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Summary

Conditions for the emergence of cooperation in a spatial common-pool resource game are studied. This combines in a unique way local and global interactions. A fixed number of harvesters are located on a spatial grid. Harvesters choose among three strategies: defection, cooperation, and enforcement. Individual payoffs are affected by both global factors, namely, aggregate harvest and resource stock level, and local factors, such as the imposition of sanctions on neighbors by enforcers. The evolution of strategies in the population is driven by social learning through imitation. Numerous types of equilibria exist in these settings. An important new finding is that clusters of cooperators and enforcers can survive among large groups of defectors. We discuss how the results contrast with the non-spatial, but otherwise similar, game of Sethi and Somanathan (1996).

Keywords: Common property, Cooperation, Evolutionary game theory, Global interactions, Local interactions, Social norms

JEL Classification: C72, Q2

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1 Introduction

The management of common-pool resources (CPRs), such as forests, fishing grounds, and groundwater basins, is characterized by a conflict between individual and social interests. While the collective interest of the group is to limit harvesting to a sustainable level, the combined actions of individual harvesters pursuing their own interest inevitably result in a suboptimal outcome, characterized by excessive exploitation of the resource (Dasgupta and Heal, 1979: Chapter 3). This dilemma can take the form of a game played by two types of harvesters: namely, defectors and cooperators, adopting high and low levels of harvest, respectively (Ostrom et al., 1994). In the finitely repeated CPR game, unilateral defection is the unique Nash equilibrium, while privatization of the resource is often the suggested management solution.

Privatization is, however, not always feasible in the case of common-pool resources, or it may destroy the culturally evolved social norms. Moreover, while economic theory predicts defection, case studies and laboratory experiments have provided evidence that, in real life, cooperation can be sustained among harvesters (Ostrom, 1990; Hackett et al., 1994; Chermak and Krause, 2002). Accordingly, cooperative outcomes can be reached as long as norms or rules, such as trust, reward or punishment, prevail in the group. The imposition of sanctions on harvesters that adopt excessive exploitation levels has proved to be particularly effective in sustaining cooperation, even in the case of non-repeated interactions among unrelated individuals or in very large groups. Evidence from the field suggests that some agents voluntarily engage in 'altruistic punishment', that is, penalizing free-riders, even if this implies an individual cost. Often, a small proportion of these altruistic punishers is sufficient to enforce cooperation in the group (Fehr and Gächter, 2002).

A rare theoretical analysis of the role of altruistic punishers or 'enforcers' in solving CPR dilemmas is presented in Sethi and Somanathan (1996). They consider an evolutionary CPR game played by a fixed population of players with three strategies: defection, cooperation, and enforcement. Payoffs of defectors are lowered by a sanction that depends on the number of enforcers in the population, while enforcers bear a cost that depends upon the total number of defectors. Players experience social learning and imitate the strategy that yields the highest payoffs. The evolution of strategies is captured by a replicator dynamics equation, according to which the share of the best-performing strategy in the population increases due to agents imitating it. Sethi and Somanathan combine replicator and resource dynamics to show how changes in the resource stock affect harvesting behavior, and vice versa. They identify two equilibria in the system:

namely, a final population composed of only defectors, and a cooperative equilibrium with only cooperators and enforcers.

The model considered in this paper adds a major innovation to Sethi and Somanathan's work, namely spatial interactions between agents. While Sethi and Somanathan restrict themselves to aggregate population dynamics, our model more realistically emphasizes the role of locality. The approach is, therefore, unlike replicator dynamics, based on the explicit modeling of micro-interactions among individuals. This approach results in a combination of local and global interactions. Global interactions include effects that run through aggregate harvest and the resource stock, and feed back to profits associated with harvesting strategies employed by individual agents.

The objective of the present paper is to find conditions for the emergence of cooperative equilibria in the spatial evolutionary CPR game. The objective comes down to testing the robustness of Sethi and Somanathan's findings in an evolutionary game with spatial interactions. In particular, it will be examined whether other types of equilibria than found by Sethi and Somathan emerge.

The present CPR game with spatial interactions has connections with two different bodies of literature. First, it relates to studies on local interaction games within the field of evolutionary game theory (Eshel et al., 1998; Lindgren and Nordahl, 1994; for an overview, see Nowak and Singmund, 1999). The structure of our game relates most closely to Nowak and May (1992). A well-known result of the literature on local games is that the introduction of local interactions between agents enhances the survival of cooperation. The game presented in this article differs from these approaches in that it combines both local and global interactions.

Second, the approach presented here also relates to the wide body of experimental and theoretical work on the evolution of social norms in CPR games (Ostrom et al., 1994). In this literature, only a very few studies have formally analyzed an evolutionary CPR game with a variable resource stock (Akiyama and Kaneko, 2000; Janssen, 2001; Sethi and Somanathan, 1996). Among these studies, Sethi and Somanathan's analysis provides an attractive benchmark because of its simplicity, which is due to a combination of only three types of strategies and replicator dynamics. The present study adds insights to this literature as it illustrates how results from local interaction games can be applied to the problem of overexploitation of common-pool resources. For this purpose numerical simulation techniques are used.

The problem of local interaction in a common-pool resource game is also studied by Noailly et al.

