A Common Pool Resource Experiment with a Dynamic Stock Externality [*]

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Abstract

The common pool resource environment introduced by Ostrom, Walker and Gardner may be interpreted as the steady state of a fully dynamic model in which rent-maximizing fishermen exploit biomass which evolves according to a logistic growth function. We conduct a laboratory experiment to compare observed behavior in such a dynamic environment with behavior in the static environment that is its steady state. We focus on the effect of free form, non-binding communication in the two environemts. We hypothesize that the complexity of the dynamic environment will reduce the ability of fishermen to cooperate in reducing fishing effort.

We run 12 sessions with groups of eight subjects in a 2x2 design benchmarks of static and dynamic efficiency, Nash equilibrium, and open access (zero profit) equilibrium. Contrary to our expectations, subjects in some of the dynamic sessions were clearly able to restrain harvest and build up stocks. Within session variation in effort is higher in the dynamic environment. Analysis of mean effort and efficiency across sessions shows a significant communication effect, no significant model specification effect, and no strong evidence of any interaction effect.

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Contents

1 Introduction

A common pool resource (CPR) is an economic resource which is both *subtractable* (in the sense that one person's use of the resource diminishes its value for other users) and *non-excludable* (in the sense that it is difficult to control access to the resource). Examples of open access resources are road networks, fisheries, and the global atmosphere. Because exclusion is costly, management of the resource is often difficult. Frequently CPRs are managed as *common property*, that is, property which multiple individuals have the right to use. In the extreme case of *open access* resources, this right of use is essentially unlimited.

It is well known that open access to CPRs causes overcrowding and degradation. Hardin (1968) calls this "The Tragedy of the Commons". However, not all CPRs suffer this fate. Social institutions may evolve which explicitly or implicitly restrict access to the CPR, thus preserving its value (Feeny, Berkes, McCay & Acheson 1989). Thus factors facilitating social coordination, such as communication among users, may be important in determining the extent of overexploitation.

There are two ways of modelling the tragedy of the commons: as a static externality or a dynamic one. In a static model users of the resource diminish the value of the resource to those using it at the same time, but the future value of the resource is undiminished. Formal analysis of these models in the case of the fishery goes back at least to Gordon (1954). In general the conclusion is simple: fishermen will enter the industy until the value of their average product equals the opportunity cost of fishing. At this point all rents are exhausted and (under extreme assumptions) the fishery is worthless. In a dynamic model current users of the resource reduce the stock of the resource and thereby harm future users of the resource. Such models typically require integration of an economic model of human behaviour with a underlying model of resource dynamics. Clark (1990) was a pioneer in this literature. Munro (1982) provides an early and elegant exposition of these models, showing how Gordon's static model can be interpreted as the steady state of a fully dynamic model in which rent-maximizing fishermen interact with an underlying Schaefer (1957) logistic growth model.

The static CPR model has been extensively studied in the laboratory. A particularly influential research program was initiated by Walker, Gardner & Ostrom (1990). They implemented the basic CPR game as a laboratory environment and convincingly demonstrated over-harvesting in the basic environment. They also showed that subjects were willing to incur private costs to punish excessive effort and that a combination of non-binding communication and costly punishment was sufficient to create much higher efficiencies.

A natural question is whether the results of static CPR experiments carry over to a dynamic environment. It is natural to expect that it will be even harder to coordinate behaviour in the dynamic case, partly because the benefits of immediate cooperation are deferred in the dynamic case and partly because the computation of an optimal strategy is so much harder. The evidence here is very sparse. A few experiments have investigated dynamic CPRs. Herr, Gardner & Walker (1997) and Bru, Carera, Capra & Gomez (2003) are two examples, but neither explored a specific fishing model.

The purpose of this experiment is to begin a systematic comparison of the properties of static and dynamic CPRs in a laboratory context. We focus on comparing a behaviour in a dynamic fishery environment with behaviour in a static environment that is the steady state of the dynamic environment.

2 Static and Dynamic Fishery Models

2.1 A Static Model

The classic CPR model, as developed by Gordon (1954), contemplates an industry of price-taking fishermen who in aggregate supply e units of fishing effort at an opportunity cost of

w per unit. The catch of fish (*i.e.* the yield, y) is a quadratic function of the rate of effort, e.

$$y = ae - be^2, \quad a, b > 0 \tag{1}$$

Industry profits are

$$\begin{aligned} \pi &= py - we \\ &= p(ae - be^2) - we \end{aligned} \tag{2}$$

where p is the exogenously determined price of fish. Under these circumstances social welfare is maximized by maximizing π. This occurs at the efficient effort level

$$e^* = \frac{a - w/p}{2b} \tag{3}$$

Under an open access regime, however, new effort enters the industry until all fishermen earn zero profits. This occurs at the open access effort level

2.2 A Dynamic Model

The yield-effort curve (1) may be interpreted as the steady state of a dynamic system in which the fish stock grows according to a logistic growth function and the harvest is proportional both to effort and to the biomass of the fish stock (Munro 1982). Let the natural rate of growth (in the absence of harvesting) be

$$g = F(x) = rx(1 - \frac{x}{k}) \tag{4}$$

where g is the rate of growth in tons per period, x is the stock of fish in tons, k is the carrying capacity of the fishing ground (also measured in tons), and r is the intrinsic rate of growth (i.e. the growth rate in an unconstrained environment).

As before, the stock of fish is exploited by an industry of price-taking fishermen who in aggregate supply e units of fishing effort at an opportunity cost of w per unit of effort. In the dynamic case the rate of harvest, h, depends on the rate of effort, e, and the current stock of fish x:

$$h = qex \tag{5}$$

Here q is a "catchability" coefficient which may be interpreted as the fraction of the stock harvested by one day's fishing effort. The evolution of the stock is described by the stock equation

$$\begin{aligned} \dot{x} &= g - h \\ &= rx(1 - \frac{x}{k}) - qex \end{aligned} \tag{6}$$

The value of the harvest is ph where p is the price of fish. Fishing effort is supplied by fishermen at an opportunity cost of w so that the rate of profit in the fishing industry is

$$\pi = pqex - we \tag{7}$$

Under conditions of open access fishermen increase or decrease effort according to whether their profits are positive or negative. We may model this by specifying

$$\dot{e} = \mu\pi \tag{8}$$

where $\mu > 0$ is an adjustment coefficient. Equations (6) and (8) characterize the dynamic behaviour of the system.

2.3 The Static Model as a Steady State of the Dynamic Model

The system of Equations (6) and (8) will be in steady state if the stock and effort levels are both unchanging over time, *i.e.* if $\dot{x} = \dot{e} = 0$. By (6)

$$rx(1 - \frac{x}{k}) = qex \tag{9}$$

Solving (9) we obtain the steady-state stock, x^s, as a function of sustained effort

$$x^s = k - \frac{qke}{r} \tag{10}$$

Substituting into (5) yields the steady-state harvest, y, as a function of the steady-state effort.

$$y = qke - \frac{q^2k}{r}e^2 \tag{11}$$

Equation (11) is the sustained yield-effort curve. Note that it is of the same form as (1) with

$$a = qk \tag{12a}$$

$$b = q^2k/r \tag{12b}$$

For future use we note

$$q = \frac{a}{k} \tag{13a}$$

$$r = \frac{aq}{b} \tag{13b}$$

In the next section we describe how we implemented these models in a laboratory environment.

