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Original Research Article

The resilience of social norms of cooperation under resource scarcity and inequality — An agent-based model on sharing water over two harvesting seasons

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ABSTRACT

Water governance remains a challenge for human societies, especially when the variation in resource inflow is large and the resource users are heterogeneous. We analyze with a coupled social-ecological systems (SES) model how socioeconomic and environmental changes affect the resilience of social norms governing resource use. In our model, agents have access to water as a common-pool resource and allocate it between rainy and dry seasons. While it is socially optimal to save water for the dry season, it is individually optimal to take water immediately. In our model, punishment of norm violators is the mechanism that may sustain cooperation. We show that the resilience of social norms could be affected by changes in socioeconomic and environmental conditions. Particularly, we find that social norms may collapse in times of resource scarcity and variability, especially if several drivers act in concert. Finally, we find that user heterogeneity in the form of different skills and inequality in land endowments may undermine cooperation. This implies that climatic changes and increased inequality – both potential drivers in the field – may affect community resilience and may lead to an erosion of social norms.

1. Introduction

Sharing a common-pool resource (CPR), such as water, remains a challenge for human societies. Wasteful overuse of such a resource typically arises from a social dilemma, which is defined as the conflict between individual and group interests. This form of collective action problem is especially pronounced in the case of a CPR, which is a rival resource (i.e. extraction by one user makes it unavailable to others) and non-exclusive (i.e. excluding others from appropriating such a resource is difficult or costly) (Gardner et al., 1990). In the absence of enforcement mechanisms, an individual has no incentive to restrain resource use, since benefits of taking the resource immediately are private, whereas the benefits of saving it for later use are shared by all resource users.

A CPR is usually part of an interconnected system of users, governing institutions and the biophysical system, which is often referred to as a social-ecological system (SES) (Ostrom 2009). A SES is generally understood as a complex adaptive system, in which micro-level interactions of agents lead to emergent properties at a macroscopic level that, in turn, affect actions and behavior of the agents (Levin et al. 2012). Such a system is characterized by complexities, namely nonlinear feedbacks, tipping points, heterogeneity of agents, and scale-dependences, which may pose obstacles for successful governance of CPR (Liu et al. 2007; Levin et al. 2012).

A wealth of case studies have documented that local communities are able to sustain the commons by self-organizing and solving collective action problems (Ostrom 1990). Various key factors and mechanisms that may affect collective action have been identified, which include system productivity and scarcity, as well as the existence of norms or social capital (Ostrom 2009). However, how these factors and mechanisms link across scales to affect the long-term sustainability of resource use is not clearly understood (Ostrom 2009). Experimental work has shown that social norms – in the form of restraining individual resource use and punishing noncooperative behavior – play crucial roles in sustaining resource use (Ostrom et al., 1992, 1994). Using evolutionary game theory, Sethi and Somanathan (1996) have shown that punishments can enforce sustainable resource use, provided that defection is not very common initially. Their model features two alternative stable states – full cooperation and full defection – depending on initial conditions. The fragility of social norms has been further documented by Richter et al. (2013), who show that cooperation can suddenly collapse in response to exogenous drivers, such as

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technological progress or climatic changes. Nyborg et al. (2016) have suggested that tipping points may also play a role when social norms are established. For example, by making agents' behavior more observable (e.g. resource extraction) social sanctioning can create a tipping point from a vicious cycle of norm-violation to a virtuous cycle of norm-following behavior.

Despite empirical and theoretical evidence suggesting that cooperation can be maintained or suddenly collapse, an open question is how the resilience of social norms could be affected by socioeconomic and environmental changes. By altering biophysical conditions of resources, climate change can obscure the nature of social dilemmas in relation to resource sharing, which requires an understanding of contextual factors such as agents' heterogeneity to overcome social dilemmas (Bisaro and Hinkel 2016). For example, climate change is expected to aggravate water scarcity (Schewe et al. 2014; Haddeland et al. 2014) and increase water variability in time and space (Jaeger et al. 2017). How severe the impact is, however, depends on the spatial location of the irrigation areas and the strategic decisions of neighboring farmers who share the water (Esteve et al. 2015).

The objective of this paper is to analyze how the emergence and resilience of social norms of cooperation depends on external disturbances, as well as heterogeneity and inequality of users. In particular, we develop an agent-based model (ABM) to investigate how resource scarcity and inequality among agents may jointly affect the resilience of social norms in a community that extracts water for irrigation from a joint river. Our contribution to the literature is twofold. First, we analyze the case where water is used in two seasons for irrigation purposes, which is relevant in many real world settings. This is especially true for irrigation systems in Asia, where water availability varies considerably between rainy and dry seasons due to the effect of monsoon precipitation (Schewe et al. 2014; Elliott et al. 2014). A social dilemma arises, because it is socially optimal to save water in the rainy season, while the benefits of doing so are shared among all farmers, including those who have not restrained their water use in the rainy season. We analyze to what extent social norms can mitigate such social dilemma. Second, we investigate how the resilience of social norms could be affected in times of resource scarcity and variability and by changes in socioeconomic and environmental conditions.

Previous theoretical studies have demonstrated the crucial roles of social norms and punishment in facilitating cooperation and the implications for the sustainable use of a shared resource in a small community (Sethi and Somanathan 1996; Noailly et al., 2003). On the one hand, such studies aim at understanding the emergence and evolution of cooperative harvesting strategies (Sethi and Somanathan 1996; Tavoni et al., 2012; Richter et al., 2013; Lewis and Dumbrell 2013) including cases where cooperation and defection may co-exist. On the other hand, such studies contribute to understanding the extent to which such norm-guided cooperation is robust against socioeconomic and environmental changes (Schlüter et al., 2016; Richter and Dakos 2015; Brandt and Merico 2013).

Agent-based modeling (ABM) has been extensively used in various disciplines (Heath et al., 2009), including agricultural and ecological economics (Berger 2001; Rasch et al. 2016), and for analysis of SES dynamics and tipping points (An et al. 2014; Schlüter et al., 2016; Siekmann 2015). ABM is widely used for its flexibility to incorporate heterogeneity of agents (An 2012; Schlüter et al. 2012), and particularly suited to analyze the emergence of collective action from micro-level interactions (Bonabeau 2002). For instance, Janssen and Ostrom (2007) use agent-based modeling to examine how heterogeneity among agents could contribute to the emergence and evolution of social norms, a feature which is difficult to include in a traditional game theoretical model that studies the evolution of cooperation. Similarly, Bausch (2014) employs agent-based simulations to test mechanisms that contribute to cooperation between groups, which is similar to the work of Gavrilets and Richerson (2017), who focus more on competition between groups.

ABM is a useful tool to analyze resilience, which is understood as the capacity of the system to accommodate changes, while maintaining the system states within the equilibrium domains (Liu et al. 2007; An et al. 2014). For instance, Schlüter and Pahl-Wostl (2007) use ABM to assess resilience of the SES under different water governance regimes to uncertainties of water availability in a river basin. In their study, resilience is evaluated as the capacity of the system to maintain both agricultural and fish production at or above an exogenously specified level, below which each production system collapses. Schlüter et al. (2016) analyze the resilience of social norms of cooperation to environmental changes such as changes in resource availability and variability. Similarly, Rasch et al. (2016) show that social norms emerge in times of ecological crises and enhance resilience of SES.

