The Effect of Access to Clean Technology on Pollution Reduction: an Experiment*

Svetlana Pevnitskaya† and Dmitry Ryvkin
Florida State University

Preliminary and Incomplete. Comments welcome.

October 26, 2010

Abstract

We study decisions in a dynamic game where firms' private production leads to accumulation of a public bad, for example in the form of pollution. Firms have an option to invest in clean technology, which lowers emissions, or contributions to the public bad. The main treatment variable is access to clean technology, or benefits from such investment, which can be *private* or *common*. In the private access treatment, investment reduces firm's own propensity to pollute. In the common access treatment, each firm's investment reduces all firms' propensity to pollute. For each treatment we characterize two alternative solution concepts – the Markov perfect equilibrium and social optimum. The level of public bad, or pollution, is lowest with public access to clean technology. This result is preserved when the group size is doubled and also in the presence of communication. The option to communicate induces coordination of investments in clean technology, leading to lower average pollution levels in both treatments. We categorize chat messages to identify communication patterns associated with higher levels of cooperation and efficiency.

JEL classification codes: C90, C72, Q50, Q01, C61.
Keywords: dynamic games, public bad, experimental economics, environmental economics.

---

[*] We thank the participants of the 2010 ESA World meeting and FSU Experimental reading group for valuable comments. Sean Collins provided excellent research assistance with programming the experiment. This study is funded in part by the Institute for Energy Systems, Economics and Sustainability (IESES) at Florida State University.

[†] Corresponding author. Address: 288 Bellamy Building, Department of Economics, FSU, Tallahassee, FL 32306-2180, spevnitskaya@fsu.edu. Ryvkin: dryvkin@fsu.edu.

1 Introduction

Many social dilemma type problems like pollution, climate change and provision of public infrastructure are dynamic in nature. Although the majority of experimental work on social dilemmas focused on the static or repeated game environments, there is an emerging literature that focuses on dynamic problems in the context of public goods, pollution and climate change and common pool resources.[1] In this paper we contribute to this literature by exploring an environment with a dynamic public bad where agents can investment in the reduction of the public bad. In this setting, we study different institutions governing access to benefits from such investment. For example, consider a scenario where firms' private production generates emissions that accumulate over time and lead to pollution that acts as a public bad and imposes costs on all participants. Each firm can invest to improve its technology and reduce pollution propensity. We investigate how the technology sharing institution affects decision making and whether is allows the group to reach socially optimal outcome without the presence of exogenous enforcement or sanctioning mechanism. The two institutions we consider are *private access*, when the firm uses the technology it invested in exclusively, and *common* access, when the technological improvement is available to other firms. The two institutions differ by the degree of interconnectedness of subjects' decisions based on the positive effect of investment in clean technology, which may affect free-riding considerations and deviations from social optimum.

Extensive literature on experiments with a static public good (see, e.g., Ledyard 1995) indicates that observed behavior, at least initially, rarely coincides with Nash equilibrium (NE), suggesting that the free riding problem in public good games may not be strong. Results for games with an interior equilibrium, however are mixed, and contributions often come close to Nash equilibrium or even below it (see, e.g., Holt and Laury 2008). Battaglini et al. (2009) report that in a setting with a dynamic public good, public good levels approximate the Markov equilibrium in the long run, and they do not find evidence for significant voluntary cooperation. In games with a dynamic public bad without the option to reduce environmental impact, Saijo et al. (2009) report mixed results for the interior case and Pevnitskaya and Ryvkin (2010) observe lower than NE levels of the public bad, but in the case of a boundary equilibrium.

In the previous experimental studies of the dynamic public bad, curbing production was the only way to reduce pollution. Such approach is not practical since it is unlikely that economic prosperity will be compromised by agencies to reduce pollution. We

---

[1] Examples include Battaglini et al. (2009), Saijo et al. (2009), Chermak and Krause (2002), Ostrom (2006), Pevnitskaya and Ryvkin (2010).

introduce two mechanisms that provide the opportunity to invest in clean technology, possibly eliminating environmental impact of production, i.e. when production has no emissions leading to zero provision of public bad. We characterize two alternative solutions concepts, Markov perfect equilibrium and socially optimal allocations, which are in the interior range of the decision space. Such environment provides fertile ground for exploring the sustainability of institutions without external sanctions for emissions and also brings insights into behavior in games with a dynamic public bad.

We also investigate the effect of open form communication through anonymous chat. The effect of communication on cooperation in social dilemmas and other settings has been investigated by numerous authors in psychology (see, e.g., Caldwell 1976, Dawes et al. 1977, Sally 1995) and economics (see, e.g., surveys by Crawford 1998 and Brosig 2006; see also Cooper et al. 1989, 1992 for the earlier studies of communication in the battle of the sexes and coordination games). Generally, face-to-face communication has a strong positive effect on cooperation (e.g., Isaac and Walker 1988), and the effect does not go away for communication through anonymous chat interface (Bochet et al. 2006). Especially relevant to the present study are the findings of Ostrom and Walker (1991) and Hackett et al. (1994) on the positive role of communication in self-governing common pool resources.

It is still an open question, however, why and how open-ended communication facilitates cooperation in social dilemmas. Bochet et al. (2006) conjecture that the ability of subjects to formulate contingent promises and explain the game to one another is what drives the efficiency of open-ended communication, as opposed to restricted communication with only numerical messages, in their setting. Cooper and Kagel (2005) analyzed the within-teams communication of teams playing the limit-pricing entry game. By explicitly analyzing chat messages, Cooper and Kagel (2005) found that the teams that reason in game-theoretic terms, i.e., discuss strategies taking into account the behavior of others, are more successful. In the present study, we analyze chat messages to see how different environments affect communication, and what communication is associated with more successful groups in a dynamic public bad setting.

We find that the institution with *common* access to clean technology leads to higher investment, lower levels of the public bad and higher payoffs. The availability of the open-ended chat communication significantly reduces production inputs, increases investment and reduces public bad levels. The *common* access treatment with chat approaches the socially optimal outcome in the absence of external enforcement mechanisms. The *private* access mechanism without chat leads to highest levels of the public bad and lowest payoffs. The institution with common access to technology enhances subjects understanding of the game and interdependence of their decisions leading to correct comments about the game during communication in the very first period. We find almost no indication of conditional, or trigger, strategies in both mechanisms. The greater efficiency of the *common* access mechanism may be also explained by heterogeneity of subjects pro-environmental preferences and decisions. The *common* access institution allows prosocial or pro-environmental subjects manifest their preferences at the expense of own profit but for the greater "good" of lower levels of the public bad. On the other hand, the *private* access institution does not allow own investment to reduce the environmental damage imposed by other subjects who choose high production and allocate little or none to investment in clean technology.

The rest of the paper is organized as follows. Section 2 presents the model and investment mechanisms. Section 3 describes experimental design and research questions. We present results in Section 4. Section 5 concludes.

2 The model

There are n identical risk-neutral players. In each period $t = 1, 2, ...,$ each player i receives endowment $m > 0$ and allocates it between three options: production input (x_{it}), investment in clean technology (r_{it}) and amount kept ($m - x_{it} - r_{it}$). Thus, player i's decision in period t is an allocation (x_{it}, r_{it}) satisfying $x_{it} \geq 0$, $r_{it} \geq 0$, $x_{it} + r_{it} \leq m$.

Production input x_{it} generates production revenue ax_{it}, $a > 1$, for player i. All players' production contributes to a public bad. Player i's contribution to the public bad in period t is $q_{it}x_{it}$, where $q_{it} \geq 0$ characterizes player i's technology in period t in terms if its (negative) environmental impact, in other words, it is i's emission propensity. Since the focus of this paper is investment in clean technology and the production effectiveness a remains constant, we will refer by *technology* to the environmental impact factor q_{it}. In the next two subsections we describe two approaches to modeling the benefits of investment in clean technology, i.e. investment that reduces q_{it}.

The level of the public bad in the end of period t, Y_t, is based on the depreciated level of the public bad in the end of the previous period and contributions in the current period

$$Y_t = \gamma Y_{t-1} + \sum_{i=1}^{n} q_{it}x_{it}; \qquad Y_0 = 0. \tag{1}$$

where, $\gamma \in [0, 1]$ is the public bad retention rate.

The payoff of player i in period t includes revenue from production and the cost of the public bad

$$\pi_{it} = m - x_{it} - r_{it} + ax_{it} - b\gamma Y_{t-1}, \tag{2}$$

where $b > 0$ is the unit cost of the public bad.

At the end of each period, the next period happens with probability $\beta \in (0, 1)$. Player i's total payoff in the game is her cumulative payoff at the moment of termination. Thus, in any period t, player i's expected future payoff that the player is maximizing is

$$V_{it} = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \pi_{i\tau}. \tag{3}$$

In the following two sections, we describe two types of investment in clean technology. We assume that all players start with the same level of technology, $\bar{q}$. In the *private* investment case, the person making the investment reduces the environmental impact of his own production only. In the *common* investment case, each player's investment in clean technology reduces negative environmental impact of all players in the group.

