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

Svetlana Pevnitskaya† and Dmitry Ryvkin‡

April 19, 2017
(Preliminary draft)

Abstract

We use a laboratory experiment to study decisions in a dynamic game where firms' private production leads to accumulation of a public bad, such as pollution. Firms have an option to invest in clean technology, which lowers their emissions, or contributions to the public bad. The main treatment variable is the type of 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 common access to clean technology. This result is preserved 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, experiment, environmental economics

*We thank the participants of the ESA World Meeting, FSU Experimental Readings Group, [**Add other places**] for valuable comments on the earlier versions of this paper. Sean Collins provided excellent research assistance with programming the experiment. This study was 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, Florida State University, Tallahassee, FL 32306-2180, spevnitskaya@fsu.edu.

‡Department of Economics, Florida State University, dryvkin@fsu.edu.

1 Introduction

Many social dilemma-type problems, such as pollution, climate change or the provision of public infrastructure, are dynamic in nature. Although the majority of experimental work on social dilemmas focused on static or repeated game environments, there is an emerging literature that focuses on dynamic problems in the context of public goods, pollution, climate change, and common pool resources.[1] In this paper, we contribute to this literature by exploring experimentally an environment with a dynamic public "bad" where agents can invest 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 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 it allows the group to reach socially optimal outcome in the absence of exogenous enforcement or sanctioning mechanisms. The two institutions we consider are *private access* where the firm uses the technology it invested in exclusively, and *common access* where each firm's technological improvement becomes available to other firms. The two institutions differ by the degree of interconnectedness of agents' decisions in terms of the positive effect of investment in clean technology, which may affect free-riding considerations and deviations from the social optimum.

The extensive experimental literature on static linear public good games (see, e.g., reviews by Ledyard 1995, Zelmer 2003) indicates that the observed behavior, at least initially, rarely coincides with the zero-contribution Nash equilibrium (NE), suggesting that the free riding problem in public good games may not be as strong as predicted. At the same time, the results for nonlinear public good games with an interior equilibrium are mixed, and contributions often come close to NE or even fall below it (see, e.g., Holt and Laury 2008). In a setting with a dynamic public good, Battaglini et al. (2012) observe public good levels in agreement with the Markov perfect Nash equilibrium (MPNE) predictions in the long run and do not find evidence for significant voluntary cooperation. Battaglini et al. (2016) compare the dynamics of contributions to a durable public good in the case of reversible investment (where agents can either increase or decrease the stock of the public good) and in the case of irreversible investment (where agents can only invest non-negative amounts). In both cases, subjects start with investment levels significantly above MPE predictions, but the stock of the public good falls sharply to about 2% of

[1]Examples include Battaglini et al. (2012, 2014, 2016), Guererk et al. (2010), Saijo et al. (2009), Chermak and Krause (2002), Ostrom (2006), Pevnitskaya and Ryvkin (2011, 2013a,b).

the efficient level in the case of reversible investments, while in the case of irreversible investments it remains at about 50% of the efficient level. In games with a dynamic public bad without the option to reduce environmental impact, Saijo et al. (2009) report mixed results for a nonlinear setting with an interior MPNE, while Pevnitskaya and Ryvkin (2011, 2013a,b) observe the levels of the public bad above the social optimum but below the MPNE predictions in the linear case. These studies show that the free-riding problem in voluntary contribution settings with dynamic public goods or bads is, generally, at least as severe as in the static case.

In the existing experimental studies of dynamic public bads, curbing production is the only way to reduce pollution. Such approach is not practical in many cases since it is unlikely that short-term economic prosperity will be compromised by agencies to reduce pollution. In this study, we allow firms to invest in clean technology, thereby reducing and possibly eliminating the negative environmental impact of the firm's production. For each of the two technology sharing institutions – private access and common access – we characterize the MPNE and socially optimal production and investment levels, which are in the interior range of the decision space. For comparability between treatments, we calibrate parameters of the two institutions so that their social optimum and MPNE solutions coincide.

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. *Common* access mechanism allows for the possibility of asymmetric provision of the efficient level of group investment in clean technology, and if there are subjects who choose to invest more in order to compensate for underinvestment by others, they can improve (group) efficiency. Therefore observed greater efficiency of the *common* access mechanism may be explained by heterogeneity of subjects' "pro-environmental" preferences and decisions. The *common* access institution allows pro-social (or pro-environmental) subjects to manifest their preferences at the expense of own profit but for the "greater good" of lowering the levels of the public bad. On the other hand, the *private* access institution does not allow one to reduce the environmental damage imposed by less cooperative subjects via own investment.