Our paper contributes to the question how resource scarcity affects cooperation in the commons, which remains poorly understood. One strand of literature argues that resource scarcity enhances cooperation. For example, using dynamic game theory, Osés-Eraso and Viladrich-Grau (2007) show that concerns for resource scarcity can dampen resource extraction. Testing this in an experimental setting, Osés-Eraso et al. (2008) find that users tend to react to actual scarcity by reducing the appropriation level when resources become scarcer. In addition, it matters whether the sources of scarcity are environmental or human-induced (Osés-Eraso et al., 2008). Considering changes in availability and variability of a resource, Schlüter et al. (2016) have demonstrated that cooperation can collapse even in the case of resource abundance as long as norm-violators benefit in times of resource abundance. Increased scarcity, potentially mediated through resource variability, can enhance cooperation because scarcity favors cooperation in the sense that the benefits of violating the norms are smaller (less is to be extracted), while the sanctioning strength against norm-violators remains high when the resource becomes scarcer (Schlüter et al., 2016).

The other strand of literature posits that resource scarcity may give rise to collapse of cooperation among the users of the commons. For instance, resource scarcity may increase competition for resource appropriation which can lead to a faster rate of depletion (Grossman and Mendoza 2003). This finding is in line with experimental evidence from Blanco et al. (2015), who have found that resource users increase their appropriation levels when the resource becomes scarcer, no matter whether the reduction in resource availability is abrupt or gradual. Users even tend to appropriate more resources if they experience scarcity in the past (Blanco et al., 2015). This is further supported by Pfaff et al. (2015), who find in another experiment that users tend to extract more if the resource is initially scarce, leading to erosion of collective action. In a similar vein, theoretical work has shown that cooperation may collapse in the wake of scarcity if scarcity increases the temptation to defect because cooperatively-minded individuals restrain themselves as an attempt to restore the resource (Richter et al., 2013).

Contextual factors such as inequality and user heterogeneity may interact with external disturbances and hence affect the evolution of social norms and self-organization (Bisaro and Hinkel 2016). In the context of water governance at a local scale, unequal land endowments may have significant implication for the emergence of collective action. Land inequality may pose an obstacle towards cooperation, depending on the complementarity between land and water (Marchiori 2014). Kun and Dieckmann (2013) have also demonstrated that user heterogeneity has important implications for the emergence of cooperation. Inequality of an initial resource endowment can facilitate or hinder cooperation depending on the benefits of defection (Kun and Dieckmann 2013).

Clearly, both inequality among users and resource scarcity can impact the emergence and maintenance of cooperation in the commons. Previous papers have analyzed (i) how social norms emerge and overcome social dilemmas in the case of equal access to the resource (Sethi and Somanathan 1996; Tavoni et al., 2012; Richter and Grasman 2013); (ii) how availability and variability of the resource inflow affect cooperation among agents and the long-term use of a CPR (Schlüter et al., 2016); and (iii) how resource inequality affects collective use of a resource (Marchiori 2014; Kun and Dieckmann 2013; Rasch et al. 2016). However, how resource scarcity and inequality interact and hence affect cooperation in the use of common resources remains unexplored.

The organization of the paper is as follows. Section 2 is the presentation of the SES model, which consists of three components, namely the biophysical model, the economic model and the social dynamics model. Section 3 presents the results, investigating how resource scarcity and user heterogeneity affect cooperation. Section 4 concludes and discusses the findings.

2. The model

We consider a case of small-scale irrigation system in a community, which is part of a social-ecological system (SES). The community consists of N farmers having access to a common-pool resource – a joint river from which water is withdrawn for irrigating a single crop in two seasons of the year, namely rainy and dry seasons. In this irrigation system, a proportion of water can be saved in the rainy season for later use in the dry season to cope with seasonal variability.

When sharing a common-pool resource, farmers face a social dilemma in which individual and group interests are misaligned. While it would be socially optimal to save water in the rainy season for farming in the dry season, this is not individually rational, as the saved water may potentially be used by other farmers, making the individual who saved the water worse off. In the model, we allow social norms of cooperation to evolve that guide resource users' behavior regarding water use. Following the tradition of Sethi and Somanathan (1996), we assume that some agents act cooperatively, while others act selfishly. The selfish agents (called defectors) are generally short-sighted and maximize their own short-term interests. Using the amount of water extracted as a yardstick to define behavioral choice, a defector thus extracts an amount of water greater than the social optimum. The cooperators follow social norms that guide water use in both seasons and punish defectors. If water is scarce, cooperators restrain water use in the rainy season and save for the dry season so that everyone is potentially better off.

Furthermore, the resilience of social norms of cooperation may be threatened by socioeconomic and environmental changes. When the sales price of the agricultural commodity increases in the rainy season, farmers may be tempted to use more water in the rainy season because the marginal profit from doing so is higher. Likewise, when water becomes scarcer, farmers who take water early on are the ones who benefit from farmers who are modest and try to save. Fig. 1 shows a conceptual model on how the dynamic interplay between water scarcity and variability in the natural system and inequality among agents in the socio-economic system may affect the behavior of farmers in water allocation.

To analyze inequality among agents in promoting or reducing cooperation, we distinguish two cases of our model: the basic case in which each agent is homogeneous in terms of farming skills and land endowments and the extended case in which agents are heterogeneous.

2.1. Resource dynamics

Water flows in a river are determined primarily by rainfall, which is stochastic. Water availability in the river thus fluctuates intra- and inter-annually. For simplicity, we define a random variable $Q_{r,t}$ as the total available water in the rainy season at year t with a mean value of $\bar{Q}$ and a stochastic term ε_t, which denotes water variability. We assume that ε_t is normally distributed, with zero mean and standard deviation σ_Q, i.e. $\varepsilon_t \sim N\{0, \sigma_Q{}^2\}$. The quantity of water available in the rainy season ($Q_{r,t}$) and dry season ($Q_{d,t}$) is given by

$$Q_{r,t} = \bar{Q} + \varepsilon_t, \tag{1}$$

$$Q_{d,t} = Q_{r,t} - W_{r,t}, \tag{2}$$

where $W_{r,t}$ is the total amount of water withdrawn by all agents in the rainy season at year t. We assume that water can be saved in the rainy season for the dry season, and all water will be exhausted in the dry season. Water availability at a given year thus depends solely on water inflow occurring in the rainy season of that particular year. Hence, the social dilemma concerns inter-seasonal water allocations where agents make decision on water use in a given year. Water availability is influenced by external disturbances, e.g. climatic change, which induces shifts in rainfall patterns causing changes in both quantity and distribution of water inflow. We model the potential effects of climate change on water resource dynamics by varying the values of mean inflow ($\bar{Q}$) and standard deviation of water inflow (σ_Q).

