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Abstract

Greenhouse gases generate impacts that can last longer than human civilization itself. Such persistence may affect the behavioral ability to cooperate. Here we study mitigation efforts within a framework that reflects key features of climate change and then contrasts a dynamic versus a static setting. In a treatment with persistence, the pollution cumulates and generates damages over time while in another treatment it has only immediate effects and then disappears. We find that cooperation is not hampered, on average, by pollution persistence. Mitigation efforts, though, should not be delayed, because cooperation levels appear to deteriorate for high stocks of pollution.

Keywords: Myopia; Stock externalities; Social dilemma; Inequality
JEL codes: C70; C90; D03; Q54

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1 Introduction

Unless major efforts are undertaken to reduce greenhouse gas emissions, climate change will reach dangerous levels within this century (IPCC, 2014; Stern et al., 2006). The impacts will be global, with uncertainties in their magnitude and geographical distributions, and with high degrees of irreversibility and persistence (Wagner and Weitzman, 2015). Coordinating international actions toward mitigation is notoriously difficult. A major reason is the temptation of opportunistic behavior by each single country that can benefit from the mitigation efforts of others without paying the costs to reduce the carbon intensity of their economy (Nordhaus, 2013). Here we study the role of the long-run persistence of greenhouse gases (GHGs) in the atmosphere, which makes climate change a *dynamic* social dilemma. In particular, carbon dioxide is the most important pollutant responsible for anthropogenic climate change and a considerable portion of its current stock will last for well over a millennium, which – on the time scale of human civilization – basically means forever (Inman, 2008; Solomon et al., 2010).

The research question is whether and how such long-term persistence of pollution affects the ability of societies to cooperate. This aspect has been singled out in the literature as one of those features that hampers cooperative efforts in mitigating climate change (Wagner and Weitzman, 2015). The implicit assumption behind this concern is that decision-makers are myopic. In the sense of properly considering the short-run consequences of their actions but not those in the long run. That would undermine cooperation in any dynamic social dilemmas, of which climate change is a prominent example, given that its cause is the persistent pollution cumulating over the centuries. This concern is fundamentally behavioral. Here we study it by means of a laboratory experiment that allows us to causally identify the effect of pollution persistence on the ability to cooperate (Falk and Heckman, 2009). This will be relevant for the research agenda on climate change and its policy implications.

In this paper, we develop a platform to study the behavioral role that the long-term persistence of pollution has on favoring or hampering cooperation on mitigation efforts (Dutta and Radner, 2009). We characterize this platform from a theoretical point of view and then study its behavioral properties via experimental methods. We designed our model in order to capture several salient characteristics of the field, such as the large income difference that exits across countries, the actual level of persistence of pollution, and the damage function that maps any stock of pollution into payoffs (Greiner et al., 2012; Bosetti et al., 2012).

We model the climate change game as a strategic interaction among countries over an indefinite horizon in the absence of a legally binding treaty, where each country independently chooses its level of GHG emission at each point in time. Pollution benefits the country that emits it because it is linked to economic production, but has negative externalities in the form of damages for all countries. Across three treatments, we vary the degree of persistence of GHGs emissions. In the *Persistent* treatment, the global emissions generated in one round fully remain in the atmosphere in the next rounds and cumulate into a stock of pollution. This stock of pollution keeps damaging countries in the present round and all future rounds. Conversely, the *Immediate* treatment reproduces a static although repeated social dilemma, where the whole damage of the current emissions is suffered within the current round. Finally, the *Halving* treatment represents an intermediate case, in which emissions cumulate from one round to the next but the stock depreciates – halving every round – because pollution dissipates.

In all treatments the indefinite horizon gives rise to multiple equilibria, opening opportunities for partial and full cooperation. Our theoretical benchmarks are the socially optimal level of emissions and the constant action Markov Perfect Equilibrium. We have calibrated the parameters of the experiment in a way that these benchmarks are identical across all treatments. Hence, differences in behavior will easily reveal which scenario is most conducive for cooperation in mitigation efforts.

Existing public goods experiments provide only limited empirical guidance on the voluntary mitigation of climate change because their setup is generally static, involves no losses, and has both socially optimal and equilibrium strategy placed at the boundaries of the action space. Instead, climate externalities are dynamic as they depend on the stock of emissions accumulated in the atmosphere, not just on the yearly flow. There exist only a handful of economic experiments with dynamic externalities (for instance, Battaglini et al., 2016) and the climate experiments most related to ours are Pevnitskaya and Ryvkin (2013) and Sherstyuk et al. (2016). The former reports the impact on cooperation of the time horizon, definite versus indefinite; the latter compares cooperation among long-lived agents versus overlapping generations. The main novelty here is the focus on irreversibilities and pollution persistence.