2.1 Private investment

In the *private* treatment, player i's technology factor in period t is affected by her own investment only, specifically

$$q_{it} = \max\{0, \bar{q} - \alpha r_{it}\}.$$

Here, $\bar{q} > 0$ is the default technology, and $\alpha > 0$ is the investment efficiency. The resulting technology factor, q_{it}, cannot be negative, therefore, the values of impact reduction $r_{it} > \bar{q}/\alpha$ lead to a waste of resources and are strictly dominated by $r_{it} = \bar{q}/\alpha$.

The dynamic game defined above has multiple equilibria. For our analysis, we restrict attention to two solution concepts. The first is symmetric Markov Perfect equilibria (MPNE), in which strategies can only be conditioned on the state of the game in the current period but not on the prior actions of players. The result is a stationary problem descibed in proposition 2 in Appendix A which has a solution. For any given set of parameter values, solving problem (4) is straightforward and we present below the solution to the problem for our class of parameters.

The second solution concept we apply is the utilitarian social optimum defined as the profile of allocations that maximizes the total expected payoff of the group. One of our research questions is investigating which solution concept is more successful in explaining observed behavior. Proposition 3 describing the socially optimal outcome (SO) is presented in Appendix A.

2.2 Common investment

In the *common* treatment, each player's technology factor is affected by investment decisions of all players. Specifically, the technology factor of all players in period t is the same and equal to

$$q_{it} = q_t = \max\{0, \bar{q} - \rho \sum_j r_{jt}\}.$$

Here, as before, $\bar{q} > 0$ is the default technology, $\rho > 0$ is the investment efficiency. The resulting factor cannot be negative, therefore, all combinations of investment allocations such that $\sum_j r_{jt} > \bar{q}/\rho$ are strictly dominated.

Restricting attention to symmetric Markov Perfect equilibria (MPNE) and Social Optimum (SO), we arrive at propositions 4 and 5 that are presented in Appendix A. Similarly to the case of *private* investment in each case each optimization reduces to to a static problem that has a straightforward solution.

2.3 Conditions on parameters of the model

In the experiment, we choose the investment efficiency parameters so that the socially optimal allocations under private and common access are in the interior range. For the experimental design we also impose an additional constraint described in Proposition 1.

Proposition 1 *If $\alpha = n\rho$ then*

(i) the SO allocations in the games with private and common investment coincide;

(ii) the MPNE allocations in these games also coincide.

The proof of Proposition 1 is straightforward. Both parts follow directly from the equivalence, for $\alpha = n\rho$, of the optimization problems obtained in Propositions 2 and 4, and in Propositions 3 and 5. Part (i) is quite intuitive.

For our class of parameters, the calculations of MPNE and SO allocations, $(r^*, m - r^*)$ and $(r^{SO}, m - r^{SO})$, follow directly from reduced problems described in Propositions 2 - 5 and are presented in the experimental design section for our parameter values. It is straightforward that $r^{SO} > r^*$and $x^{SO} < x^*$. We use MPNE and SO predictions as benchmarks to evaluate the consistency of the predictions of these solution concepts with observed behavior.

	n=2	n=4	n=4, Chat
	$\bar{q} = 1$	$\bar{q} = 0.8$	$\bar{q} = 0.8$
Private Investment, $\alpha = .2$	2 (44)	3 (52)	2 (36)
Common Investment, $\rho = \{.1, .05\}$	2 (36)	3 (48)	2 (40)
Nash equilibrium, (x_t^*, r_t^*)	(7.54, 2.46)	(8.04, 1.96)	(8.04,1.96)
Social Optimum, (x_t^{SO}, r_t^{SO})	(5.02, 4.98)	(6.00, 4.00)	(6.00, 4.00)
No Investment option	2 (44)	2 (44)	

Table 1: Experimental design and theoretical predictions for decision variables, by treatment.

3 Experimental Design

3.1 Experimental design and research questions

Our main treatment variable is the type of access to investment in clean technology. We also investigate the predictions of two solution concepts (MPNE and SO) and the effect of communication. The experimental design as well as Nash equilibrium and socially optimal allocations in each treatment are summarized in Table 1.

We start with the two-person group size that allows us to have many independent observations per treatment and minimize the complexity of coordination. We then double the group size to $n = 4$ and test, in addition to the main treatment effect, for the effect of communication. The other parameters of the model are as follows: $m = 10$, $a = 5$, $b = 1$, $\gamma = 0.75$. The continuation probability $\beta = 0.95$. In the experiment, a random number between 1 and 20 was drawn after each round and shown to subjects. Subjects were informed that if any number between 2 and 20 comes up, there will be next round, while if number 1 comes up the experiment stops. Four random sequences were pre-drawn and used in our sessions. The minimal number of time periods in the four sequences was 18, so for consistency we use the first 18 rounds of data for analysis.[2] The corresponding MPNE and SO allocations for our set of parameters are presented in Table 1. We also use data from sessions without the option to invest and confirm that, as predicted by both solution concepts, the availability of investment option is utilized by subjects, reducing public bad and increasing the payoffs.

In our analysis that follows we use four main variables to address our research questions: two decision variables - investment in clean technology, r_{it} and production inputs, x_{it}; and two level variables - the size of the public bad, Y_t, and cumulative payoffs, Π_{it}.

---

[2] In one session with chat there were only 17 periods. We therefore use data from 17 periods for chat analysis.

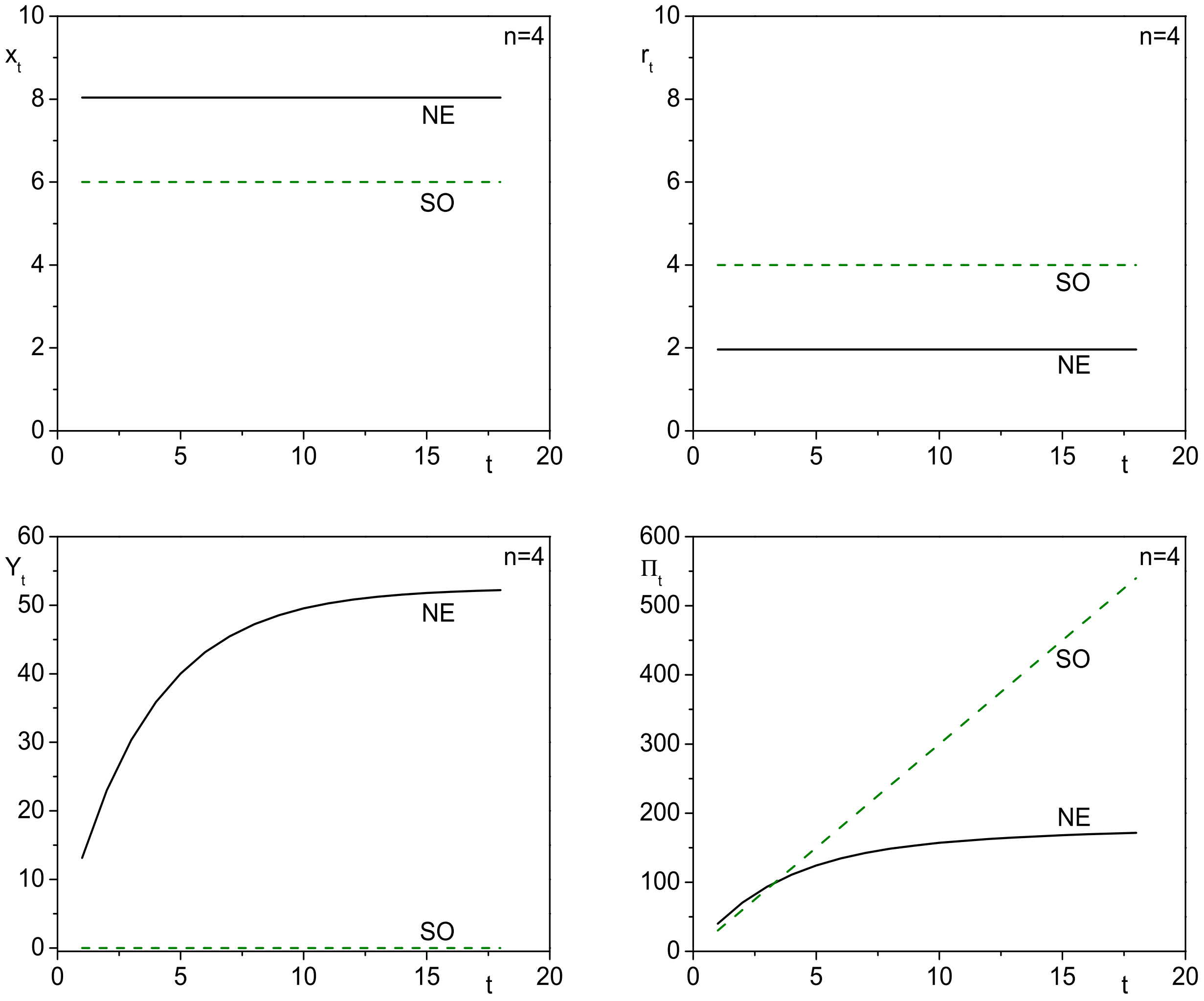

Figure 1: Nash equilibrium (NE) and socially optimal (SO) predictions for production inputs (left), pollution (center) and payoffs (right), by period for each treatment.