The availability of the open-ended chat communication significantly reduces production inputs, increases investment and reduces public bad levels. The *common* access technology sharing mechanism with chat approaches the socially optimal outcome without external enforcement. Not surprisingly, at the other end of the spectrum, the *private* access mechanism without chat leads to the highest levels of the public bad and lowest payoffs. The presence of common access to clean technology enhances subjects' understanding of the game and interdependence of their decisions, leading to a higher frequency of correct statements about the game during communication in the very first period. We find almost no indication of subjects discussing conditional, or trigger, strategies in both mechanisms, supporting applying non history dependent solution concepts.

The rest of the paper is organized as follows. Section 2 presents the model and investment mechanisms. Section 3 describes our experimental design and research questions. The results are presented in Section 4, and 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 of its (negative) environmental impact; in other words, q_{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}.[2]

The level of the public bad at the end of period t, Y_t, is based on the depreciated level of the public bad at 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]We model clean technology investment as maintenance or abatement costs that have to be incurred in each period. Alternatively, such investment can be modeled as a one-time payment having a lasting (permanent, or gradually depreciating) effect on technology. While this alternative model is reasonable, we adopt a simpler version in order for subjects in the experiment to have only one dynamic process (the evolution of the public bad) to deal with. A model with lasting effects of technology investment is an extension for future research.

2.1 Private Access

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 Nash equilibrium (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 described in Proposition A.1 in Appendix A which has a solution. For any given set of parameter values, solving problem (A.1) is straightforward, and in Section 3 we present the solution for the parameters used in the experiment.

The second solution concept we apply is the utilitarian social optimum (SO) 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 A.2 describing the SO outcome is presented in Appendix A.

2.2 Common Access

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 the symmetric MPNE and SO, we arrive at Propositions A.3 and A.4 that are presented in Appendix A. Similarly to the case of *private* investment, in both cases optimization reduces to a static problem that has a straightforward solution.

	Sessions (subjects, groups)	
	No Chat	Chat
Private Investment	3 (52, 13)	2 (36, 9)
Common Investment	3 (48, 12)	2 (40, 10)
Nash Equilibrium, (x^*, r^*)	(8.04, 1.96)	
Social Optimum, (x^{SO}, r^{SO})	(6.00, 4.00)	

Table 1: Number of sessions (subjects, groups) by treatment and theoretical predictions (the same across all treatments).

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 A.1 and A.3, and in Propositions A.2 and A.4. Part (i) is quite intuitive.

As shown in Propositions A.1 through A.4, the MPNE and SO allocations of production input and investment in clean technology, (x^*, r^*) and (x^{SO}, r^{SO}), are stationary. It is straightforward to show that, generally, $x^{SO} \leq x^*$ and $r^{SO} \geq r^*$. For the parameter values used in the experiment, the MPNE and SO allocations are provided in the next section.

3 Experimental design

3.1 Experimental design and research questions

The experiment follows a 2×2 between-subjects design. Our main treatment variable is the type of access to investment in clean technology (Private, Common). The other dimension of the design is the absence or presence of unrestricted chat communication (No Chat, Chat). The number of sessions, subjects and groups in each treatment, as well as the MPNE and SO allocations are shown in Table 1.

In all treatments, we use fixed groups of size $n = 4$.[3] Other parameters of the model are as follows: $m = 10$, $a = 5$, $b = 1$, $\bar{q} = 0.8$, $\alpha = 0.2$, $\rho = 0.05$, $\gamma = 0.75$. 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.[4]

In the 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 stock variables – the size of the public bad, Y_t, and cumulative payoffs, Π_{it}. Figure 1 illustrates the MPNE and SO predictions for the dynamics of each of these variables. The MPNE 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?*

The existing experimental literature on static and dynamic public goods (or bads)[5] provides mixed results. Generally, the observed behavior rarely coincides with Nash equilibrium (or MPNE) initially, but may converge to it in the long run or remain between the equilibrium and SO levels. In our experiment, the clean technology investment allows subjects to reduce contributions to the dynamic public bad, thereby providing an additional public good for the group. By comparing behavior and outcomes between the treatments with private and common access to investment, we explore whether a variation in how this public good is provided – with or without spillovers – affects subjects' decisions and leads to a more efficient outcome that approaches the SO allocation. Note that, as shown in the previous section, the two treatments have the same MPNE and SO allocations; therefore, any differences in subjects' behavior would be consistent with subjects switching towards an alternative solution concept, or with some other behavioral considerations such as social preferences or bounded rationality.