Another specificity of the climate game is the possibility of net losses for countries in the case of lack of international cooperation. Minimal cooperation in a public goods game typically preserves small but positive earnings. Missed earnings can trigger a rather different behavioral response than net losses (Sonnemans et al., 1998). Finally, in public goods game, the social optimum and the Nash equilibrium are typically not interior points, which has a behavioral impact on cooperation levels (Ostrom et al., 1992; Laury and Holt, 2008).

We report average levels of cooperation that were remarkably similar for immediate and persistent pollution (Result 1). Cooperation was positive, ranging from 25% to 35% depending on the treatment, but with no significant differences under static or dynamic externalities. In a sense, this constitutes good news for our chances to successfully tackle climate change through mitigation efforts. An in-depth data analysis reveals less benign patterns. In the experiment, cooperation levels dropped as the situation got worse in terms of pollution stock. Despite the similarity in averages across treatments, trends and strategies could differ. For instance, while with static externalities the average emission was quite stable over time, with dynamic externalities, the representative participant seemed to follow strategies prescribing emissions increasing in the stock of pollution (Results 3-5). One implication for climate policy may be to kick-start mitigation efforts early on when the pollution stock is modest, as a degraded environmental situation seems to have the behavioral effect of harming the ability to cooperate. Finally, we discuss the limited difference in the emission choices of rich and poor participants (Result 2).

The contribution of the paper is placed into the context of the experimental literature on climate change (Section 2). We then present the theoretical platform of analysis (Section 3) and describe the experimental design (Section 4). Finally, we report the results (Section 5) and conclude (Section 6).

2 Literature Review

This paper contributes to the growing literature that studies cooperation in a climate change context by employing laboratory experiments. Within this literature, one can identify two main perspectives. One perspective is to model climate change as a collective catastrophe that can happen if cooperation remains below a threshold. The other perspective, instead, treats all emissions as causing an incremental damage on welfare.

In Milinski et al. (2008), participants could either keep their endowment in a private fund or invest it in mitigation, which can ensure that everyone will preserve their private funds. If, by the end of the experiment, the group's cumulated investment in mitigation is below a *known* threshold the catastrophe of losing everything takes place with some probability. Consistent with the theoretical benchmark for rational selfishness (Barrett, 2011), a higher probability of a catastrophe reduced the empirical frequency of mitigation investments below the threshold. Tavoni et al. (2011) follow a similar setup to investigate two potential obstacles to cooperation in climate change: the multiplicity of equilibria and the income gap between poor and rich countries, exacerbated by the responsibility of rich countries' historical emissions.[1] The authors report a negative impact of economic inequality on cooperation. Moreover, groups who successfully avoided the catastrophe managed to eliminate inequality over the play, in particular when participants could communicate.

Another study that builds on Milinski et al. (2008) is Brick and Visser (2015). They elicit preferences for burden-sharing in a cross-country experiment, finding that the decisions of American and Chinese participants are in line with self-interest. Bosetti et al. (2015) employ a public bad experiment with tipping point to explore the interplay between mitigation and investments in a clean technology. The adoption of clean technologies is positively correlated with the capacity of the members of an investment coalition to appropriate its benefits. Finally, Hauser

[1]The type of inequality studied by Tavoni et al. (2011) is different from the one of our experiment, which is based on the idea that poor countries *today* achieve a lower per capita output than rich countries for the same emission due to a larger population size.

et al. (2014) investigate an indefinite horizon common pool with threshold where the catastrophe is suffered by the next generation if the current one over extracts. They find that binding voting on the amount to extract enhances intergenerational cooperation because the majority of individuals is fair.

While in the experiments mentioned above participants know the precise threshold they should avoid to prevent the catastrophe, Barrett (2011) notes that there is large scientific uncertainty on this parameter. A handful of studies embed uncertainty and ambiguity into climate tipping points. Some show that the threat of a catastrophe enhances cooperation if the uncertainty on the tipping point is low. However, this deterrence effect disappears for high level of uncertainty (Barrett and Dannenberg, 2012, 2014). Cooperation further drops with severe ambiguity about the tipping point (Dannenberg et al., 2015).