(2004). But its setup differs substantially from the present one, in two respects. First, it studies interaction when agents are located on a circle, whereas here we consider interaction between agents situated on a torus. On the one hand, the circle allows for more theoretical insights, because of the fact that the structure is less complicated. On the other hand, the torus provides a richer and more realistic spatial structure of interactions and learning among agents. Most real world interactions, like in agriculture or in fisheries, occur in two-dimensional space. Second, Noailly et al. (2004) employ a different learning rule. In their settings, agents imitate the strategy yielding the highest average payoffs. For most parts of the present paper, we assume that agents are more 'naive' and simply imitate their most successful neighbor. We find that changing the learning rule does not qualitatively affect the results found in Noailly et al. (2004). We also find the emergence of equilibria in which cooperators and enforcers coexist in our settings. In this sense, our analysis can be seen as a robustness test of the analysis of Noailly et al. (2004). Yet, we find quantitative differences between the two models. A main new insight of the present study is that cluster equilibria of cooperators and defectors are favored when agents are learning in a 'naive' way. This study presents in addition new results regarding the role of certain parameters, like population size and the productivity of harvesting technology.

The paper is organized as follows. Section 2 presents the benchmark neoclassical CPR game and its evolutionary spatial version. Section 3 identifies the equilibria of the system with a fixed resource level and shows how these contrast with Sethi and Somanathan's findings. In addition, we test for the effects of changes in parameters. Section 4 discusses the impact of adding resource dynamics to the evolutionary system. Section 5 concludes.

2 The Model

2.1 The CPR game

The benchmark neoclassical CPR game (Dasgupta and Heal, 1979: Chapter 3; Chichilnisky, 1994) is presented briefly here. This game relies on the assumption of maximizing behavior and thus contrasts sharply with the evolutionary version of the game that will be discussed further on.

A fixed population of m ($m > 1$) harvesters has access to a natural resource. The individual effort level of harvester i ($i = 1, \dots, m$) in period t ($t = 0, 1, \dots$) is denoted by x_{it}. Total effort of the population is simply the sum of all individual efforts:

$$X_t = \sum_{i=1}^{m} x_{it}. \tag{1}$$

Aggregate harvest H is a strictly concave and increasing function of total effort X_t and of the total stock of natural resources N_t. In a first stage, we ignore resource dynamics to simplify the analysis and fix the resource stock N_t at N_0. Suppressing N_0, we can write the harvest rate as a function of X only and we can ignore time subscripts for all variables. We define F as the total harvest rate, which is strictly concave and increasing with $F(0) = 0$, $F'(0) > w$, $F'(\infty) < w$, where w is the constant cost per unit of effort employed.

$$H(X, N_0) = F(X). \tag{2}$$

Each agent receives a share of total profits in proportion to the amount of effort invested. Individual profits are then given by:

$$\pi_i(x_i, X) = \frac{x_i}{X} F(X) - w x_i, \tag{3}$$

where it is assumed that the harvested commodity is the numeraire. Individual payoffs are thus a function of a global factor, namely aggregate harvest. The larger aggregate harvest is, that is, the more defectors are present, the lower individual payoffs are. Thus, the level of aggregate profits is:

$$\Pi = \sum_{i}^{m} \pi_i(x_i, X) = F(X) - wX. \tag{4}$$

At X_P, which is the Pareto efficient level of effort defined by $F'(X_P) = w$, total profits are maximized and the resource is used efficiently. When access to the resource is open to everyone, entry of harvesters continues until X_0, where $F(X_O) = wX_O$, i.e., no harvester enjoys positive profits. In the case of a fixed population of agents, maximization of individual profits in the CPR game leads to a suboptimal outcome X_C. This is the unique Nash equilibrium that is inefficient ($X_C > X_P$) but yields positive rents ($X_C < X_O$).

An evolutionary version of this standard framework has been studied by Sethi and Somanathan (1996). In an evolutionary game, harvesters are boundedly rational, which means that they do not solve any optimization problem. Instead, they rely on simple forms of social learning like imitation of the best-performing strategy. Diffusion of strategies occurs through the learning process and drives the evolution of strategies towards an equilibrium that falls between the benchmark equilibrium aggregate harvest rates X_P and X_O.

In the remainder of the paper, we base our analysis on a similar evolutionary framework but introduce spatial interactions between the agents.

2.2 A spatial evolutionary CPR game without resource dynamics

The spatial evolutionary CPR game embodies the following four main features:

Space. A fixed population of m harvesters is distributed on a two-dimensional torus. A torus is a lattice whose corners are pasted together to ensure that all cells are connected, so that there are no edge-effects. On a torus, all cells in the first row (column) are connected to cells in the last row (column). For example, the cell in the top-left corner is connected not only to its right and bottom neighbors, but also to the cells in the bottom-left corner and top-right corners. Each single cell of the torus is occupied by one, fixed player during the game. We define the neighborhood of each player as the set of the four closest neighbors, located North, South, East, and West of the player, as shown in Figure 1. An alternative definition of neighborhood entails eight neighbors (adding North- and South-East and North- and South-West neighbors). We will not go into this.

[INSERT Figure 1 about here]

Strategies. Just as in Sethi and Somanathan (1996), we consider three possible different types of strategy for every player: defection, cooperation, and enforcement. Enforcers punish defectors. Both cooperators and enforcers choose a low level of effort x_L to avoid overexploitation of the resource, while defectors choose a high level of effort x_H, which yields higher profits ceteris paribus. Individual effort levels x_L and x_H are fixed such that:

$$X_P \leq m x_L < m x_H \leq X_O, \tag{5}$$

with X_P and X_O as defined in the previous section, and $m x_L$ ($m x_H$) the total harvest when all agents harvest low (high).

In each round τ ($\tau = 0, 1, \ldots$) of the game, the aggregate effort X_τ is calculated according to the distribution of strategies in the population:

$$X_\tau = m_{D,\tau} x_H + (m_{E,\tau} + m_{C,\tau}) x_L, \tag{6}$$

where $m_{D,\tau}$, $m_{E,\tau}$ and $m_{C,\tau}$ are, respectively, the number of defectors, enforcers and cooperators present in the system in round τ.