[3]In addition to the treatments reported here, we also ran Private and Common access treatments (without Chat) with group size $n = 2$. All the results reported in this paper regarding the comparison of the two types of access to clean to technology (without chat) have been reproduced at least as strongly for $n = 2$.

[4] One session with chat was taking too long, and we were only able to conduct 17 periods. We, therefore, use data from 17 periods for chat analysis when comparing the number of various types of messages across treatments.

[5]See, e.g., Ledyard (1995), Holt and Laury (2008), Battaglini et al. (2012), Pevnitskaya and Ryvkin (2010).

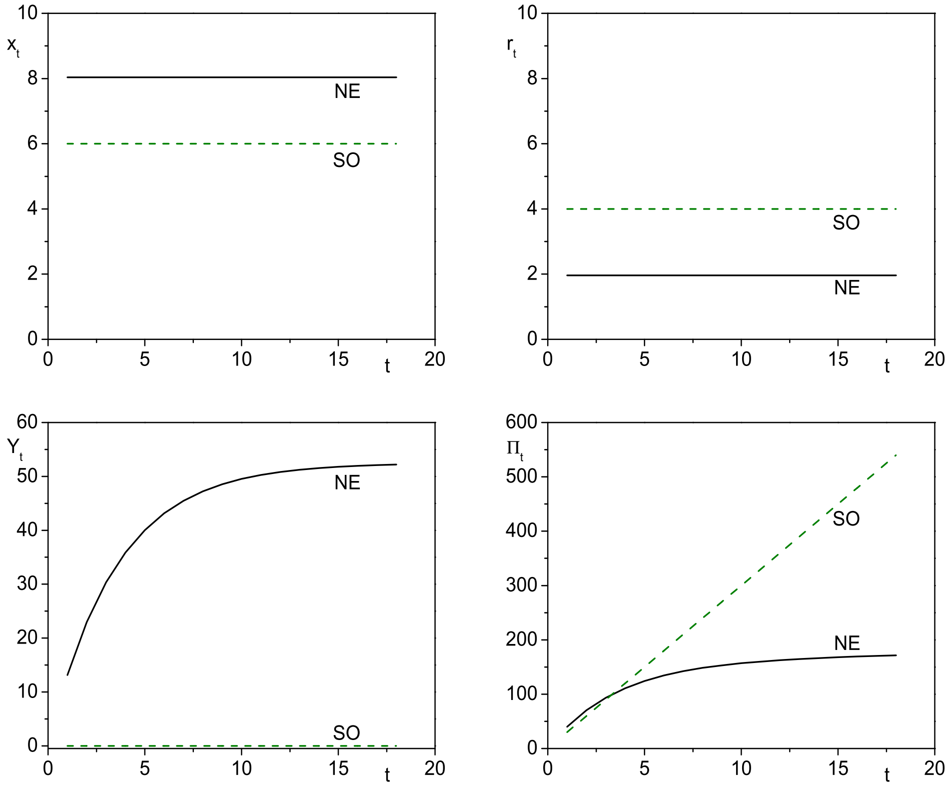

Figure 1: Nash equilibrium (NE) and socially optimal (SO) predictions for production inputs (x_t), investment in clean technology (r_t), public bad (Y_t), and cumulative payoffs (Π_t), by period for each treatment.

Question 2 *Are investment decisions affected by institutions, i.e., the type of access to 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 the MPNE is full production, $x_{it} = m$. At the same time, increased interconnectedness of subjects' decisions through the (negative) effect of the public bad and also the (positive) effect 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 game. Given the complexity of the dynamic problem subjects face, better understanding should at the very least result in reduced levels of the dominated "keep" option. Communication may allow subjects to form stronger group association and coordinate on lower levels of the public bad via increased investment, which is more consistent with the SO allocation.

We are also interested in a detailed analysis of open-form chat messages. As demonstrated in the previous research in other contexts (see, e.g., Cooper and Kagel 2005), analysis of chat content is a powerful tool in understanding what aspects of communication are associated with more efficient outcomes.

