Commons and Anticommons in a simple Renewable Resource Harvest Model

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We consider a model where agents harvesting from a renewable resource can impose limitations on the harvesting efforts of other agents. Obstructing the harvesting of others comes at a cost, and is viewed as regulation of resource access. Thus, the agent population comprises agents that don't obstruct ("cooperators") and agents that obstruct ("obstructors"). As the economically better performing strategy spreads in the population, the system self organizes at a level of ostruction which depends on the costs of obstruction, the obstruction efficiency and the history of the system. We show that commons and anticommons can be considered as the end points of a continuum of varying degrees of obstruction and we identify three regimes for the stationary state of the evolution dynamics: (i) a state where the system ends up in a tragedy of the commons, (ii) a tragedy of the anticommons state and (iii) a moderately regulated state in between both extremes. The more a policy environment in the moderately regulated state is tuned for optimality, the higher the danger that a fluctuation destabilizes the system into severe overexploitation.

key words: renewable resources, commons, anticommons, agent-based, evolutionary game theory

1 Introduction

"By definition, in a commons, multiple owners are each endowed with the privilege to use a given resource, and no one has a right to exclude another" [1]. As Garett Hardin has argued in his seminal article [2], in such a situation the resource is prone to overuse. Economically competing resource users, each striving for an advantage over the other, typically favour an expansion of resource use, ending in a spiral of over-exploitation and resource degradation. Depleted fisheries or overgrazed pastures or, in the early days of oil exploration, overexploited oil wells are well known examples of this phenomenon.

Conversely, a situation where multiple owners are each endowed with the right to exclude others from a scarce resource, and nobody has an effective privelege of use, has been described as an anticommons [1, 3]. In contrast to a commons situation, in this a situation a resource is prone to underuse. As such, the anticommons can be understood as the reverse of the familiar commons situation. To our knowledge, anticommons scenarios have chiefly been described for intellectual proporty rights, particularly in Biomedical research [3, 4], and for the transition in the East European property market after the fall of socialism [1].

In this article, we will argue that commons and anticommons can be considered as the end points of a continuum of varying degrees of obstruction, that members of a community impose on each other. Here, "obstruction" represents a player's action to limit access of a resource to others. As such it could also be viewed as regulation imposing restraints to resource access, in which regulation is not an autonomous action from some central authority exterior to the system, but is caused by the players in the system by lobbying the central authority, which then implements the regulation. Lobbying, however, is only achieved at a cost to the obstructing players. Since we assume obstruction is motivated by an economically rational decision, each player will then strive for rules that will improve its resource access over competitors.

Since G. Hardins article about the "Tragedy of the Commons" appeared, it has been pointed out that the tragedy is actually avoided in many commons situations [5]. At times, this is possible via complicated sets of regulations restraining resource access. In our terminology a commons where some level of regulation for resource use is imposed is not considered a "pure" commons, but lies somewhere on the axis between commons and anticommons, where the degree and the severity of regulation determines its exact shade of grey.

Thus in a pure commons situation, there is no restriction, and everybody is free to use the resource without restraint. Contrariwise, in the anticommons situation, users exclude each other such that effective resource use is suboptimal. We will hold that the one can be understood as a reaction to the other: over-exploited resources favour the introduction of regulation, that is, mutual exclusion or obstruction.

In the following, we cast the problem in a game theoretic framework, where agents harvest a renewable resource. We assume that the market price per unit of resource depends on the resource supply. Harvesting a renewable resource is considered the standard action of an agent. At an additional cost c an agent can choose to obstruct the harvesting effort of all other agents.

The motivation for doing so is threefold: (i) obstructing –or imposing regulations on– others improves the relative position of the reference agent by increasing the price the agent can get for its harvest at the market and (ii) by limiting resource use agents can attempt to protect the resource, possibly conserving it for their own later use. As we will also see later, in certain situations an additional motive can be identified: (iii) by limiting the resource use of some, the overall resource situation can be improved for all. Thus, obstruction or regulation can result in an overall increased total harvest from the resource.

To clarify the framework for obstruction and harvesting let us consider the simple example of three fishermen, one of whom uses equipment A, the second equipment B and the third equipment C, which are different from each other. In this example, the first fishermen would try to obstruct the others by lobbying, e.g., for regulation that limits the fishing of vessels using equipment B or C. This might for instance be a rule that fishermen using equipment B or C are not allowed to fish during the weekend. In a more extreme case, he might even try to exclude them completely. The second fishermen, however, might attempt for regulation limiting the catch of vessels operating with equipment A or C, whereas the third would lobby for exclusion of equipment A or B. Thus, if each of them has complete success in establishing his rules, a situation could arise in which everybody is excluded and no-one allowed to fish.

So far, game theoretic models combining economic evolution and renewable resource dynamics are rare [6]. Particularly relevant for our work is [7]. In contrast to Sethi and Somanathan, however, we do not focus on how a community maintains a sustainable level of harvesting, but on how such a level can be found by mutual regulation. For this, in our framework, agents do not punish defectors, but, at a cost to themselves, regulate the harvesting of the whole community by imposing rules that reduce the harvesting efficiencies of all but themselves.

