectors.

Row	Variable	Regime 1	Regime 2	Regime 3
A		$X \geq \frac{2vN\hat{e}}{Pq}$	$\frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)} \leq X < \frac{2vN\hat{e}}{Pq}$	$0 \leq X < \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)}$
B	e^C	$\hat{e}$	$PqX/(2vN)$	$PqX/(2vN)$
C	e^D	$\hat{e}$	$\hat{e}$	$PqX(2N-C)/(2vN(N-C+1))$
D*	E	$N\hat{e}$	$CPqX/(2vN)+(N-C)\hat{e}$	$PqXZ(C)/v \approx pqX/v$
E*	$\frac{dX/dt}{X}$	$r(1-X)-qN\hat{e}$	$r(1-X)-q\left(\frac{CPqX}{2vN}+(N-C)\hat{e}\right)$	$r(1-X)-Pq^2XZ(C)/v \approx r(1-X)-Pq^2X/v$
F*	$X(C)$	$\begin{cases}(r-qN\hat{e})/r & \text{if } \hat{e} \leq e_0 \\ \text{NA} & \text{if } \hat{e} > e_0\end{cases}$	$\begin{cases}\text{NA} & \text{if } \hat{e} \leq e_0 \\ \frac{2vN[r-q\hat{e}(N-C)]}{2vNr+Pq^2C} & \text{if } \hat{e} > e_0\end{cases}$	$\begin{cases}\text{NA} & \text{if } \hat{e} \leq e_0 \\ \frac{vr}{Pq^2Z(C)+vr} \approx \frac{vr}{Pq^2+vr} & \text{if } \hat{e} > e_0\end{cases}$
G	$\frac{dC/dt}{C}$	$\frac{\alpha}{N}(N-C)$	$\frac{\alpha}{N}(N-C)-\beta\left(1-\frac{PqX}{2vN\hat{e}}\right)$	$\frac{\alpha}{N}(N-C)-\beta\left(\frac{N-1}{2N-C}\right)$
H	$C(X)$	N	$(2v(\alpha-\beta)N\hat{e}+\beta PqX)/2v\hat{e}\alpha$	$\frac{3}{2}N-\frac{1}{2}\sqrt{N^2+\frac{4\beta N}{\alpha}(N-1)}>0$

*Here, $Z(C)=\frac{N-C+C/2N}{N-C+1} \approx 1$, $\frac{\partial Z(C)}{\partial C}=\frac{(1/N)-1}{2(N-C+1)^2} \approx 0$, and $e_0 \equiv \frac{rPq/N}{2rv+Pq^2}$.