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 2015). 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.[6] 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[7] 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 (one minute). 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 the aggregate allocation decisions of other group members, total contribution 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). Figure 2 shows the time dependence of each of the variables averaged across subjects by treatment.[8] The figure also shows theoretical predictions (the SO and MPNE values of the variables). Recall that the parameters are chosen such that the SO and MPNE decisions and outcomes are the same across treatments.

As seen from Figure 2, there are significant differences between treatments at both the decision and outcome levels. In the *private* access treatment without chat, production

[6]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.

[7]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 the one minute period allocated for chat, ensuring that all subjects are able to view all group communications.

[8]Figure 2 also shows 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-subject nature of the design, the error bars provide a way to run a conservative "eye-balling" t-test for equality of the average values in each time period.

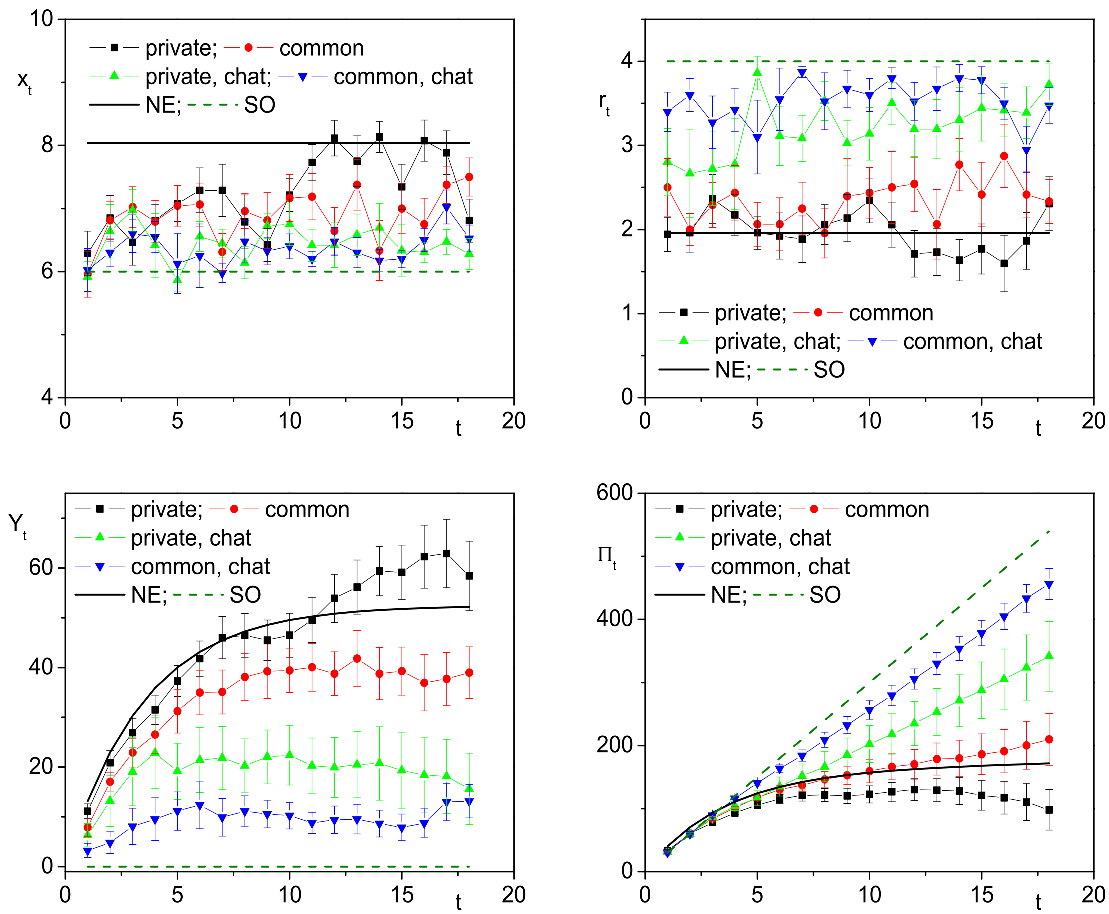

Figure 2: Average production input (x_t), investment (r_t), public bad (Y_t), and payoffs (Π_t) in the (Private, Common)×(No Chat, Chat) treatments. The error bars show standard errors of the averages clustered at the group level. Theoretical predictions are shown with the solid (NE) and dashed (SO) lines.