The second perspective in the literature, which is the one taken in this paper, comes from the realization that cooperative efforts below or above the tipping point are not really wasted, since each single ton of emissions contributes to global warming (Barrett, 2011). What sets climate change apart from the usual social dilemmas experiments is a dynamic feature: damages stem from the yearly emissions as well as from the stock of pollution accumulated in the atmosphere.

Two recent dynamic experiments on climate change are Pevnitskaya and Ryvkin (2013) and Sherstyuk et al. (2016) that adapt the theoretical model of Dutta and Radner (2004) under an infinite horizon. These studies have a setup that is close to ours, although their focus is not on pollution persistence.[2] In particular, Pevnitskaya and Ryvkin (2013) study the role of time horizon on cooperation. Under finite horizon, participants were faster in learning to cooperate, but they increased emissions in the last round. Moreover, when the experiment was presented with an environmental framing, participants were more cooperative. Sherstyuk et al. (2016) compare overlapping generations to long-lived agents allowing for access to past history and intergenerational advices. With overlapping generations, cooperation became harder to sustain due to both limited incentives and larger strategic uncertainty.

There are other experiments with dynamic externalities that do not explicitly refer to climate change (e.g. Vespa and Wilson, 2015; Battaglini et al., 2016), but they are just a handful. The seminal paper in the experimental literature is Herr et al. (1997), who investigate extraction in a finite horizon common-pool resource experiment, contrasting a static externality, where a person's extraction increases the extraction costs of others in the current round only with a dynamic externality, where the increase persists also in future rounds. Lower payoffs are reported with dynamic externalities.

[2]With respect to our paper, Pevnitskaya and Ryvkin (2013) and Sherstyuk et al. (2016) study scenarios with lower persistence (with persistence rates of 0.75 and 0.3, respectively); they experiment with smaller groups (two and three group members, respectively).

3 The Model

3.1 The Climate Game

We consider a group with an even number $N \geq 2$ of long-lived countries interacting over an indefinite number of rounds. At any round $t \in \{0, 1, \ldots\}$ of the supergame, there will be an additional round after t with probability $\delta \in [0, 1)$, else the supergame will end at t with probability $(1 - \delta)$. The continuation probability δ is common knowledge; countries do not observe whether or not they are in the last round.

In every round t of the supergame (*sequence*, henceforth), each country $i = 1, 2, ..., N$ chooses its level of GHGs emission $e_i(t)$ from an interval ranging from 0 to a common upper-bound e. Choices are simultaneous. Emissions are the sole input in the production of an output that is enjoyed exclusively by the emitting country according to a production function specified below. After any round, everyone observes current individual emission $e_i(t)$, and the entire history of the game.

Over the rounds, global emissions accumulate in the atmosphere according to the following dynamic equation:

$$E(t) = \sigma E(t-1) + \sum_{i=1}^{N} e_i(t) \ , \tag{1}$$

where $\sigma \in [0, 1]$ is the persistence rate of past emissions, and $(1-\sigma)$ is the rate at which the stock dissipates. So, if $\sigma = 0$ all emissions dissipate at the end of every round, while if $\sigma = 1$ emissions last forever. At the beginning of the sequence, the initial stock of pollution is $E(0) = E_0 \geq 0$.

Each country privately benefits from the output produced through its *own* current emission, but all countries are equally damaged by the stock of *global* emissions (pollution) accumulated up to the current round. The instantaneous payoff of country i is

$$u_i(t) \equiv \gamma ln\left(a_i e_i(t)\right) - \frac{c}{N} E(t) \ . \tag{2}$$

Let's see four features of countries' payoffs. First, we assume a constant carbon intensity in production, which is captured by a linear relationship between individual emission and output that does not change over time, i.e. $a_i e_i$, where a_i is a constant. Second, the payoffs are a natural logarithmic function of the output, which models decision-makers with a declining marginal utility of income. In their climate cost-benefit analysis, Nordhaus (2013) and Stern et al. (2006) assume a utility function that takes the natural logarithm of GDP per capita, which has a constant level of relative risk aversion that is equal to 1. Finally, the parameter $\gamma > 0$ serves only for rescaling.