The article will be organized as follows. We start with a simple toy model that illustrates commons and anticommons in a situation in which the resource availability is always constant and does not suffer from depletion. Reviewing some theory on renewable resource use, we extend the model to harvesting a renewable resource. The paper concludes with a discussion of the results.

2 Commons and Anticommons in a Game Theoretic Model

Consider a group of N agents that harvests from a resource that yields a harvest of at most h_0 to each agent. Subject to the behavior of the other agents that we explain below an agent harvests an amount h_i of the resource. Let us assume that the price P agents obtain per unit of resource on the market depends on the total supply $H = \sum_{i=1}^{N} h_i$, i.e. $P = P(H)$. For simplicity, we assume

$$P(H) = P_0 - \beta H, \tag{1}$$

where P_0 gives the hypotetical price of the resource if no resource is supplied and β characterizes the price sensitivity to supply. As a consequence of the price-dependence on the harvest, the optimal payoff $\Pi = HP(H)$ of the community is not necessarily achieved for the largest possible harvest.

Let us first consider the optimal harvest from the perspective of the whole group. Elementary calculations prove that $H_{\text{opt}} = P_0/(2\beta)$. Thus, if one central decision maker coordinates the harvesting effort of the group, optimal harvesting is reached when each individual harvests an amount $h_{\text{opt}} = P_0/(2\beta N)$. Below, this will be contrasted to the case without centralized control, in which each agent makes its own decisions, based on economic rationality.

Before the harvesting, every agent decides whether to obstruct the harvesting effort of all other agents (but not its own) at a cost c. An agent that obstructs (or regulates) the harvesting of the others will be termed an "obstructor". By this obstruction, the harvesting effort of all other agents is reduced by an amount α, the obstruction efficiency. Thus, if the agent population is composed of N_o obstructors and $N_c = N - N_o$ non-obstructors (that we name "cooperators"), the harvests of obstructors and cooperators are

$$h_c = \max(h_0 - N_o\alpha, 0) \tag{2}$$

and

$$h_o = \max(h_0 - (N_o - 1)\alpha, 0), \tag{3}$$

such that obstruction can decrease the harvest to zero, but not cause a 'negative' harvest.

These translate into payoffs $\pi = hP(H)$ of

$$\pi_c = h_c P(H) \tag{4}$$

and

$$\pi_o = h_o P(H) - c, \tag{5}$$

respectively.

We will first consider the case where $N_o < N_0^{\max} = h_0/\alpha$, i.e. where the resource is not completely blocked. The payoff difference $\Delta\pi = \pi_o - \pi_c$ between obstructors and cooperators becomes

$$\Delta\pi = \alpha\left(P_0 - \beta N h_0 + \alpha\beta(N-1)N_o\right) - c, \tag{6}$$

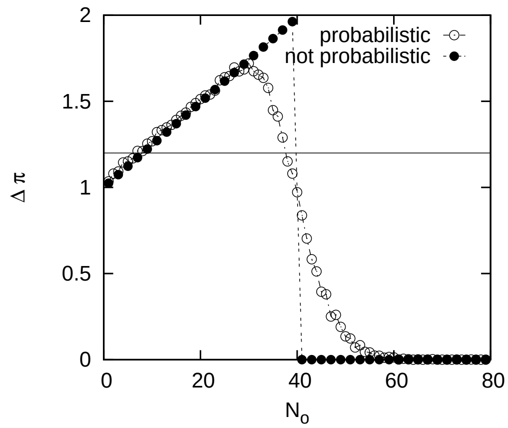


Figure 1: $N = 80$, $h_0 = 1$, $P_0 = 80$, $\beta = 1/2$, $\alpha = .05$. Dependence of the payoff difference on the number of obstructors N_o. The solid line for $\Delta\pi = 1.2$ gives an example for a cost of obstruction. Consequenly, the intersection of the line with the curve $\Delta\pi(N_o)$ defines the numbers of obstructors for which obstruction pays off. The dark circles show the modelled data for $\alpha = .1$. The empty circles represent data points when an obstruction becomes effective with a probability $p = .5$. This models declining obstruction effectiveness with growing obstruction in a natural way and avoids the sharp cut-off of the simpler, non probabilistic, model.

which grows linearly with the proportion of obstructors in the group. This implies that there is a lower threshold number of obstructors

$$N_o^{\min} = \frac{c/\alpha - P_0 + \beta N h_0}{\alpha\beta(N-1)}, \tag{7}$$

for which obstruction becomes economically viable. If, on the other hand, $N_o \geq N_0^{\max}$, one simply has $\Delta\pi = -c$, i.e. obstruction cannot be viable because the harvest is zero.