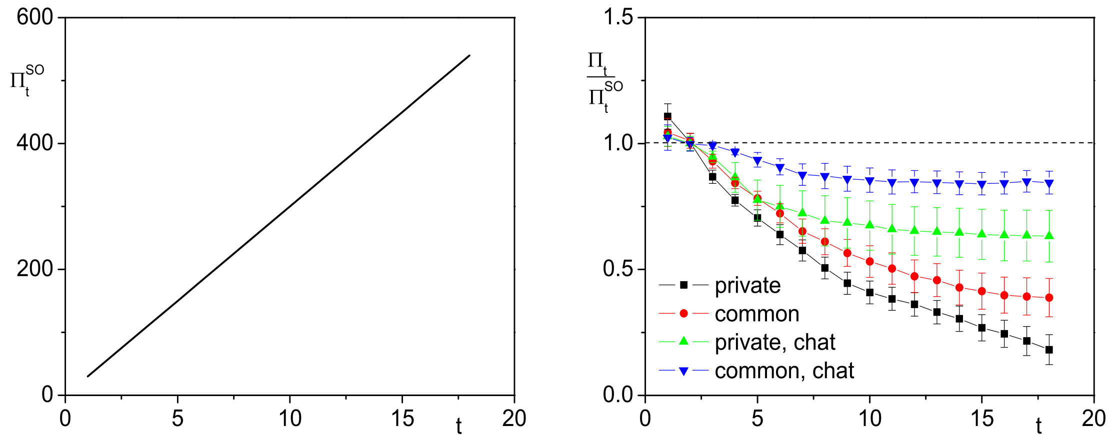

Figure 3: The socially optimal payoff (left) and the ratio of observed to SO payoff (right) by treatment. The error bars show standard errors of the averages clustered at the group level.

inputs are below MPNE in the first half of the session but reach the MPNE level in the second half. Investment levels are close to MPNE levels in most time periods and even fall below MPNE 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 MPNE in all periods but remain higher than the SO levels in most periods. Investments are significantly lower than SO in all periods and significantly higher than MPNE in a few later periods.

The decisions in both treatments with chat are closer to SO than decisions in the 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.

Figure 3 shows the average *efficiency* defined as the ratio of observed average payoffs to SO payoffs. As expected, the four treatments are clearly ranked. Efficiency starts above one, due to the short-run gains from overproduction. It falls below one relatively quickly, however. Without chat, efficiency falls below 0.5, although it appears to be stabilizing in the *common* treatment. In the treatments with chat efficiency is much higher and stabilizes well above 0.5.

Result 1 *(i) The symmetric MPNE 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 MPNE 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.

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 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 otherwise), *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.

As seen from Table 2, the coefficient estimate on *Chat* is statistically significant for all variables. The coefficients on *Common* have the expected 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.[9]

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

	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 (coefficients on period dummies are not reported).

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

	Group Investment
GroupInvLag	0.598***
	(0.061)
GroupInvLag×Common	-0.366***
	(0.131)
GroupInvLag×Chat	-0.037
	(0.106)
GroupInvLag×Common×Chat	-0.017
	(0.179)
Common	3.969***
	(1.303)
Chat	2.597**
	(1.284)
Common×Chat	1.854
	(2.184)
Constant	3.222***
	(0.415)
Observations	748
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.

	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

significant.

The following results summarize our findings.

Result 2 *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 3 *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. 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 4 sessions with chat (see footnote 4).

We coded each chat 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), discussion 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).

(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

Treatments with chat	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. Group standard errors in parentheses. Based on 9 groups with private access and 10 groups with common access to clean technology investment.

the total number of messages between treatments. There are, however, significantly more correct and fewer incorrect messages in the treatment with common access ($p < 0.01$).[10]

Result 4 *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.*

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 5 *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.*

[10]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.

Treatments with chat	Non-numerical proposal Total	Numerical proposal 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: 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.

Treatments with chat	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. Group standard errors in parentheses. Based on 9 groups with private access and 10 groups with common access to clean technology investment.

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.

Result 6 *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 reasoning 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 proposals, suggests that stronger interconnectedness promotes better understanding of the mechanism and, as described earlier, leads to more efficient outcomes.