Third, in the model there exist two types of countries in equal numbers: poor (type p) and rich (type r), which differ only in the level of one parameter, $a_r > a_p$. One way to interpret this is that all countries share the same production technology, but differ in population size so that, for the same level of emission, poor countries exhibit a lower per-capita output than rich countries.[3] The parameter $a_i > 0$ represents a population weight.[4]

To better illustrate the climate game the following aspects should be made explicit. Poor and rich countries can contribute equally to climate change. The aggregate volume of emissions is in potency the same for poor and rich, because the upper-bound e in emission is the same for every country. Rich countries in our experiment best resemble high income countries with a per capita GNI above $12,745 (World Bank threshold in 2010), whose GHG emissions amounted to 18.7Gt in 2010 (IPCC, 2014). Instead, we will roughly consider as poor countries with a per capita GNI below $12,745: while upper-middle income countries' emissions were quite similar to high income countries' emissions (18.3Gt), total emissions from low and lower-middle income countries were lower (11.3 Gt).

Fourth, countries payoffs embed an additive function for climate damages. Hence, payoffs may be negative. In the literature, some scholars follow a multiplicative function (Nordhaus, 2013) while others prefer an additive function (Dutta and Radner, 2004; Harstad, 2012). Damages increase linearly in the stock of emissions according to the parameter $c > 0$.[5]

Moreover, in this set-up, climate change damages will harm poor countries more than rich countries, which roughly reproduce the expectations that the economies of tropical countries, which happened to be on average poor, will particularly suffer from climate change (Tol, 2009). In the model, the damage from climate change is a negative externality that is – in absolute terms – equal for poor and rich countries, while per capita output is not. This feature derives from the additive function in Equation 2 and reproduces an aspect of the field: poor countries are predicted to suffer from climate change more than rich countries. The channels though are somewhat different: in the field damages will be higher for poor countries because they are located in warmer climates (IPCC, 2014), while in the model an equal damage is subtracted from a lower per-capita income.

Each country maximizes the present expected value of its current and future payoffs (Equation 2),

$$v_i = \sum_{t=0}^{\infty} \delta^t u_i(t) \ . \tag{3}$$

[3] This experiment rules out technological change, although this can help to achieve climate policy objectives (Bosetti et al., 2012; Gerlagh and Van der Heijden, 2015).

[4] We do not claim that population is the only driver of inequality in per capita output among rich and poor countries. Yet, differences in population are relevant. An alternative interpretation of $a_r > a_p$ is that country r has a better technology than country p.

[5] There is consensus that the stock of GHG emissions linearly impact temperature. Most scholars argue for a damages function convex in temperatures (Burke et al., 2015) but others argue for a linear approximation (Dutta and Radner, 2004). Linearity allows keeping the experimental design simple. The number of countries at the denominator of the damage rescales payoffs so that the social optimum emission e^* does not depend on N (see Proposition 1).

We interpret the continuation probability δ as the discount factor of an (intertemporally) risk-neutral country (Camera and Casari, 2009).

3.2 Theoretical Benchmarks with Perfect Foresight

Here we provide some theoretical considerations on the equilibria and the social optimum for countries with perfect foresight (F). In Section 3.3, we will consider myopic countries (M).

A strategy of country i is a mapping from the set of all possible histories into the set of emissions. As in most of the applications of dynamic games, we will (mainly) consider Markov strategies that at any round t map the current state, i.e. the current stock of pollution $E(t)$, into the set of emissions, and associated Markov Perfect Equilibria (MPE).

Social Optimum We first determine the level of individual emission e_i which would ensure the achievement of the social optimum, as if countries were cooperating in the maximization of the unweighted sum of individual present-valued payoffs:

$$v = \frac{N}{2}(v_r + v_p).$$

Proposition 1. *The socially optimal emission is constant over the rounds for any country with perfect foresight, and is equal to*

$$e^* = \gamma \frac{1 - \sigma\delta}{c} \ ,$$

regardless of the type of the country.

The socially optimal emission e^* is constant because of the linearity of the damage in the stock of pollution E, and is obtained by equating the marginal benefit from the individual emission γ/e_i to the marginal present-valued *group*'s damage,

$$N \times \frac{c}{N}\left[1 + \delta \frac{\sigma}{(1 - \delta\sigma)}\right] = \frac{c}{1 - \delta\sigma} \ ,$$

which is itself independent of the stock E. The socially optimal emission e^* is the same for all countries (because with the logarithmic function the marginal benefit does not depend on the population weight a_i) and it is decreasing in the persistence of pollution σ.

Constant-Actions Markov Perfect Equilibrium (C-MPE) A simple MPE is that associated with constant-actions Markov strategies, i.e. strategies that neither depend on the stock E, nor on the history of past emissions (both on and off the equilibrium path).