Figure 1 illustrates the MPNE and SO predictions for the dynamics of each of these variables. The NE and SO paths serve as alternative hypotheses for our first research question.

Question 1. To what extent is the observed behavior consistent with either of the two benchmark solution concepts, MPNE and SO?

Extensive literature on experiments with a static public good (see, e.g., Ledyard 1995) indicates that observed behavior, at least initially, rarely coincides with NE, suggesting that the free riding problem in public good games may not be strong. Results for games with an interior equilibrium, however are mixed, and contributions often come close to Nash equilibrium or even below it (see, e.g., Holt and Laury 2008). Battaglini et al. (2009) report that in a setting with a dynamic public good, public good levels approximate the Markov equilibrium in the long run and they do not find evidence for significant voluntary cooperation. In games with a dynamic public bad without the option to reduce environmental impact, Saijo et al. (2009) report mixed results for the interior case and Pevnitskaya and Ryvkin (2010) observe lower than NE levels of the public bad, but in a case of the boundary equilibrium. Our design explores the mechanism with a dynamic public bad that allows to reduce the contributions to the public bad, so the investment decision has the "public good" affect on the group.

Our main treatment variable, common or private investment, explores whether this variation in the mechanism affects subjects decisions and leads to the more efficient outcome that approaches the socially optimal allocation. Note that, as shown in the previous section, both the NE and SO allocations between the two treatments coincide, so any changes in subjects' behavior would be consistent with subjects switching towards an alternative solutions concept, or some other behavioral considerations.

Question 2. Are investment decisions affected by institutions, i.e. the type of investment provided by the mechanism?

The null hypothesis, based on theory and a given solution concept, is no change of behavior. Intuitively, the common investment treatment may trigger the desire to free ride on the investment decisions by other group members; therefore reducing own investment level and increasing own production. This would be consistent with the direct free riding incentives in the absence of the investment option, where MPNE is full production, $x_{it} = m$. At the same time, increased interconnectedness of subjects' decisions through the (negative) effect of public bad and also the (positive) affect of investment in the *common* treatment may lead to subjects viewing the decision problem from a perspective of social optimization, thus leading to greater investment and lower levels of the public bad.

Question 3. What is the effect of communication on investment decisions and the level of public bad?

Our hypothesis is that communication leads to higher investment, lower levels of public bad and greater payoffs. As shown in previous experimental studies (see, e.g., Bochet et al. 2006), open-ended communication improves subjects' understanding of the problem. Given the complexity of this dynamic problem, better understanding should in the very least result in reduced levels of the dominated "keep" option. Communication may allow subjects to form some group association and coordinate on lower levels of the public bad via increased investment, which is more consistent with SO allocation. We are also interested in a detailed analysis of open form chat.

3.2 Procedures

All sessions took place in the XS/FS laboratory at Florida State University. Decisions were made via computer interface using z-Tree (Fischbacher 2007). Subjects were volunteers from the population of undergraduate students at FSU recruited through the online announcement system ORSEE (Greiner 2004). Each subject participated in the experiment only once. Subjects were randomly assigned to groups and remained in the same group for the entire sequence of decisions. Subjects were unaware of the identities of other group members. Experimental instructions were read out loud, with a paper copy distributed to subjects to follow. After the instructions, subjects were guided through a sample round of decisions to become familiar with the interface, and then filled out a paper-based questionnaire to make sure they understood how the game works. The experimenters checked each subject's questionnaire individually.[3] In the treatment with *chat*, at the beginning of each period subjects had an active chat window in the lower part of their decision screen[4] where they could type and/or view chat messages from all members of their group. Each subject was identified in the chat interface by a unique letter (P, R, S, or T), and could send any number of messages during the time allotted. Messages appeared in the chat window visible to all subjects in the order they were sent. After every round the results screen reported back to subjects (combined) allocation decisions of other group member(s), contributions to the public bad, updated level of the public bad and their own payoffs. Instructions are presented in Appendix B. Each session lasted about 100 minutes, with subjects earning about \$20 on average, including a \$10 show-up fee.

4 Results

4.1 Summary statstics

In this section we present the experimental results at the aggregate level for four key variables: two decision variables – production input (x_t) and investment in clean technology (r_t), and two outcome variables – the level of the public bad (Y_t) and payoffs (Π_t).

---

[3] We used extra care not to steer subjects towards any particular decision. During practice with the interface, subjects made their own choices and did not interact with each other. The practice results screen replaced all numbers, except own choices, by "xx" to minimize any learning during practice. At the questionnaire stage, subjects also made their own choices and then performed calculations with those. Experimenters only checked that the calculations are consistent with choices.

[4] Otherwise the decision screen was identical to the treatment with no chat option. The chat window would remain active even if a subject were to make a decision prior to the end of a one minute period insuring that all subjects view all group communications.

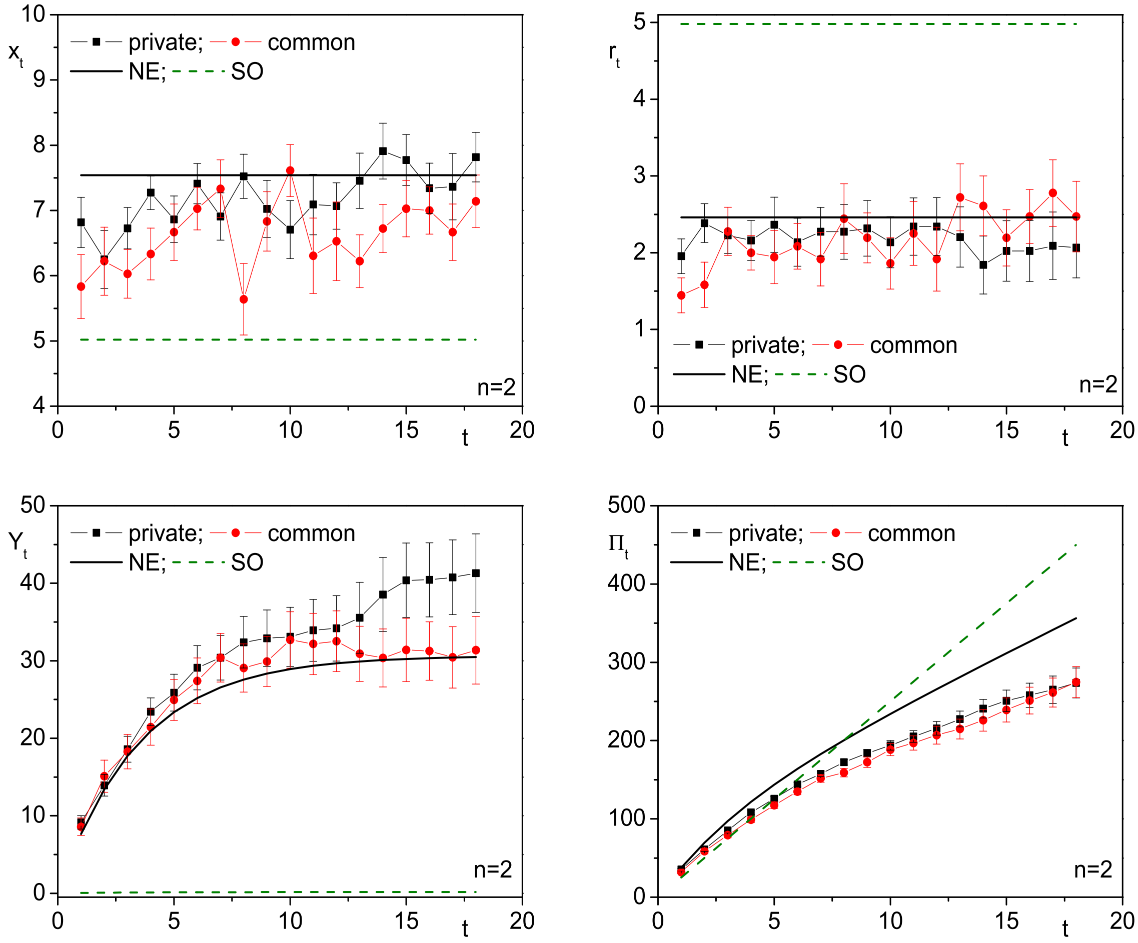

Figure 2: Average production input (x_t), investment (r_t), public bad (Y_t), and payoffs (Π_t) in the private and common access treatments for group size $n = 2$. The error bars show standard errors of the averages clustered at the group level. Theoretical predictions are shown with the solid (NE) and dashed (SO) lines.

