Cooperation in a dynamic fishing game: A framed field experiment

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Abstract

We derive a dynamic theoretical model that tests the social optimum and selfish Nash equilibrium of a renewable resource, a stock of fish. In the social optimum, maximum fishing effort is observed in the last period only. The predictions are tested at a recreational fishing pond. The subjects, experienced recreational fishermen, are placed in groups of four and face a dynamic social dilemma. The results show strong support for the selfish Nash equilibrium. Fishermen exert as much effort in the last period as in the preceding periods, and effort is independent of the stock of fish.

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Since Hardin (1968)'s seminal paper, the 'Tragedy of the Commons' is the standard metaphor to describe how the unregulated use of natural resources can result in the depletion of these resources. Hardin used overgrazing of the local commons as a motivating example, but the metaphor has also been applied to the overuse and depletion of other resources, including fish stocks in the high seas. Indeed, Hardin's paper helped to popularize earlier work, especially by Gordon (1954) and Scott (1955), on fishery management. The work of the latter two authors, as well as that of Schaefer (1957), gave rise to the 'canonical renewable resource model' that has been used in hundreds of papers in natural resource and environmental economics (Brown (2000)).

The core of this model is that resource regeneration is a logistic function of the size of the stock. When left untouched, stocks tend to increase according to an S-function, with growth being fastest at intermediate stock sizes.[1] Hotelling (1931) argued that natural resources can be viewed as assets, and hence the socially optimal stock is the one at which the rate of return on the resource equals the rate of return on other assets – the risk adjusted interest rate. However, standard game theory predicts that non-cooperative users over-extract relative to this optimum, as the benefits of catching additional fish are private, whereas the costs (increased search costs, or reduced regeneration of the stock) are borne by all.

Experimental study of the behavioral properties of the canonical model has been scant. Laboratory research has established that individuals have social preferences, but how prominently they appear depends on the context. It is therefore important to conduct experiments to study whether, and to what extent, behavior conforms to the non-cooperative or cooperative benchmarks in this canonical model. The few studies that are published in this domain yielded mixed results regarding the observed level of cooperation (see Keser and Gardner (1999), Herr, Gardner and Walker (1997), Mason and Phillips (1997), Chermak and Krause (2002), and Fischer, Irlenbusch

[1] When stocks are small, there is little offspring because of the small number of females producing offspring. When the number of surviving offspring is also small when stocks are large because of fierce competition for food and other base resources.

and Sadrieh (2004)).

We construct a framed field experiment to evaluate the canonical renewable resource model. The experiment, conducted at a recreational fishing facility, offers a unique opportunity to test its predictions in a contextualized setting. The subjects of the experiment are all experienced recreational fishers. For fishermen at this site the task of fishing and imposing negative externalities on other fishers comes naturally. While the fishermen are all better off if they cooperate and reduce their catch, we find no evidence of such behaviour. Rather, we find strong support for the Nash equilibrium prediction of our model.

1 The canonical model of renewable resource use

A finite number ($n > 1$) of homogenous agents indexed i have access to a fish stock. Access may be indefinite, but it may also be restricted to a specific time period. Let us denote this time horizon by $T \in \langle 0, \infty \rangle$. The size of the resource stock at time t is denoted by $x(t)$, which evolves over time according to:

$$dx(t)/dt = g(x(t)) - \sum_{i=1}^{n} h_i(t). \tag{1}$$

where $g(x(t))$ is the net natural increase in the resource stock that emanates from a stock of size $x(t)$, and $h_i(t)$ is the quantity harvested by agent i at time t. The natural increase of a stock with size $x(t)$, $g(x(t))$, is captured by a logistic growth function:

$$g(x(t)) = \gamma x(t) \left(1 - \frac{x(t)}{K}\right). \tag{2}$$

Here, $\gamma > 0$ is the intrinsic growth rate and $K > 0$ denotes the maximum size of the resource stock the ecosystem can sustain. Agent i's catch at time t, $h_i(t)$, is given by the standard Schaefer (1957) production function:

$$h_i(t) = \alpha q_i(t) x(t), \quad 0 \le q_i(t) \le \bar{q}, \tag{3}$$

where $q_i(t)$ is agent i's harvesting effort at time t, and $\bar{q}$ is the maximum amount of effort an agent can put in at any moment. The marginal productivity of effort, $\partial h_i/\partial q_i$, depends on the harvesting technology (α, e.g. nets or fishing rod, etc.), and also on the size of the fish stock, $x(t)$. For a given effort and technology, the larger the stock size, the greater the fish density, and the more fish will be caught per unit of effort.