3 Experimental Design

3.1 Laboratory Environment

Using z-Tree (Fischbacher 2002) we created a laboratory environment in which groups of eight subjects faced repeated opportunities to choose a level of appropriation from a CPR. To facilitate understanding we chose to present the decision problem in a natural context. Subjects were told they represented villagers who could spend 25 days per month either fishing or farming. Each day spent farming yielded a fixed return of 5 laboratory dollars (L$). Each day spent fishing yielded a proportionate share of the total catch of fish. The total catch was a function of the total fishing effort and the stock of fish.

Each decision period represented one month. In each period subjects were first presented with a calculator screen in which they could compute the consequence of any combination of their own and others' fishing effort. After all subjects had finished with the calculator each was required to state an actual effort level. The outcome of the period was computed and reported to the subjects and a new period began. Each session began with three practice rounds which did not affect payoffs. Following the practice session the experiment was re-initialized. Each session then ran for a further fixed and known number of periods. At the end of the session subjects' earnings were totalled, converted to local currency and paid privately in cash.

The experiment was conducted under four conditions created by crossing a communication factor (No Communication / Communication) with a model specification factor (Static / Dynamic). In the No Communication sessions subjects were not permitted to communicate at any stage of the experiment. In the Communication treatments subjects were permitted up to five minutes of free form communication before each group of four paid rounds beginning with the fifth. Communication was restricted only by the requirements that side payments not be discussed, that there be no threats of violence, and that subjects were not permitted to view each others' screens.

The Static and Dynamic sessions differed in the the nature of the externality, as described below.

3.2 The Static Environment

The static environment, introduced by Walker et al. (1990), is an adaptation of the Gordon (1954) model to a fishery with a finite number of identical fishermen. Let there be $J = 8$ individuals. Let d_j be each individual's time endowment, measured in days per month. We assume $d_j = d \; \forall j$. Let e_j be the j-th individual's fishing effort in days per month and let $e = \sum_{j=1}^{J}$ be the total fishing effort of all members of the group. In the static model the fishery output follows the static yield function (1) modified to exclude negative returns.

$$h = \max(ae - be^2, 0) \tag{14}$$

The payoff for individual j is

$$\pi_j = w(d - e_j) + p\frac{e_j}{e}(\max(ae - be^2, 0)) \tag{15}$$

Assuming that the harvest is strictly positive, *i.e.* that $0 < e < \frac{a}{b}$, three benchmark equilibria can be easily computed. The socially optimal solution (or efficient) equilibrium maximizes joint profits and can be expressed as

$$\{e_j^*\} = \underset{\{e_j\}}{\text{argmax}}(\sum_{j=1}^{J} \pi_j) \tag{16}$$

with solution

$$\sum_{j=1}^{J} e_j^* = \frac{a - w/p}{2b} \tag{17}$$

Note that (17) restricts only aggregate effort; any set of $\{e_j\}$ satisfying (17) will be an efficient outcome.

The Nash equilibrium satisfies

$$e_j^N = \underset{e_j}{\operatorname{argmax}}(\pi_j) \quad \forall j \in \{1..J\} \tag{18}$$

Equation (18) gives rise to the J first order conditions

$$-w + ap - 2bpe - bpe_j = 0 \quad \forall j \in \{1..J\} \tag{19}$$

Equating any two members of Equations (19) shows that the solution is symmetric, *i.e.* $e_i^N = e_k^N \quad \forall i, k$. Summing Equations (19) over all j yields the Nash equilibrium aggregate effort

$$e^N = \frac{J}{J+1} \frac{a - w/p}{b} \tag{20}$$

and because the solution is symmetric, each agent's effort is

$$e_j^N = \frac{1}{J+1} \frac{a - w/p}{b} \tag{21}$$

A third benchmark is the open-access equilibrium characterized by $\pi_j = 0 \quad \forall j$. This corresponds to Gordon's (1954) original formulation in which individual fishermen are assumed to ignore their own impact on the average product of fishing effort. The open-access equilibrium is

$$e_j^{oa} = (a - w/p)/b \quad \forall j \tag{22}$$

In this experiment we adopt the parameters chosen by Walker et al. (1990), as shown in the first column of Table 1.

symbol	item	static	dynamic
d	endowment of effort per month	25	25
p	price of fish	1	1
w	opportunity cost of effort	5	5
a	linear coefficient in harvest function	23	23
b	quadratic coefficient in harvest function	0.25	0.2035
k	carrying capacity of fishery		10000
q	catchability coefficient		0.0023
r	unconstrained growth rate		0.26
e^*	socially optimal aggregate effort	36	44
e^N	Nash equilibrium aggregate effort	64	79
e^{oa}	Open Access equilibrium effort	72	88
x^*	Socially optimal stock		6174.569
x^N	Nash equilibrium stock		3043.478
x^{oa}	Open Access equilibrium stock		2174
π^*	Total Payoff at Social Optimume	1324	1407
π^N	Total Payoff at Nash Equilibrium	1068	1147
π^{oa}	Total Payoff at Open Access	1000	1000

Table 1: Parameters and Benchmarks

3.3 The Dynamic Environment

The dynamic environment is the same as the static environment except that the harvest now depends explicitly on the stock of fish at the beginning of the period, x_t.

$$h_t = qe_t x_t \tag{23}$$

where the subscript refers to decision period. Note that the marginal and average products of fishing effort, qx_t, are equal and independent of output any period.

The payoff to individual j in period t is

$$\pi_{jt} = w(d - e_j) + pqe_{jt}x_t = \pi_{jt}(x_t, e_{jt}) \tag{24}$$

and the group payoff is

$$\pi_t = w(dJ - e) + pqe_t x_t = \pi_t(x_t, e_t) \tag{25}$$

The stock evolves according to a discrete approximation to (6)

$$\begin{aligned} x_{t+1} &= x_t + g_t - h_t \\ &= x_t + r x_t \left(1 - \frac{x_t}{k}\right) - q e_t x_t \end{aligned} \tag{26}$$

We chose parameters $k = 10000$, $q = 0.0023$ and $r = 0.26$ so as to make the steady state of the dynamic model correspond approxmately equal to the static yield - effort curve of the static model. The corresponding benchmarks for the steady state of the dynamic model are reported in Table 1.[1]

It is important to note that that the steady state benchmark values in Table 1 are not the predicted or optimal values for effort in the dynamic model. In the dynamic model the efficient trajectory of effort solves the following control problem.

$$\begin{gathered} \max_{\{e_{jt}\}} \sum_t \sum_j \pi_{jt}(x_t, e_{jt}) \\ \text{subject to} \\ x_{t+1} = x_t + r x_t \left(1 - \frac{x_t}{k}\right) - q e_t x_t \end{gathered} \tag{27}$$

We solved this problem by brute force, restricting attention to integral values of effort and stock. The trajectory of efficient effort is shown in Figure 1. Note that the optimal strategy calls for pulse fishing. Stocks are built up by abstaining from harvesting for four or five periods. Then maximum effort is exerted for one period, after which stocks are allowed to rebuild. The corresponding stock levels are shown in Figure 2. Under the pulse fishing stragegy the stock gradually builds to a maximum somewhat above the static benchmark, then is reduced rapidly to a level well below the static optimum but still above the Nash

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[1] For a=23, b= 0.25 and k = 10000, Equations (13) imply $q = 0.0023$ and $r = 0.2116$. Due to a clerical error, the dynamic sessions actually used a value of $r = 0.26$. These imply $a = 23$ and $b = 0.2034615$. Consequently, the steady state benchmarks are 44.23440, 78.63894, and 78.63894 for efficiency, Nash equilibrium and open access respectively.