Proposition 2. *The constant-actions Markov Perfect Equilibrium contemplates a constant level of emission over the rounds for any country with perfect foresight, and is equal to*

$$e^F = N\gamma \frac{1 - \sigma\delta}{c} \ ,$$

regardless of the type of the country.

The intuition behind the C-MPE is the same as for the social optimum, with the only difference that each country disregards the damages to the other countries generated by its own emission. Thus, the C-MPE is obtained by equating the marginal benefit γ/e_i to the marginal present-valued *individual* damage $\frac{c}{N(1-\delta\sigma)}$. Clearly, $e^F = Ne^*$. [6]

One can write the associated value function as (see proof in Appendix A)

$$V_i^F(E_0) = U_i^F - \frac{c\sigma}{N(1-\delta\sigma)}E_0,$$

where

$$U_i^F = \frac{1}{1-\delta}\left[\gamma ln(a_i\ e^F) - \frac{c}{1-\delta\sigma}e^F\right].$$

Trigger Strategies Equilibria As usual for dynamic games, also in our settings there exists equilibria based on the history of play (i.e. non-Markov equilibria). In particular, we investigate under which conditions the social optimum can be supported as an equilibrium outcome when countries punish deviations with a perpetual reversion to the C-MPE, e^F. We label the associated equilibrium as "Constant Trigger" Equilibrium.

Proposition 3. *A Constant Trigger Equilibrium which contemplates an emission equal to the socially optimal emission e^* for any country i exists if $\delta \geq \bar{\delta}$, where*

$$\bar{\delta} = \frac{1}{N-1}\left[ln(N)\frac{N}{N-1} - 1\right].$$

The social optimum is implementable if the discount factor δ is sufficiently high, i.e. larger than the threshold $\bar{\delta}$ that, for the structure of the payoffs in our model, only depends on N. For future reference we notice that with $N = 4$, the threshold $\bar{\delta}$ is close to 0.28.

When $\delta > \bar{\delta}$, all emissions levels $e_i \in [e^*, e^F]$ can be supported as equilibrium outcomes. For any emission level e_i constant over the rounds, the stock of pollution E converges to the steady-state

$$E_i = \frac{Ne_i}{1-\sigma},$$

as long as $0 < \sigma < 1$ and diverges to an infinite stock if pollution persists forever ($\sigma = 1$).

Equilibria with Non-Constant Strategies So far we have focused on strategies prescribing an emission that does not depend on the level of the stock of pollution, i.e. constant strategies. However, countries can also follow strategies that specify different emissions depending on the

[6] When pollution entirely dissipates at the end of each round ($\sigma = 0$), the game becomes a repeated one, and the C-MPE corresponds to the Nash equilibrium.

stock's level, i.e. non-constant strategies. Let us define a non-constant strategy to be "simple" if it is a continuous (and continuously differentiable) combination of polynomials, logarithms and exponential functions.

Proposition 4. *Let $e_i(E)$ be a non-constant Markov strategy that is "simple" (as described above in the text). No MPE exists in which countries play the "simple" strategy $e_i(E)$.*

Proposition 4 highlights that countries cannot sustain as an equilibrium strategies prescribing an emission that smoothly varies with the stock of pollution E such as, for example, a proportionality rule $e_i(E) = \beta_i \times E$. However, Proposition 4 does not imply that all strategies that constitute a MPE are constant. With arguments similar to those used to identify the Constant Trigger Equilibria (Proposition 3), one can prove the existence of non-constant MPE that are based on threshold levels of the stock E, and that specify different emissions when such thresholds are reached.

3.3 Theoretical Benchmarks with Myopia

We study myopic decision-makers who underestimate the future damages of their emission choices. We model a "k-myopic" country as one that expect current emissions to only generate a damage lasting for k rounds (the current and the $k - 1$ future rounds). Countries know that their emissions affect at least their current payoffs, hence $k \geq 1$. When $k = 1$ the country is completely myopic, because it *only* considers the effect of emissions in the current round. Instead, if $k = +\infty$, we are back to the perfect foresight model, in which the country foresees the effect of emissions on the current round and *all* future rounds (albeit with the smaller impact implied by the dissipation of the stock when $0 < \sigma < 1$).