We now derive $x(t)$, the size of the stock at every point in time. For any initial $x(t_0)$, and as long as aggregate effort ($Q \equiv \sum_{i=1}^{n} q_i$) is constant during a specific time interval, $[t_0, t_1]$, the size of that stock at t_1 can be found by substituting (2) and (3) into (1) and integrating:

$$x(t_1; t_0, x(t_0), Q) = \frac{K(\gamma - \alpha Q)/\gamma}{\left(\frac{K(\gamma-\alpha Q)/\gamma - x(t_0)}{x(t_0)}\right) e^{-(\gamma-\alpha Q)(t_1-t_0)} + 1}.$$

We assume that $\alpha n\bar{q} > \gamma$: given the effort constraint and the technology used, the fishery can be depleted. We also assume that $x(0) = K$: when harvesting begins, the fish stock is maximal. Finally, if fishermen care only about their own catch, and there are no (variable) harvesting costs, then the net present value of an agent's welfare is then equal to:

$$\int_{t=0}^{T} \bar{p} h_i(t) e^{-rt} dt, \tag{4}$$

where $\bar{p}$ is the marginal value of a resource unit extracted (assumed to be exogenous and time invariant), and r is the appropriate discount rate (possibly the interest rate).

Maximizing group welfare requires to

$$\max_{h_i(t)} \int_{t=0}^{T} \sum_{i=1}^{n} \bar{p} h_i(t) e^{-rt} dt \tag{5}$$

subject to (1)-(3) and $x(0) = K$.

Proposition 1 The socially optimal program is:

$$
Q^{SO}(t) = \begin{cases} n\bar{q} & \text{if } 0 \leq t < T^0, \\ \frac{g(x^*)}{\alpha x^*} & \text{if } T^0 \leq t < T^1, \\ n\bar{q} & \text{if } T^1 \leq t \leq T, \end{cases}
$$

with $x^* \equiv K(\gamma - r)/(2\gamma)$ and with T^0 and T^1 implicitly defined by $x(T^0; 0, K, n\bar{q}) = x^*$ and $x(T; T^1, x^*, n\bar{q}) = 0$ (see (4)).

Proof Substituting (1) into (5) and integrating by parts, the social welfare maximization problem becomes

$$
\max_{x(t)} \left\{ \bar{p} \left[x_0 - x(T)e^{-rT} \right] + \bar{p} \int_{t=0}^{T} \left[g(x(t)) - rx(t) \right] e^{-rt} dt \right\},
$$

with transversality condition $x(T)e^{-rT} = 0$.

Suppose that $T \to \infty$. Because $\lim_{T\to\infty} e^{-rT} = 0$, we may have $\lim_{T\to\infty} x(T) > 0$. In (6), the per-period profit flow is maximized if $x^* = K(\gamma - r)/(2\gamma)$ – the stock where $g'(x) \equiv dg(x)/dx = r$. Starting from $x(0) = K$, social welfare is therefore maximized if x^* is reached as quickly as possible. Hence, $Q^{SO}(x) = n\bar{q}$ for all $x > x^*$, while $Q^{SO}(x^*)$ is implicitly defined by $\alpha x^* Q^{SO} = g(x^*)$. The moment at which harvesting effort switches from $Q^{SO}(x) = n\bar{q}$ to $Q^{SO}(x^*)$, T^0, is implicitly determined by $x(T^0; 0, K, n\bar{q}) = x^*$.

With finite T and because harvesting is costless, the transversality condition requires that $x(T) = 0$. To deplete the resource at T, aggregate harvesting effort should increase, from Q^* to $n\bar{q}$, at time T^1, where T^1 is implicitly defined by $x(T; T^1, x^*, n\bar{q}) = 0$. ■

The socially optimal program has a Most Rapid Approach Path (MRAP), as the two focal stock sizes, $x = x^*$ and $x = 0$, should be reached at maximum speed ($Q^{SO}(t) = n\bar{q}$ if either $t < T^0$ or $t > T^1$).

Regarding the non-cooperative game, we cannot rule out that there are many potential Nash equilibria. Because the social optimum is MRAP, we focus on the class of Nash equilibria that are MRAP too (see Clark (1980), or Dockner et al. (2000)). Absent cooperation, each agent's objective function is

$$\max_{h_i(t)} \int_{t=0}^{T} \bar{p} h_i(t) e^{-rt} dt$$

subject to (1)-(3) and $x(0) = K$. We state the following proposition.