Enforcers punish all defectors located in their neighborhood. Monitoring is thus conducted locally among close neighbors. This is a major difference with Sethi and Somanathan's model in which sanctions are imposed by the group of enforcers on the group of defectors at the aggregate level. Here, each enforcer punishing a defector bears a cost γ per defector, while each defector being punished by an enforcer pays a sanction δ. The maximum sanction falling on a defector is thus 4δ, when he is surrounded by four enforcers. Similarly, the maximum cost borne by an enforcer is 4γ.

Payoffs can be formulated for each possible strategy, given aggregate effort X_τ and strategies located in the neighborhood:

$$\pi_{C,\tau} = \frac{x_L}{X_\tau}\left(F(X_\tau) - wX_\tau\right) \tag{7}$$

$$\pi_{Dk,\tau} = \frac{x_H}{X_\tau}\left(F(X_\tau) - wX_\tau\right) - k\delta \tag{8}$$

$$\pi_{El,\tau} = \frac{x_L}{X_\tau}\left(F(X_\tau) - wX_\tau\right) - l\gamma, \tag{9}$$

Here $\pi_{j,\tau}$ denotes payoffs in round τ for strategy j ($j \in \{C, D, E\}$), k $(k \in \{0, 1, 2, 3, 4\})$ denotes the number of enforcers in the neighborhood of any given defector, and l $(l \in \{0, 1, 2, 3, 4\})$ the number of defectors in the neighborhood of any given enforcer. We use the notations Dk to refer to a defector punished k times and thus paying the sanction $k\delta$. Similarly, El refers to an enforcer surrounded by l defectors. Thus, e.g. $\pi_{D3,2}$ refers to the payoffs of a defector surrounded by three enforcers in round $\tau = 2$. Obviously, $\pi_{Dh,\tau} > \pi_{Dh+1,\tau}$ and $\pi_{Eh,\tau} > \pi_{Eh+1,\tau}$ ($h \in \{0, 1, 2, 3\}$). In addition, from (5), (7), (8), and (9), we have $\pi_{D0,\tau} > \pi_{C,\tau} > \pi_{E1,\tau}$ and $\pi_{E0,\tau} = \pi_{C,\tau}$ for all τ.

We make one additional assumption regarding the level of punishment in the system, namely:

$$\pi_{D4,\tau} < \pi_{E0,\tau}, \quad \forall\tau. \tag{10}$$

This implies that a defector incurring the maximum sanction level, regardless of X, earns a lower payoff than any enforcer who does not punish ($E0$). This is to ensure that enforcers can actually win over defectors.

We further assume that $H(X, N_0)$ is a Cobb-Douglas production function:

$$F(X) = \alpha X^{\beta} N_0^{1-\beta} \qquad \alpha > 0, \quad 0 < \beta < 1. \tag{11}$$

As discussed in Section 2.1, we can solve $F'(X_P) = w$ and $F(X_O) = wX_O$ to find X_P and X_O, respectively. This gives:

$$X_P = (\tfrac{w}{\alpha\beta})^{\frac{1}{\beta-1}} N_0 \quad \text{and} \quad X_O = (\frac{w}{\alpha})^{\frac{1}{\beta-1}} N_0 \tag{12}$$

Learning, i.e., updating of strategies, is driven by expectations of larger profits in the next period. In each round, every player updates his current strategy by imitating the strategy that yields the highest payoffs in his neighborhood. Similar learning rules, where agents simply pick up the strategy with the largest score, were used by Axelrod (1984, Chapter 8) and Nowak and May (1992). Eshel et al. (1998) instead impose a learning rule in which the on average best performing strategy in the observed neighbourhood is imitated. This rule is examined with a spatial evolutionary analysis in another paper (Noailly et al., 2004). When the best strategy in the neighborhood is identical to the player's current strategy, the player sticks to his current strategy. When multiple strategies other than the player's current strategy yield the largest (equal) payoffs in the neighborhood, that is, when there is a tie between two strategies, the player randomizes among these strategies with probability $p = 0.5$.

Time. We assume that agents exhibit synchronous behavior. In other words, interactions and learning occur simultaneously. Huberman and Glance (1993) have shown that asynchronous learning can lead to different outcomes than synchronous learning. In our model, seasonal harvesting of the resource suggests the existence of a 'global clock' that governs the learning process. Therefore, it is reasonable to assume that all harvesters modify their strategy simultaneously at the beginning of each new season. A season or a 'round' of the game can be described by the following sequence:

(i) Aggregate effort X_τ is computed given the number of defectors, cooperators and enforcers on the torus.

(ii) Aggregate harvest $F(X_\tau)$ is calculated.

(iii) Individual payoffs π_C, π_{Dk} and π_{El} are computed for all agents, given $F(X_\tau)$, the strategy chosen by each single agent and the distribution of strategies in his neighborhood.

(iv) Agents observe the payoffs of their neighbors' strategies and decide whether to stick to their current strategy or to adopt the strategy of their most successful neighbor. All agents update their strategy simultaneously. This updating process yields a new distribution of strategies in the population.

3 Spatial evolutionary dynamics

In this section we study the spatial evolutionary dynamics using numerical simulations. An equilibrium is a spatial distribution of strategies in which no player has an incentive to change strategy. It is important to realize that in our setting it is possible for a neighboring strategy to earn a larger profit than the player's current strategy even when these strategies are identical. For example, enforcers punishing one defector are in an equilibrium, even if they earn the lowest payoffs, as long as their neighbor with the highest payoff is a non-punishing enforcer. A similar reasoning applies to defectors. This contrasts with Sethi and Somanathan's model, in which agents belonging to the same (sub)group always earn equal payoffs, since sanctions and costs falling on defectors and enforcers are determined at the aggregate level. Such aggregation evidently leads to a loss of information and accuracy of description.