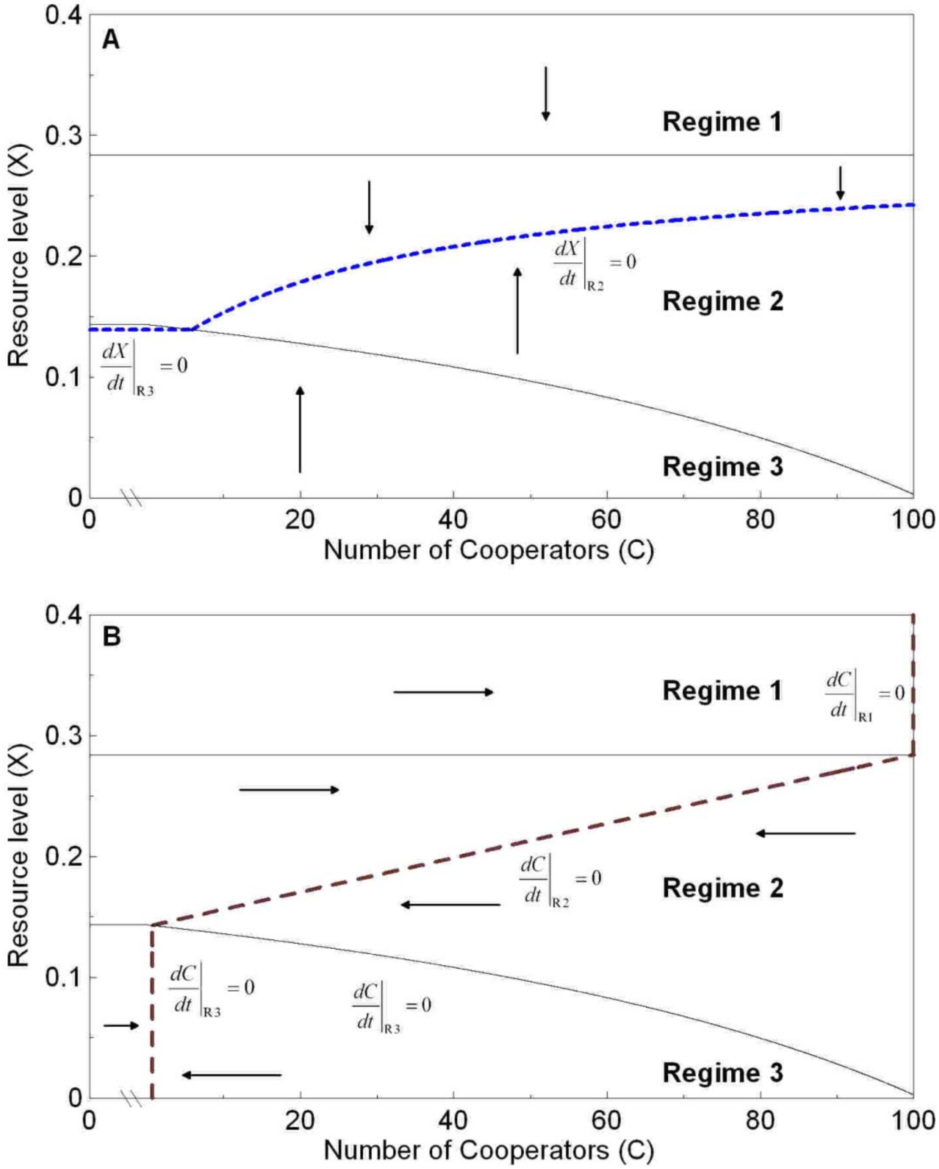

Figure 1. The nullclines of the resource stock (panel A) and of the number of cooperators (panel B).[9]

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[9] Trivial nullclines ($dC/dt = 0$ at $C = 0$ and $dX/dt = 0$ at $X = 0$) are not shown. Unless stated otherwise, all figures are drawn using the following parameter values: $\hat{e} = 0.71$, N=100, P=50,000, q=0.01, v=1, r = 0.8, α=0.1 and β=0.2.