In our simple model the number of obstructors $N_0^{\max}$ defines a sharp threshold for which obstruction payoffs drop drastically if one more obstructor enters the population. See Fig. 1 for an illustration. This is certainly unrealistic. Rather one would expect that further obstruction becomes the harder the more obstructed the resource already is. For example, the more regulation for resource use already is in place, the harder it would be to convince a government agency that even more regulation is needed. Thus, more money would have to be spent on lobbying, resulting in less regulation per amount spent. This would imply that because of this decline of the obstruction efficiency c/α a state would be approached where the marginal costs of obstruction match the benefits. Because not important for the essentials of the following, we do not model this explicitely, but just assume the existence of such a state of maximum obstruction.

Hence clearly, in an adapting population where better performing agents follow the strategies of less well performing agents, two principal stationary outcomes can be imagined. For high costs of obstruction and low initial numbers of obstructors in the population a situation where every agent harvests at its maximum h_0 is likely. This corresponds to an unregulated commons regime, but no real tragedy of the commons, because the resource is not depleted[1]. On the other

[1] In the model developed so far in this section, we have not yet introduced a resource dynamics.

hand, if obstruction is cheap and efficient, a stationary number of obstructors oscillating around $N_o^{\max}$ (the maximum obstruction state) will be found. This regime represents an anitcommons, where agents almost completely exclude each other from the resource.

3 A Renewable Resource, Commons and Anticommons

In this section, we model a limited renewable resource as for instance a forestry, fishery or cattle on a pasture; that is, the resource is no longer constant, but follows a conventional logistic dynamics

$$\frac{dR}{dt} = g_R R(1 - R/K), \tag{8}$$

where g_R is the resource growth rate and K the carrying capacity of the resource. After the resource evolved for a time Δt_{rec} according to (8) the agents harvest. For this, they access the resource in parallel, harvesting proportional to their allowed individual harvesting efforts. Thus, an agent with effort e harvests $h = eR$ and the total harvest $H = \sum_{i=1}^{N} h_i$ is obtained from the total effort as $H = ER$ [2]. After the harvesting the resource is decreased according to $R \to R(1 - E)$.

As previously, we assume that agents face a choice between obstruction and cooperation, where the harvesting effort depends on the behavior of the other agents as given by Eq.'s (2) and (3), where h is substituted by e. The value of e_0 denotes the harvesting effort level players would choose if not impeded. Subsequently, we typically set e_0 sufficiently large that the resource will be depleted without regulation. Also the linear market price dependence on resource availability is assumed to hold.

Accordingly, the payoff of cooperators is

$$\pi_c = P(H)e_c R, \tag{9}$$

while for an obstructor one obtains

$$\pi_o = P(H)e_o R - c. \tag{10}$$

The payoff difference $\Delta\pi = \pi_o - \pi_c$ then is

$$\Delta\pi = \alpha R P(H) - c. \tag{11}$$

Because the strategy determination requires treating harvests as a discrete event, the framework in this paper differs slightly from the conventional way of treating harvests from a renewable resource [8]. However, the linear decrease of the available stationary resource R^* with increasing harvesting pressure E is still recovered, see appendix. Using Eq. (1) one realizes that the total payoff (without obstruction costs) $\Pi = P(H)H$ has extremal points for $(P_0 - 2\beta H)\partial H/\partial E = 0$. Closer inspection shows there are generally two global effort levels $E_{1,2}$ for which Π is maximized and one E_3 for which Π is at a minimum. The latter corresponds to the maximum sustainable harvest $\partial H/\partial E = 0$ while the first two are zeros of $P_0 - 2\beta H$. Maximum payoff can be reached in two ways: (i) for relatively low harvest and high price and (ii) for high global harvest and low price.

Using Eq. (18) from the appendix we find

$$\Delta\pi = \alpha K \frac{g_{\text{eff}} - E}{(1 - E)g_{\text{eff}}} \left(P_0 - \beta K E \frac{g_{\text{eff}} - E}{(1 - E)g_{\text{eff}}} \right) - c, \tag{12}$$

for $E < g_{\text{eff}}$ and zero otherwise. In the latter we defined an effective resource growth rate by $g_{\text{eff}} = 1 - \exp(-g_R \Delta t_{\text{rec}})$ and used $E = (N - N_o)e_c + N_o e_o$ for the total harvesting effort of the group.

[2] Where, without loss of generality, we assumed that $E < 1$.