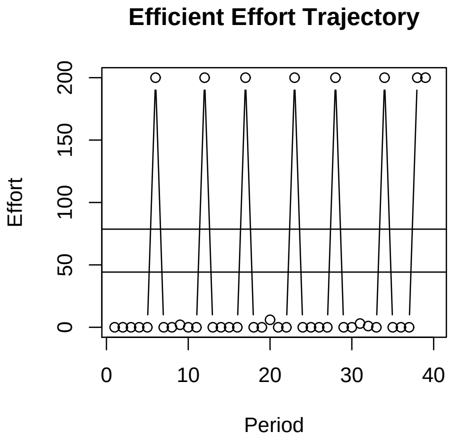

Figure 1: Efficient Effort in the Dynamic Model

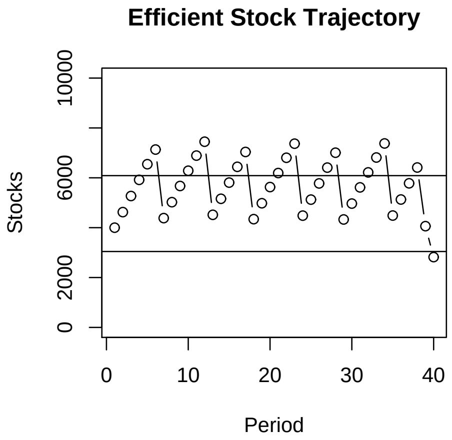

Figure 2: Efficient Stock in the Dynamic Model

No. of Periods	Efficient Payoff Total	per Period
10	12,160	1316
16	21,713	1357
20	27,392	1370
40	55,866	1397

Table 2: Maximum Payoffs for Dynamic Sessions

Equilibrium benchmark. The optimal value of the game depends on the number of periods played. These values are reported in Table 2. To improve comparability across sessions these are also expressed as mean values per period.

Subjects were informed of the nature of the growth function in the Instructions. In addition, the calculator screen reported current and predicted future stock and average return to effort.

4 Hypotheses

Following the results of Walker et al. (1990) we expect effort in the static, no-communication (SNC) condition will approach the Nash equilibrium benchmark of 68 reasonably quickly. at an aggregate effort level of 72 days of fishing. Because cheap talk has been shown to raise coordination in public goods games we expect to see some increase in efficiency in the static communication condition (SC) compared to the SNC condition. In addition we expect to see a clear breakdown in coordination at the end of the session, due to a strong endgame effect, and we might observe some decline over the four periods following each communication period.

In the dynamic no-communication (DNC) environment we expect subjects to follow something of a best-response strategy leading to the static Nash equilibrium bench mark. We have not computed the dynamic equilibrium although it would be possible to do so, in principle. Instead we infer from the incentive structure of this experiment that there will be a strong tendency for subjects to allocate all their endowment according to the value of the fish caught per day(CPD). When the value of the fish caught per day is above the opportunity cost of fishing (when value of fish CPD $> w$) then they will invest all of their endowed days to fishing. When the value of the catch per day is below the opportunity cost of fishing then subjects will allocate their endowed days to farming. If subjects followed this best response function for an infinite number of periods, the average allocation to fishing would be 73.498, the same level as predicted by the open-access equilibrium. [2] Since the stock begins at 4000 tonnes, we should observe the stock level rapidly decline and then oscillate around the 2173.8 tonne level. Effort levels should be either full investment or zero depending on the value of the fish caught per day.

We expect subjects to be able to achieve significant cooperation in the dynamic, communication (DC) condition but the exact nature of this increase is, of course, the focus of our investigation. *A priori* it seems more difficult to compute the optimal strategy for the dynamic model and consequently we might expect that communication would be less effective in increasing efficiency.

5 Results

5.1 Overview

Figures 3 and 4 summarize the time paths of aggregate effort for all five treatments and the beginning-of-period stock of fish for the three dynamic treatments. The horizontal lines on the figures represent the open-access, Nash, and socially-optimal bench marks. The static, no communication sessions behave as expected. Aggregate effort converges almost

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[2] TODO: I don't see how this statement follows from the model. Surely it depends upon the growth dynamics. Should we simulate?

instantaneously to the Nash benchmark and then seems to cycle around the equilibrium value. Introducing non-binding communication has mixed results: in two sessions (SCS 2 and SCS 3) it appears to have had little or no effect, whereas in session SCS 1 subjects were successful in fishing at almost the socially optimal level in Periods 5 through 8 and again in Periods 13 through 19.

The behaviour of effort changes dramatically in the dynamic sessions. Recall that returns to fishing do not vary with instantaneous effort, so that myopic one-period profit maximization implies that fishing effort should be maximized when the stock exceeds the open access benchmark and should be zero when it falls below. Thus we expect oscillating behaviour, with fishermen alternating between maximium and zero effort. This oscillating behaviour is clearly evident in the dynamic no communication sessions. Effort begins at a high level, well above the static open access level, and declines relatively slowly until about period five, after which it clearly alternates between high and low effort levels. Interestingly enough, subjects do not fully exploit the corner solution nature of the problem: in two sessions out of three the minimum effort level is well above zero and in many cases the peaks in fishing effort are well below the maximum of 200. Figure 4 suggests, however, that net effect on the stock is very similar to open access fishing. The stock declines rapidly from its peak of 4000 and closely approaches the open access benchmark in all three sessions.

Figure 5 reveals a close interaction between stock and effort levels. Recall that at the open access level of effort the average return per unit of effort is equal to its opportunity cost. Figure 5 plots the beginning of period stock and aggregate effort for each of the three Dynamic, No Communication Sessions. In all three sessions the stock begins above the open access level and declines rapidly. Aggregate effort falls over the first few periods, indicating an attempt of some subjects to restrain their fishing. Once the stock falls below open access levels, aggregate effort is cut back to a point where the stock begins to recover. As noted above, however, subjects in Sessions DNS1 and DNS2 failed to reduce their effort to zero.