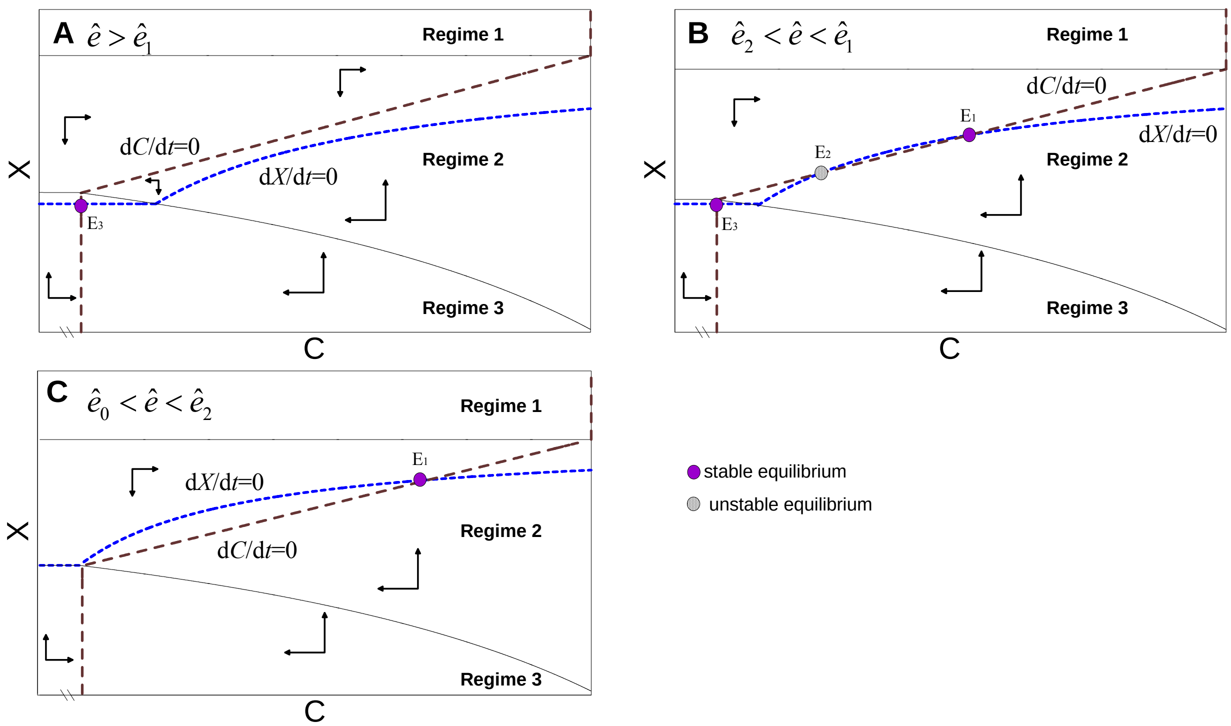


Figure 2. Phase planes for different values of $\hat{e}$ giving rise to either no non–trivial equilibrium in regime 2 and one in regime 3 (panel A), two equilibria in regime 2 and one in regime 3 (panel B), or one equilibrium in regime 2 and none in regime 3 (panel C).[10]

[10] Values for all parameters as before, except for the focal parameter $\hat{e}$, which is 0.75 (panel A), 0.713, (panel B) 0.689 (panel C). Again, the trivial nullclines are not shown. Note that the intersection point of $dC/dt = 0$ and the horizontal axis ($X = 0$) and the intersection point of $dX/dt = 0$ and the vertical axis ($C = 0$) are equilibria too, and so is the origin of the system; cf. (13) and (14). As these three equilibria are unstable, we omit them in this figure.

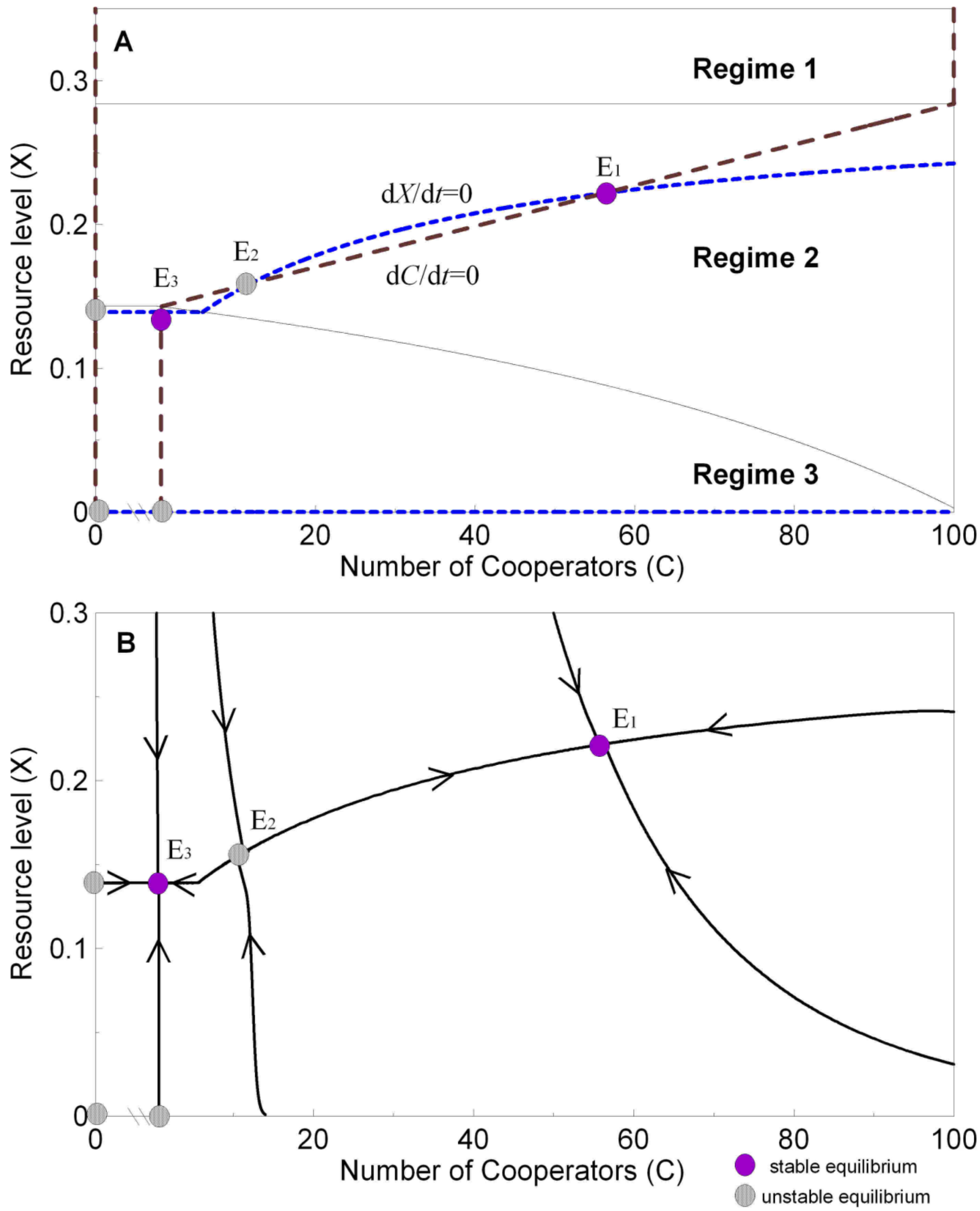


Figure 3. A phase diagram of the system with alternative stable states (panel A) and the associated
740 trajectories towards these steady states (panel B).