2.2. Agent heterogeneity and inequality

While the basic model comprising homogenous agents will be an important benchmark, we also consider the case where agents are heterogeneous. First, we introduce skill heterogeneity and take into account that not only water use determines yields, but also the skill of each agent, denoted by ρ_i. Skill ρ_i is time-invariant and randomly distributed with mean $\bar{\rho}$ and standard deviation σ_ρ. Second, we consider land heterogeneity by assuming that each farmer is endowed with acreage a_i, which is agent-specific and randomly distributed with mean $\bar{a}$, and standard deviation σ_a. Furthermore, we introduce the presence of small and large landholders in the community by considering a bimodal distribution of land among the two groups. Specifically, it is modeled as the mixture of two Gaussian distributions, with two means and two variances, each representing the attributes of each farmer group with equal mixing proportions. The small landholders are endowed with a mean land size of $\bar{a}_S$ and the large landholders with $\bar{a}_L$. Both are assumed to have the same variance of land endowment and

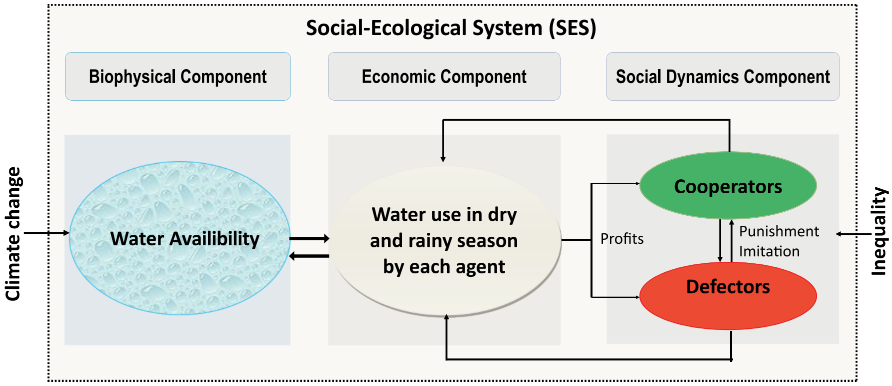

Fig. 1. A conceptual model on the emergence of social norms in the wake of climate change and inequality. Climate change induces changes in rainfall pattern, which modifies the water inflow conditions in terms of quantity and seasonal variation. The changes in water availability thus affect the decisions of agents regarding seasonal water allocation following their norms that govern resource use, which then affect water availability. Differences in water use translate into differences in profits, giving rise to social dynamics. Cooperators punish defectors, while the more successful strategies are imitated. Inequality may act as a driver on the social dynamics, as individuals who are better off have a higher probability to be imitated.

hence the same standard deviation ($\sigma_{a,S} = \sigma_{a,L}$).

2.3. Water allocations

The economic model presents farmers' optimal land and water allocations for irrigating a single crop in the rainy (subscripted r) and dry (subscripted d) season at a given year. Each farmer (indexed by i) is endowed with land a_i, which can be cultivated twice a year: once in the rainy season denoted by $a_{i,r}$ and once in the dry season denoted by $a_{i,d}$. Yield per unit of land of agent i is given by

$$Y_i/a_i = \alpha + \beta w_i - \gamma w_i^2, \tag{3}$$

where Y_i is the total production, w_i is the amount of water use per unit land, and $\alpha, \beta,$ and γ are yield parameters. We assume that the price of the agricultural product is exogenous and the community can be considered a price-taker. However, the sales price in the rainy season (P_r) is different from the price in the dry season (P_d). We also assume a fixed farming cost c for each unit of land cultivated, which may differ between seasons. Total profit of farmer i in both seasons is given by

$$\pi_i = \rho_i P_r Y_{i,r}(a_{i,r}, w_{i,r}) - c_r a_{i,r} + \rho_i P_d Y_{i,d}(a_{i,d}, w_{i,d}) - c_d a_{i,d} \tag{4}$$

Since profits depend linearly on land a_i (see Eqs. (3) and (4)), the optimal use of land is prescribed by a "bang-bang" solution. If farming is profitable, $\rho_i P \partial Y_i/\partial a_i \geq c$, it is optimal to use all land in the relevant seasons. If it is profitable in both seasons, we have $a_r^* = a_d^* = a_i$. However, if farming is not economically viable, no land is used.

The decision on how much water to use is more complex. Defectors are short-sighted and withdraw water from the river system at the individual myopic optimum ignoring any benefits of saving water for the dry season. Cooperators use water at a socially optimal rate, typically saving water in the rainy season for the dry season. In particular, cooperators withdraw their "fair share" of water, i.e. the social optimal use of water divided by the number of farmers. When water becomes scarce, a social dilemma arises and short-sighted defectors are strictly better off than sustainably-minded cooperators. The main difference between cooperators and defectors is thus in how much water is used in the rainy season. In the dry season all water is used as long as marginal benefits are positive. For simplicity, we assume that the remaining water in the dry season is divided symmetrically among all agents, since the cooperative solution and the competitive solution (defined by the Cournot–Nash equilibrium) coincide in the dry season.

Formally, short-sighted farmers simply maximize the profits from each farming season separately, subject to land constraints $a_{i,r} \leq a_i$ and $a_{i,d} \leq a_i$, which implies that using the same plot of land in both seasons (i.e. double cropping) is possible. The water constraint is the total water available in the system determined at the beginning of the year, while for the second season their water constraint corresponds to the amount of water left in the system. Hence, water constraints are given by $w_{i,r} \leq Q_r/a_i$ for the rainy season and $w_{i,d} \leq (Q_r - W_r)/(Na_i)$ for the dry season. In optimum, a short-sighted farmer equates marginal return from a unit of land with marginal cost of cultivating the land in each season, i.e. $\rho_i P \partial Y_i/\partial a_i = c$. For water allocation, water is used until marginal returns from using water is zero in each season, i.e. $\rho_i P \partial Y_i/\partial w_i = 0$.

Cooperators allocate water for both seasons at the beginning of the year by maximizing total profit (see Eq. (4)), subject to land constraints $a_{i,r} \leq a_i$ and $a_{i,d} \leq a_i$ and water constraints according to water availability in the system. In the rainy season, the water constraint for cooperators is the proportional share of the total water available in the system ($w_{i,r} \leq Q_r/(Na_i)$). In the dry season, their water constraint corresponds to the total water left ($w_{i,d} \leq (Q_r - W_r)/(Na_i)$). In optimum, a sustainably-minded farmer equates the marginal return to water in both seasons, i.e. $\rho_i P_r \partial Y_{i,r}/\partial w_{i,r} = \rho_i P_d \partial Y_{i,d}/\partial w_{i,d}$, and equates marginal returns to a unit of land used in each season with marginal costs of cultivated land, i.e. $\rho_i P \partial Y_i/\partial a_i = c$.

The optimization problem of cooperators and defectors can be solved analytically with inequality constraints, by forming the Lagrangian and using the Kuhn-Tucker conditions. It can also be solved numerically using the fmincon solver in MATLAB (Mathworks Inc.).