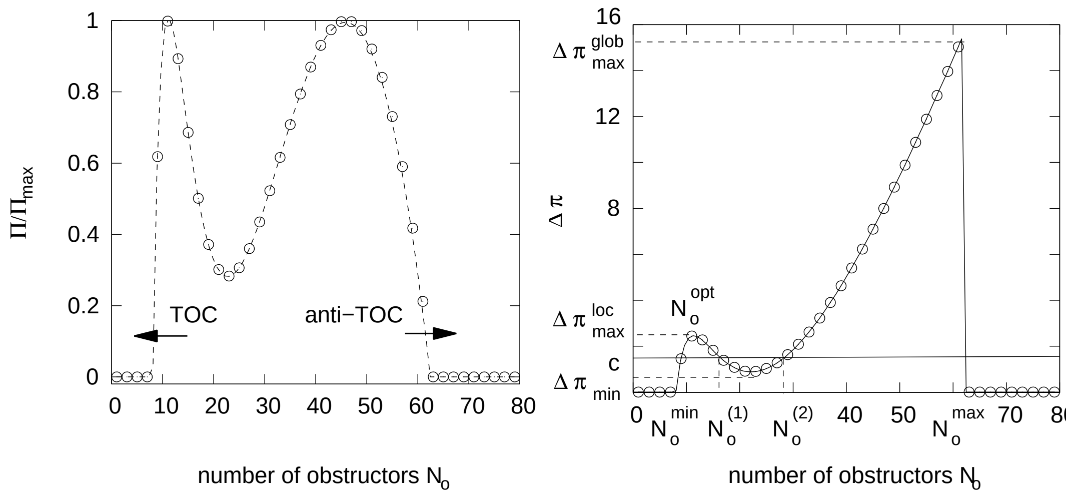


Figure 2: A crowd of 80 fishermen harvesting from a renewable resource (growth rate $g_R = 1$, carrying capacity $K = 400$, and $\Delta t_{\mathrm{rec}} = 2$, implying $g_{\mathrm{eff}} \approx .86$), some of which follow a cooperative strategy (cooperators), some obstructing the effort of others (obstructors). (a) Dependence of the payoff (income from fishing) on the number of obstructors. The situation in which scarcely any obstructors are present is characterized by strong overharvesting. This corresponds to a tragedy of the commons. The situation in which more than $N_o^{\max}$ obstructors are present is characterized by complete mutual exclusion, a tragedy of the anticommons. (b) Dependence of the payoff difference on the number of obstructors. The parameters are: cost of obstruction $c = 0$, harvesting efficiency $e_0 = .0125$, obstruction efficiency $\alpha = .0002$, $\beta = 1$ and $P_0 = K = 200$. The line at $\Delta\pi = 1.6$ gives an example for a cost of obstruction. Intersection points with $\Delta\pi$ define $N_o^{\min}$, $N_o^{(1)}$ and $N_o^{(2)}$. The data points are simulation results, the connecting curves are calculated on the basis of Eq.s (12) and (2, 3) and (18).

In Figure 2 we give an example for the dependence of the global average payoff and of the payoff difference on the number of obstructors in the group. Clearly, when no obstructors are present the resource is strongly overharvested (Fig. 2a) and –as the harvesters take out all the resource at every harvest– completely depleted. Since no agent has any interest to reduce the global harvest level this corresponds to a tragedy of the commons situation. The resource starts to recover only when enough obstructors are present to limit resource access such that $E < g_{\rm eff}$, i.e. for $N_o > N_o^{(0)} = (Ne_0 - g_{\rm eff})/((N-1)\alpha)$.

Then, with an increasing number of obstructers, the payoffs not only of the obstructors but of the community as a whole increase. Hence, the action of an agent that understands that reduced harvest improves the returns of the entire community, and decides to obstruct as a result, could be seen as constructive. On the other hand, if too many obstructors are present, complete mutual exclusion is found and resource access is completely blocked. Albeit the resource is ample, resource use is small and inefficient — a situation characteristic for a tragedy of the anticommons.

As shown by the calculation in section 2, we also note that for zero cost of obstruction the payoff of obstructors is always superior to that of cooperators (cf. Figure 2b), unless resource access is completely blocked. However, interestingly, the payoff difference depends on resource availablity, i.e. on the number of obstructors themselves. This allows the resource to recover and harvests of all agents, but particularly of the obstructors, increase.

We now consider $c > 0$. Obstruction pays off when $\Delta\pi(N_o) > 0$. There is a threshold number of obstructors $N_o^{\rm min}$, such that for $N_o > N_o^{\rm min}$, the obstruction strategy is viable. Initially the payoff grows with N_o (cf. Fig. 2b). As can be seen from Fig. 2b (or calculated from Eq. (12)), the slope of $\Delta\pi$ is very large at this point. Slight changes in the number of obstructors lead to large differences in the payoffs. Thus, if the number of obstructors perchance drops below $N_o^{\rm min}$ obstruction all for a sudden becomes much less attractive.

We also note a second threshold number of obstructors $N_o^{\rm max} = e_0/\alpha$, which characterizes the amount of obstruction required to completely block the resource. Thus, for $N_o > N_o^{\rm max}$, the obstruction efficiency suddenly declines, obstructors are faced with the cost of obstruction without a benefit. See section 2 for a more thourough discussion of this.