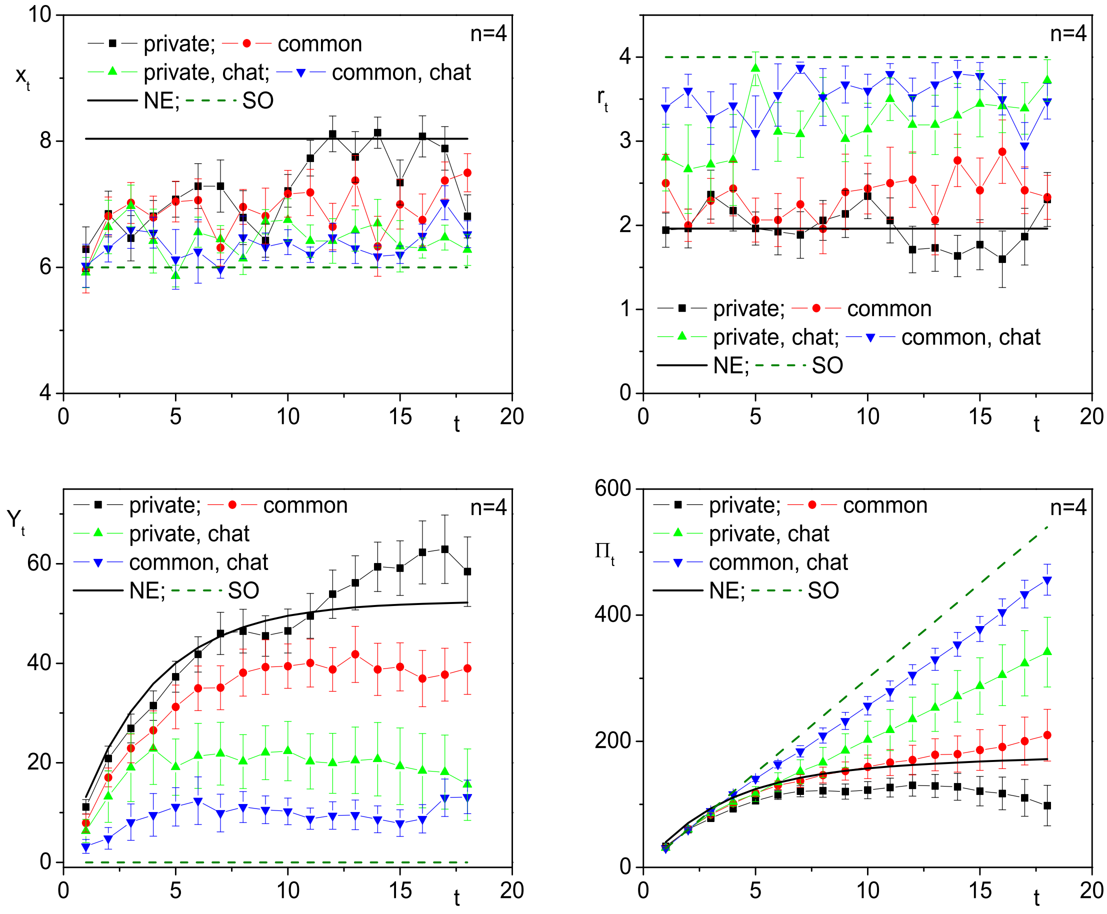

Figure 3: Average production input (x_t), investment (r_t), public bad (Y_t), and payoffs (Π_t) in the (private, common)×(no chat, chat) treatments for group size $n = 4$. The error bars show standard errors of the averages clustered at the group level. Theoretical predictions are shown with the solid (NE) and dashed (SO) lines.

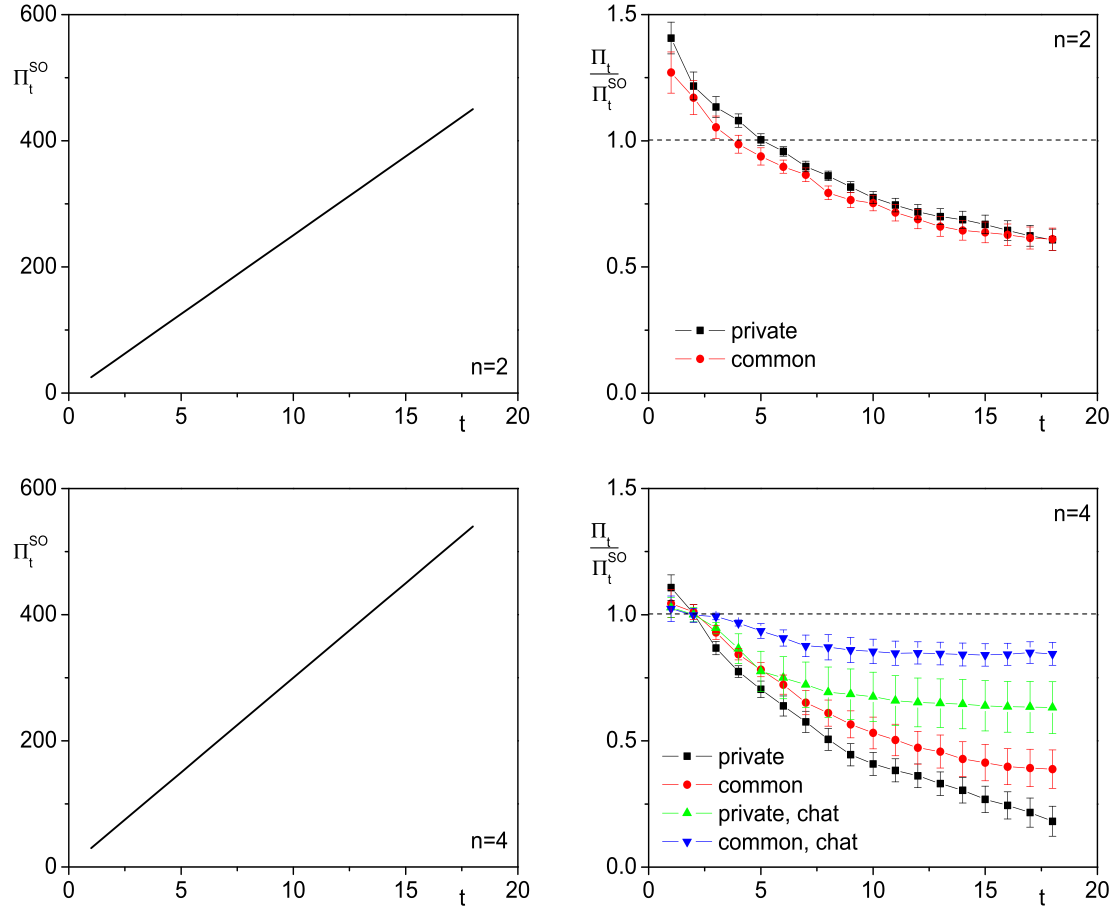

Figure 4: The socially optimal payoff (left) and the ratio of observed to SO payoff (right) by treatment for $n = 2$ and $n = 4$.

Figure 2 shows the time dependence of each of the variables averaged across subjects by treatment for the treatments with group size $n = 2$. Similarly, Figure 3 shows the time dependence of the average of each variable in the treatments with group size $n = 4$.[5] The figures also show theoretical predictions (the SO and NE values of the variables). Recall that the parameters are chosen such that the SO and NE decisions and outcomes are the same across treatments for each group size.

As seen from Figure 2, for $n = 2$, decisions for the production input and investment, x_t and r_t, are significantly different from the SO allocations in both *common* and *private* treatments. Although the standard errors are too high to make a conclusive period-by-period comparison of production inputs between treatments, the hypothesis that production input, x_t, is equal to the NE level cannot be rejected in about half of time periods in the *private* treatment, whereas in the *common* access treatment production input is lower than the NE level in almost all periods. The production input in *common* treatment generally lower than in the *private* treatment, however the difference is significant only in six periods. Investment allocations, r_t, are not statistically different from the NE level in both treatments. It is worth noting, however, that in the *common* access treatment, production inputs are consistently lower and investment higher in later rounds, which leads to the significant differences in the levels of the public bad, Y_t, in later periods. The reason is that the public bad accumulates over time and small period-by-period differences in decisions can accumulate into large long-run differences in the amount of the public bad. The level of public bad almost exactly follows the NE prediction in the *common* treatment and remains at the steady level after period 6. In the *private* treatment, the level of public bad exceeds NE. Payoffs, Π_t, are not distinguishable between treatments even in the long run. The reason is that the loss from the lower earnings due to reduced production inputs is compensated by the gain from having lower costs of the public bad. We conclude that, the common access treatment is better for the "society as a whole" as it leads to lower levels of the public bad without compromising the economic growth.

Result 1 *For $n = 2$:*

(i) the symmetric MPNE predicts behavior reasonably well in the private treatment. In the common treatment, production inputs are lower than MPNE levels in most periods;

(ii) common access mechanism leads to lower long-run levels of the public bad than the private access, while maintaining the same level of long-run payoffs.

---

[5] Figures 2 and 3 also show the error bars corresponding to the estimated standard error of the corresponding average in each time period, with clustering at the group level. Given the between-subjects nature of the design, the error bars provide a way to run a conservative "eye" t-test for equality of the average values in each time period.

As seen from Figure 3, when we double the group size to $n = 4$, the difference between treatments becomes more substantial. In the *private* access treatment without chat, production inputs are below NE in the first half of the session but reach the NE level in the second half. Investment levels are close to NE levels in most time periods and even fall below NE in later periods. It appears that in the *private* treatment subjects tend to "keep" part of their endowment. *Private* treatment without chat leads to the highest level of the public bad across all treatments. Production inputs in the *common* investment treatment without chat are significantly lower than NE in all periods but remain higher than SO levels in most periods. Investments are significantly lower than SO in all periods and significantly higher than NE in a few later periods.