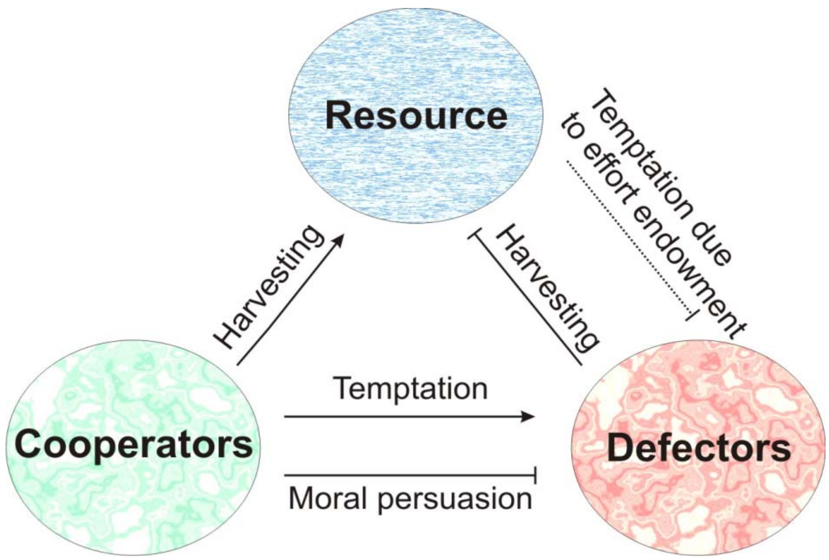


Figure 4. The socio-economic dynamics of the system. Changes are driven by moral persuasion and temptation. The presence of the effort endowment leads to a non–linearity, giving rise to alternative stable states. Positive feedbacks are indicated by arrows and negative feedbacks are depicted by bars.