From (11) one can also anticipate that $\Delta\pi(N_o)$ will either have a maximum and a minimum or– if the price of the resource is not sufficiently sensitive to supply– no extremal point. The latter case has in principle already been eleborated on in Section 2, so we concentrate on the more interesting case of relatively high price sensitivity. Then, because variations in $1/E$ are small in comparison to variations in Π, the maximum in $\Delta\pi$ roughly corresponds to the large harvest-low price maximum in the total payoff (Eq. (11)).

In the following, one has to distinguish three main parameter regimes:
(a) $c > \Delta\pi_{\rm max}^{\rm glob}$. Obstruction never pays off, independent of how many obstructors are in the population.
(b) $c < \Delta\pi_{\rm min}$ or $c > \Delta\pi_{\rm max}^{\rm loc}$, but $c < \pi_{\rm max}^{\rm glob}$. In both cases the payoff difference between obstructors and cooperators is positive for some $N_o > N_o^{\rm min}$ and negative otherwise.
(c) $\Delta\pi_{\rm min} < c < \Delta\pi_{\rm max}$. After being negative for $N_o < N_o^{\rm min}$, $\Delta\pi$ becomes positive for $N_o^{\rm min} < N_o < N_o^{(1)}$, but changes sign again at $N_o^{(1)}$, till finally growing positive at $N_o^{(2)}$.

In the section below we will see how these two regimes distinguish different stationary outcomes for an evolving agent population, in which agents are allowed to change strategies.

4 Evolution of Obstruction

In the following, we will consider obstruction and cooperation in the population as the outcome of an evolutionary process. As often used in Evolutionary Game Theory [9], we will assume that strategies of successful agents spread in the population and replace strategies of the less successful. In our experiments success is defined as the average pay-off of an agent over a period T of harvesting iterations.

More precisely, we consider the following experiment:

1. Agents harvest for T iterations as described above.
2. The average pay-off $\{\phi_i\}_{i=1}^{N}$ of every agent is calculated. Agents have 'offspring' in proportion to their relative success modelled by a discretized version of the replicator equation. The 'offspring' population of agents replaces the old population. These dynamics have also been derived from models for individual learning behaviour, e.g. in [10].
3. With a small probability p_{invade} agents are replaced by agents that follow a randomly picked strategy, i.e. with $p = 1/2$ obstruction or with $q = 1/2$ cooperation.
4. Steps 1., 2. and 3. are iterated.

The outcome of this procedure is an evolving number of agents following the 'cooperate' and 'obstruct' strategies.

As we have seen in the previous section the stationary state of the evolving system will generally depend on the obstruction efficiency and cost of obstruction as well as on the initial state, i.e. the initial number of obstructors $N_o(t = 0)$. In the analysis below we concentrate on fixed points of the evolution dynamics, which are characterized by $\Delta\pi(N_o^*) = 0$, i.e. situations in which both strategies perform equally well. The three principal parameter regimes introduced in the previous section distinguished different outcomes of the dynamics (see also Figures 2,3 and 4):

(a) $\Delta\pi_{\max}^{\text{glob}} < c$. Obstruction never pays off. Any obstructors initially present in the population will die out, the system will evolve towards $N_o = 0$. The system is trapped in a tragedy of the commons (cf. Figure 4a).

(b) $c < \Delta\pi_{\min}$ or $c > \Delta\pi_{\max}^{\text{loc}}$, but $c < \pi_{\max}^{\text{glob}}$. $N_o^* = N_o^{\min}$ represents an unstable fixed point of the dynamics. The evolutionary dynamics leads to $N_o = 0$, i.e. a tragedy of the commons for $N_o(t = 0) < N_o^{\min}$ and to oscillations around $N_o = N_o^{\max}$, i.e. a tragedy of the anticommons, for $N_o(t = 0) > N_o^{\min}$.

(c) $\Delta\pi_{\min} < c < \Delta\pi_{\max}^{\text{loc}}$. There are three fixed points of the dynamics (cf. Figures 4b and c). As before, $N_o^* = N_o^{\min}$ represents an unstable fixed point, but there are two more fixed points, i.e. $N_o^* = N_o^{(1)}$ which is locally stable and $N_o^* = N_o^{(2)}$ which is unstable. $N_o^{\min}$ and $N_o^{(2)}$ mark the boundaries of the basin of attraction for $N_o^{(1)}$. For $N_o < N_o^{\min}$ the dynamics ends up in the unregulated $N_o = 0$ tragedy of the commons scenario, whereas for $N_o > N_o^{(2)}$ the stationary outcome is the above anticommons situation. For an initial number of obstructors $N_o^{\min} < N_o(t = 0) < N_o^{(2)}$ the dynamics approaches the fixed point $N_o^{(1)}$. As long as the stochastic fluctuations[3] in the system are small compared to $\min(N_o^{(1)} - N_o^{\min}, N_o^{(1)} - N_o^{(2)})$, oscillations around $N = N_o^{(1)}$ are expected.