3.1 Notation and parameter values

We use D, C and E to refer to equilibria composed of only defectors, cooperators and enforcers, respectively. In addition, DE, CE and CDE refer to equilibria composed of the corresponding mixes of strategies. In contrast with D, C and E-equilibria, many diverse equilibrium configurations can constitute DE, CE or CDE-equilibria. In addition, note that there cannot be any CD-equilibrium for the simple reason that this corresponds to the case where there is no local punishment between the agents. In this case, defectors are never punished and spread quickly over the lattice.

Which equilibrium emerges depends on three factors:

1. The initial spatial distribution of strategies. Initially, strategies either form clusters or are scattered irregularly. Section 3.3 studies how different equilibria can be reached by varying the initial spatial arrangement of the strategies, while initial shares remain fixed.

2. The initial share of each strategy in the population. Strategy shares in round τ are denoted by $z_\tau = (\frac{m_{D,\tau}}{m}, \frac{m_{E,\tau}}{m}, \frac{m_{C,\tau}}{m})$, which corresponds to a population composed of a mix of m_D defectors, m_E enforcers and m_C cooperators in round τ. We will study how different initial shares (z_0) lead to diverse types of equilibria in Section 3.2.

3. Parameter values. Most of the simulations were performed on a 10x10 ($m = 100$) spatial grid. A simulation run corresponds to 50 time steps, which appears to be sufficiently long for the system to settle into an equilibrium. The following parameters were used:

$$\begin{array}{cc} \alpha = 0.2 & \beta = 0.2 \\ N_0 = 500 & w = 0.2 \\ x_H = 4 & x_L = 2 \\ \delta = 0.4 & \gamma = 0.1. \end{array} \tag{13}$$

Given the other parameter values, the levels of harvest x_H and x_L satisfy (5).[1] The level of sanction $\delta = 0.4$ satisfies condition (10).[2] A sensitivity analysis of critical parameters is conducted in Section 3.4.

3.2 The effects of initial strategy shares in the population

In this section, we study the effects of variation in initial strategy shares. To reduce the number of runs necessary to cover the whole simplex, only initial strategy shares that are multiples of 0.05 are considered. The set of initial coordinates $Z = \{(1;0;0), (0.95;0.05;0), \ldots, (0.30;0.40;0.30), \ldots, (0;0.05;0.95), (0;0;1)\}$ is composed of 231 coordinates z_0. For every $z_0 \in Z$, we compute 100 runs of 50 rounds, each run corresponding to a spatial configuration drawn from a uniform distribution, such that each player has a probability of $1/100$, to be assigned to a particular position. In total, therefore, 23,100 runs are necessary to cover the

[1] $X_P = 67$ and $X_O = 500$ according to (12).

[2] Condition (10) is rewritten as:

$$x_H \left(\frac{\alpha X_\tau^\beta N_0^{1-\beta}}{X_\tau} - w \right) - 4\delta < x_L \left(\frac{\alpha X_\tau^\beta N_0^{1-\beta}}{X_\tau} - w \right).$$

After simplification, it follows that this is satisfied for all X_τ, i.e. in every round τ, whenever the following condition holds:

$$\left[\frac{1}{\alpha} \left(\frac{4\delta}{x_H - x_L} + w \right) \right]^{\frac{1}{\beta - 1}} N_0 < m x_H.$$

set Z. We use simplex representations to present the results. In a simplex, each point corresponds to a three-dimensional coordinate.

Figure 2 provides results about the frequencies of occurrence of each equilibrium for each initial strategy share, where every $z_0 \in Z$ is represented by a dot. The grey-black scale indicates the frequency of occurrence of each type of equilibrium out of 100 random spatial distributions. A black colored coordinate indicates that, starting with the respective z_0, all runs converge to the given type of equilibrium.

As expected, Figure 2a shows that D-equilibria are more easily achieved for initial populations with few enforcers and, inversely, CE-equilibria are more likely to be reached for initial populations composed of many enforcers (Figure 2b). This is consistent with Sethi and Somanathan's findings. Second, DE-equilibria are most likely to be achieved for middle-range initial shares with a slight majority of defectors (Figure 2c), while CDE-equilibria are most frequently achieved for middle-range initial shares with a slight majority of enforcers (Figure 2d). This makes sense intuitively, since a large number of enforcers needs to surround cooperators to allow CDE-equilibria to emerge, as we will explain in Section 3.3. When there are more defectors in the system, cooperators find it difficult to survive, and DE-equilibria emerge.

In this example, we find that, on average, 41% of the runs (out of 23,100) converge to a D-equilibrium, 18% converge to a CE-equilibrium, 18% to a DE-equilibrium, 20% to a CDE-equilibrium, 3% to a E-equilibrium[3] and 0.4% to a C-equilibrium. Note that frequencies do not add up to 1 due to rounding off.

In order to compare our results with the ones obtained by Noailly et al. (2004), we perform additional simulations on the torus using their 'sophisticated' learning rule. This rule states that agents imitate the strategy that is the most successful on average. Using the same parameters as above, we find that with the sophisticated learning rule, 79% of the runs (out of 23,100) converge to a D-equilibrium, 23% converge to a CE-equilibrium, 3% to an E-equilibrium and 0.4% to a C-equilibrium. There are no occurrences of CDE- and DE-equilibria. In other words, the main consequence of changing the learning rule is that such equilibria are more difficult to sustain. Qualitatively, tehse equilibria remain possible with the sophisticated learning rule.