Proposition 2 The unique MRAP solution to the non-cooperative game is that $Q^{NE}(x) = n\bar{q}$ for all $x > 0$. The time at which the stock is depleted, T^{NE}, is implicitly defined by $x(T^{NE}; 0, K, n\bar{q}) = 0$.

Proof Let us use $Q_{-i} = \sum_{j \neq i} q_j$ to denote aggregate effort by all agents other than i. Using $g_{-i}(x) = g(x) - \alpha x Q_{-i}$ to denote the 'residual regeneration function' faced by agent i, she maximizes

$$\max_{x(t)} \left\{ \bar{p} \left[x_0 - x(T) e^{-rT} \right] + \bar{p} \int_{t=0}^{T} \left[g_{-i}(x(t)) - r x(t) \right] e^{-rt} dt \right\}.$$

A candidate solution to (6) is to choose $q_i = \bar{q}$ if $x > \widetilde{x}$, $q_i = 0$ if $x < \widetilde{x}$, and $q_i = g_{-i}(\widetilde{x})/\alpha \widetilde{x}$ if $x = \widetilde{x}$, where $\widetilde{x}$ solves $g'_{-i}(\widetilde{x}) = r$. We prove that this cannot be an equilibrium.

Consider the case where $T \to \infty$. For $\widetilde{x} > 0$ to be a symmetric Nash equilibrium steady state, all agents must harvest at $q_j = g(\widetilde{x})/(n\alpha\widetilde{x})$ if $x = \widetilde{x}$, and choose $q_j = 0$ ($q_j = \bar{q}$) if $x < \widetilde{x}$ ($x > \widetilde{x}$). That means that the amount of net regeneration agent i faces for any stock level x, $g_{-i}(x)$, equals:

$$g_{-i}(x) = \begin{cases} g(x) - (n-1)\alpha x \bar{q} & \text{if } x > \widetilde{x}, \\ g(\widetilde{x})/n & \text{if } x = \widetilde{x}, \\ g(x) & \text{if } x < \widetilde{x}. \end{cases}$$

If agent i decreases the stock infinitesimally below $\widetilde{x}$, her residual regeneration would increase by almost a factor n (from $g(\widetilde{x})/n$ to infinitesimally less than $g(\widetilde{x})$), yielding a net present value of (almost) $\bar{p} g(\widetilde{x})/r$ for agent i and a zero payoff for all other agents $j \neq i$ in an infinite time horizon model. Clearly, this holds for all agents $i = 1, \ldots, n$ and for all $\widetilde{x} \in \langle 0, K]$. Hence,

the only steady state equilibrium stock is $\widetilde{x} = 0$ if the time horizon is finite.
■

2 The experiment

2.1 Experimental design

In each session, sixteen fishermen were assigned to groups of four ($n = 4$), with fixed membership. Fishing took place in four periods of 1 hour each ($T = 4$). Subjects could catch as many fish as they liked, as long as total catch did not exceed the stock available to their group. Regeneration was mimicked by throwing in extra fish at the end of each period depending on the number of fish remaining.

We implemented the experiment as follows. First, in the experiment the continuous growth equation (2) was approximated by a discrete function. We set $K = 8$ and $\gamma = 2$ in (2), giving rise to the dotted line in Figure 1; the solid line represents the discretized version implemented at the fishing pond. For example, if a group had 2 fish remaining at the end of a period, then an additional 3 fish would be thrown into the pond, implying that 5 fish would be available for the group to catch in the next period.

Second, in the experiment time is discrete, and the discrete time equivalent of (1) is:

$$x_{t+1} - x_t = H_t + g(x_t - H_t), \qquad (6)$$

where $H_t = \sum_{i=1}^{n} h_{it}$. The size of the stock at the beginning of period t is denoted x_t, and the total amount of fish harvested in that period, H_t, cannot be larger than x_t. In the instructions, x_t was referred to as the 'allowable catch remaining' (ACR) at the beginning of period t. Third, we did not pay 'interest' on the payments received in any period, and subjects plausibly attach the same value to the n^{th} fish they catch, independent of whether this fish was caught in the first or the fourth period. Hence, in the experiment $r = 0$. Fourth, each subject was allowed to keep and take home all fish she caught, and to avoid problems with negative marginal utility of