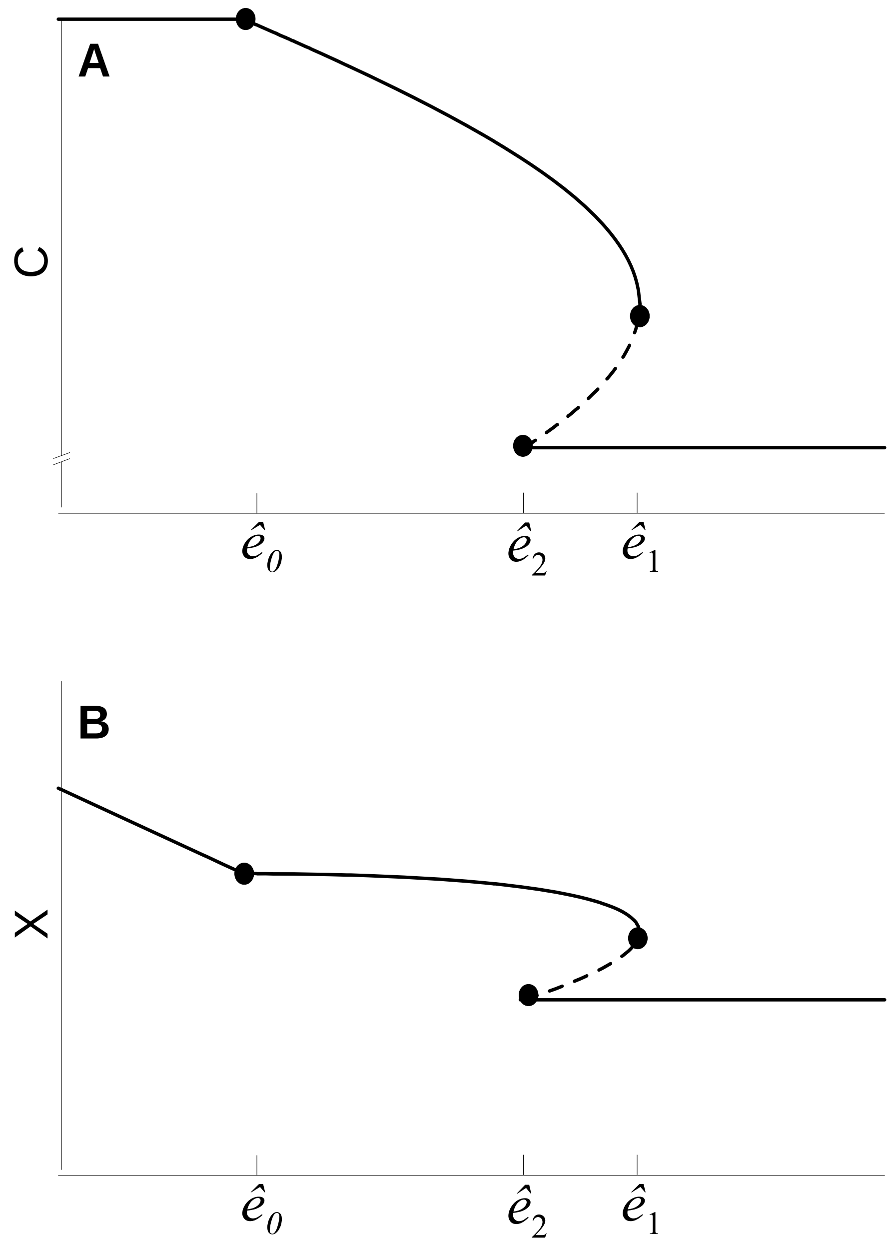


Figure 5. Bifurcation diagram showing internal equilibria of the number of cooperators *C* (panel A) and the resource stock *X* (panel B) for different values of the effort endowment $\hat{e}$. Stable equilibria are shown by solid lines, unstable equilibria are shown by dotted lines. Dots denote the two tipping points $\hat{e}_1$ and $\hat{e}_2$ and the point $\hat{e}_0$ where the social dilemma materializes.