4.4 Over-the-top investments

In the treatments with private access to clean technology, investments r_{it} above $\bar{q}/\alpha$ represent a waste of resources and are strictly dominated. At the same time, in the treatments with public access, investments above the "fair share" level $\bar{q}/n\rho$ are not necessarily wasteful or dominated because they allow subjects to act unilaterally or form small coalitions to reduce the impact factor of their group in the absence of global cooperation.

Table 8 shows the percentage of such over-the-top investment decisions, and the percentage of subjects who made an over-the-top investment decision at least once, in each treatment. As seen from Table 8, although more than 20% of subjects tried an over-the-top investment at least once in the treatments with private access, the share of such investments under private access is very small. It suggests that for the most part subjects learned from their mistakes. There is a slight increase in over-the-top investments in the presence of chat but it is not statistically significant.

In the treatments with common access, both the percentage of decisions and the percentage of subjects are significantly higher than in the treatments with private access. The effect is especially strong in the absence of chat. This results suggest that with chat

	Treatments			
$r_{it} > 4$	Private/No Chat	Common/No Chat	Private/Chat	Common/Chat
% decisions	1.9	12.6	2.5	5.7
	(0.5)	(2.2)	(0.9)	(1.9)
% subjects	21.2	70.8	27.8	47.5

Table 8: The percentage of investment decisions with r_{it} greater than $\bar{q}/\alpha$ or $\bar{q}/n\rho$, by treatment, with standard errors clustered at group level. The last row shows the percentage of subjects who invested more than $\bar{q}/\alpha$ (in the Private treatments) or $\bar{q}/n\rho$ (in the Common treatments) at least once.

subjects can better coordinate on the "fair share" investment levels and thus over-the-top investments are not needed as much. Without chat, over-the-top investments can serve as a coordination and strategic teaching device.

As a robustness check, we estimated a probit model at the individual level, where the dependent variable is one if the subject chooses an over-the-top investment in a given period and zero otherwise. The results are shown in Table 9. It is confirmed that in the absence of chat over-the-top investments occur more frequently in the treatment with common access. With chat, the effect of common access disappears ($p = 0.847$ for the Wald test of the sum of the coefficients on *Common* and $Common \times Chat$ being zero). Interestingly, there is also a significant upward trend in over-the-top investments under common access.

Result 7 *(i) Without chat, there are more over-the-top investments in the treatment with common access than in the treatment with private access (both in terms of the number of investment decisions and the number if subjects making them), the effect disappears in the presence of chat.*

(ii) The frequency of over-the-top investment decisions increases over time in the treatments with common access, but not in the treatments with private access.

Result 7 suggests that over-the-top investments play an important role in the observed efficiency of common access as compared to private access, especially in the absence of chat which serves as an alternative coordination mechanism. With chat the average investment approaches social optimum and there is lower need for compensating over-the-top investments in the common access treatment.

$\Pr(r_{it} > 4)$	
Period	-0.0252
	(0.0195)
Common	0.5026**
	(0.2201)
Chat	0.2434
	(0.3182)
Common×Chat	-0.4358
	(0.4092)
Period×Common	0.0457**
	(0.0217)
Period×Chat	-0.0178
	(0.0307)
Period×Common×Chat	-0.0073
	(0.0357)
Constant	-1.848***
	(0.177)
Observations	3,168
Groups	44

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

Table 9: Probit regression coefficients. The dependent variable is a dummy equal 1 for investment decisions with r_{it} greater than $\bar{q}/\alpha$ (in the Private treatments) or $\bar{q}/n\rho$ (in the Common treatments).

5 Discussion and conclusions

We conducted an experimental study of an environment with a dynamic public bad where players have an opportunity to invest in reducing own negative impact on the group welfare. Compared to previous studies of dynamic public bads, this setting allows reducing or even eliminating the public bad while maintaining own production. Such institution is relevant for policy analysis since it is often impractical, or politically infeasible, to reduce or eliminate economic activity for the sake of pollution reduction. We analyzed two basic institutions governing investment in clean technology. One is investment with *private access*, where each agent's investment reduces only that agent's own rate of public bad generation. The other institution is investment with *common access*, where each agent's investment reduces all agents' public bad generation rates.

For comparability, we chose parameters so that the social optima in the two treatments coincide. Interestingly, the Markov perfect Nash 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 as a response to the treatment mechanism.

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 games group decision-making and 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.