2.4. Social dynamics

After harvesting in both seasons has taken place, social dynamics unfold. The social dynamics build upon principles from evolutionary game theory (Sigmund and Nowak 1999; Nowak 2006a) that depicts how cooperation and defection as strategies evolve. The key idea is that strategies will be imitated depending on the relative utility derived from each strategy. In our model, cooperators restrain themselves to a socially optimal level of water extraction and punish defectors who extract water at an individually optimal level.

Our model builds upon Sethi and Somanathan (1996) regarding how the social norm of restraining water and punishing non-cooperative behavior evolves. A key difference is that Sethi and Somanathan (1996) use a deterministic model building on ordinary differential equations, while we develop a probabilistic agent-based model.

Punishment takes place upon encounters between two agents. We model encounters as a Poisson processes (Richter et al., 2013), meaning that encounters occur randomly between two agents. The probability that agent i is part of such encounters is thus equal to $2/N$. At time t in total k encounters take place in the community, so that agent i has an expected number of encounters equal to $(2/N)k$. Denoting $\lambda = 2k/N$, we define λ as the community social capital which indicates how frequently an agent encounters others in the community. For example, when $k = N$, then $\lambda = 2$, meaning that an agent has a chance of encountering at least two other agents in the community at time t.

If a cooperator and a defector encounter each other, social sanctions, i.e. punishments occur. We assume that a cooperator incurs a utility loss μ from punishing a defector who, in turn, bears a utility loss ω from being punished. We refer to μ and ω as a unit cost of punishing and being punished respectively for cooperators and defectors and assume $\mu < \omega$. This can be thought of as social disapproval or actual destruction of material (Masclet et al. 2003). The expected utility loss of a cooperator from sanctioning defectors is thus increasing with the number of defectors being caught and punished. The expected utility loss of a defector from being punished is increasing with the number of cooperators imposing punishment. Punishment is probabilistic, i.e. a cooperator may punish more than one agent and a defector may be punished by more than one cooperator.

In each interaction loop, the number of social encounters are counted. For example, the number of defectors being caught and punished by an agent i (a cooperator) at time t is given by $D_{i,t}$, while the number of cooperators imposing punishment on individual agent j (a defector) at time t is given by $C_{j,t}$. The utility of cooperator i ($U_{i,t}^C$) and defector j ($U_{j,t}^D$) at time t are, thus, given by

$$U_{i,t}^C = \pi_{i,t}^C - \mu D_{i,t}, \tag{4}$$

$$U_{j,t}^D = \pi_{j,t}^D - \omega C_{j,t}. \tag{5}$$

An agent who bears excessive punishment costs (either as a punisher or as being punished) considers changing behavior. Whether agents change behavior depends on how successful the current strategy is compared to what others in the community are doing. Again, this process is random. We assume that – after all punishment has taken place – two agents are matched randomly. The probability of switching to the other strategy depends on how successful both strategies are. If the utility of agent i is lower than that of agent j, the probability of agent i switching from strategy i to j is equal to $(U_j - U_i)/(U_j + U_i)$. Otherwise, the agent i keeps using the same strategy.

For the analysis in the next section, three key parameters are chosen, namely the initial proportion of cooperators (C_o), punishment

Table 1
Model variables and parameters with default values.

Symbol	Definition	Values		Unit
Variables				
Q	Total water available			m^3
w	Individual water withdrawal			m^3/ha
W	Total water withdrawal			m^3
C	Number of cooperators			
D	Number of defectors			
Parameters		Rainy season	Dry season	
$\bar{Q}$	Mean inflow	700,000		m^3
σ_Q	Standard deviation of inflow	200,000		m^3
α	Yield parameter	0	0	kg/ha
β	Yield parameter	2	2.5	kg/m^3
γ	Yield parameter	1/1500	1/1500	[kg/m^3]. [m^3/ha]$^{-1}$
p	Unit sale price	0.25	0.3	$/kg
c	Fixed cost per unit land	200	200	$/ha
$\bar{a}$	Mean acreage	3	3	ha
$\bar{a}_S$	Mean acreage of small landholders	2	2	ha
$\bar{a}_L$	Mean acreage of large landholders	4	4	ha
$\sigma_{a,S}$, $\sigma_{a,L}$	Standard deviations of acreage	1	1	ha
C_o	Initial proportion of cooperators	0.5		
N	Community size	100		
λ	Social capital	1		
μ	Unit cost of punishing	400		$
ω	Unit cost of being punished	600		$
$\bar{p}$	Average skill factor	1		

strength (ω/μ) which depicts how costly it is for an agent to be punished for violating norms, and social capital ($\lambda = 2k/N$) which depicts how likely and frequently agents encounter and perform punishment in a single year.

3. Results

The agent-based model is solved for the given parameter values by MATLAB (Mathworks Inc.). All parameter values and their definitions are summarized in Table 1. In Sections 3.1 and 3.2 we illustrate the effect of changing water availability and variability on cooperation in cases where agents are homogeneous in terms of skills and land endowments. In Section 3.3 we analyze whether cooperation can be maintained when agents differ in terms of skills and land endowments. For the same amount of water use, agents possessing higher skill can produce higher yields than those who possess lower skill. Similarly, agents endowed with larger landholding can generate more income than those endowed with smaller landholding, as income is directly proportional to land.

3.1. *Dynamic patterns of emergence and collapse of cooperation*

We started the simulation with default value of parameters except that of punishment strength and observed temporal patterns of cooperation under two conditions: low punishment strength ($\omega/\mu = 1.2$) and high punishment strength ($\omega/\mu = 3.5$), as peer punishment is the mechanism in our model that may sustain cooperation. High punishment strength means it is very costly to defect. Through 100 repeated runs, we observed that the model reaches only two possible equilibria: full cooperation (full-C) and full defection (full-D). Mixed equilibria comprising cooperators and defectors were not found, consistent with the results of Sethi and Somanathan (1996). For a certain range of parameter values (see Section 3.2), however, the model could reach bistability where the system rests in either full-C equilibrium or full-D equilibrium, depending on stochastic dynamics. In general, the model reaches the equilibrium well before the 100th time step. When agent heterogeneity is considered, however, equilibrium time varies. For each repeated run, we thus run the model until it reaches equilibrium. In Fig. 2, we show the two possible outcomes where cooperation collapses under the low punishment condition and emerges under the high punishment condition. The collapse of cooperation (Fig. 2(a)) is preceded by an widening gap in utility between cooperators and defectors with defectors' utility being higher. In a similar vein, the emergence of cooperation is followed by an increasing utility of cooperators over utility of defectors.

3.2. *Effects of key social, economic and environmental parameters on cooperation*

We conduct a series of simulations to analyze how key social, economic and environmental parameters affect cooperation. The model reaches only two possible equilibria – full cooperation (full-C) and full defection (full-D) – depending on social and environmental parameters (Fig. 3).