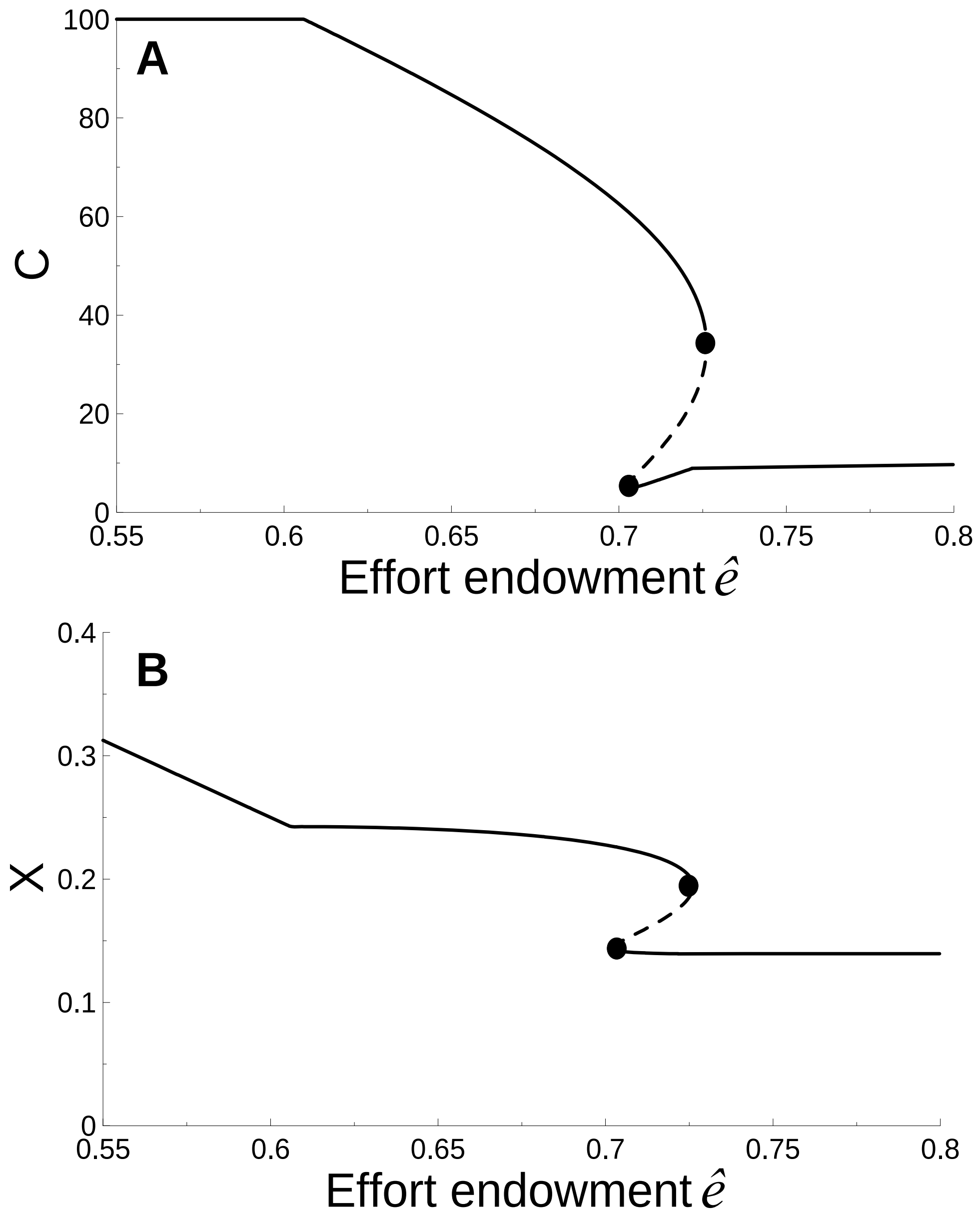
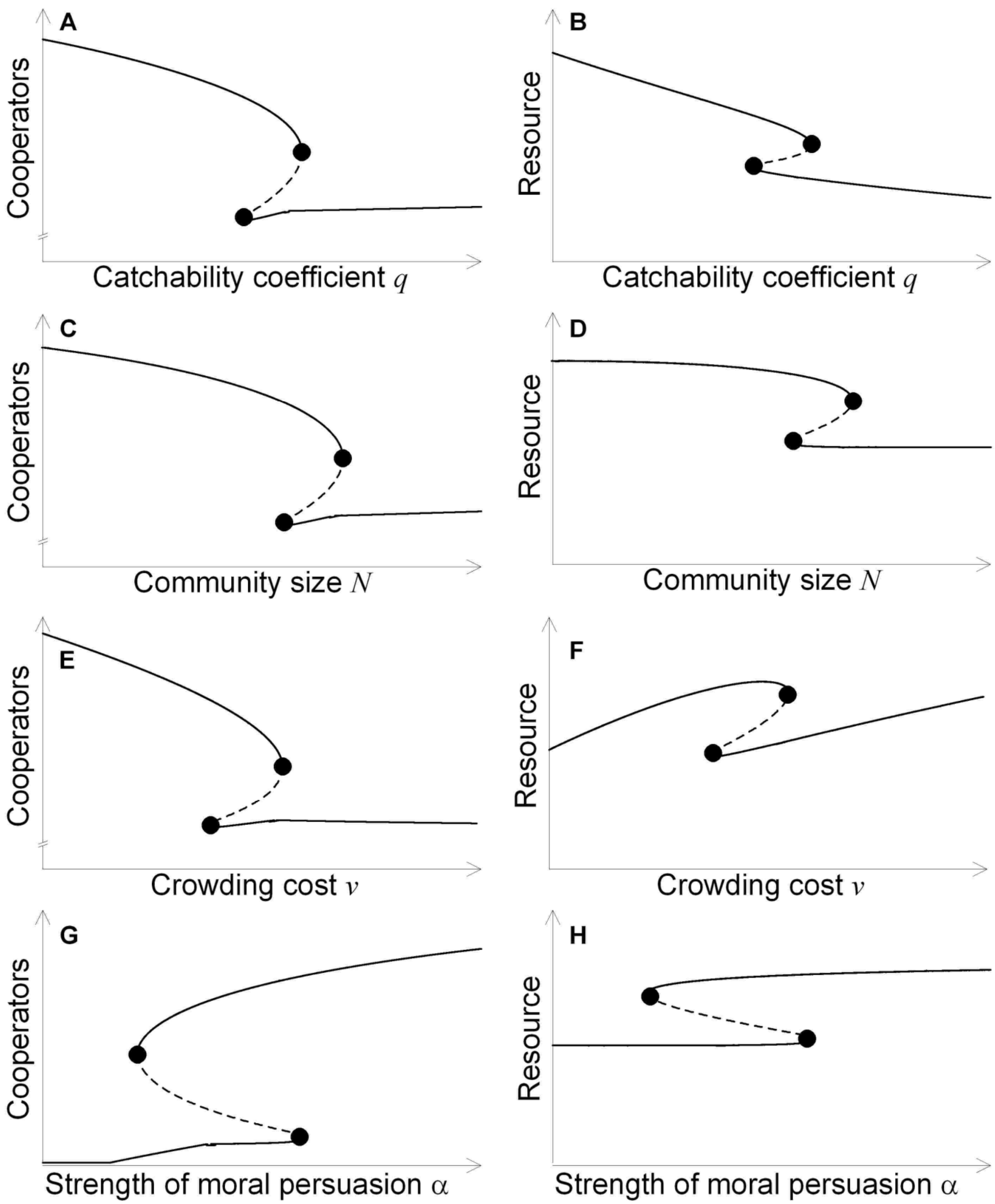