This is illustrated in Figure 4b, where we calculated the dependence of the critical numbers of obstructors on the effective resource growth rate g_{eff}. As seen in Fig. 4a for $g_{\text{eff}} < .76$ the locally stable fixed point corresponding to intermediate regulation disappears. For $g_{\text{eff}} \geq .76$ the branches for $N_o^{(2)}$ (upper branch, dotted line) and $N_o^{\min}$ (lowest branch, small dashes) limit the basin of attraction of the moderately regulated state. By adjusting efficiency α and cost c of lobbying the actual fixed point can be 'tuned' within the interval between the upper branch and $N_o^{\text{opt,loc}}$ (long dashes). The solid line gives the dependence of the global optimum on g_{eff}. The economically best regulation maximizing the groups payoff is achieved for values of c and α that realize $N_o^{\text{opt,loc}}$. This, however, brings one also close the the lower boundary of the basin of attraction, leading to a higher risk of destabilisation.

[3] Stochastic fluctuations here chiefly arise from the stochastic invasion of new strategies into the population in the evolution dynamics.

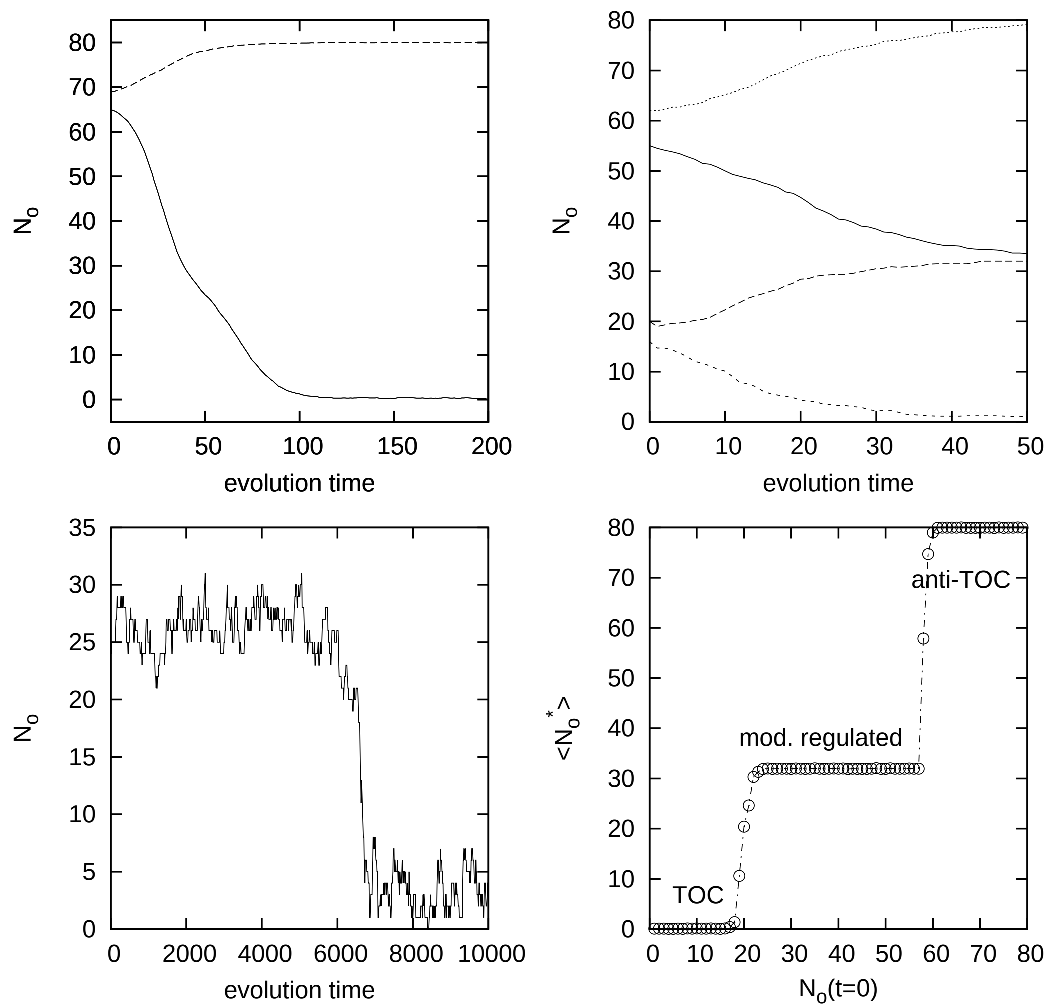
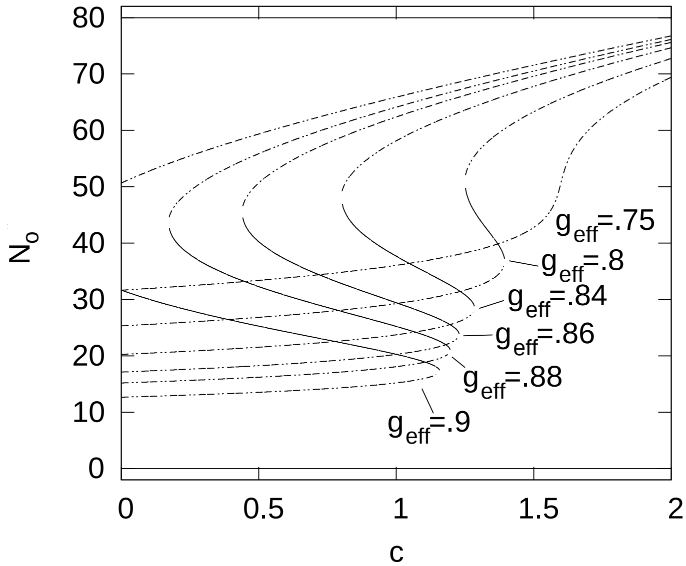