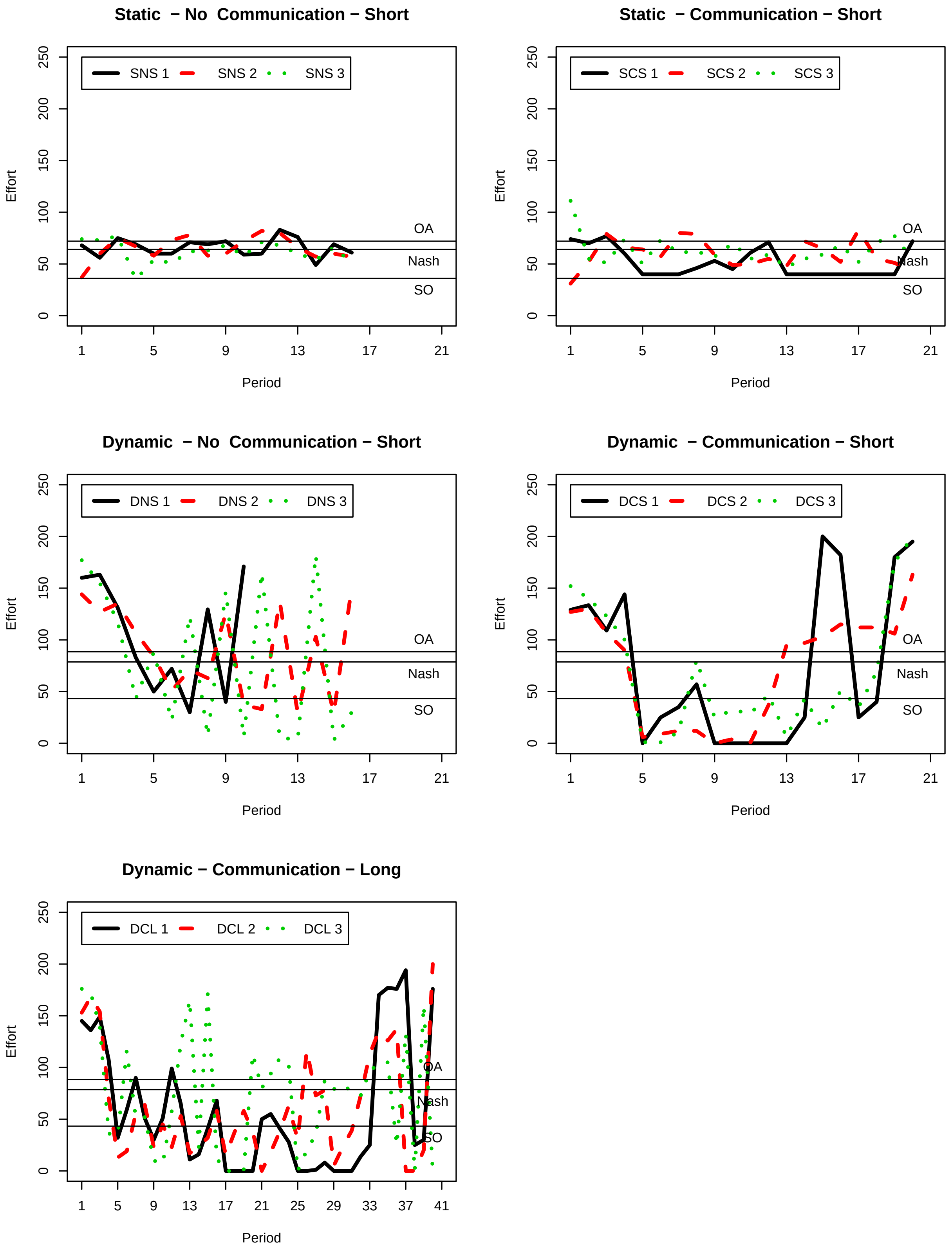

Figure 3: Effort by Session and Period

Subjects in Session DNS3 appear to have understood their incentives better. Figure 5 shows that these subjects reduced their contributions to close to zero as soon as the average return to fishing fell below their opportunity costs. The result is a pronounced oscillation of effort and very little deviation of stock from the open access level.

Introducing communication improved performance in most of the dynamic sessions. In general, effort falls after each communication round and then rises slowly as subjects defect in reponse to increased incentives to fish. There is substantial variation from session to session. Figure 6 plots stock and effort for the short communication sessions. Communication occurred at the beginning of Periods 5, 9, 13, and 17. In Session DCS1 subjects successfully coordinated on a reduction to zero effort in Period 5 but defection increased in each of the next three periods. In Period 9 they returned to zero effort and successfully maintained coordination for the next three periods. By Period 13 stock had reached close to optimal levels. Harvesting increased greatly in Period 15. It appears that subjects had decided to go for maximum exploitation. In Session DCS2, subjects maintained coordination after Periods 5 and 9, but by Period 12 stock had approached optimal levels and were unable to sustain it after Period 13. Effort increased to non-sustainable levels and the stock gradually decreased. In Session DCS3, substantial defections occurred following Period 5. Stock grew less rapidly than in the other sessions. Nevertheless, subjects exercised some restraint until the last group of four periods.

We had expected that increasing the length of the experiment would allow longer runs of cooperative behaviour before the end-game effect dominated. Somewhat unexpectedly, subjects in these sessions seemed to take somewhat longer to achieve coordination. Indeed, Session DCL3 shows almost a complete lack of coordination. Although aggregate effort was clearly reduced in a number of the communication periods, this was almost always coincident with low stocks, making zero effor consistent with myopic profit maximization. Effort rises whenever the stock exceeds myopic profit maximizing levels and consequently the stock never has a chance to grow.

Session DCL1 shows the opposite behaviour. After a slow start in Periods 5 and 9, some agreement was reached in Period 13. By Period 17 defections had been greatly reduced and the stock was building up rapidly. Indeed the stock overshoots optimal levels by Period 27 and remains at inefficiently high levels until Period 33, when subjects clearly decided to go for rapid harvest. Session DCL2 shows a pattern intermediate between DCL1 and DCL3.

5.2 Aggregate Effort and Efficiency

We now seek statistical evidence of any treatment effects in behaviour across sessions. We focus on aggregate effort devoted to exploitation of the CPR and on the efficiency with which available rents have been extracted. We compensate for the differing length of sessions by expressing both variables as mean values per period. We adjust for differences in parameters across treatments by creating two indexes which are scaled to the difference between open access and socially optimal benchmarks.

The first is an index of excess effort, by which we mean effort devoted to appropriation of the CPR in excess of the socially optimal levle. We define an index

$$\texttt{x.effort} = \frac{e_s - e_s^*}{e_s^{oa} - e_s^*} \tag{28}$$

where e_s denotes mean aggregate fishing effort per period in session s and the e_s^* and e_s^{oa} denote optimal and open access benchmarks respectively. For the dynamic sessions the optimal benchmark is the optimal steady state effort. A value of 1.00 for `x.effort` means that excess effort is as great as predicted under open access.

The second is an index of efficiency, by which we mean the success of subjects at raising