Figure 6. Bifurcation diagram showing internal equilibria of the number of cooperators *C* (panel A) and the resource stock *X* (panel B) for different values of the effort endowment $\hat{e}$ and with w=0.1. Dots denote the two tipping points.



760 **Figure 7.** Bifurcation diagrams showing the internal equilibria of the number of cooperators and the resource stock for different focal parameters. Dots denote the two tipping points.

Appendix A: Derivation of the equilibria and tipping points for all possible values of $\hat{e}$

Deriving the non–trivial equilibria in each of the three regimes requires identifying the intersection points of the *X* and C nullclines as provided in rows F and H in Table 1.

Consider first the case where $\hat{e} \leq \frac{rPq/N}{2rv + Pq^2} \equiv \hat{e}_0$. Noting that $C = N$ in regime 1, the system then has only one non–trivial equilibrium with the following coordinates:

(A1) $(C_0, X_0) = (N, (r - \hat{e}Nq)/r)$.

Next, consider the case where $\hat{e} > e_0$. Then there are zero steady states in regime 1. The steady states in regime 2 can be identified by equating $X = \frac{2vN\left[r - q\hat{e}(N-C)\right]}{2vNr + Pq^2C}$ and $X{=}2v\hat{e}\left(\alpha C - \left(\alpha - \beta\right)N\right)/\beta Pq$. This system potentially provides two interior solutions, $\left(C_1, X_1\right)$ and $\left(C_2, X_2\right)$, where

(A2) $$X_1 = \frac{\sqrt{\hat{e}}\sqrt{N}\cdot v\left(\sqrt{\alpha}\sqrt{\alpha\hat{e}N\left(4r^2v^2+4rPvq^2+P^2q^4\right)+4\beta Pq^2\left(rPq-\hat{e}N\left(2rv+Pq^2\right)\right)}-\sqrt{\hat{e}}\sqrt{N}\left(\alpha\left(2rv+Pq^2\right)-2\beta Pq^2\right)\right)}{\beta P^2q^3},$$

(A3) $$C_1 = \frac{\sqrt{N}\left(\sqrt{\alpha\hat{e}N\left(4r^2v^2+4rPvq^2+P^2q^4\right)+4\beta Pq^2\left(rPq-\hat{e}N\left(2rv+Pq^2\right)\right)}+\sqrt{\alpha}\sqrt{\hat{e}}\sqrt{N}\left(Pq^2-2rv\right)\right)}{2\sqrt{\alpha}\sqrt{\hat{e}}Pq^2},$$

(A4) $$X_2 = -\frac{\sqrt{\hat{e}}\sqrt{N}\cdot v\left(\sqrt{\alpha}\sqrt{\alpha\hat{e}N\left(4r^2v^2+4rPvq^2+P^2q^4\right)+4\beta Pq^2\left(rPq-\hat{e}N\left(2rv+Pq^2\right)\right)}+\sqrt{\hat{e}}\sqrt{N}\left(\alpha\left(2rv+Pq^2\right)-2\beta Pq^2\right)\right)}{\beta P^2q^3},$$

(A5) $$C_2 = -\frac{\sqrt{N}\left(\sqrt{\alpha\hat{e}N\left(4r^2v^2+4rPvq^2+P^2q^4\right)+4\beta Pq^2\left(rPq-\hat{e}N\left(2rv+Pq^2\right)\right)}+\sqrt{\alpha}\sqrt{\hat{e}}\sqrt{N}\left(2rv-Pq^2\right)\right)}{2\sqrt{\alpha}\sqrt{\hat{e}}Pq^2}.$$

Here, (C_1, X_1) and (C_2, X_2) are the coordinates of the equilibrium points E_1 and E_2, respectively; see panel B of Figure 2 and also Figure 3. Whether these equilibria exist depends on the parameter constellations. We find that $X_1 = X_2$ and $C_1 = C_2$ (so that E_1 and E_2 coincide) if

$$\text{(A6)}\quad \hat{e} = \frac{4\beta r P^2 q^3}{N\left(4\beta P q^2\left(2rv + Pq^2\right) - \alpha\left(4rv\left(rv + Pq^2\right) + P^2 q^4\right)\right)} \equiv \hat{e}_1.$$