Figure 3: Evolution of strategies in a crowd of $N = 80$ fishermen. Parameters are (renewable resource $K = 400$, $g_R = 1$; $e = .0125$, $\alpha = 0.0001$). (a) $c = 1.5$ such that $c > \Delta\pi_{\max}^{\mathrm{loc}}$ (scenario as in section 4). The systems evolves either into an anticommons ($N_o(0) > 67$) or a commons ($N_o(0) < 67$). (b) Scenario b in section 4, with $c = .8$ such that $\Delta\pi_{\min} < c < \Delta\pi_{\max}^{\mathrm{loc}}$. For $20 < N_o(0) < 55$ the system evolves into the moderately regulated state in which some obstructors coexist with cooperators. For $N_o(0) < 20$ the system evolves to a tragedy of the commons, for $N_o(0) > 55$ into an anticommons. (c) Scenario b in section 4, with $c = 1.1$ so that the difference $N_o^{\max} - N_o^{\min}$ becomes small (cf. Fig. 2). After hovering around the moderately regulated state a fluctuation pushes the system into a tragedy of the commons. $p_{\mathrm{invade}} = .01$. (d) $c = .8$, dependence of the stationary state on the initial condition.



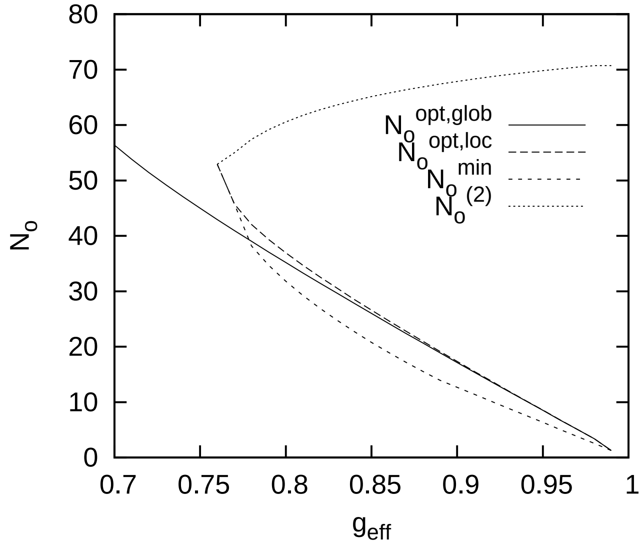


Figure 4: (a) Bifurcation diagram for the evolutionary dynamics, stable branches are drawn as solid lines, unstable ones as dotted lines. There are always two stable states, no obstruction $N_o = 0$ and complete obstruction $N_o = 80$. The family of curves corresponds to different regeneration rates of the resource, $g_{\text{eff}} = .9, .88, .86, .84, .8, .75$. The higher the regeneration rate of the resource, the larger the stable branch corresponding to an intermediate level of regulation, till for $g_{\text{eff}} = .9$ the moderately regulated regime even becomes possible when obstruction is extremely cheap. (b) Dependence of the crucial points characterizing the dynamics on the resource recovery rate g_{eff}. The number of obstructors for which the group is optimally regulated $N_o^{\text{opt,glob}}$ (i.e. the first maximum in Π) is always close to the local maximum in the payoff difference $N_o^{\text{opt,loc}}$. The basin of attraction of this optimally regulated regime is marked by the unstable fixed points N_o^{min} and $N_o^{(2)}$. The curves are calculated on the basis of (12) for $\alpha = 0.0001$.

In our model, the system consists of actors who aim to manage the common resource via lobbying some governing agency in order to limit resource access under certain conditions; in this scenario, the efficiency of the system is determined by the parameters c (at which cost can the government be caused to act?) and α (how drastic is the action taken?).

Obviously, the main desired outcome for the policymaker who sets the framework defining α and c is to allow the system to self-regulate to a level of resource access that avoids both the tragedy of the commons and the anticommons, but ends up in a moderately regulated regime at $N_o^{(1)}$. A further aim is to strife for a total payoff as close as possible to $\Pi_{\max}$, which corresponds to a number of obstructors close to N_o^{opt}. This, however, implies that the basin of attraction of the fixed point representing the regulated environment $N_o^{(1)}$ shrinks. That is, the more a policy environment is tuned for optimality, the higher the danger that a fluctuation destabilizes the system into severe overexploitation. Similar to the results of [7], the hurdles to escape the basins of attraction of the commons and (in our case also) the anticommons states are then very large so that a well-regulated regime is hard to recover.