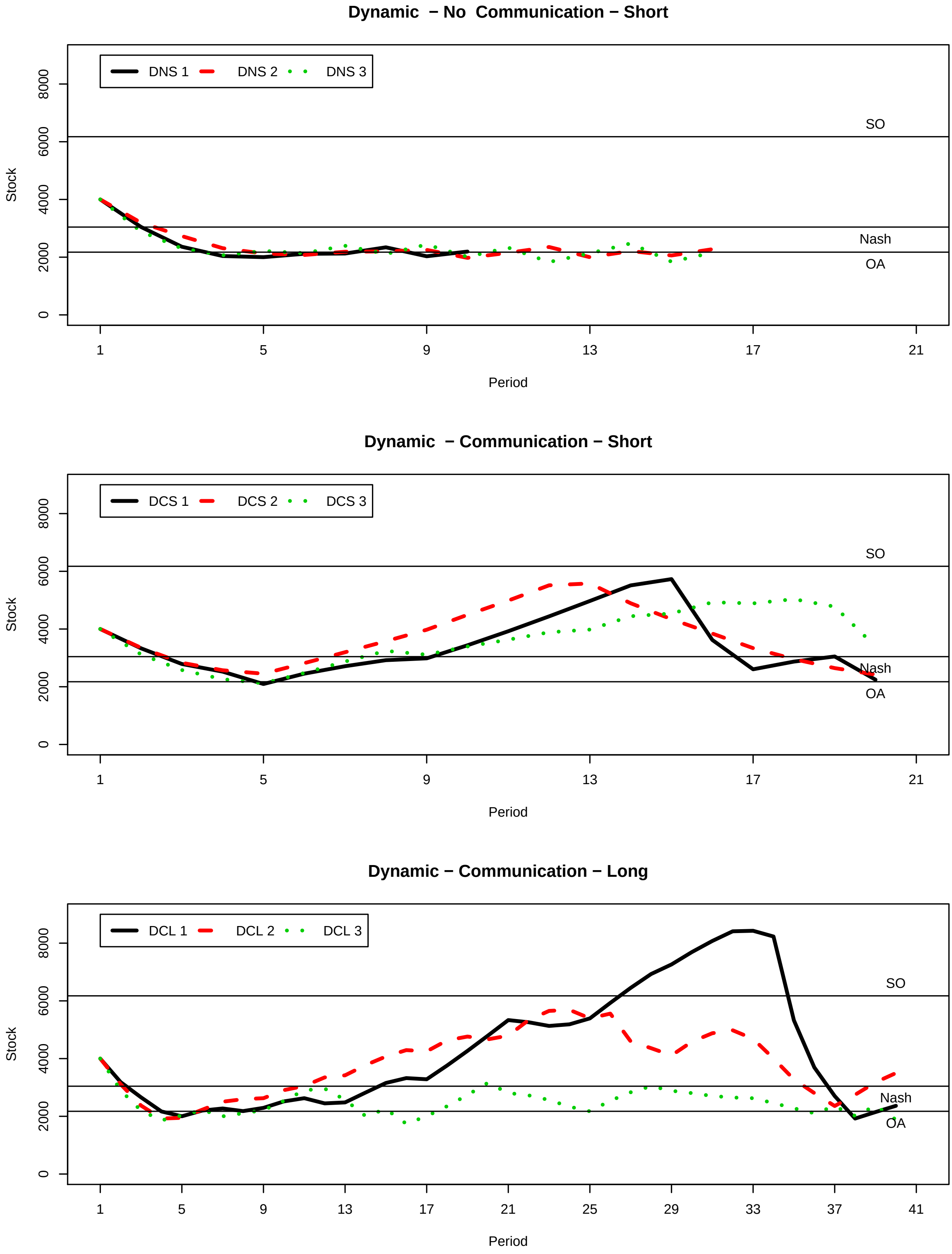

Figure 4: Stock by Session and Period

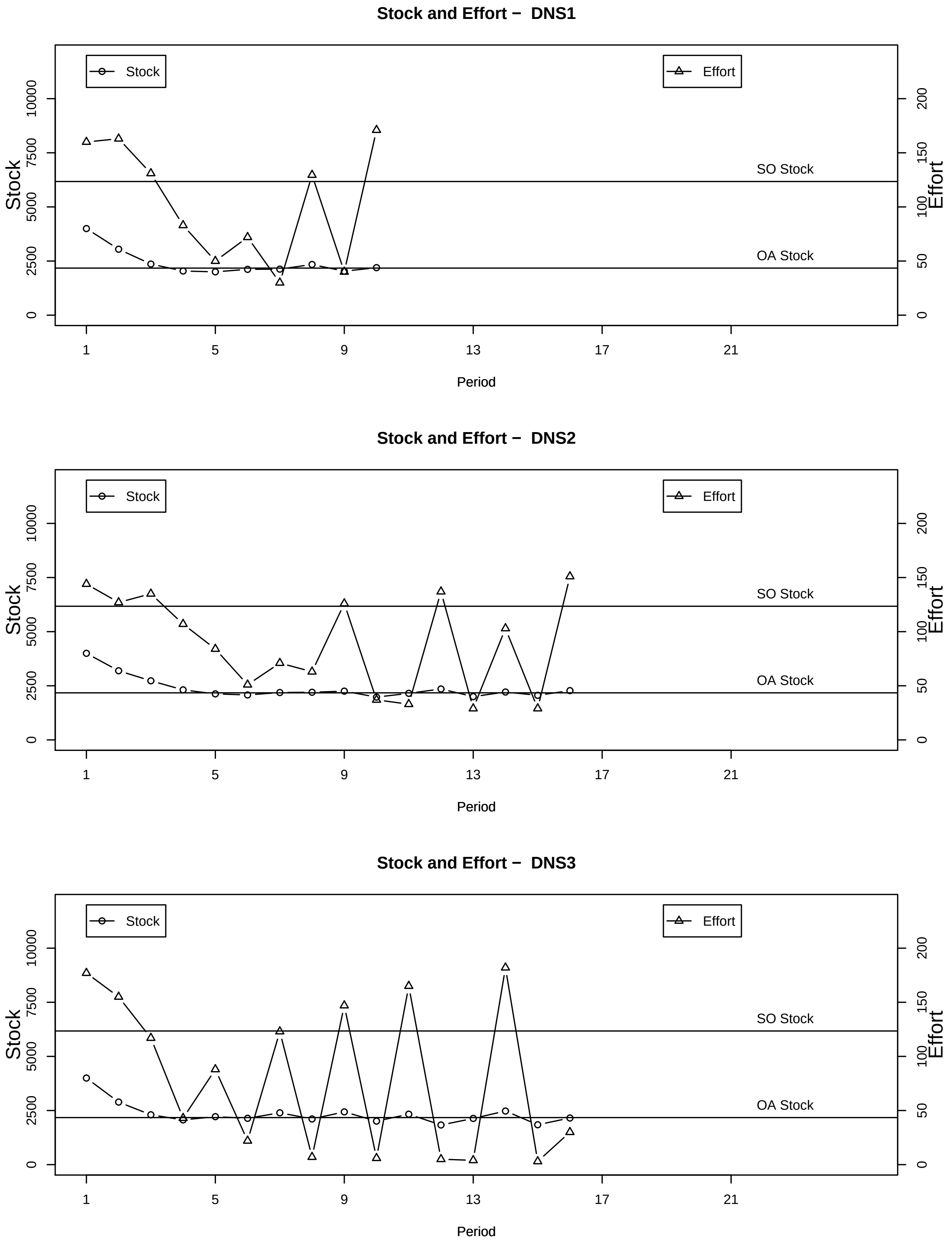

Figure 5: Stock and Effort by Session and Period - No Communication

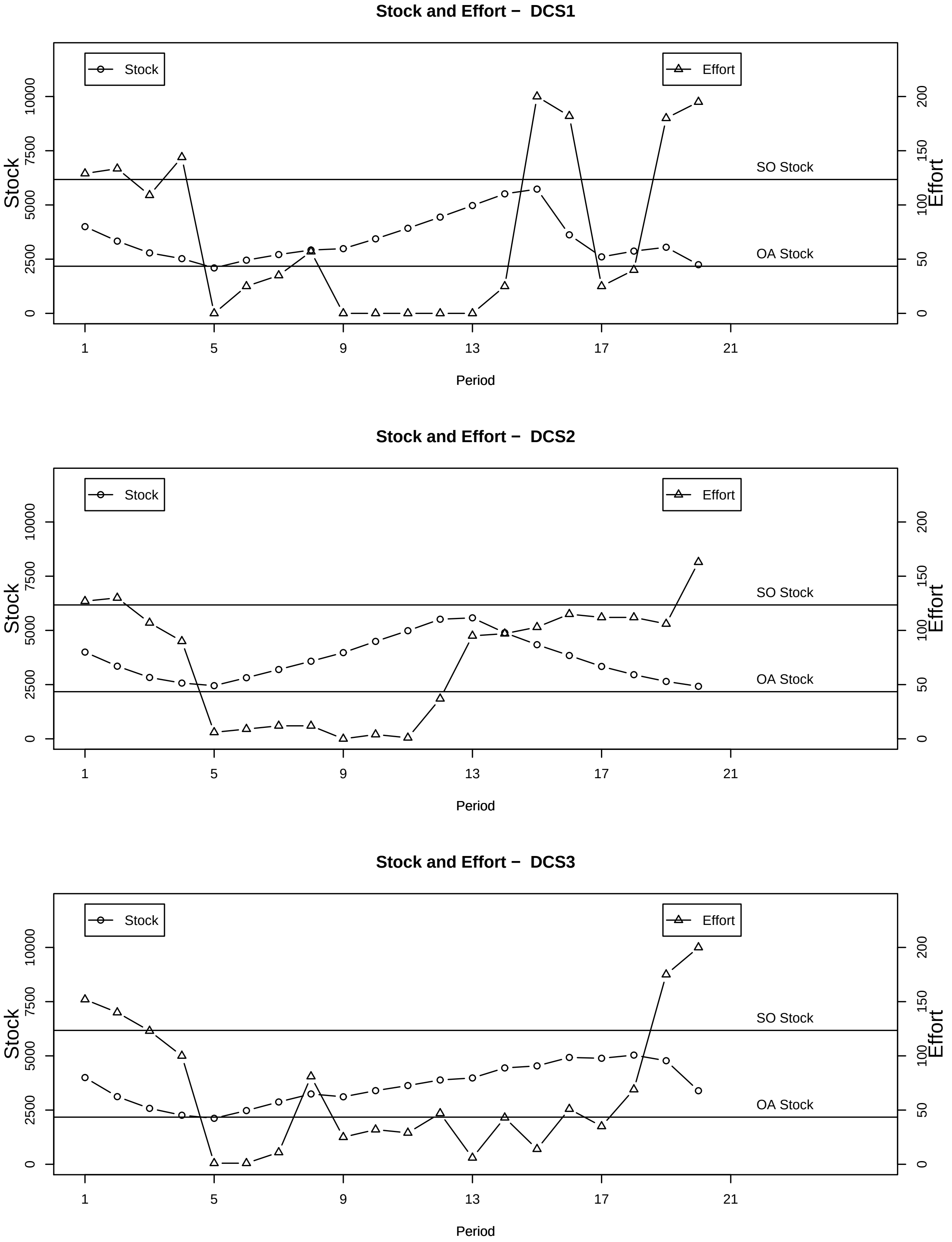

Figure 6: Stock and Effort by Session and Period - Short Communication Sessions

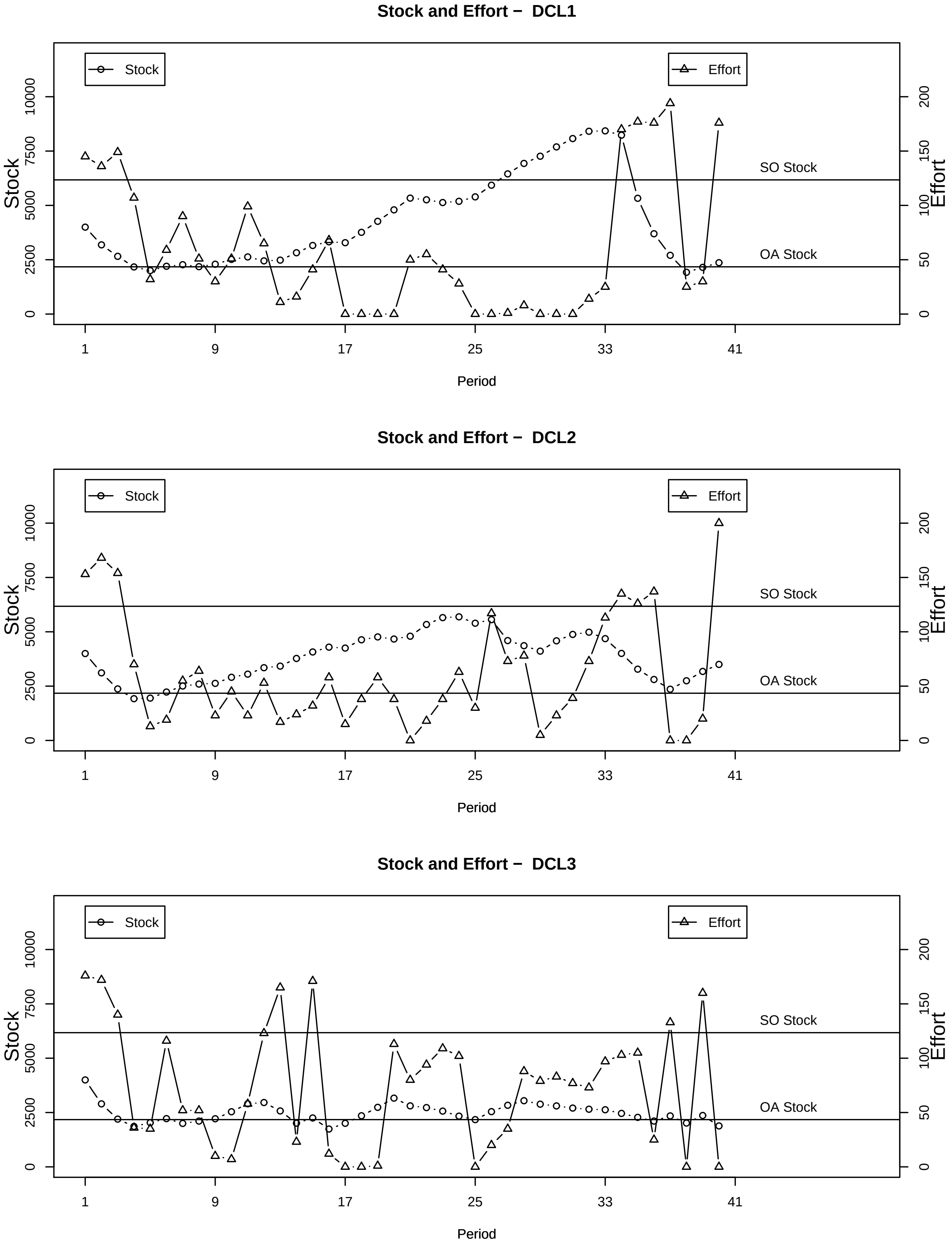

Figure 7: Stock and Effort by Session and Period - Long Communication Sessions

payoffs above open access levels. The index is defined as

$$\texttt{efficiency} = \frac{\pi_s - \pi_s^{oa}}{\pi_s^* - \pi_s^{oa}} \tag{29}$$

where π_s is mean aggregate payoff per period in session s and π_s^* and π_s^{oa} denote the optimal and open access benchmarks for session s respectively. For the dynamic sessions, the optimal benchmark is the optimal value of the dynamic program (27).

Table 3 reports the values of these indices for each session.