The decisions in both treatments with chat are closer to SO than decisions in treatments without chat. While production inputs are not distinguishable between the *common* and *private* treatments, the investment levels are higher in *common* investment treatment with chat in most periods. The difference in investment decisions leads to significant differences in outcome variables; therefore we investigate the investment decisions in detail in the next section. Again, we conclude that in the *common* access treatment with chat subjects "keep" less than in the *private* access treatment with chat.

Differences in decisions translate into even larger differences in the accumulating variables – public bad, Y_t, and payoffs, Π_t. There is a clear ranking of the four treatments in terms of efficiency, with *common* with chat approaching the SO outcome, followed by *private* with chat, then by *common* without chat, and by *private* without chat. Payoffs in all treatments except private without chat are upward sloping over time. Thus, chat improves efficiency for both types of access, and common access is still superior to private.

Result 2 *For $n = 4$:*

(i) the symmetric NE predicts behavior reasonably well only in the private treatment without chat. In the treatments with chat, both the production and investment decisions are closer to SO than NE allocations;

(ii) common access leads to more efficient outcomes than private access and chat leads to more efficient outcomes than no chat. Moreover, private access with chat generates greater efficiency than common access without chat.

Figure 4 shows the average *efficiency* defined as the ratio of observed average payoffs to SO payoffs, for $n = 2$ and $n = 4$,. This definition of efficiency does not take into account the outside effect of the public. As expected, there is no difference between treatments for $n = 2$, while the four treatments are clearly ranked for $n = 4$. Efficiency starts above one in both cases, due to the short-run gains from overproduction. It falls below one

$n = 4$	Input	Investment	Keep	Public Bad
Common	-0.346	0.383	-0.037	-11.714**
	(0.219)	(0.232)	(0.205)	(5.199)
Chat	-0.801***	1.248***	-0.448**	-26.345***
	(0.212)	(0.273)	(0.170)	(6.257)
Common×Chat	0.263	-0.070	-0.193	2.208
	(0.284)	(0.345)	(0.236)	(7.772)
Constant	7.283***	2.155***	0.563***	50.796***
	(0.214)	(0.221)	(0.156)	(4.631)
Observations	3,168	3,168	3,168	3,168
Groups	44	44	44	44
R^2	0.043	0.122	0.065	0.490

Group-level robust standard errors in parentheses.
Significance levels: ***–$p < 0.01$, **–$p < 0.05$, *–$p < 0.1$.
Time dummies are included in the regressions.

Table 2: Regression results for production input, investment in clean technology, amount kept, and the level of the public bad, $n = 4$ (coefficients on period dummies are not reported).

relatively quickly, however. For $n = 2$, it is still above 0.5 by period 18 but maintains a downward slope. For $n = 4$ without chat efficiency falls below 0.5, although it stabilizes for the *common* treatment. In the treatments with chat efficiency is much higher and stabilizes well above 0.5.

4.2 The effect of investment type and communication

This section presents more detailed results of the combined effects of the type of investment and communication. We therefore restrict our attention to data from $n = 4$ sessions. We compare subjects' behavior between treatments using three types of regressions. The first type of regressions captures the difference between average levels of the variables across treatments. Here, we regress a variable of interest on period dummies and the dummy variables representing treatments: *Common* (=1 for common access to investment in clean technology and 0 other wise), *Chat* (=1 if chat is allowed and 0 otherwise), and interaction $Common \times Chat$. The results of these regressions for production input, investment in clean technology, amount kept, and the level of the public bad are presented in Table 2. Period dummies are used as a way to control, in the most general way, for non-individual-specific temporal variations in the variables and are not reported in Table 2. Standard errors are clustered at the group level.

$n = 4$	Group Investment
GroupInvLag	0.598***
	(0.061)
GroupInvLag×Common	-0.366***
	(0.131)
GroupInvLag×Chat	-0.037
	(0.105)
GroupInvLag×Common×Chat	-0.017
	(0.178)
Common	3.969***
	(1.299)
Chat	2.597**
	(1.280)
Common×Chat	1.854
	(2.177)
Constant	3.222***
	(0.414)
Observations	2,992
Groups	44
R^2	0.429

Group-level robust standard errors in parentheses.
Significance levels: ***–$p < 0.01$, **–$p < 0.05$, *–$p < 0.1$.

Table 3: Regression results for group investment in clean technology, $n = 4$.

As seen from Table 2, the coefficient estimate on *Chat* is statistically significant for all variables. The coefficients on *Common* have the correct sign for all categories but it is statistically significant only for the public bad level. The presence of chat leads to lower production inputs, higher investment in clean technology, lower amount kept and lower levels of the public bad. The presence of common access to clean technology investment leads to lower public bad levels.

In the following two regressions we focus on the impact of treatments on the dynamics of investment in clean technology. Table 3 reports the results of a regression of group investment on its own lag, treatment dummies, and the interactions of the lagged group investment with treatment dummies.[6]

As seen from Table 3, both treatment variables, common access and chat, have significant affect on investment. The positive and significant coefficients on *Common* and

---

[6] The lagged group investment captures the persistence, or learning, effects, while the interactions allow for differences in learning across treatments.

Chat dummies show that group investment is higher in the presence of chat and in the presence of common access, as compared to the treatment with private access and no chat. Lagged group investment is positive and statistically significant, pointing at strong persistence in group investment. The negative and significant coefficient on the interaction of lagged investment with *Common* dummy shows that in the presence of common access to investment the persistence is suppressed. Thus, groups adjust their investment more rapidly from one period to the next as compared to the private access treatment.

Table 4 reports the regression results for individual investment in clean technology. As explanatory variables, we use own lagged investment, the combined lagged investment of other group members, and the interactions of these variables with treatment dummies. As seen from Table 4, there are strong positive effects of chat and common access on individual investments, in line with the results for group investments in Table 4. Subjects react positively to the lagged investment of others in treatments with private access to investment. In treatments with common access, however, this reaction disappears, as manifested by the negative coefficient on the interaction $InvOthersLag \times Common$, which cancels the positive coefficient on $InvOthersLag$. Chat appears to reduce persistence in own investment, as compared to treatments without chat, but the effect is only marginally significant.

The following results summarize our findings.

Result 3 *Common access leads to higher investment in clean technology, both at the individual and group level, and faster adjustment in group investment. There is no statistically significant response of individual investment to investment of others in the common access treatment, while such response is positive in treatment with private access.*

Result 4 *Chat leads to higher investment in clean technology, both at the individual and group level.*

4.3 Detailed chat analysis

In this section, we present the analysis of chat messages subjects sent during the experiment. Chat was only present in the Private and Common treatments with $n = 4$. For comparability across treatments, we restrict our sample for the purposes of chat analysis to 17 time periods, which is the lowest number of periods among the 8 sessions/4 treatments with $n = 4$.

We coded chat each message with 5 attributes:

(i) *Code* is the main attribute describing message category. We use nine mutually exclusive categories: miscellaneous/neutral chat (1), instructions/rules chat (2), discus-

$n = 4$	Individual Investment
InvLag	0.294***
	(0.043)
InvOthersLag	0.101***
	(0.018)
InvLag×Common	0.034
	(0.071)
InvOthersLag×Common	-0.133***
	(0.029)
InvLag×Chat	-0.117*
	(0.070)
InvOthersLag×Chat	0.027
	(0.028)
InvLag×Common×Chat	0.041
	(0.110)
InvOthersLag×Common×Chat	-0.019
	(0.048)
Common	0.992***
	(0.251)
Chat	0.649***
	(0.242)
Common×Chat	0.464
	(0.457)
Constant	0.806***
	(0.121)
Observations	2,992
Individuals	176
R^2	0.225

Individual-level robust standard errors in parentheses.
Significance levels: ***–$p < 0.01$, **–$p < 0.05$, *–$p < 0.1$.

Table 4: Regression results for individual investment in clean technology, $n = 4$.

Treatment, $n = 4$	Total msg.	Correct msg.	Incorrect msg.
Private	146.3	32.4	8.1
	(15.0)	(7.5)	(4.1)
Common	144.8	52.2	2.5
	(21.6)	(12.9)	(0.7)
Total	145.5	42.8	5.2
	(13.1)	(7.8)	(2.0)

Table 5: Average number of messages per group in treatments with chat, $n = 4$. Group standard errors in parentheses. Based on 9 groups with private access and 10 groups with common access to clean technology investment.

sion of allocation strategy/conditional (on behavior of others) (3), discussion of allocation strategy/unconditional (on behavior of others) (4), numerical proposal of allocation strategy/conditional (5), numerical proposal of allocation strategy/unconditional (6), general statements about strategy or outcomes (7), discussion of experiment in general (8), discussion of other group members or group as a whole (9). Examples of messages in each category are provided in the Appendix.

(ii) *Correct* is the attribute equal one if the message is correct (w.r.t. the game), 0 if it is incorrect, and 2 in all other cases.

(iii) *Level* is the attribute dealing with messages proposing or discussing numerical allocation strategies. It changes from 0 to 4 depending on the discussed amount of investment in clean technology.

(iv) *Time* is the attribute equal 0 if the message refers to the present, 1 if it refers to the past, 2 if it refers to the future, and 3 if the time reference of the message is undefined.

(v) *Positive* attribute is 1 for positive messages, 0 for negative messages, and 2 for neutral messages.