Our definition of k-myopia is a form of bounded rationality that has milder consequences than those put forward in other dynamic experiments. Unlike Sherstyuk et al. (2016), our myopic agents correctly perceive the shadow of the future (δ is positive and equal to 0.92). As such, they will be able to support trigger strategies that can lead to positive cooperation levels. Our model also differs from Pevnitskaya and Ryvkin (2013), where, by definition, myopic agents will achieve a zero cooperation level. We simply assume that k-myopic agents emit while neglecting all pollution damages beyond a given future cutoff date k. As already mentioned, we can accommodate various degrees of myopia, including the most severe that involves the present round as the cutoff date ($k = 1$). This seems to be the definition followed in Herr et al. (1997), although applied to a different framework with finite horizon and thus limited possibilities of cooperation.

A k-myopic country perceives the social optimum and the C-MPE differently than a country with perfect foresight:

Proposition 5. *The perceived social optimum and the perceived C-MPE for any k-myopic* *country* $(1 \leq k < +\infty)$ *are respectively*

$$e_k^{*M} = e^* \times \frac{1}{1-(\sigma\delta)^k} > e^* \qquad and \qquad e_k^M = e^F \times \frac{1}{1-(\sigma\delta)^k} > e^F \ ,$$

regardless of the type of the country.

In the extreme case of $k = 1$, the equilibrium emission of this completely myopic country is the same that would emerge with no persistence of pollution ($\sigma = 0$), although pollution actually accumulates according to Equation 1 with $\sigma > 0$. At the other extreme, when k tends to infinity, the myopic equilibrium tends to the equilibrium with perfect foresight.

For intermediate values of k, both benchmarks are clearly higher under myopia than under perfect foresight, but this difference decreases in k. Furthermore, e_k^M is declining in the damage coefficient c as e^F, although to a smaller extent:

$$\frac{\partial e_k^M}{\partial c} = \frac{\partial e^F}{\partial c}\frac{1}{1-(\sigma\delta)^k} < \frac{\partial e^F}{\partial c} \ .$$

This difference reduces in k.[7]

Finally, we notice the following.

Proposition 6. *With myopic countries, if* $\delta \geq \bar{\bar{\delta}}$ *there exists a Constant Trigger Equilibrium with emission equal to the perceived social optimum.*

Also with myopic countries if the discount factor is large enough, i.e. $\delta > \bar{\bar{\delta}}$ as in Proposition 3, then socially optimal emission e_k^{*M} can be sustained as an equilibrium. The proof shows that $\delta > \bar{\bar{\delta}}$ is actually a sufficient condition and that cooperation among myopic countries could be sustained also with a lower δ (Appendix A).

4 Experimental Design

4.1 Treatments

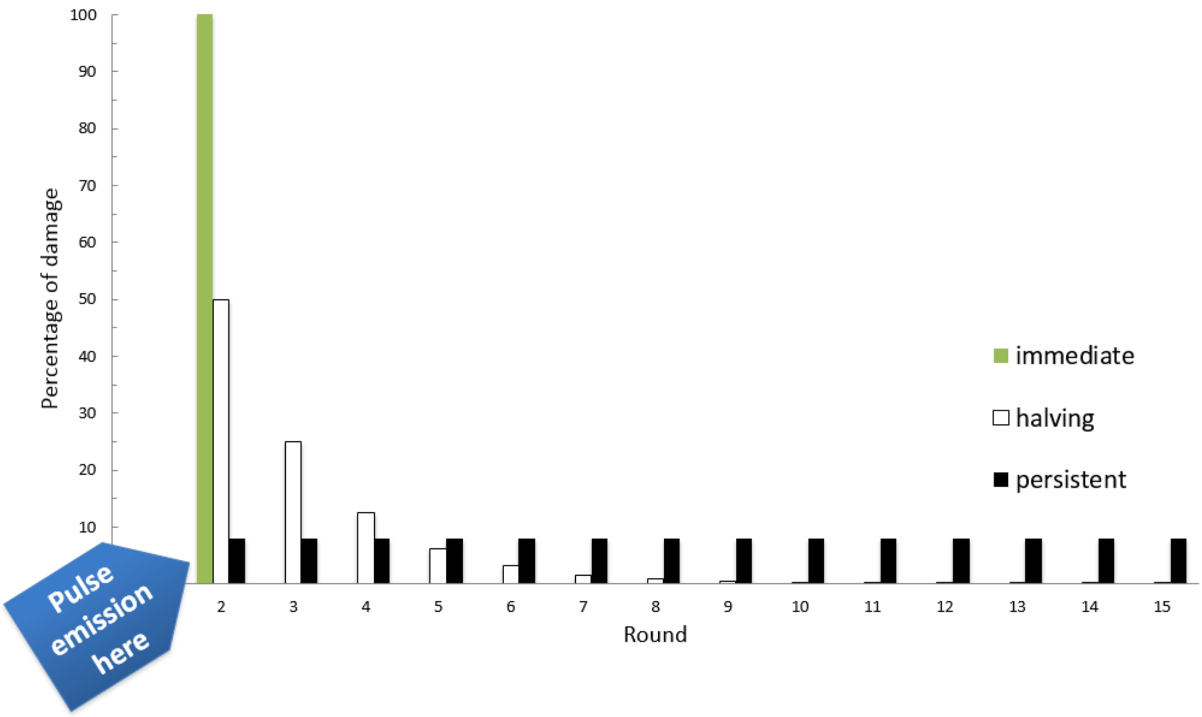
The experiment comprises three treatments: Persistent and Halving – where the externality is dynamic –, and Immediate – where the externality is static. In the Persistent treatment emissions never dissipate ($\sigma = 1$). This scenario roughly approximates the climate change problem where the most relevant greenhouse gases persist in the atmosphere for a very long time. Out of one ton of Carbon Dioxide – the major driver of climate change – emitted today about 50% will remain after 30 years and about 20% to 40% of will remain after 1,000 years (IPCC, 2007; Solomon et al., 2010). The corresponding value of σ that will generate this degree