session	treatment	effort	Profit	x.effort	efficiency
050531NE	SNC	66.06	1080.36	0.84	0.25
050622NF	SNC	65.00	1082.72	0.81	0.26
050627L5	SNC	61.56	1132.89	0.71	0.41
050704N8	SC	51.45	1216.09	0.43	0.67
050706NH	SC	59.50	1140.55	0.65	0.43
050715NA	SC	63.05	1092.39	0.75	0.29
050321R7	DNC	102.95	1104.25	1.33	0.33
050601NB	DNC	89.19	1073.81	1.02	0.21
050624NE	DNC	79.62	1084.80	0.80	0.24
050705N9	DCS	73.97	1212.07	0.67	0.57
050707NA	DCS	71.90	1227.03	0.63	0.61
050718NB	DCS	66.75	1232.53	0.51	0.63
060213PL	DCL	58.00	1201.19	0.31	0.51
060214PH	DCL	60.20	1224.25	0.36	0.57
060215P9	DCL	73.12	1076.98	0.65	0.19

Table 3: Excess Effort and Efficiency by Session

5.2.1 Aggregate Effort

Figure 8 displays the 15 observations on excess effort grouped by Treatment.[3] A Kruskal-Wallace test confirms that the differences in medians across treatments are significant ($p = 0.034$).