First, as the punishment strength (ω/μ) increases – which measures how costly it is for a defector to violate the norm, the percentage of runs that reach full-C increases. When $\omega/\mu > 2.0$, all simulations result in full-C. Intuitively, if the costs of punishing free-riders decrease vis-a-vis the costs of being punished for free-riding, social norms of cooperation spread more easily in the community. Second, the greater the initial proportion of C, the higher the percentage of runs that reach the full-C equilibrium. Intuitively, if only a small number of cooperators attempt to discipline many defectors, they will quickly give up – leading to the

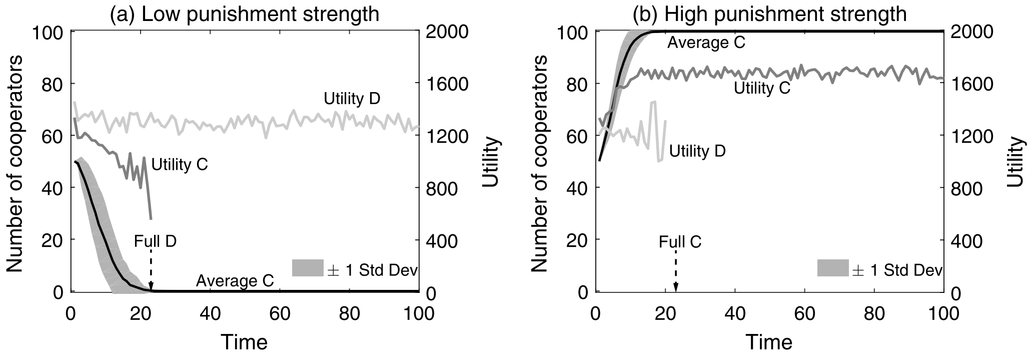

Fig. 2. Temporal patterns of emergence and collapse of cooperation under (a) low punishment condition ($\omega/\mu = 1.2$) and (b) high punishment condition ($\omega/\mu = 3.5$). The model was simulated with default parameter values for 100 repeated runs. The number of cooperators at each time step and the utility of defectors (D) and cooperators (C) were averaged over 100 runs, where standard deviations were also shown.

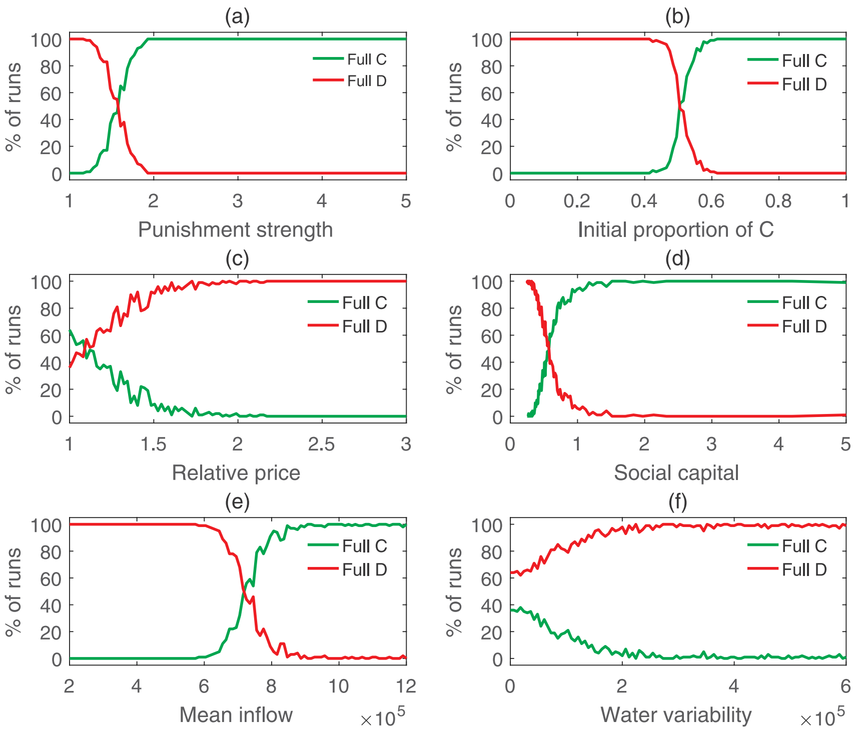

Fig. 3. We present the effects of key parameters on cooperation in the form of one-at-a-time sensitivity plots where the *x*-axis stands for the varying values of (a) punishment strength, (b) initial proportion of cooperators, (c) relative sales price, (d) social capital, (e) mean water inflow, and (f) water variability. To account for stochasticity in the model, we run the model 100 times repeatedly for each single value of the parameters and count the percentage of model runs that reach the full-cooperation equilibrium (green line) and full-defection equilibrium (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

full-D equilibrium. At the same time, many cooperators will be very successful in punishing a small number of defectors, leading to the full-C equilibrium. If the initial proportion of C is neither too small nor too large ($0.4 < C_0 < 0.6$), the model may reach either full-C or full-D equilibrium, giving rise to bistability. Third, increasing the relative price (P_d/P_r), which measures the benefits of saving water for the dry season, leads to less cooperation. Tragically, when cooperation is most beneficial, least cooperation is observed. Intuitively, this happens because cooperators are doing what is socially optimal (saving more water), while the defectors are the ones who benefit, increasing the temptation to defect. Fourth, social capital (λ), which measures the frequency of encounters in the community, has a positive effect on cooperation. Intuitively, more interactions imply that defection is detected and sanctioned more often, disciplining defectors. Finally, an increasing water inflow increases the chance of reaching full cooperation, as more water can potentially be saved for use in the dry season, decreasing the incentive for defecting. Increasing resource variability favors defection, mostly because in times of scarcity cooperators are the ones who restrain water use, increasing the temptation to defect.

3.3. *Effects of changing resource conditions*

3.3.1. *Effects of resource scarcity*

In Fig. 4 we show that increasing water scarcity may lead to the collapse of cooperation in various social and economic circumstances. Overall, under the scarcity condition where the mean inflow is less than 7×10^5, full defection is the outcome for a large parameter space of the initial proportion of cooperators (Fig. 4(a)), punishment strength (Fig. 4(b)), social capital (Fig. 4(c)), and relative price (Fig. 4(d)). In all those cases, cooperation collapses because the water that is saved by cooperators for potential use in the dry season is taken out by defectors, which makes the profits of the latter relatively higher than the former. If water is abundant, cooperation can thrive for most of the parameter space for all social and economic parameters. Here, when water is almost sufficiently available for all agents for farming in both seasons, the difference between the profits of cooperators and defectors is small, making the defecting strategy inferior as the utility loss due to punishment is larger than the potential gains from using slightly more water.

3.3.2. *Effects of resource variability*

In Fig. 5 we show that variation in water inflow has a small negative effect on cooperation under various social and economic conditions. If the water inflow varies widely from year to year, it is more difficult to maintain cooperation in the community. For almost the whole parameter space for the initial proportion of cooperators, social capital, and relative price, the defectors dominate in the community, especially when the degree of variability is high ($\sigma_Q > 2 \times 10^5$). Cooperation can be maintained, however, if the punishment strength is high ($\omega/\mu > 2$). Note that water variability has a much weaker effect on cooperation than changes in mean inflow. Intuitively, a high degree of water variability leads to a reduction in profits of both cooperators and defectors. However, as the profit function is concave in water use, a high variability slightly favors defection. Also, increased variability increases the zone of bistability, as stochasticity is more pronounced.