[7] The same holds for the perceived social optimum.

of persistence is 0.98 for the 30-years horizon and 0.998-0.999 for the 1,000-year horizon. Other greenhouses gases, instead, are short-lived. Methane, for instance, can be removed from the atmosphere by a much faster chemical reaction and persists for decades.

In the Halving treatment half of the stock of pollution dissipates after every round ($\sigma = 0.5$). Finally, in the Immediate treatment there is no stock accumulation and all the damage happens in the current round ($\sigma = 0$) (Figure 1). The three treatments cover the full range of possible persistence levels, with the Immediate treatment serving as benchmark for a static externality.[8]

Figure 1: Illustration of Damage Profiles across Treatments.



Note: Damage generated by an occasional emission in round 2 (=pulse) and zero emission in all other rounds. The emission is identical in all treatments but the distribution of the damage over time differs.

[8]Some pollution externalities not related to climate change are best approximated by the Immediate treatment, such as noise pollution, while others by the Persistent treatment, such as radioactivity from nuclear waste elements like Plutonium 244 (with an half-life of 80 million years).

Climate change is a long-term problem and the experimental set-up incorporates this aspect through the indefinite repetition. After every round there is a continuation probability of interaction of $\delta = 0.92$. This implementation of a supergame was first introduced by Roth and Murnighan (1978). Many simulations of climate change consider scenarios for the year 2100, which is 85 years away from today. In the experiment, each sequence has an expected length of $1/(1-\delta) = 12.5$ rounds, which can be interpreted as a decision every 7 years up to 2100.[9] Consider also that for risk-neutral agents this set-up is theoretically equivalent to an infinite time horizon with a discount factor of 0.92. While individuals have a finite life, countries and societies can be treated as long-lived. This calibration of δ creates favorable conditions for the emergence of cooperation because the shadow of the future is sufficiently large to sustain the socially optimal emission. From a theoretical point of view, what is required is that δ is larger than 0.28 (Proposition 3).[10]

We chose a design with a damage from emissions that is identical across treatments in terms of its present value. For each unit of emission, the expected damage is 33.375 in all treatments but varies in the way it is spread over time. In the Immediate treatment the damage occurs entirely in the round in which the emission is done ($c = 33.375$). In the Halving treatment, half of the damage occurs in the current round ($c = 18.0225$) and the other half in the future. In the Persistent treatment, there is a damage of $c = 2.67$ in current round and of 2.67 in each one of all future rounds. The expected value of the damage in the Persistent treatment is 33.375, given an expected duration of 12.5 rounds (Table 1).

Given this calibration of σ and c, the socially optimal level of emissions and the equilibrium with perfect foresight remain the same *in all treatments* (Propositions 1 and 2). This feature allows for an easy comparability of experimental results. Both theoretical benchmarks are away from the boundaries of the action space to allow for excessive restraint or overshooting in emissions. Participants could emit any integer amount between 1 and 18, while the social optimum is at 3 and the equilibrium with perfect foresight at 12.[11]

A group comprises four members, each of whom represents a country or a group of countries.