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[3] Figure 8 is misleading because there are actually only 3 observations per treatment - the median observation is given by the heavy horizontal line in each box and the other two observations are given by the extremities of the whiskers. The figure will be replaced in a future version of this paper.

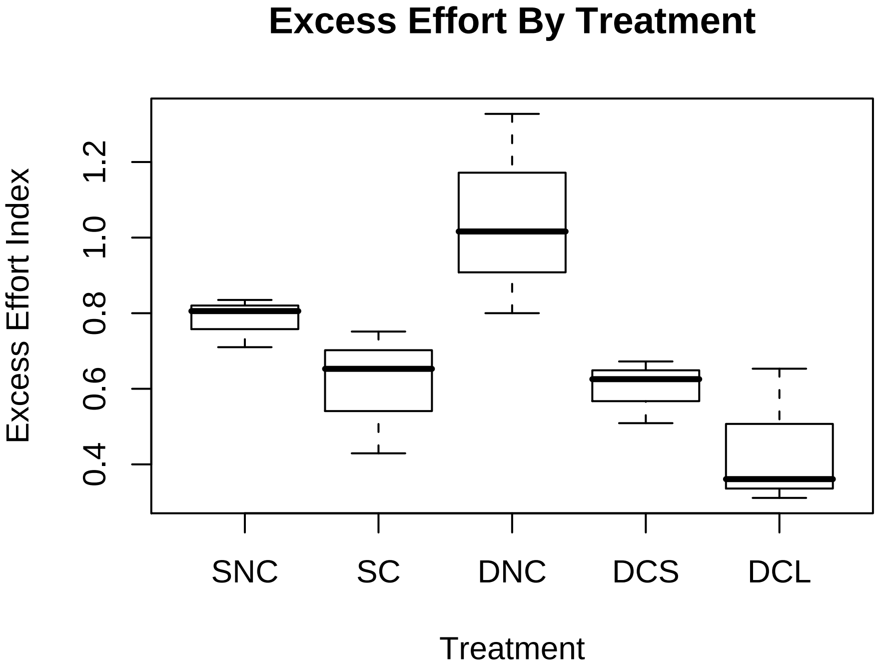

Figure 8: Excess Effort by Treatment

Table 4 reports the mean of the observations by treatment.

	Static	Dynamic	Mean
No Communication	0.78	1.05	0.92
Communication/Short	0.61	0.60	0.61
Communication/Long		0.44	0.44
Mean	0.70	0.70	0.70

Table 4: Excess Effort by Treatment

There is no difference in mean effort levels across the static and dynamic sessions (both equal 0.70) but the mean of the no-communciation sessions (0.90) is distinctly above the mean of the communication sessions (0.41 and 0.61 for long and short sessions repectively).

Analysis of variance (Table 5) shows that the main effect of communication is strongly significant ($p = 0.002$) while there is no evidence of a model specification effect ($p = 1.000$) and neither the effect of session length nor the interaction of model specification and com-

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Dynamic	1	0.00	0.00	0.00	0.9997
Communication	1	0.49	0.49	17.16	0.0020
LongSession	1	0.09	0.09	3.14	0.1069
Dynamic:Communication	1	0.06	0.06	1.96	0.1921
Residuals	10	0.29	0.03		

Table 5: Analysis of Variance in Excess Effort Model

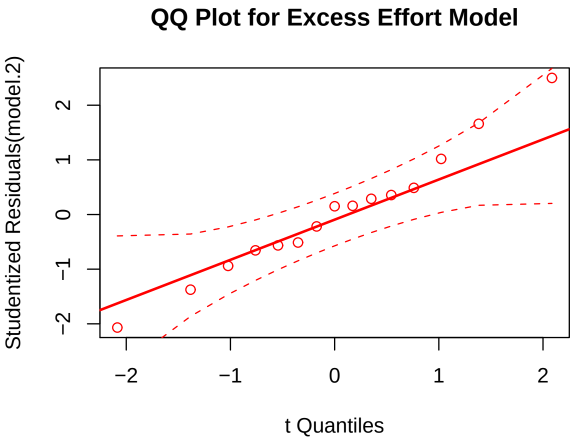

Figure 9: QQ-Plot for Excess Effort Model

munication are significant at conventional levels ($p = 0.107$ and $p = 0.192$ respectively). Analysis of the residuals from this regression (Figure 9) shows that they all lie within a simulated 95% confidence interval, suggesting that the OLS model may be broadly applicable and giving us some confidence in these parametric results despite the small number of degrees of freedom.

5.2.2 Efficiency

Figure 10 displays the 15 observations on efficiency by treatment and Table 6 reports the mean values. The data overlap more than in the case of excess effort, but nevertheless median efficiency in the communication sessions is clearly above that in the non-communication

	Static	Dynamic	Mean
No Communication	0.30	0.26	0.28
Communication/Short	0.46	0.61	0.53
Communication/Long		0.42	0.42
Mean	0.38	0.43	0.41

Table 6: Efficency by Treatment

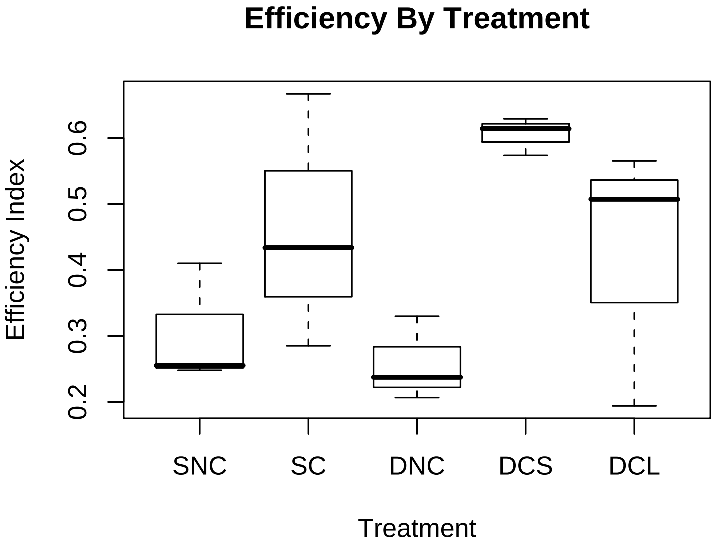

Figure 10: Efficiency by Treatment

sessions. The non-parametric Kruskal-Wallace test retains the null of no treatment effects ($p = 0.106$) at conventional significance levels, but the more powerful OLS estimator weakly rejects the null ($p = 0.065$). Analysis of variance (Table 7) shows that the main effect of communication is strongly significant, while the remaining factors and the interaction of communication and model specification are not significant. The QQ plot for this model (Figure 11) shows one residual outside the simulated 95% confidence interval but nevertheless fails to indicate any strong violations of the OLS model. Accordingly we accept the qualitative conclusion that there is strong evidence of a communication effect while the results are broadly the same across model specifications.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Dynamic	1	0.01	0.01	0.41	0.5357
Communication	1	0.16	0.16	8.86	0.0139
LongSession	1	0.03	0.03	1.75	0.2148
Dynamic:Communication	1	0.03	0.03	1.50	0.2483
Residuals	10	0.18	0.02		

Table 7: Analysis of Variance in Efficiency Model

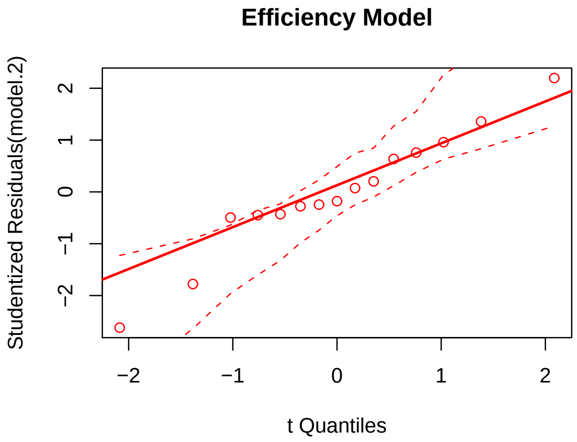

Figure 11: QQ Plot for the Efficiency Model

6 Summary and Discussion

In this paper we have systematically compared the laboratory performance of a dynamic common pool resource environment with that of the static environment which is its steady state. We were were particularly interested in whether the additional difficulties of coordinating behavior in a dynamic environment would reduce the ability of agents to coordinate their actions with non-binding communication. We deviated from standard practice in providing subjects with a clear common pool resource context for their decisions.