3.3.3. *Combined effects of resource scarcity and variability*

So far we have explained the effects of water scarcity and water variability on cooperation separately. Here, we consider the case where water scarcity and water variability may interact and affect cooperation in the community. Fig. 6 shows that the combined effects of water scarcity and water variability on cooperation become much more pronounced when the two interact. If punishment strength and social capital are low, it is impossible to maintain cooperation under the condition of highly variable inflow ($\sigma_Q > 4 \times 10^5$), even if water is abundant ($\overline{Q} > 10 \times 10^5$) (Fig. 6(a)). Cooperation is only stable when the mean inflow is high and the degree of variability is low. However, if the punishment strength is high (Fig. 6(b)), cooperation can be enhanced, even if social capital is low and water is scarce, as long as the degree of water variability is not too high. Furthermore, if punishment is low and the community has strong social capital, cooperation can be maintained in various levels of water scarcity and variability (Fig. 6(c)). Finally, under high social capital and high punishments cooperation can be supported, unless the mean inflow is very low ($\overline{Q} < 3 \times 10^5$).

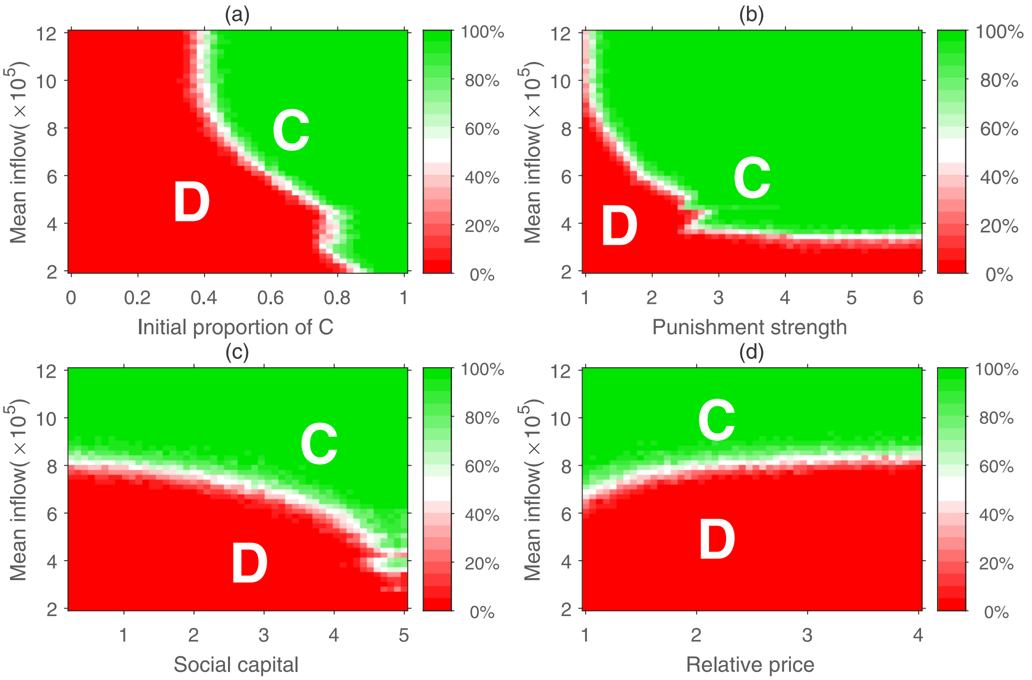

Fig. 4. Heat map illustrating the effects of mean water inflow on cooperation for key social and economic parameters. The lower the mean inflow is compared to the default value (7×10^5), the greater the scarcity is. Here, we performed 100 repeated runs for each single value of the parameters and count the percentage of model runs that reach the full-cooperation or the full-defection equilibrium. The color bar shows the percentage of model runs that reach full-cooperation equilibrium (light green) and full-defection equilibrium (red). The white color represents the case where the model features bistability and may reach either full cooperation or full defection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

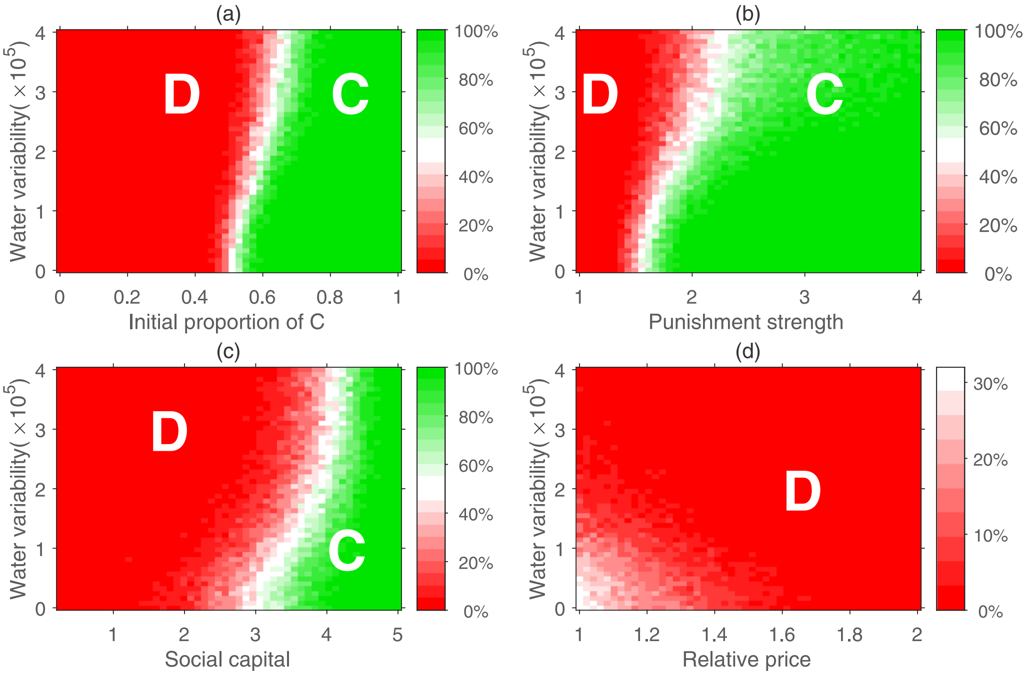

Fig. 5. Heat map illustrating the effects of water variability on cooperation for key social and economic parameters. The higher the standard deviation of resource inflow is compared to its default value (2×10^5), the more variable the resource is from year to year. To account for stochasticity, we performed 100 repeated runs for each single value of the parameters and count the percentage of model run that reach full-cooperation or full-defection equilibrium. The color bar shows the percentage of model runs that reach full-cooperation equilibrium (light green) and full-defection equilibrium (red). The white color represents the case where the model features bistability and may reach either full cooperation or full defection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. *Effects of inequality and heterogeneity*

3.4.1. *Skill heterogeneity*

In the previous section we have analyzed water scarcity and water variability without considering different capacities or skills of farmers. Here, we observe in Fig. 7 that skill heterogeneity has only a weak effect on cooperation. For instance, if water becomes scarcer, cooperation will collapse regardless of the degree of heterogeneity (Fig. 7(a)). In addition, if water varies greatly from year to year, skill heterogeneity reduces the probability of reaching full cooperation. (Fig. 7(b)). In our model, a more skillful agent is able to produce higher yield than a low-skill agent for the same amount of water use. Intuitively, cooperation is affected because heterogeneous skills blur the relationship between decisions and outcomes. A low-skill defector is potentially worse off even if subjected to mild punishment, while a very skillful defector may be able to succeed in spite of large social disapproval, even though he would have been outperformed by cooperators if skills were homogenous.