Table 5 reports the average total number of messages, and the average number of correct and incorrect messages per group in the treatments with chat. There is no difference in the total number of messages between treatments. There are, however, significantly more correct and fewer incorrect messages in the treatment with common access ($p < 0.01$).[7]

Result 5 *There is no difference in the total number of messages between the private and common access treatments. There are significantly more correct and fewer incorrect messages in the treatment with common access.*

---

[7] This and further results in this section are obtained by regressing the average number of corresponding messages per group on the *Common* treatment dummy. The reported p-value is the for the coefficient estimate on the *Common* dummy in these regressions.

	Non-numerical proposal	Numerical proposal		
Treatment, $n = 4$	Total	Total	Correct	Incorrect
Private	17.6	40.8	32.1	7.9
	(5.1)	(11.4)	(7.5)	(4.1)
Common	11.1	54.6	50.9	2.0
	(1.3)	(13.0)	(12.5)	(0.6)
Total	14.2	48.1	42.0	4.8
	(2.6)	(8.6)	(7.6)	(2.0)

Table 6: Average number of messages per group by category in treatments with chat, $n = 4$: non-numerical proposal of allocation strategy, unconditional (code 4) and numerical proposal of allocation strategy, unconditional (code 6). Group standard errors in parentheses. Based on 9 groups with private access and 10 groups with common access to clean technology investment.

In most cases, allocation strategies are discussed in an unconditional fashion. There is only one instance of a non-numerical conditional allocation strategy message (code 3) and 5 instances of a numerical conditional allocation strategy message (code 5), and all of them occur in the treatment with common access.

Table 6 reports the average number of messages per group in the non-numerical (code 4) and numerical (code 6) unconditional allocation strategy categories. Code 6 messages are additionally divided into total, correct and incorrect. Code 4 messages are not divided in this fashion because with the exception of 2 messages all of them fall into the neither correct nor incorrect category.

There are significantly fewer code 4 messages, and significantly more code 6 messages, in the treatment with common access ($p < 0.01$). Additionally, there are more correct and fewer incorrect code 6 messages in the treatment with common access ($p < 0.01$).

Result 6 *There are fewer messages involving non-numerical discussion of allocation strategies, and more messages involving numerical discussion of allocation strategies, in the treatment with common access to clean technology investment. Also, there are more correct and fewer incorrect messages involving numerical discussion in the treatment with common access.*

We next look at the number of positive and negative messages by treatment. Table 7 reports the average number of positive and negative messages per group. As seen from the table, there are more negative messages, as compared to positive, in both treatments. We find no difference in the numbers of positive and negative messages between treatments, however.

Treatment, $n = 4$	Positive msg.	Negative msg.
Private	2.44	8.44
	(1.41)	(3.35)
Common	2.40	9.10
	(0.60)	(2.64)
Total	2.42	8.79
	(0.71)	(2.05)

Table 7: Average number of messages per group by category in treatments with chat, $n = 4$. Group standard errors in parentheses. Based on 9 groups with private access and 10 groups with common access to clean technology investment.

Result 7 *There is no difference in the number of positive and negative messages between treatments. In both treatments, there are more negative than positive messages.*

For each group, we identify the time period in which the first correct statement was made in the chat. Interestingly, in all groups in the two sessions of the *common* access treatment the first correct statement was made in the very first period. This is in contrast with the *private* access treatment where the first correct statement was made, on average, in period 2.0, with standard deviation across groups 0.41. The same is true regarding the first correct numerical statements. First round communication depends only on subjects initial thinking and understanding of the game, it is not affected by decisions. The significant difference in the first round chat, particularly with respect to correct statements about the game or strategy proposal suggests that stronger interconnectedness promotes better understanding of the mechanism and, as described earlier, leads to closer to SO outcomes.

5 Discussion and conclusions

We conducted an experimental study of behavior in an environment with a dynamic public bad where players have an opportunity to invest in reducing the effect of private production to the public bad. Compared to previous studies, this setting allows reducing or eliminating public bad while maintaining production. Such institution is relevant for policy analysis since it may be not practical to reduce or eliminate economic growth for the sake of pollution reduction. We analyzed two basic institutions governing investment in clean technology. One is investment with *private access*, where each player's investment reduces only that player's rate of public bad generation. The other institution is investment with *common access*, where each player's investment reduces all players' public bad generation rates.

For comparability, we chose parameters so that the social optima in the two treatments coincide. Interestingly, the Markov perfect equilibrium behaviors in this case coincide as well, implying that there is no additional free-riding coming from the public-good aspect of clean technology investment in our common access treatment. Thus, differences in behavior between treatments are due to behavioral considerations.

In addition to manipulating the institution of access to clean technology investment, we studied the effect of unrestricted chat communication. The possibility of non-binding communication is an important feature of international relations and negotiations between agents in other situations where centralized enforcement is not feasible. It is well-known from prior research on the voluntary contribution mechanism and collective management of common pool resources that communication facilitates cooperation. It is also known that in complex competitive games between groups within-group communication enables subjects to play more strategically and understand the environment better. Our goal, apart from the obvious question of whether or not communication increases efficiency, was to explore the interaction between communication and institutions and, by analyzing chat messages, to identify what features of communication are associated with more successful outcomes.

We find that common access to clean technology is more efficient than private access. In groups of two players, the level of public bad is lower in treatment with common access, although we do not observe a significant difference in decisions. The significant difference in outcomes is likely driven by the accumulating nature of the public bad and the differentiated effect of heterogeneity in decisions across institutions. For groups of four players, the result is even more pronounced and the difference between mechanisms is significant already at the level of decisions.

We find, in line with the results of previous studies, that chat improves cooperation. The difference between institutions is preserved under chat. By analyzing chat messages, we find that in the common access treatment subjects make correct statements in the very first round of the game (before any decisions) in all groups, whereas in the private access treatment correct statements arise, on average, in round 2. The reason might be that the feeling of additional interdependence and shared responsibility in the common access treatments makes subjects think more as a group.

Surprisingly, we found almost no conditional promises. Thus, subjects practically do not reason (or at least do not to show that they do) in the "trigger" terms. Most of chat messages are discussions of how the game works and explicit suggestions of allocations. This suggests that the improved efficiency in the presence of chat is mainly due subjects being able to explain the game to one another and convince each other that the socially optimal strategy is "the best," and not so much due to the ability to formulate complex strategies that may sustain social optimum as equilibrium.

Our results have implications for policies governing access to the outcomes of environmental R&D that leads to creation of technologies reducing a public bad. Opening access to such technologies, as our results suggest, would lead to more engagement, higher investment, lower pollution levels and higher efficiency. This can be implemented at the international level, for example, by governments sharing the results of government-sponsored R&D taking place in their countries. At the local level, common pool resource users can form a club requiring members to share the results of their private pollution reduction R&D with other club members.

References

Battaglini, M., Nunnari, S. and T. R. Palfrey (2009). Political institutions and the dynamics of public investment. Working Paper.

Brosig, J. (2006). Communication Channels and Induced Behavior. Unpublished manuscript, University of Magdeburg.

Bochet, O., Page, T., Putterman, L. (2006). Communication and punishment in voluntary contribution experiments. Journal of Economic Behavior and Organization, 60, 11-26.

Caldwell, M. D. (1976). Communication and sex effects in a five-person prisoner's dilemma game, Journal of Personality and Social Psychology 33, 273-280.

Chermak, J. M. and Krause, K. (2002). Individual Response, information, and intergenerational common pool problems. Journal of Environmental Economics and Management, 43, 47-70.

Cooper, D.J., Kagel, J.H. (2005). Are two heads better than one? Team versus individual play in signaling games. American Economic review, 95, 477-509.

Cooper, R., D. V. DeJong, R. Forsythe, T. W. Roth (1989). Communication in the battle of the sexes game: some experimental results, RAND Journal of Economics 20, 568-587.

Cooper, R., D. V. DeJong, R. Forsythe, T. W. Roth (1992). Communication in coordination games, Quarterly Journal of Economics 107, 739-771.

Crawford, V. (1998). A survey of experiments on communication via cheap talk, Journal of Economic Theory 78, 286-298.

Dawes, R. M., J. McTavish, H. Shaklee (1977). Behavior, communication, and assumptions about other people's behavior in a commons dilemma situation, Journal of Personality and Social Psychology 35, 1-11.

Fischbacher, U. (2007). z-Tree: Zurich Toolbox for Ready-made Economic Experiments. Experimental Economics, 10, 171-178.

Greiner, B. (2004). An Online Recruitment System for Economic Experiments. In: Kurt Kremer, Volker Macho (Eds.): Forschung und wissenschaftliches Rechnen 2003. GWDG Bericht 63, Göttingen : Ges. für Wiss. Datenverarbeitung, 79-93.

Isaac, R.M.,Walker, J.M. (1988). Communication and free-riding behavior: the voluntary contributions mechanism. Economic Inquiry 26, 585–608.

Hackett, S., E. Schlager, J. M. Walker (1994). The role of communication in resolving commons dilemmas: experimental evidence with heterogeneous appropriators, Journal of Environmental Economics and Management 27, 99-126.