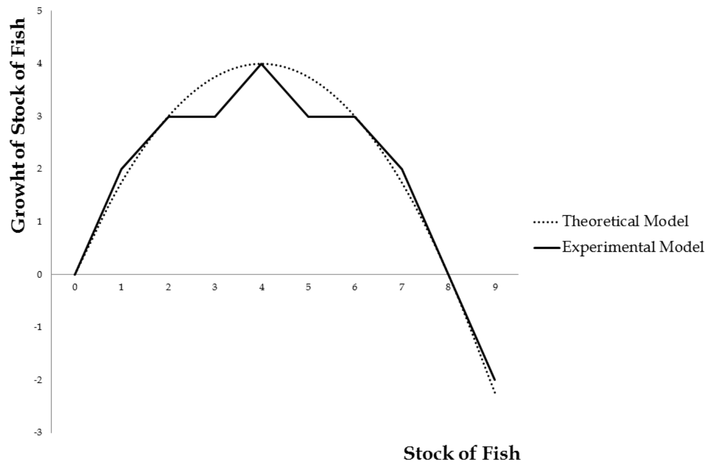


Figure 1: Theoretical and experimental specification of the regeneration function (with $\gamma = 2$ and $K = 8$).

fish, subjects also received €5 for every fish caught.[2] Fifth, if the last fish of a group's allowable catch remaining was caught, its members would be required to leave the pond.

The above design gives rise to the following predictions. Proposition 1 shows that social welfare is maximized if the fish stock is reduced to the point where the *rate* of regeneration, g', equals the discount rate, r. Hence, harvesting should be at maximum speed until $K(\gamma - r)/(2\gamma) = K/2 = 4$ fish are remaining. All agents should then stop harvesting to allow the remaining fish to regenerate. The allowable catch remaining at the beginning of the next period then equals $(2 + \gamma + r)K(\gamma - r)/(4\gamma) = 8$ fish, and harvesting should again be at maximum speed until $K(\gamma - r)/(2\gamma) = K/2 = 4$ fish are remaining – except in the last period, in which all 8 fish available at the beginning of the last period, should be caught. From Proposition 2 we infer that the Nash equilibrium harvesting program in discrete time is to harvest at maximum intensity until the stock is depleted, which should happen within the first period.

[2]Because harvesting costs are zero, neither the socially optimal nor the Nash equilibrium harvesting paths are affected if the marginal value of fish would not be constant as long as it is strictly positive.

Comparing the cooperative and non-cooperative solutions, our experiment thus poses a social dilemma in three respects: fishing time, number of fish caught, and amount of money earned. If subjects cooperate, groups can fish for (almost) four hours, catch twenty fish (four in each of the periods 1-3, and eight in period 4) and receive €100. In the subgame perfect Nash equilibrium harvesting path, groups can fish for (at most) one hour, catch eight fish, and receive €40.

2.2 Experimental procedure

We conducted two sessions. Four groups of four fishermen participated in each session, yielding a total of eight observations. At the beginning of the first period, 38 rainbow trout were released into the pond (two per participant, plus an additional six). At the beginning of each subsequent period, a quantity of fish was released, equal to the number caught in the previous period by all groups in the session that had not exhausted their stock yet. Hence, the actual number of fish in the pond, per fisherman participating, was the same at the beginning of each period. Replacing fish caught avoids the possibility that one group's harvesting path affects the feasible catch of other groups in the same session.

Participants were aware of which other individuals were in their group. Each wore a colored ribbon indicating her group. We gave this information because the model presented in section 1 has a closed-loop solution. We believe that if this feature of the design affects behavior, it would enhance cooperativeness (Duffy, Ochs and Vesterlund (2007)). Hence, if we do not find any evidence of cooperation, the results would be even more convincing than in the absence of the group affiliation information.

At the end of each period, subjects were informed of (i) their total earnings in the period, (ii) total group catch in the period, H_t, (iii) the total group quota still remaining, $x_t - H_t$, (iv) the increase in the group's quota, $g(x_t - H_t)$, and (v) the size of the resulting ACR for the next period, $x_{t+1} = x_t - H_t + g(x_t - H_t)$.