It is of interest to examine how the size of the basin of attraction of the moderately regulated state depends on the model parameters. Quantitative statements can be made on the basis of equation (12). We note the following qualitative relations: (i) larger recovery rates of the resource and larger obstruction efficiencies lead to a larger basin of attraction, and (ii) lower price sensitivity of the resource price on supply leads to a smaller basin of attraction of the moderately regulated state. Enhancing obstruction efficiencies (α) allows to tune (via adjusting the cost of regulation c) the moderately regulated state closer to the global optimum payoff for the group, but also enhances the effect of fluctuations in the number of obstructors in the population. Larger group sizes reduce the relative payoff difference, particularly if obstruction efficiencies are low.

5 Summary and Discussion

In this paper, we have presented a simple model for harvesting from a renewable resource, in which the regulation regime is determined by the strategy decisions of the agents. A tragedy of the commons situation can be avoided if agents chose to obstruct the harvesting of others, which results in regulating access to the resource. However, overregulation can lead to complete mutual exclusion and a tragedy of the anticommons situation in which nobody can access the abundant resource.

In our model, agents have based their decisions on purely economic reasoning: obstructing others (i) improves an agent's relative economic position by increasing the price per unit of resource (ii) preserves resource for his own later use and (iii) can improve aggregate community outcome. Obstruction, however, comes at a cost. In section 3 we have presented an analysis of the costs and benefits of obstruction, which are determined by the obstruction efficiency, the resource state and the number of agents following each stategy. Three parameter regimes were identified: (i) a regime in which obstruction never pays off in economic terms (ii) a regime in which obstruction always pays off and (iii) a locally stable regime in which a limited degree of obstruction pays off.

Considering the distribution of strategies in the population as an evolving mix, where 'fitter' strategies replace less well performing ones, these three regimes are linked to three states towards which the system will evolve. For (i), all agents cooperate and a tragedy of the commons ensues. For (ii), complete obstruction and hence mutual exclusion prevails, equivalent to a tragedy of the anticommons. However, in the third parameter regime, the system can evolve to a state of intermediate obstruction, i.e. is regulated to a degree that avoids both commons and anticommons. The latter state of the dynamics is locally stable, but if fluctuations (stemming, for example, from an addition of new players to the system) are large enough, the system can be driven into a tragedy of the commons situation. This becomes the more likely the better cost and obstruction efficiency are tuned towards achieving an outcome maximising the global pay-off. It is noteworthy that the stationary regime of the evolution dynamics is path-dependant. Thus, once driven into a commons regime, the moderately regulated regime cannot easily be recovered without outward interference.

6 Appendix

Consider a renewable resource, evolving according to the logistic equation:

$$\frac{dR}{dt} = g_R R(1 - R/K). \tag{13}$$

It is convenient to rescale to $x = R/K$ and express harvesting and resource dynamics in terms of fractions of the carrying capacity. After every interval of time $\Delta t_{\rm rec}$ a harvesting event takes place in which an amount proportional to the resource is harvested, i.e. $x \to (1-E)x$, where $E < 1$ is the harvested fraction of the resource. Integrating (13) from 0 to $\Delta t_{\rm rec}$ yields

$$x(\Delta t_{\rm rec}) = \frac{1}{1 + e^{-g_R \Delta t_{\rm rec}}(1 - x_0)/x_0}. \tag{14}$$

Harvesting and resource regeneration can now be expressed as a series

$$x_t = \frac{(1-E)}{1 + e^{-g_R \Delta t_{\rm rec}}(1 - x_{t-1})/x_{t-1}}. \tag{15}$$

Introducing $g_{\rm eff} = 1 - e^{-g_R \Delta t_{\rm rec}}$, this series converges to

$$x^* = 1 - E/g_{\rm eff} \tag{16}$$

for $E < g_{\rm eff}$ and $x^* = 0$ otherwise, similar to the continuous formulation of harvesting as in [8], where `in which`

$$\frac{dx}{dt} = g_R x(1 - x) - Ex, \tag{17}$$

for which $x^* = 1 - E/g_R$.

However, Eq. (16) gives the stationary state of the resource after the harvest. Combining (14) and (15) the resource before the harvest is obtained as

$$x^*_{\rm pre} = \frac{g_{\rm eff} - E}{g_{\rm eff}(1 - E)} \tag{18}$$

for $E < g_{\rm eff}$ and zero otherwise. Accordingly, the harvest for an effort level E is $Ex_{\rm pre}$, which we use above in section 3. Thus, the maximum sustainable harvest is achieved for an effort level

$$E_{\rm max} = 1 - \sqrt{1 - g_{\rm eff}}. \tag{19}$$

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