Holt, C., S. Laury (2008). Voluntary Provision of Public Goods: Experimental Results with Interior Nash Equilibria. In Handbook of Experimental Economics Results, C. Plott and V. Smith eds. North Holland: Amsterdam.

Ledyard, J. O. (1995). Public Goods: A Survey of Experimental Research. In Handbook of Experimental Economics, J.H. Kagel and A. Roth eds., Princeton University Press.

Ostrom, E. (2006). The value-added of laboratory experiments for the study of institutions and common-pool resources. Journal of Economic Behavior and Organization, 61, 149-163.

Ostrom, E., J. M. Walker (1991). Communication in a commons: cooperation without external enforcement, in: T. Palfrey (ed.): Laboratory research in political economy, University of Michigan Press, Ann Arbor, 287-322.

Pevnitskaya, S., D. Ryvkin (2010). Behavior in a Dynamic Environment with Costs of Climate Change and Heterogeneous Technologies: an Experiment. Research in Experimental Economics, vol. 14, Eds. Mark Isaac and Douglas Norton, Emerald Press (forthcoming)

Sally, D. (1995): Conversation and cooperation in social dilemmas. A meta-analysis of experiments from 1958 to 1992, Rationality and Society 7, 58-92.

Saijo, T., Sherstyuk, K., Tarui, N., Ravago, M. (2009). Games with dynamic externalities and climate change experiments. Working paper.

A Propositions

Proposition 2 *The symmetric MPNE in the game with private impact reduction is a stationary profile of allocations* $\{(x_{it}, r_{it})\} = \{(x_P^*, r_P^*)\}$ *for all* i *and all* t*, where* (x_P^*, r_P^*) *is the solution to the following problem:*

$$\max_{x,r} A_P^* x - r + B_P^* xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{\alpha}, \quad x + r \leq m. \tag{4}$$

Here,

$$A_P^* = a - 1 - \frac{b\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_P^* = \frac{\alpha b\beta\gamma}{1-\beta\gamma}. \tag{5}$$

Proof of Proposition 2

From Eq. (1), the public bad in period t can be written as

$$Y_t = \sum_{k=1}^{t} \gamma^{t-k} \sum_i q_{ik} x_{ik}. \tag{6}$$

Combining Eqs. (6), (2) and (3), player i's expected future payoff in period t can be written as

$$V_{it} = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)x_{i\tau} - r_{i\tau} - b\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \sum_j q_{jk} x_{jk} \right]. \tag{7}$$

Only allocation (x_{it}, r_{it}) is relevant for decision making of player i in period t, therefore, in Eq. (7) we are only interested in the terms containing x_{it} and/or r_{it}. This gives player i's objective function in period t:

$$\tilde{V}_{it} = (a-1)x_{it} - r_{it} - b\gamma \sum_{\tau=t+1}^{\infty} \beta^{\tau-t} \gamma^{\tau-1-t} q_{it} x_{it}.$$

After summing up the geometric series and expressing q_{it} through r_{it}, the objective function becomes

$$\tilde{V}_{it} = \left(a - 1 - \frac{b\beta\gamma\bar{q}}{1-\beta\gamma} \right) x_{it} - r_{it} + \frac{\alpha b\beta\gamma}{1-\beta\gamma} x_{it} r_{it}.$$

Player i's dominant strategy in period t is to choose an allocation (x_{it}, r_{it}) that maximizes $\tilde{V}_{it}$ subject to the constraints shown in Eq. (4). The maximization problem is the same in all periods, and the result is given by Proposition 2.

A solution to problem (4) exists due to the continuity of the objective function and compactness of the choice set.[8] The objective function in problem (4) is a hyperbolic

---

[8] The solution is unique with the exception of cases when special relationships between parameters hold. Such cases constitute measure zero in the parameter space, and we avoid them in the experimental design.

paraboloid, i.e., it does not have a local maximum, therefore, solutions lie on the boundary. For any given set of parameter values, solving problem (4) is straightforward. The same remark applies to the three propositions that follow.

It is also of interest to identify the utilitarian social optimum defined as the profile of allocations that maximizes the total expected payoff of the group. The result is given by the following proposition.

Proposition 3 *The symmetric social optimum in the game with private impact reduction is a stationary profile of allocations* $\{(x_{it}, r_{it})\} = \{(x_C^o, r_C^o)\}$ *for all* i *and all* t*, where* (x_C^o, r_C^o) *is the solution to the following problem:*

$$\max_{x,r} A_P^o x - r + B_P^o xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{\alpha}, \quad x + r \leq m. \tag{8}$$

Here,

$$A_P^o = a - 1 - \frac{nb\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_P^o = \frac{n\alpha b\beta\gamma}{1-\beta\gamma}. \tag{9}$$

Proof of Proposition 3

Starting with Eq. (7) and assuming symmetry, the per capita value function for the social optimum is

$$V_t^S = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)\bar{x}_\tau - \bar{r}_\tau - nb\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \bar{q}_k \bar{x}_k \right]. \tag{10}$$

Here, $(\bar{x}_t, \bar{r}_t)$ is the symmetric allocation chosen by each player in period t, and $\bar{q}_t = \bar{q} - \alpha\bar{r}_t$ is the resulting symmetric impact factor.

As in the proof of Proposition 2, only the terms containing $\bar{x}_t$ and $\bar{r}_t$ are relevant for optimization in period t. This gives the value function

$$\tilde{V}_t^S = (a-1)\bar{x}_t - \bar{r}_t - nb\gamma \sum_{\tau=t+1}^{\infty} \beta^{\tau-t}\gamma^{\tau-t-1}\bar{q}_t\bar{x}_t,$$

which has exactly the same form as in the proof of Proposition 2 except the factor n in the last term. The result is

$$\tilde{V}_{it}^S = \left(a - 1 - \frac{nb\beta\gamma\bar{q}}{1-\beta\gamma} \right) \bar{x}_t - \bar{r}_t + \frac{n\alpha b\beta\gamma}{1-\beta\gamma} \bar{x}_t\bar{r}_t.$$

This proves that the socially optimal profile of allocations is stationary and solves maximization problem (**??**).

Proposition 4 *The symmetric MPNE in the game with common impact reduction is a stationary profile of allocations* $\{(x_{it}, r_{it})\} = \{(x_C^*, r_C^*)\}$ *for all* i *and all* t*, where* (x_C^*, r_C^*)

is the solution to the following problem:

$$\max_{x,r} A_C^* x - r + B_C^* xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{n\rho}, \quad x + r \leq m. \tag{11}$$

Here,

$$A_C^* = a - 1 - \frac{b\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_C^* = \frac{n\rho b\beta\gamma}{1-\beta\gamma}. \tag{12}$$

Proof of Proposition 4

In the case of common impact factor reduction, the objective function of player i is, from Eq. (7),

$$V_{it} = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)x_{i\tau} - r_{i\tau} - b\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \sum_j \left(\bar{q} - \rho \sum_l r_{lk} \right) x_{jk} \right]. \tag{13}$$

Dropping all terms other than those containing x_{it} and/or r_{it}, obtain the reduced objective function:

$$\tilde{V}_{it} = (a-1)x_{it} - r_{it} - b\gamma \sum_{\tau=t+1}^{\infty} \beta^{\tau-t}\gamma^{\tau-1-t} \left(\bar{q}x_{it} - \rho r_{it}x_{it} - \rho x_{it} \sum_{j\neq i} r_{jt} - \rho r_{it} \sum_{j\neq i} x_{jt} \right).$$

Summing up the geometric series, further obtain

$$\tilde{V}_{it} = (a-1)x_{it} - r_{it} - \frac{b\beta\gamma}{1-\beta\gamma} \left(\bar{q}x_{it} - \rho r_{it}x_{it} - \rho x_{it} \sum_{j\neq i} r_{jt} - \rho r_{it} \sum_{j\neq i} x_{jt} \right).$$

Differentiating function $\tilde{V}_{it}$ with respect to x_{it} and r_{it} and applying symmetry assumptions ($x_{it} = x_t$ and $r_{it} = r_t$ for all i), obtain for the symmetrized derivatives:

$$\left(\frac{\partial \tilde{V}_{it}}{\partial x_{it}} \right)_{symm} = a - 1 - \frac{b\beta\gamma}{1-\beta\gamma}(\bar{q} - n\rho r_t), \qquad \left(\frac{\partial \tilde{V}_{it}}{\partial r_{it}} \right)_{symm} = -1 + \frac{n\rho b\beta\gamma}{1-\beta\gamma} x_t.$$

Finally, note that the objective function in Proposition 4 has the same derivatives, therefore, maximization of $\tilde{V}_{it}$ subject to the symmetry condition and constraints gives the same result as problem (11).

The following proposition characterizes the utilitarian social optimum.