Our paper contributes to the emerging literature on dynamic or durable public goods. The existing studies show that in the absence of an external enforcement mechanism free-riding in such environments can be very severe. For issues such as global pollution reduction, finding successful decentralized mechanisms is critical as possibilities for credible third-party enforcement may be limited for political reasons. By augmenting a dynamic public bad generation process with a public good "clean-up" process, we show that nearly full efficiency can be reached in the case of common access to the results of this clean-up. We find that common access to clean technology is more efficient than private access, and leads to a significantly lower long-run level of the public bad. This is mainly driven by subjects' heterogeneity and the ability, under common access, of participants with pro-environmental (or pro-social) preferences to contribute more than their symmetric social optimum share. Such "over-the-top" investments can compensate the negative impact on the group of other subjects who pollute too much. This effect is stronger than the classical social dilemma incentive to free-ride on others' investment. In a mechanism with private access the most pro-environmental subjects can do is fully clean their own technology, but they are not able to improve the efficiency beyond that. We conclude that in environments with heterogeneity in preferences, mechanisms that allow for beneficial spillovers perform better. As a policy implication, these results suggest that more efficient outcomes can be reached if such spillovers are encouraged. For example, the Adopt-a-Highway and Sponsor-a-Highway initiatives undertaken by some US states allow volunteers to collect litter (after less pro-environmental others) and keep public roads clean.

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 to 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. Another option is for the government to provide matching grants to private companies investing in pollution-reducing R&D under a condition that the results of such R&D are made publicly available.

References

Battaglini, M., Nunnari, S., Palfrey, T.R. (2012). Legislative bargaining and the dynamics of public investment. American Political Science Review, 106(02), 407-429.

Battaglini, M., Nunnari, S., Palfrey, T.R. (2014). Dynamic free riding with irreversible investments. American Economic Review, 104, 2858-2871.

Battaglini, M., Nunnari, S., Palfrey, T.R. (2016). The dynamic free rider problem: A laboratory study. American Economic Journal: Microeconomics, 8, 268-308.

Brosig, J. (2006). Communication channels and induced behavior. MPRA paper 14025, https://mpra.ub.uni-muenchen.de/14035/1/MPRA_paper_14035.pdf.

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. (2015). Subject pool recruitment procedures: organizing experiments with ORSEE. Journal of the Economic Science Association, 1, 114-125.

Guererk, O., Rockenbach, B., Wolff, I. (2010). The effects of punishment in dynamic public-good games. Working paper available at SSRN 1589362.

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., Ryvkin, D. (2011). Behavior in a dynamic environment with costs of climate change and heterogeneous technologies: an experiment. In *Research in Experimental Economics*, Vol. 14, edited by R.M. Isaac and D. Norton, pp. 115-150, Emerald.

Pevnitskaya, S., Ryvkin, D. (2013a). Environmental context and termination uncertainty in games with a dynamic public bad. Environment and Development Economics, 18, 27-49.

Pevnitskaya, S., Ryvkin, D. (2013b). Experimental studies of games with dynamic public bads. In *Analyzing Global Environmental Issues: Theoretical and Experimental Applications and Their Policy Implications*, edited by A. Rapoport and A. Dinar, pp. 89-102, Routledge.

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 available at `http://www.researchgate.net/profile/Majah-Leah_Ravago/publication/228821528_Games_`

with_Dynamic_Externalities_and_Climate_Change_Experiments/links/0046352820582de3b00
pdf.

Zelmer, J. (2003). Linear public goods experiments: A meta-analysis. Experimental Economics, 63, 299-310.

A Propositions

Proposition A.1 *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:*

$$\max_{x,r} A_P^* x - r + B_P^* xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{\alpha}, \quad x + r \leq m. \tag{A.1}$$

Here,

$$A_P^* = a - 1 - \frac{b\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_P^* = \frac{\alpha b\beta\gamma}{1-\beta\gamma}. \tag{A.2}$$

Proof of Proposition A.1

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

$$Y_t = \sum_{k=1}^{t} \gamma^{t-k} \sum_i q_{ik} x_{ik}. \tag{A.3}$$

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

$$V_{it} = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)x_{i\tau} - r_{i\tau} - b\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \sum_j q_{jk} x_{jk} \right]. \tag{A.4}$$

Only allocation (x_{it}, r_{it}) is relevant for decision making of player i in period t, therefore, in Eq. (A.4) 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. (A.1). The maximization problem is the same in all periods, and the result is given by Proposition A.1.