Solutions (C_1, X_1) and (C_2, X_2) only have real solutions if $\hat{e} < \hat{e}_1$. In fact, $\hat{e}_1$ is a so–called tipping point because the equilibria E_1 and E_2 vanish if $\hat{e}$ is infinitesimally larger than $\hat{e}_1$. So, if $\hat{e} > \hat{e}_1$ the system only has one equilibrium, E_3, which is located in regime 3. Its coordinates are:

$$\text{(A7)}\quad X_3 = \frac{2rv\sqrt{N}\left(\sqrt{N}\sqrt{\alpha N + 4\beta(N-1)} + \sqrt{\alpha}(2-N)\right)}{\left(2rNv + Pq^2(2N-1)\right)\sqrt{\alpha N + 4\beta(N-1)} - \sqrt{\alpha}\sqrt{N}\left(2rv(N-2) + Pq^2(2N-3)\right)},$$

$$\text{(A8)}\quad C_3 = \frac{3}{2}N - \frac{1}{2}\sqrt{N^2 + \frac{4\beta}{\alpha}(N^2 - N)} > 0.$$

The equilibrium in regime 3 only exists if (C_3, X_3) as defined by (A7) and (A8) is located below the regime boundary separating R2 from R3, that is, if $X_3 < \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)}$. Substituting C_3 and X_3 into $X(C)\big|_{R2/R3} = \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)}$ and solving, we find that this is the case if $\hat{e} < \frac{Pq(2N-C_3)X_3}{2vN(N-C_3+1)} \equiv \hat{e}_2$, or, after having substituted in the state variables C_3 and X_3,

$$\text{(A9)}\quad \hat{e}_2 = \frac{\beta r P q}{\alpha N\left(rv + Pq^2\right) + \beta\left(2rNv + Pq^2(2N-1)\right) - \sqrt{\alpha}\sqrt{N}\sqrt{\alpha N + 4\beta(N-1)}\left(rv + Pq^2\right)}.$$

Appendix B: Analysis of the consequences of a change in the endowment of effort

Taking the first derivative of (16) and (17), we have

(B1) $\frac{\partial X(C)|_{R1/R2}}{\partial \hat{e}} = 2vN / Pq > 0$, and

(B2) $\frac{\partial X(C)|_{R2/R3}}{\partial \hat{e}} = \frac{2vN(N-C+1)}{Pq(2N-C)} > 0.$

So, if $\hat{e}$ increases, both regime boundaries shift upward in (C,X) space. Because $\frac{\partial^2 X(C)|_{R2/R3}}{\partial \hat{e} \partial C} < 0$ an increase in $\hat{e}$ induces the R2/R3 boundary to rotate to the North–East.

Next, we analyze the consequences of increasing $\hat{e}$ for the two nullclines. Taking the first derivatives of the nullclines of X and C (as presented in rows F and H of Table 1) with respect to $\hat{e}$, we have:

$$\text{(B3)} \quad \frac{\partial X(C)|_{dX/dt=0}}{\partial \hat{e}} = \begin{cases} \frac{-2vNq(N-C)}{2vNr + Pq^2C} \leq 0 & \text{if} \quad \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)} \leq X < \frac{2vN\hat{e}}{Pq} \qquad \text{(R2)} \\ 0 & \text{if} \quad 0 < X < \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)} \qquad \text{(R3)} \end{cases}$$

$$\text{(B4)} \quad \frac{\partial C(X)|_{dC/dt=0}}{\partial \hat{e}} = \begin{cases} 0 & \text{if} \quad X \geq \frac{2vN\hat{e}}{Pq} \qquad \text{(R1)} \\ \frac{-\beta PqX}{2v\alpha\hat{e}^2} < 0 & \text{if} \quad \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)} \leq X \leq \frac{2vN\hat{e}}{Pq} \qquad \text{(R2)} \\ 0 & \text{if} \quad 0 \leq X < \frac{2vN(N-C+1)\hat{e}}{Pq(2N-C)} \qquad \text{(R3)} \end{cases}$$

Hence, the $dX/dt = 0$ isocline shifts down in (C,X) space in regime 2 while the vertical intercept in regime 3 remains unchanged. The $dC/dt = 0$ isocline shifts to the left in (C,X) space in regime 2 while the horizontal intercept in regime 3 remains unchanged.

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