Proposition 5 *The symmetric social optimum in the game with common impact reduction is a stationary profile of allocations* $\{(x_{it}, r_{it})\} = \{(x_C^o, r_C^o)\}$ *for all* i *and all* t, *where* (x_C^o, r_C^o) *is the solution to the following problem:*

$$\max_{x,r} A_C^o x - r + B_C^o xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{n\rho}, \quad x + r \leq m. \tag{14}$$

Here,

$$A_C^o = a - 1 - \frac{nb\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_C^o = \frac{n^2\rho b\beta\gamma}{1-\beta\gamma}. \tag{15}$$

Proof of Proposition 5

Starting with Eq. (13) and assuming symmetry ($x_{it} = \bar{x}_t$, $r_{it} = \bar{r}_t$ for all i), the per capita value function for the social optimum is

$$V_t^S = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)\bar{x}_\tau - \bar{r}_\tau - nb\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k}(\bar{q} - n\rho\bar{r}_k)\bar{x}_k \right]. \tag{16}$$

As above, only keeping the terms containing $\bar{x}_t$ and/or $\bar{r}_t$, obtain the reduced value function

$$\tilde{V}_t^S = (a-1)\bar{x}_t - \bar{r}_t - nb\gamma \sum_{\tau=t+1}^{\infty} \beta^{\tau-t}\gamma^{\tau-t-1}(\bar{q} - n\rho\bar{r}_t)\bar{x}_t,$$

which, after summing up the geometric series, takes the form as in Proposition 5.

B Instructions

Instructions – experimenter

Thank you for participating in today's experiment. During the experiment you will make decisions and may earn money. Your earnings may depend on *your own decisions* and the *decisions of other participants*.

All amounts are expressed in *tokens*. The exchange rate is 100 tokens = $1. At the end of the experiment your total earnings in tokens will be exchanged into dollars and cents and added to your $10 show-up fee. You will be given a check for the total amount *in private*. No other participant will be informed about your payment.
At the beginning of the experiment all participants will be randomly divided into groups and stay in the same group for the entire sequence of decisions. The experiment will consist of a series of decision-making rounds. You will be given an initial balance of 300 tokens.

Decision

At the beginning of each round you will be endowed with 10 tokens. You can allocate these 10 tokens between three options: *keep, invest in production* and *invest in impact reduction*.

Production

Each token you *invest in production* yields you 5 tokens of *production revenue*.

Tokens *invested in production* of all members of your group lead to accumulation of a *common stock*. Specifically, *investment in production* of each member is multiplied by the member's common stock impact factor and added to the common stock. If the member's impact factor is 0.8 then *invested in production* tokens, multiplied by 0.8 (or decreased by 20%) are added to the common stock. If, the impact factor is 0.6 then *investment in production* of a group member decreased by 40% (or multiplied by 0.6) is added to the common stock and so on. If the members impact factor is zero, *invested in production* tokens are multiplied by zero so nothing is added to the common stock.

Each group member has to pay *maintenance cost* proportional to the total size of the common stock. The cost of maintaining 1 unit of the common stock is 1 token, so the maintenance cost is equal to the size of the common stock. The maintenance cost each round is based on the size of the common stock at the beginning of this round. The size of the common stock at the beginning of the first round is zero. At the end of each round total group production investments multiplied by corresponding impact factors are added to the common stock.

At the beginning of each round impact factors of all group members are set to 0.8. Each token you *invest in impact reduction* reduces all group participants' impact factors in this round by 0.05. So if your investment in impact reduction is 0 (and no other person is investing in impact reduction), the impact factors remain 0.8; if your *investment in impact reduction* is 2, impact factors of all group members for this period are reduced by 0.1, and so on. The impact factor cannot be negative. The smallest value of impact factor is zero. At the end of each round total group production investments multiplied by the impact factor are added to the common stock.

Only part of current common stock is transferred to the next rounds, specifically common stock retention rate is 0.75 or 75% meaning that ¾ of the common stock at the end of the current round will be the level of the common stock at the beginning of the next round.

Payoffs

Your earnings for each round are obtained by adding the number of tokens you decided to keep and production revenue to your balance while subtracting the common stock maintenance cost from your balance. This part of the experiment may consist of several rounds and your balance will be updated after every round as described above.

After each round there will be some chance that the decision-making will stop. The likelihood of next round is equal to .95 or 95% and the likelihood that this round was the last is .05 or 5%. You can think of it as rolling a 20-sided die and if any number from 2 to 20 comes up, the next round happens, while if number 1 comes up, the experiment stops. Your earnings would be your balance in the last round. You will see the draw after every round.

Practice

We will now illustrate the interface of the program and show you the decision screens.
All subjects will be randomly divided into groups of 4 and stay in the same group for the sequence of decision rounds.

Please wait for instructions to make decisions. Every round you will decide how to allocate 10 tokens as shown in the box in the center of the screen. This is practice round. In the upper left part of the screen you are reminded about the return per token you invest in production and maintenance cost per unit of common stock. Recall that every token you invest in production yields 5 tokens of production revenue. Invested in production tokens of all members of your group multiplied by the corresponding impact factors are added to the common stock. Each unit of the common stock has a maintenance cost of 1 token therefore the maintenance cost paid by each group member is equal to the size of the common stock. For example if the common stock is 0 each group member pays maintenance cost of 0, if the common stock is 10, cost is 10, if the common stock is 50, maintenance cost paid by each group participant is 50 and so forth. The next row in the upper left section is the likelihood of next round which is 0.95. This value remains the same for all rounds. The last line indicates common stock impact factors. At the beginning of each round they are set at 0.8 and can be reduced by investing in impact reduction as described above.

In the upper right part of the screen you see your current *balance* and the current size of the common stock. Since this is the first round, no common stock has been accumulated. Your initial balance is 300 tokens. Your earnings after each round will be added to your total balance. Note that if your earnings in a round are negative, your balance will decrease.

Below the decision box, you see a chat interface that will allow you to communicate with the other three members of your group. This interface consists of a large dialogue box where all chat from the round is displayed and a light purple message input box where text is input. A letter used to identify your messages is to the left of the input box and will appear next to your message in the chat box. A timer indicating “Chat Time Remaining:” is located below the input box. The identifying letter is presently X for everyone in the group for the Practice Round, but will be one of the four letters P, R, S, or T during the actual experiment. This letter will remain the same for a given person between rounds.

The messaging system is providing an option for you to communicate with other subjects in your group, with the following two provisions: (1) Please refrain from using any curse words or making any derogatory or offensive statements. (2) Please do not reveal your identify or any characteristics which would allow another individual to identify you outside of the context of the experiment. If you observe anyone violating these rules please raise your hand and inform us. We have the capability of monitoring chat communications and will ask subjects who violate these rules to leave the experiment with only their $10.00 show-up fee.

To use the chat interface, click on the light purple message input box at the bottom of the chat interface. Type a message in the box and press “Enter" to send. You will see your message appear next to your assigned letter in the dialogue box above. During the practice period, you will only see your own messages, but during the actual rounds of the experiment you will see the messages and corresponding letters of all four members of your group. Please send a few more messages now to practice using the chat interface. If the chat messages exceed the height of the message box, a scroll bar will appear allowing you to scroll back through text.

You will indicate your allocation decision in the fields provided in the box in the center of the screen. You see that the total number of tokens to allocate is 10. In the corresponding fields please enter the number of tokens for each option. Note that the numbers should be integers and sum up to 10. You are not paid for the practice round so you may want to try different options. Please make your decision, click on the Submit button and wait. Next screen reports your decision; note that the impact factors are replaced by xx since at this stage you do not know the decisions of other group members. You can change your decision by clicking on the grey Back button. Please click on the grey Back button now. You see that you are back at the decision screen. Please make another decision and click Submit. To submit your final decision you will click on the red Confirm button.

During the Practice Round you will find “xx” as the "Chat Time Remaining.” During the actual experiment, you will have 60 seconds per round to send messages. After 60 seconds have elapsed, you will still be able to view messages previously sent, but will be unable to send new messages until the next round. During this 60 seconds you will be able to send and view messages regardless whether you have already submitted and confirmed your decision or not.

When all members of your group make their decisions and click on the “confirm” button you will see the results screen. Please click Confirm.

You now see the results screen. Your allocation decision is reported back to you in a box. To the right of the box you will see combined allocation decisions of the other members of your group. In the upper left section you will see impact factors for this round. Some numbers are replaced by xx in the practice round since they may depend on the decisions of other members of your group. In the actual rounds all these numbers will be shown to you. In the left column below the box you see revenue from tokens you decided to keep, revenue from tokens you invested, maintenance cost and earnings this round. Your earnings in a round are obtained by summing these top three numbers. The maintenance cost is 0 since there was no common stock at the beginning of this round. The maintenance cost is equal to the size of the common stock at the beginning of current round. Note that your earnings have been added to your balance and your updated balance is shown in the upper right part of the screen. The right column below the box provides information on the common stock. You see the amount of common stock at the beginning of this round, which was equal to the maintenance cost this round. The next line reports the addition to the common stock based on the number of tokens you invested. The line right below it shows addition to the common stock by 3 other group members. Next you see common stock at the end of the current round, which is the sum of the first three values. Common stock retention rate is shown next. Retention rate of 75% will not change during the experiment. The last line reports the size of the common stock at the beginning of next round. It is equal to ¾ of current common stock and will be the maintenance cost of each group member next round. When you review the results please click on the Continue button. In the actual rounds please remember to click on the Continue button to go to the next round. We will proceed to the next round only after everyone has completed the previous round. You now see the transition screen that informs you of the number draw. If the draw is 1 there will be no next round, if the draw is any number from 2 to 20, there will be next round.

Are there any questions?