A solution to problem (A.1) exists due to the continuity of the objective function and compactness of the choice set.[11] The objective function in problem (A.1) is a hyperbolic

[11] 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 (A.1) 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 A.2 *The symmetric social optimum in the game with private impact reduction is a stationary profile of allocations* $\{(x_{it}, r_{it})\} = \{(x^o_P, r^o_P)\}$ *for all* i *and all* t*, where* (x^o_P, r^o_P) *is the solution to the following problem:*

$$\max_{x,r} A^o_P x - r + B^o_P xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{\alpha}, \quad x + r \leq m. \tag{A.5}$$

Here,

$$A^o_P = a - 1 - \frac{nb\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B^o_P = \frac{n\alpha b\beta\gamma}{1-\beta\gamma}. \tag{A.6}$$

Proof of Proposition A.2

Starting with Eq. (A.4) and assuming symmetry, the per capita value function for the social optimum is

$$V^S_t = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)\bar{x}_\tau - \bar{r}_\tau - nb\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \bar{q}_k \bar{x}_k \right]. \tag{A.7}$$

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 A.1, only the terms containing $\bar{x}_t$ and $\bar{r}_t$ are relevant for optimization in period t. This gives the value function

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

which has exactly the same form as in the proof of Proposition A.1 except the factor n in the last term. The result is

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

This proves that the socially optimal profile of allocations is stationary and solves maximization problem (A.5).

Proposition A.3 *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:

$$\max_{x,r} A_C^* x - r + B_C^* xr \quad \text{s.t.} \quad x \geq 0, \quad r \geq 0, \quad r \leq \frac{\bar{q}}{n\rho}, \quad x + r \leq m. \tag{A.8}$$

Here,

$$A_C^* = a - 1 - \frac{b\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_C^* = \frac{n\rho b\beta\gamma}{1-\beta\gamma}. \tag{A.9}$$

Proof of Proposition A.3

In the case of common impact factor reduction, the objective function of player i is, from Eq. (A.4),

$$V_{it} = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)x_{i\tau} - r_{i\tau} - b\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k} \sum_j \left(\bar{q} - \rho \sum_l r_{lk} \right) x_{jk} \right]. \tag{A.10}$$

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:

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

Finally, note that the objective function in Proposition A.3 has the same derivatives, therefore, maximization of $\tilde{V}_{it}$ subject to the symmetry condition and constraints gives the same result as problem (A.8).

The following proposition characterizes the utilitarian social optimum.

Proposition A.4 *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:*

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

Here,

$$A_C^o = a - 1 - \frac{nb\beta\gamma\bar{q}}{1-\beta\gamma}, \qquad B_C^o = \frac{n^2\rho b\beta\gamma}{1-\beta\gamma}. \tag{A.12}$$

Proof of Proposition A.4

Starting with Eq. (A.10) 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

$$V_t^S = \sum_{\tau=t}^{\infty} \beta^{\tau-t} \left[m + (a-1)\bar{x}_\tau - \bar{r}_\tau - nb\gamma \sum_{k=1}^{\tau-1} \gamma^{\tau-1-k}(\bar{q} - n\rho\bar{r}_k)\bar{x}_k \right]. \tag{A.13}$$

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 A.4.

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?

We will now ask you to answer a short questionnaire to make sure the description was clear. As soon as you are done raise your completed questionnaire and one of us will come and check your answers.

Questionnaire

Sample Round 1 Decisions.

Please make some allocation decision for each player and then complete the remaining fields
(note that in the actual experiment you will be making decisions only for yourself just as you did in the practice round).
Let us know if you have any questions.

Decisions

	Player 1	Player 2	Player 3	Player 4
Tokens	**10**	**10**	**10**	**10**
Keep				
Allocate to production				
Invest in impact reduction				

Common Stock at the beginning of round 1is 0

Earnings this round

	Player 1	Player 2	Player 3	Player 4
Tokens kept				
Production revenue				
Common stock maintenance (-)				
Earning this round				

Common Stock

Each token invested in impact reduction reduces all group players' impact factor, (**0.8**), by 0.05.

	Player 1	Player 2	Player 3	Player 4	Total
Investment in impact reduction					
Common stock impact factor					
Allocate to production					
Addition to the common stock					

Common Stock at the end of round 1: __________________

Common Stock at the beginning of round 2: ____________________

Maintenance cost paid by each player in round 2: _____________________

____