[INSERT Figure 2 about here]

[3] The E and C equilibria are not studied by Sethi and Somanathan because in their analysis all initial shares are positive.

3.3 The effects of the initial spatial distribution of strategies

In this section, we study the impact of the initial spatial arrangement of strategies on convergence to equilibria. It turns out that the spatial distribution of strategies matters. The graphs in Figure 3 show possible movements in such a simplex, if the system starts near the center of the simplex at point $z_0 = (0.30; 0.40, 0.30)$, i.e., with an initial population composed of 30 defectors, 40 enforcers and 30 cooperators. Each simplex in Figure 3 corresponds to a different random initial spatial arrangement of the strategies. Arrows indicate the evolution of strategy shares over time and σ denotes the number of rounds after which an equilibrium is reached.

[INSERT Figure 3 about here]

Which equilibrium actually emerges depends crucially on the initial spatial location of the strategies on the lattice. In general, the coexistence of several strategies in the long run is favored by the formation of 'clusters'. A cluster is a spatial configuration composed of a central agent and its 4 immediate neighbors. Any 'cooperating cluster' with a central cooperator surrounded by 4 cooperators or non-punishing enforcers will survive amidst a large number of non-punishing enforcers, because the central cooperator, not being punished, earns the highest possible payoff. An example is given in Figure 4a. Similarly, a defecting group will survive when surrounded by cooperators and enforcers as long as the central defector is surrounded by 4 defectors, so that he earns the highest profit (see Figure 4b). One can see that the enforcers around the cluster are needed for its 'protection'.

[INSERT Figure 4 about here]

These examples illustrates that the inclusion of a spatial dimension, or a more micro approach, leads to major differences when compared with Sethi and Somanathan's results. While in their model only two equilibria, D and CE, occur, in the spatial model additional equilibria can be observed: namely, DE and CDE-equilibria. In Sethi and Somanathan's game, enforcers always earn lower profits than cooperators as long as there are some defectors in the population, so that, ultimately, they will be completely eliminated. Instead, in the spatial game with micro-interactions, enforcers $E1$ to $E4$ can 'survive' in the long run by forming clusters. This is a crucial element for the occurrence of DE and CDE-equilibria.

With the sophisticated learning rule, however, the enforcement strategy earn less on average than the cooperative strategy. Indeed, the presence of punishing enforcers next to non-punishing ones renders the enforcement strategy less profitable for these non-punishing enforcers, who will eventually switch to cooperation. This explains intuitively why cooperative clusters can easily survive with a less naive learning rule.

3.4 Sensitivity analysis

In this section, we perform a sensitivity analysis of some central parameters, namely the sanction level δ, the parameter α that reflects harvest technology or resource price, and the population size m. Parameters are varied as follows: the level of sanctions is varied between $\delta = 0.1$ and $\delta = 1.5$; the parameter α is varied between $\alpha = 0.1$ and $\alpha = 0.7$ and the population size is varied between $m = 36$ and $m = 121$, using 5 different grids of 6x6, $\ldots$, 11x11.

For each possible parameter configuration, we performed 23,100 simulation runs as in Section 3.2. The results are given in terms of the average frequency of occurrence of a given equilibrium. Contour lines in Figure 5 delimit the set of parameters converging to D-equilibria at a given frequency. For instance, the set of parameter values for which D-equilibria are reached at an average frequency larger or equal to 90% is located below or on the contour line 0.9.

Figure 5a shows that D-equilibria are more easily achieved for low levels of sanctions. These findings make sense intuitively, and are similar to those of Sethi and Somanathan. Further, D-equilibria are more likely to be reached for a large α. An increase in the net return to harvesting, due to, for instance, an improvement in technology or an increase in the resource price, causes a rise in profits and gives an extra advantage to defectors. As a consequence, the set of D-equilibria expands. This is also in line with Sethi and Somanathan's findings.

Figure 5b shows that D-equilibria are best reached for a low level of sanctions and a small population size. As population size falls, that is, as there are fewer harvesters with the given amount of resource, total effort decreases. This effect translates into a rise in net return to harvesting, causing the size of the set of D-equilibria to expand.

Sethi and Somanathan suggest that population growth tend to reduce the importance of sanctions. Their motivation is that as the group gets larger, it becomes more difficult for enforcers to detect defectors. They coin this as an ‘anonimity’ effect which reduces the impact of individual sanctions. Since monitoring occurs locally in the spatial model, defectors cannot possibly ‘hide’ from their direct neighbors. As a consequence, there is no anonimity effect in our model. The explanation for the positive effect of population size on cooperation is that in a larger population and associated large space there are more opportunities for protected groups of cooperators and defectors to survive. This conclusion is opposite to the one by Sethi and Somanathan.

[INSERT Figure 5 about here]

4 Spatial evolutionary and resource dynamics

4.1 Resource stock equilibria

In the present section we analyse resource dynamics. Global factors enter the individual payoff functions through both aggregate effort X_t and resource stock N_t. Just like in the previous section, a large number of defectors, i.e., a large X_t, reduces individual payoffs. A large resource stock N_t, on the other hand, increases payoffs for all agents. The change in N_t in turn is influenced by the level of X_t and thus by the evolution of strategies. Hence, system dynamics are governed by the interactions between changes in the resource stock and the evolution of the distribution of strategies.

At the end of each round, the resource stock is increased according to the replenishment rate $G(N_t)$ and depleted by the total harvest $H(X_t, N_t)$, i.e., the sum of individual harvests:

$$N_{t+1} = N_t + G(N_t) - H(X_t, N_t). \tag{14}$$

For our simulation purposes, we assume that the growth rate $G(N)$ of the resource stock follows a logistic pattern:

$$G(N_t) = rN_t \left(1 - \frac{N_t}{N_K}\right), \tag{15}$$

Here r is the intrinsic growth rate of the resource, and N_K its carrying capacity.