3.4.2. *Land inequality*

Land inequality is another potential factor that can catalyze the effects of environmental changes on cooperation. We model inequality as the degree of variability in land distribution among agents (land heterogeneity) and proportion of large landholders in the community. Overall, increasing inequality can lead to a collapse of cooperation, especially under conditions of low water inflow and high degree of water variability (Fig. 8). Cooperation can only emerge if low degree of land heterogeneity goes hand in hand with (i) a very high degree of

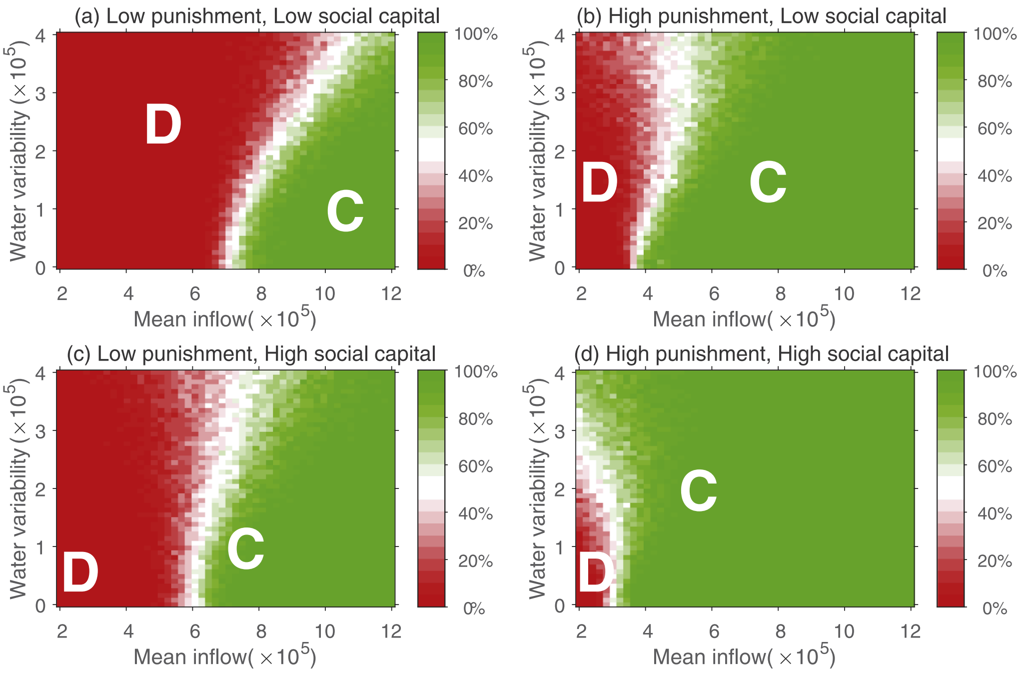

Fig. 6. Combined effects of water scarcity and variability on cooperation for (a) low punishment and low social capital, (b) high punishment and low social capital, (c) low punishment and high social capital, and d) high punishment and high social capital. To account for stochasticity, we performed 100 repeated runs for each single value of the parameters and count the percentage of model runs that reach the full-cooperation or full-defection equilibrium. The color bar shows the percentage of model runs that reach full-cooperation equilibrium (light green) and full-defection equilibrium (red). The white color represents the case where the model may reach either full cooperation or full defection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

water inflow (Fig. 8(a)) or (ii) a very low degree of water variability (Fig. 8(c)). In our model, profit is directly proportional to land, a more unequal distribution of land results in a greater discrepancy in profits as well as utility among agents, making it harder for cooperators to discipline defectors. Intuitively, inequality makes sanctioning less effective, because high-earning defectors may still enjoy relatively higher utility than poor cooperators, inducing the latter group to also defect. Similarly, increasing the proportion of large landholders can potentially reinforce the negative effects of water scarcity on cooperation (Fig. 8(b) and (d)). Intuitively, similar to the effects of land heterogeneity, large landowners will not feel sanctions sufficiently strongly to change behavior, and less fortunate individuals may end up imitating them. For example, a poor farmer with small landholding may imitate a rich farmer with large landholding regarding the decision on water use, hoping to be as successful as the rich one. The inability to separate the role of extra income gained from cultivating on a relatively large land size, can be illusive for the poor as the foundation of the success (i.e. land endowments) cannot be imitated.

4. Discussions and conclusion

We have developed an agent-based model to analyze how socioeconomic and environmental changes affect the cooperation of agents in a self-governing community who share a resource. Our model considers a community of resource users who share water from a joint river. The water availability varies between seasons and between years and the members may be exposed to some degree of heterogeneity and ineqality in terms of skills and land endowments. Social norms of restraining water use are emerging in the community and punishment of norm-violators is the enforcement mechanism to overcome the social dilemma arising from seasonal allocation of water.

The model results show that social norms may erode in response to changes in resource conditions. Particularly, we have shown that resource scarcity and variability may hinder cooperation, especially when combined, and when the community faces some degree of inequality and heterogeneity. These findings are consistent with those of Sethi and Somanathan (1996), who show that cooperation can be maintained if the number of punishers is sufficiently large, but upon collapse, cooperation cannot reemerge. Our model predictions differ from Schlüter et al. (2016), who found that scarcity may actually foster cooperation. The difference comes from the assumptions regarding performance under scarcity and abundance. While in Schlüter et al. (2016), the benefits from defecting are relatively smaller under scarcity, in our model defecting is especially lucrative under scarcity because of the

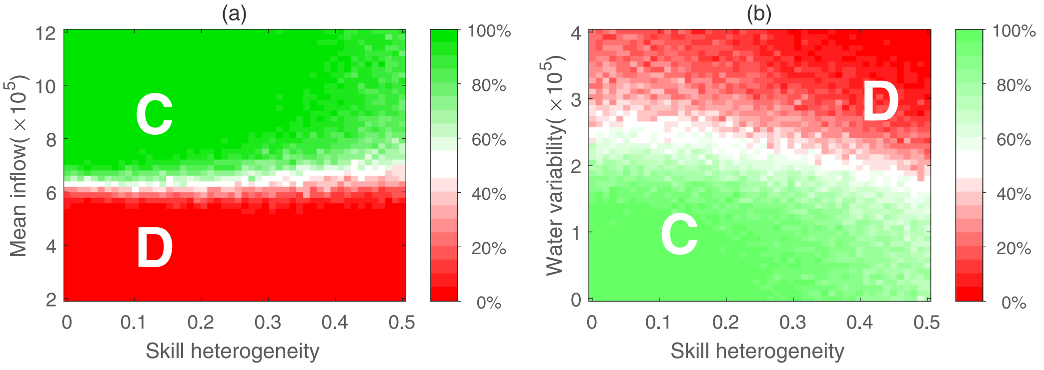

Fig. 7. The combined effects of skill heterogeneity and environmental changes on cooperation. Here, the *x*-axis represents the varying values of standard deviation of the skill parameter – the higher the value, the higher the degree of heterogeneity. The *y*-axis represents the environmental parameters, namely (a) the mean inflow and (b) water variability. Here, we performed 100 repeated runs for each single value of the parameters and count the percentage of model runs that reach the full-cooperation or full-defection equilibrium. The color bar shows the percentage of model runs that reach full-cooperation equilibrium (light green) and the full-defection equilibrium (red). The white color represent the case where the model may reach either full cooperation or full defection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