We were successful in implementing comparable static and dynamic environments. The results from the static environment were very comparable to earlier studies. In the absence of communication, appropriation effort converged rapidly to the Nash prediction and cycled around it. Introducing non-binding communication clearly reduced average effort and increased efficiency, with clear differences in the ability of groups to achieve coordination.

Behaviour in the dynamic environment was, on first impression, very different from that in the static environment. In almost all cases subjects respondend to changing stock levels by varying their fishing effort over a much wider range. Introducing non-binding communication allowed subjects to hold back on current effort to build up stocks, and most groups exploited this opportunity.

We developed two indices of performance to compare aggregate behaviour across static and dynamic environments. Analysis of these indices showed that aggregate performance was remarkably similar in the two environments. Both excess effort and efficiency responded strongly and in the expected direction to opportunities for non-binding communication. There was essentially no evidence of model specification effects (dynamic vs. static) and very little evidence of interaction between model specification, although our 15 observations were clearly insufficient to detect more than the grossest differences between environments.

The results suggest a number of directions for future work. Clearly, some additional replications would enhance the precision of our results and perhaps serve to identify an interaction effect between communication and model specification. Beyond that, the authors admit some discomfort at the discrete model of change in in stock (Equation (26)). Although it is a natural discrete approximation to the continuous equation underlying the Schaerfer model, it implies that the natural growth in the stock is independent of this season's harvest. It might be useful to revise the timing so that the growth increment depends on the stock *after* the harvest. Finally, we are intrigued with the variation in coordination that our separate groups were able to achieve. In some sessions, particularly DCL3, some participants seemed quite disengaged from the group discussions. This leads us to conjecture that factors affecting group solidarity and cohesion might prove particularly important in explaining variation in coordination in games with cheap talk.

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A Experimental Design

We began by running a thrice replicated 2x2 factorial design in two levels of modeling (Static and Dynamic) and 2 levels of Communication (No Communication and Communication). The No Communication sessions ran for 16 periods. except for the first (Pilot) session, which ran 10 periods. The first three communication sessions ran for 20 periods, with communication rounds prior to periods 5, 9, 13, and 17. In order to examine more closely the effect of communication we ran three more communication sessions lasting 40 periods each, with communication periods before every 4th period, beginning with the fifth. The final design is shown in Table 8

Communication	Model	
Treatment	Static	Dynamic
No Communication	3	3
Communication (20 periods)	3	3
Communication (40 periods)		3

Table 8: Number of Sessions by Treatment

In effect, we have three treatment variables: Model, Communication, and Length of Session, each with three levels. We fail to have a complete 2^3 design, however, because we have no long sessions for the static-no communication (SNC), Static Communication (SC), and Dynamic- No Communication (DNC) cases.

B Data Preparation

We ran 15 sessions. Table 9 shows the treatment settings for each session. We used the data from session 20050321DNP even though it was originally intended as a pilot. Table 10 shows the variables generated by the Ztree program.

	session	dynamic	communication	pilot	nPeriods	description
1	20050321DNP/Pilot	t	f	t	10.00	dynamic pilot
2	20050531SN	f	f	f	16.00	
3	20050601DN	t	f	f	16.00	
4	20050622SN	f	f	f	16.00	
5	20050624DN	t	f	f	16.00	
6	20050627SN	f	f	f	16.00	
7	20050704SC	f	t	f	20.00	
8	20050705DC	t	t	f	20.00	
9	20050706SC	f	t	f	20.00	
10	20050707DC	t	t	f	20.00	
11	20050715SC	f	t	f	20.00	
12	20050718DC	t	t	f	20.00	
13	20060213DC	t	t	f	40.00	40 periods
14	20060214DC	t	t	f	40.00	40 periods
15	20060215DC	t	t	f	40.00	40 periods

Table 9: Treatment Variables by Session

The data from each session were stored individually in separate subdirectories named `rawdata/(filename)`. The individual session files were combined by running `data/prepdata/prepdata` and the resulting data related to relating to subjects were stored in `data/session/sessionTable.csv`. We then ran `makeBasicDataFiles.R` to drop the practice periods and unused variables and to aggregate the data by subject within period. The resulting files were

dataBySubjectAndPeriod.csv , containing one observation for each subject in each period of each session.

dataByPeriod aggregating the data by subject within session and containing one observation for each period of each session

dataBySession.csv aggregating the data by subject and period within session and containing one observation for each session.

	Variable	Description
1	session	Session Number
2	f2	Event Sequence: 1 during experiment 2 after experiment
3	Dynamic	Is model dynamic? t yes f no
4	Communication	Is there communication? t yes f no
5	TableType	Table Type: subjects or global
6	Period	Period Number
7	Subject	Subject Number
8	Group	Group Number (always 1)
9	Profit	Current Period Profit
10	TotalProfit	Accumulated Profit
11	Participate	Not used in analysis
12	K	Carrying Capacity
13	E	Endowment of Effort
14	w	Farming Wage
15	q	Catchability Coefficient
16	r	Natural Growth Rate
17	p	Price of Fish
18	Xt	Stock of Fish, beginning of period
19	eii	Individual fishing effort, previous period
20	eji	Individual farming effort, previous period
21	ttlefforts	Aggregate Fishing Effort, previous period
22	eis	Last Fishing Effort input into calculator
23	ejs	Last estimate of others effort input into calculator
24	es	Last aggregate effort input into calculator
25	harvests	Harvest from final calculation in calculator
26	fishprofits	Fishing earnings from final calculation in calculator
27	farmingprofits	Farming earnings from final calculation in calculator
28	ttlprofits	Total earnings from final calculation in calculator
29	natgrowths	Natual Growth from final calculation in calculator
30	newstocks	New Stock from final calculation in calculator
31	CpD1	Value of Catch per Fishing Day, previous period
32	CpD2	Value of Catch per Fishing Day, final calculation in calculator
33	farming	Last Farming Effort input into calculator
34	TimeDoneCalculatorOK	Time taken to press done button on calculator screen
35	TimeCalculateCalculatorOK	Time taken in the final calculation
36	ei	Individual Fishing Effort current period
37	TimeOKEffortAllocationOK	Time taken to press ok button after entering fishing effort
38	ttleffort	Aggregate Fishing Effort, current period
39	harvest	Total fish harvested, current period
40	fishprofit	Individual fishing earnings in current period
41	farmingprofit	Individual farming earnings in current period
42	natgrowth	Natural Growth of Fish Stock, current period
43	CpD	Value of Catch per Day, next period
44	farmingEffort	Individual Farming Effort, current period
45	TimeOKResultsOK	Time taken to push the final ok button

Table 10: Variables Produced by Ztree