We follow Sethi and Somanathan by assuming that individual effort is increasing in N_t. The motivation for this assumption is that harvesters will intensify their effort level as the resource becomes more abundant. The effort function exhibits decreasing returns to scale in the resource stock, measured by θ (< 1):

$$x_{H,t}(N_t) = \lambda x_H N_t^{\theta} \tag{16}$$

$$x_{L,t}(N_t) = \lambda x_L N_t^{\theta}. \tag{17}$$

Here x_H and x_L are positive constants, with $x_H > x_L$, and λ is a positive constant.

An equilibrium of the game is a set of strategies over the torus and a resource stock, such that no player wants to change strategy, given the payoffs of neighboring players, and such that, given the stategies, the resource stock is constant. Three questions arise. The first question is: do equilibria exist? The second question is: which equilibria are stable? The third is: what is the role of resource dynamics?

The first question is relatively easy to answer. Equilibria do exist. A trivial example is the case of only defectors, with a resource stock satisfying $G(N) = H(m\lambda x_H N^{\theta}, N)$. But, many other equilibria exist. Note, however, that equilibrium resource stocks might be zero. This is, trivially, the case when the G and the H functions only intersect when the resource stock is zero. The resource stock will be inevitably depleted in the long run when aggregate harvest exceeds the replenishment rate of the resource for all stock levels. It is also possible that a D equilibrium will result in overexploitation of the resource for any stock level, ultimately giving rise to resource exhaustion, while a DE or a CDE-equilibrium is consistent with sustainable resource use and thus a positive equilibrium resource level. This partly answers the third question: resource regeneration characteristics may strongly affect the equilibrium.

It seems impossible to address the stability issue analytically. For that reason we have performed simulations, starting from a given distribution of shares, while varying their spatial distribution. We use the same parameters as in Section 3. In addition, we set $r = 0.5$, $N_K = 1000$, $N_0 = 500, \lambda = 0.05$, and $\theta = 0.5$. These parameters also satisfy condition (10)[4]. Figure 6 provides examples of different approach paths. Figure 6a displays the approach path to a $D-$equilibrium. The approach path shows non-monotonic behavior, for the resource stock, as well as for strategy shares. In figure 6b with a CDE-equilibrium this also holds, whereas in figure 6c monotonicity prevails. Therefore, approach paths may exhibit oscillating

[4] With resource dynamics, condition (10) is satisfied for all X_τ, i.e. in every round τ, whenever:

$$\left[\frac{1}{\alpha}\left(\frac{4\delta}{x_H - x_L} + w\right)\right]^{\frac{1}{\beta-1}} N_K < m x_H.$$

behaviors. Even cycling toward equilibrium can occur.

[INSERT Figure 6 about here]

Finally, some characterizations of the equilibria are given in Table 1, which presents statistics of the equilibrium resource stocks for 100 random runs, starting with $z_0 = (0.30; 0.40; 0.30)$. The resource equilibria for D and $CE-$equilibria are $N_H = 616.96$ and $N_L = 669.25$, respectively. Equilibrium resource stocks for DE and CDE-equilibria vary within this range. $CDE-$equilibria exist, in contrast with Sethi and Somanathan. On average, equilibrium resource stocks for CDE-equilibria are larger than equilibrium stocks for DE-equilibria. This makes sense, since CDE-equilibria are often characterized by a larger number of cooperative players. This diversity of stock equilibria contrasts with Sethi and Somanathan's (1996) results. Indeed, in their model, only N_H and N_L are possible equilibrium resource stocks, given that only two types of equilibra, D and CE, exist.

[INSERT Table 1 about here]

Table 1. Final stock levels at $\tau = 50$ for different equilibria, with $z_0 = (0.30; 0.40; 0.30)$.

	N_D	N_{DE}	N_{CDE}	N_{CE}
Max	616.96	628.60	644.37	669.25
Min	616.96	618.61	622.40	669.25
Average	616.96	621.30	627.3	669.25
Std Dev	0	2.22	4.58	0

5 Conclusions

A spatial common-pool resource game has been studied, where space is defined as a two-dimensional torus. The combination of evolution, space and resource combines in a unique way local and global interactions. This implies a complex system, which requires numerical simulation to be understood well. The results complement analytical results for a related model in a twin paper (Noailly et al., 2004). The numerical findings can be seen as a robustness test.

The main objective was to see if the findings in a non-spatial, but otherwise similar, game of Sethi and

Somanathan (1996) are robust against introducing spatial or microlevel interactions among agents. This turns out to be not the case. An important new finding is that indeed clusters of cooperators and enforcers can survive among large groups of defectors. In addition, all other strategy equilibria found by Sethi and Somathan were assessed here as well.

Because Sethi and Somanathan restrict themselves to aggregate population dynamics, all agents following the same strategy face the same punishment or sanctioning costs, and the same profits. The incorporation of local interactions in our approach means that the replicator dynamics in Sethi and Somathan is replaced by the explicit modeling of micro-interactions among individuals. A combination of local and global interactions results, where global interactions include feedback through both aggregate harvest and resource stock to profits associated with harvesting strategies. A difference with Sethi and Somathan is that in our setting it is possible for identical strategies to have different profits, due to the fact that local neighborhoods can be different. As a result, the evolutionary dynamics become difficult to predict. Such disaggregation evidently increases realism and accuracy of description, at the cost of analytical tractability.