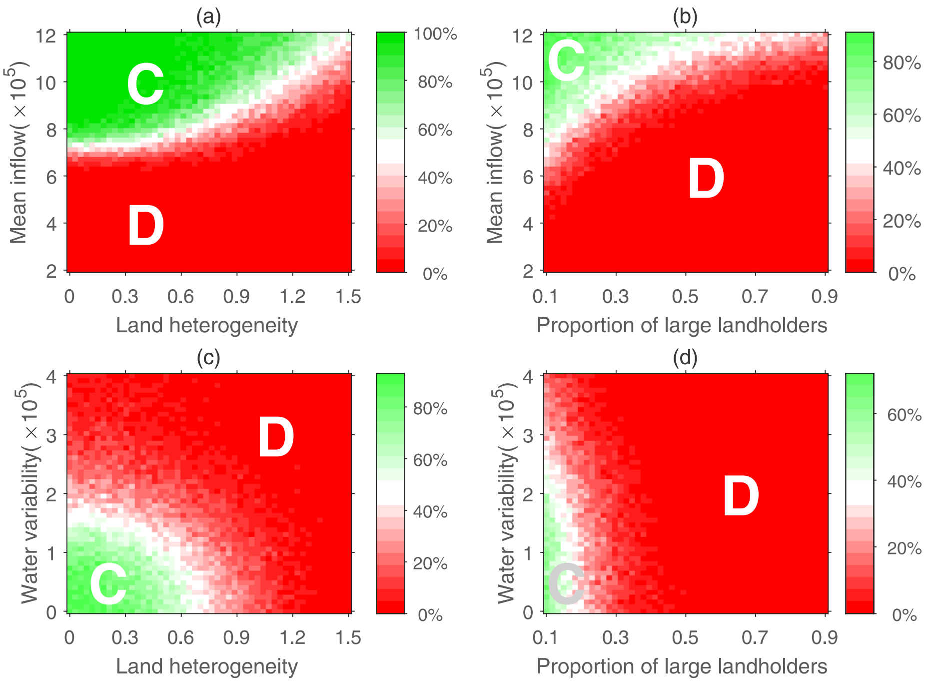

Fig. 8. The combined effects of land inequality and environmental changes on cooperation. Here, the *x*-axis represents the varying values of land heterogeneity which is characterized by the standard deviation of land and proportion of large landholders. The *y*-axis represents the environmental parameters, namely the mean inflow and the water variability. Here, we performed 100 repeated runs for each single value of the parameters and count the percentage of model runs that reach the full-cooperation or full-defection equilibrium. The color bar shows the percentage of model runs that reach full-cooperation equilibrium (light green) and the full-defection equilibrium (red). The white color represents the case where the model may reach either full cooperation or full defection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presence of rainy and dry seasons. Any attempts taken by cooperators to save water for the dry season are benefitting defectors, who may use the water in the rainy season already. On a more fundamental level, the question whether cooperation thrives or erodes in times of scarcity, depends on how (i) the benefits and costs of cooperative acts are distributed and (ii) the enforcement mechanism in place. In the real world, both elements will be case-specific and therefore the question of cooperation will be mostly an empirical, rather than a theoretical one. However, with a theoretical model like this one can produce hypotheses that will then provide good grist for our empirical mills to test key factors that facilitate or undermine cooperation in the field.

Our theoretical model is based on evolutionary game theory where agents are assumed to act cooperatively or selfishly following the tradition of Sethi and Somanathan (1996). The behavioral rules are still relatively simple and it would be interesting to add more realism to a theoretical model like this one. First, in our model the only available strategies are cooperation and defection. It would be very interesting to allow for continuous strategies, where agents could choose from a whole continuum of extraction levels and cooperation would not be an all or nothing decision (Killingback and Doebeli 2002; Doebeli et al., 2004). Second, we assumed that the community is well-mixed, i.e. encounters with other agents are entirely random. Allowing for spatial structure, either as people having neighbors (Nowak 2006b; Noailly et al., 2009) or operating in a network (Rand et al. 2014; Ohtsuki et al. 2006) would most likely create cooperative clusters and favor co-existence of cooperators and defectors. Third, we assume that the remaining water in the dry season is divided symmetrically among all agents. This assumption is obviously motivated by analytical convenience, rather than realism. Alternatively, one could consider that skillful farmers get more water, since they can use it more efficiently. Also, it seems plausible that richer farmers are more successful in appropriating water, potentially increasing the income differences between rich and poor farmers. Fourth, punishment is assumed to be only dependent on the number of cooperators, but the punishment costs are constant for punishers and defectors. In reality, both components are most likely dependent on how widespread defection is, as it seems much more difficult to sanction selfish behavior if it is in line with the empirical, i.e. observed social norm. Also, it seems plausible that users are more inclined to sanction if the resource is scarce and the social dilemma is more severe. Such adaptive punishment may be able to respond to scarcity and potentially also to the erosion of norms itself, either requiring stronger punishment or changing the cooperative strategy itself under scarcity. Richter and Dakos (2015) have shown that such a collapse of norms can be anticipated with resilience indicators, derived from, for example, fluctuations in profits. Whether such adaptive self-governance system could evolve fast enough – if at all – and how it would look like seems like an exciting topic for further research.

While our study is theoretically grounded, our paper provides some indications for the fragility of cooperation towards external pressures, such as climatic changes. In the context developed here, we have shown that the resilience of social norms could be weakened by those changes and a collapse of cooperative arrangements may occur. For policy makers, an important take-home message is that any projected changes in agricultural yields due to climate change will be dependent on how the institutional setting responds to scarcity. Our results are purely theoretical, but they suggest that welfare losses because of climate change might be higher than expected, as this would not only depend on water availability, but also on the welfare losses that may arise from the breakdown of cooperative arrangements.

While the paper mainly shows the fragility of social norms, there are also promising findings. Perhaps most importantly, cooperation is much more resilient towards external pressures if social capital (i.e. the frequency of encounters) is high. Fostering community meetings and creating common interaction places (e.g. common drying areas) seems like a relatively cheap option to maintain cooperation. Such approaches are indeed often favored by NGOs (Agrawal and Gibson 1999).

Our model is entirely theoretical and its lack of empirical grounding prevents any predictions about real world cases. Therefore, an exciting next step would be to take our model predictions to the field to validate the results and also test potential policy solutions to foster the resilience of social norms that help preserving common-pool resources.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecocom.2018.06.001.

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