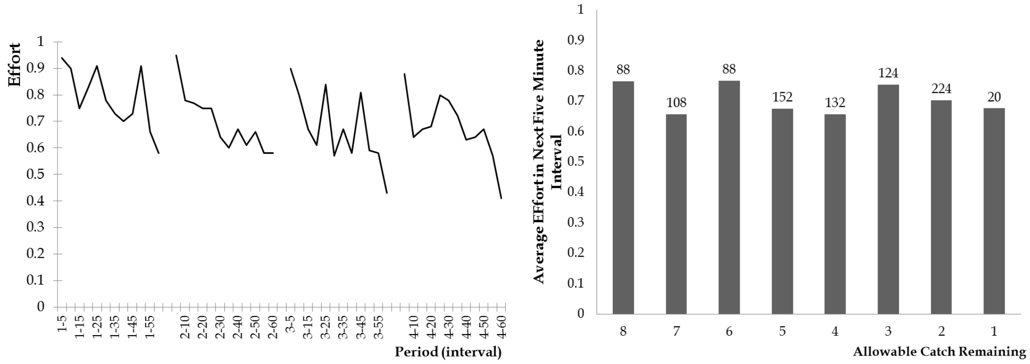
The instructions were read out aloud by the experimenter at a central location, participants were provided with a handout summarizing the instructions, and communication was strictly forbidden. We explicitly tested the participants' understanding of the game by having them answer test questions before the start of the session. The sessions were conducted in April 2009. Average earnings of the participants in this experiment were €15.30.

2.3 Measuring cooperation

The model's predictions, as well as the experimental payoffs, are based on the number of fish caught. However, catching fish involves an element of luck. Influences from, for example, the weather can prevent a fisherman from catching fish. For that reason, we measure the effort a fisherman exerts to catch fish: the amount of times a fisherman casts his rod. Rainbow trout is a predatory fish that actively pursues bait. By constantly casting and reeling back the bait, a fisherman draws the attention of a fish. Hence, the more a fisherman casts his rod, the greater the probability of getting a catch. The advantage of the effort measure is that it is independent of other factors that influence the catch of fish. A fisherman makes a conscious decision to cast the rod, and deciding to cast the rod is relatively independent of temperature, wind direction, and the like. In the online Appendix, we show that there is a positive statistical relationship between effort and catch in the data.

There are two patterns that we use to distinguish cooperation from non-cooperation in this experiment.[3] The first is that, under non-cooperative behavior, there would be no difference in behavior over the four periods. Players would fish with the same, maximum, effort in all periods. Under the social optimum, however, effort would be greater in the last period, relative to the first three periods. This would indicate an attempt to reduce catch in periods 1-3 to below the maximum feasible level. The second pattern is that, under cooperative behavior, effort would exhibit a dependence on the number of fish remaining in the group's quota in periods 1-3. If fishermen

[3] Note, an ACR close to the socially optimal level may be due to a binding feasibility constraint instead of cooperation.



(A) **(B)**

Figure 2: (A) Average group effort over the periods, (B) Average individual effort conditional on the allowable catch remaining (ACR) in period $1-3$ (each 5 minute interval is an observation, observations are indicated above the bars).

fish less intensely when the stock of fish is below the socially optimal level in any of the first three periods, this is consistent with a targeting of the social optimum. If they fish with the same intensity regardless of whether the remaining catch is above or below the social optimum in any of these periods, this is evidence of non-cooperative behavior.

3 Results

In our experiment, no cooperation is observed. Figure 2(A) shows the average group effort levels over the four periods, while Figure 2(B) shows the effort levels conditional on stock size. A Wilcoxon test indicates no difference in effort between the fourth period and the first period ($N_1 = N_2 = 6, p = 0.75$), taking the average effort levels of each group as an independent observation.[4] Similar results are found when the fourth period is compared with either the second period ($N_1 = N_2 = 6, p = 0.67$), or the third period ($N_1 = N_2 = 6, p = 0.60$).

[4]Six observations are used for this test, because two groups caught their ACR in a period before the fourth (one in period 1 and one in period 3).

The relationship between effort and the ACR is shown in Figure 2(B). The figure shows the average individual number of casts in the five minute intervals after which a specific stock level is reached. The figure reveals that the average effort level in a group is independent of the ACR. There is no evidence that effort is greater for $x > 4$ than for $0 < x \leq 4$. In the online appendix, the estimation of a a fixed effects model shows that effort at low stock sizes ($x \leq 4$) is not statistically different from effort at high stock sizes ($x > 4$). This is evidence of a lack of cooperation, since if an attempt to attain the social optimum were occurring, it would be evident in an less exploitation of the resource as the stock fell to lower levels.

4 Conclusion

In our framed field social dilemma experiment, we find no evidence of co-operation. Our results are consistent with standard economic theory that assumes selfish preferences and non-cooperative behavior. The difference between our results and abstract laboratory implementations show that contextualization is important when testing the canonical renewable resource model. To achieve good social outcomes in this field setting, voluntary co-operation is not enough, and specific institutions that promote cooperation, such as punishment technologies or voting processes, may be required.

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