The occurrence of equilibria with clusters of cooperators and enforcers, and in which all three strategies appear, can be explained as follows. Enforcers punishing defectors can survive in the long run, as long as no cooperators are located in their neighborhood. Second, cooperators are protected by the formation of clusters of cooperators and enforcers around enforcers who do not punish any defectors. As a result, the imitiation effect of the high profit of enforcing can be regarded to diffuse through space. These results stress a general insight, namely that spatial interactions favor diversity.

Conditions for the emergence of cooperative equilibria are identified by performing a range of sensitivity analyses (not all shown here). For example, population growth is shown to enlarge the set of cooperative equilibria, because it negatively affects the net return to harvesting.

Finally, some results were obtained for the case with resource dynamics. The diversity of possible equilibria is not affected by it. For each strategy equilibrium an associated resource stock equilibrium can be found, as long as the aggregate harvest does not exceeds the replenishment rate of the resource for all stock levels. As a counterpart, with a low initial stock or a low replenishment rate, fewer strategy equilibria are possible. The equilibrium stock will be larger for a cooperative equilibrium than for a defecting one.

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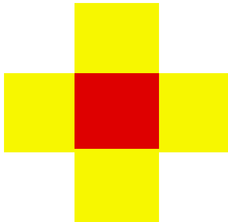
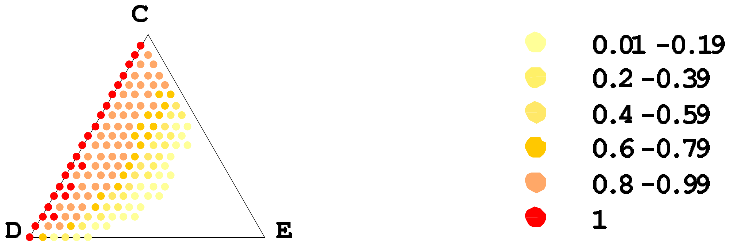
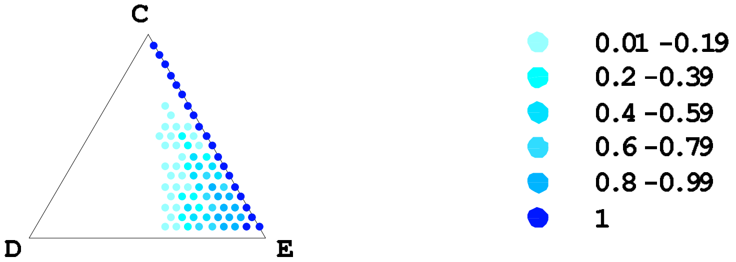


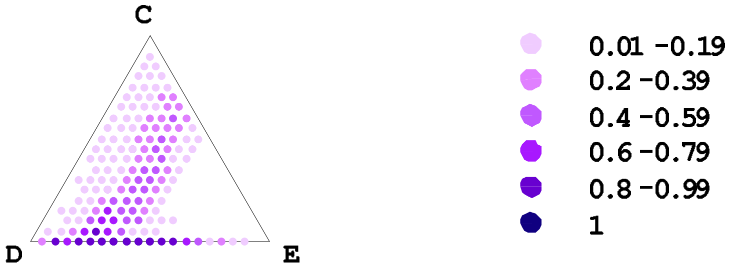
Figure 1. A neighborhood, indicated by light-colored cells.



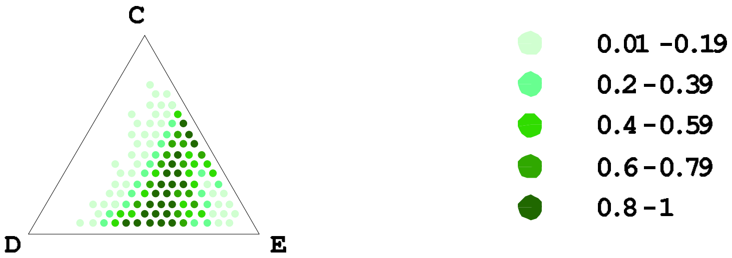
(a) Frequencies for initial coordinates converging to D-equilibria



(b) Frequencies for initial coordinates converging to CE-equilibria

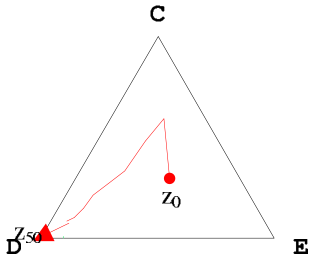


(c) Frequencies for initial coordinates converging to DE-equilibria

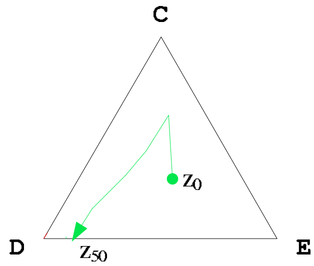


(d) Frequencies for initial coordinates converging to CDE-equilibria

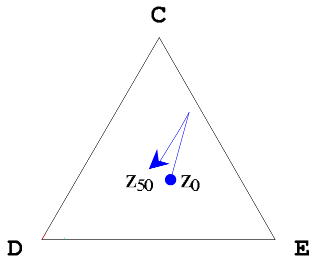
Figure 2. Frequency of occurrence of each type of equilibrium for different initial strategy shares.



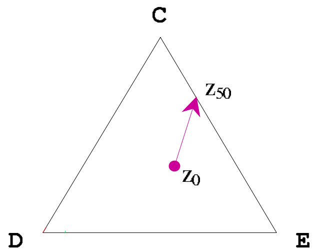
(a) D-equilibrium,
$z_{50} = (1, 0, 0)$,
$\sigma_D = 13$



(b) DE-equilibrium,
$z_{50} = (0.91, 0.09, 0)$,
$\sigma_{DE} = 10$

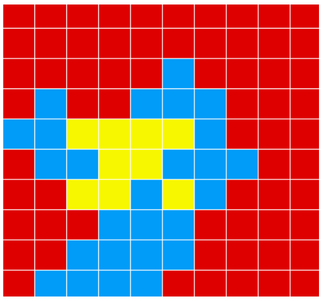


(c) CDE-equilibrium,
$z_{50} = (0.37, 0.29, 0.34)$,
$\sigma_{CDE} = 9$

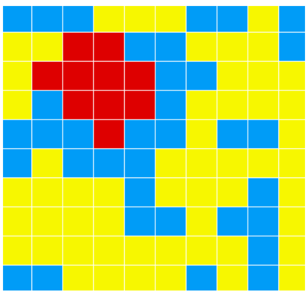


(d) CE-equilibrium,
$z_{50} = (0, 0.26, 0.74)$,
$\sigma_{CE} = 3$

Figure 3. Evolution of strategy shares over time for four different initial spatial distributions of strategies, with $z_0 = (0.30, 0.40, 0.30)$.



(a) Cooperating group in a large population of defectors



(b) Defecting group in a large population of cooperators and enforcers

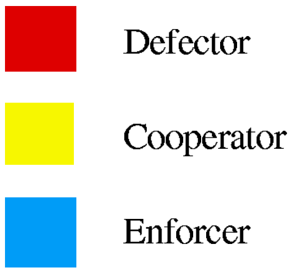
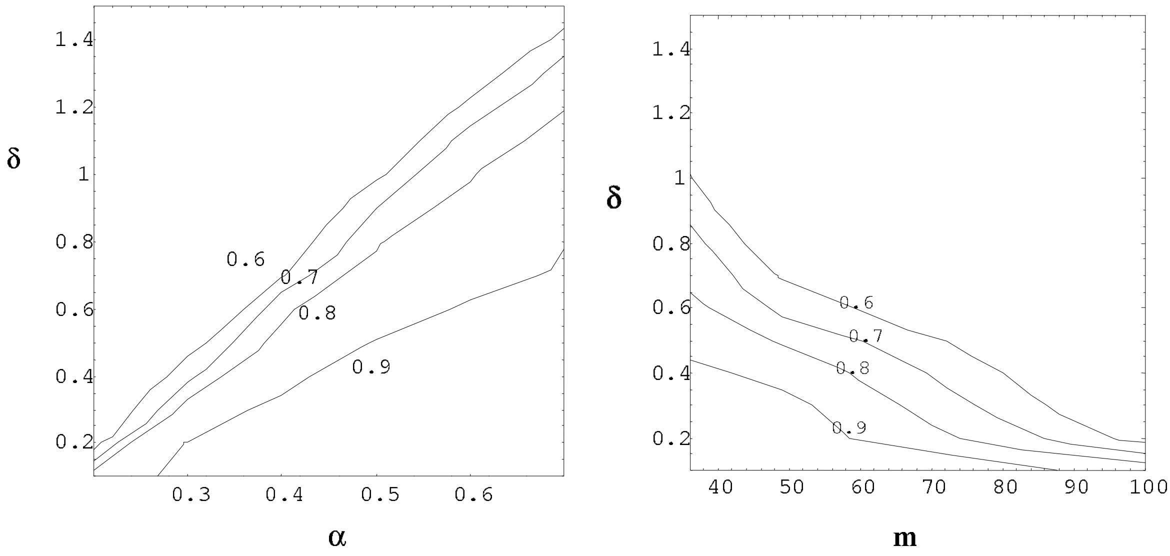


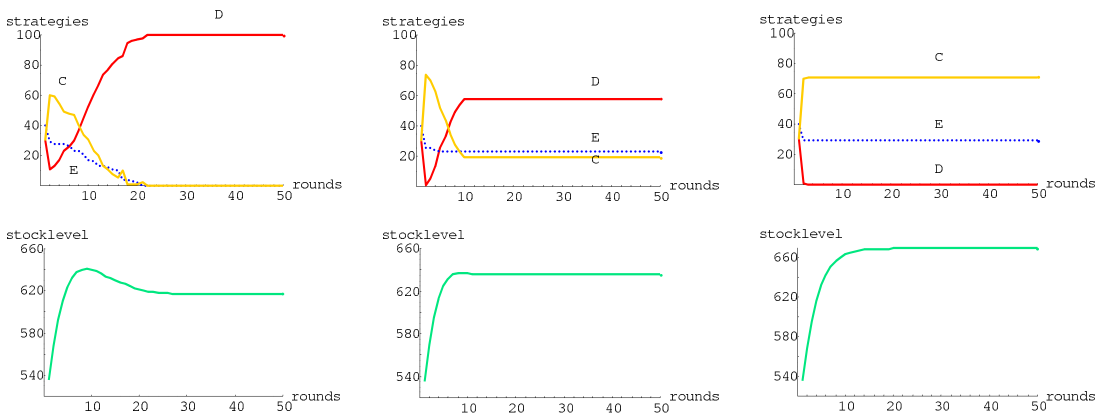
Figure 4. Examples of clustering in CDE-equilibria, at $\tau = 50$, with $z_0 = (0.30; 0.40; 0.30)$.



(a) Parameter space (α, δ), $m = 100$.

(b) Parameter space (m, δ), $\alpha = 0.2$.

Figure 5. Range of convergence to D-equilibria (contour lines denote average frequencies of occurrence over all spatial configurations)



(a) D-equilibrium

(b) CDE-equilibrium

(c) CE-equilibrium

Figure 6. Evolution of strategies and resource stock dynamics toward an equilibrium.

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