[9] The Conference of Parties for climate change negotiations, COP, have actually been meeting every year since 1995 but many meetings produce no substantive decisions. In the lab, the initial round starts with no past history of emissions, as we set the initial stock of pollution E_0 equal to 0. This feature can represent an intriguing treatment dimension (e.g. Tavoni et al., 2011) that we leave for future research.

[10] From an empirical point of view, larger continuation probabilities have been associated with higher degrees of cooperation (Dal Bó and Fréchette, 2014). In the experiment, δ is well within the boundary to support cooperative outcomes even when participants are moderately risk-averse.

[11] When taking $\sigma_h = 1$ and σ_l either equal to 0 or 0.5, the condition $e^{C-MPE}(\sigma_h) = e^{C-MPE}(\sigma_l)$ is satisfied for the following relation between the damage parameters

$$c_l = c_h \frac{1-\delta\sigma_h}{1-\delta\sigma_l}$$

Recall from Proposition 2 that $e^{C-MPE}(\sigma_h) = \gamma \frac{1-\sigma_h\delta}{c_h}$. The same condition ensures also equal social optima across treatments.

Table 1: Overview of the Experiment.

		Treatments		
		Immediate	Halving	Persistent
Parameters				
δ	Discount factor (continuation probability)	0.92	0.92	0.92
σ	Pollution persistence	0	0.5	1
c	Damage in the current round	33.375	18.0225	2.67
a_r	Population weight for rich country	40.05	40.05	40.05
a_p	Population weight for poor country	8.01	8.01	8.01
γ	Utility rescaling	100	100	100
E_0	Initial stock of pollution	0	0	0
Predictions and results				
e^*	Social optimum (individual emission)	3	3	3
e^F	Constant-Markov Perfect Equilibrium with perfect foresight	12	12	12
e_i	Result: average emission (1-18)	9.4	8.8	9.1
Sessions (dd/mm/yy)				
		20/05/15	28/05/15	13/05/15
		21/05/15	29/05/15	14/05/15
		27/05/15	18/06/15	25/05/15
				28/05/15
Number of participants (main task + side task)		60+15	60+15	80+20
Number of groups		55	60	70
Number of sequences		11	12	14
Average length of a sequence		30.4	22.5	17.6

Note: Average emissions are computed as the mean of the individual emissions in a group in a sequence. Session 2015/5/20 (Immediate) was interrupted during the third sequence following the protocol described in the main text for time constraints. Session 2015/5/13 (Persistent) was unexpectedly stopped during the second sequence because of a software problem.

That is a simplification in comparison to the over 190 countries who meet for climate negotiations. Consider, though, that in 2010 eight countries accounted for almost 2/3 of annual GHGs emissions worldwide (EDGAR database, JRC and PBL, 2016). Four countries accounted for more than half (China, USA, European Union 28, and Brazil). The RICE model for instance performs simulations using twelve blocks of countries (Nordhaus, 2010).[12] Limiting group size to four allows increasing the number of independent observations while retaining the possibility of overcoming coordination issues and some degree of heterogeneity. There are two rich and two poor members in each group, randomly assigned, with an equal potential for emissions.

The RICE model, for instance, has five poor regions and seven rich regions.[13] Our design incorporates income inequalities of a comparable magnitude of those in the field. On average the

[12]Climate change experiments in the literature employed groups with up to 10 members (Barrett and Dannenberg, 2014).

[13]We label "rich" a region with a per capita GNI greater than $12,745 in 2010 (World Bank's threshold for high income countries). Otherwise, the region is labeled "poor". Poor regions in RICE turn out to be Africa, China, Eurasia, India, and Other Asia ($N = 5$). Rich regions are EU, Japan, Latin America, Middle East, Russia, USA, and Other High Income ($N = 7$).

per-capita income in rich regions is 4.8 times higher than in poor regions (\$34,085 vs. \$7,125.9).[14] For the same level of emissions, in our design the per-capita output of a rich participant is five times larger than that of a poor participant. This is achieved by setting appropriate population weights a_r and a_p (Table 1).

4.2 Procedures

The instructions followed a neutral language and did not use any term that could recall climate change (Appendix C). For instance, we referred to emission choices as "production", and then explained that one participant's production had two effects: to increase personal "revenue" and to "damage" earnings for everyone in the group.

Overall 225 people participated in the experiment at the University of Bologna. There were 25 people in each session: 20 faced the main task described in the previous Section, while 5 performed a prediction task about the behavior of one group of participants. More specifically, they had to guess both the level of damage in the next round and the damage in ten rounds from the current round.[15]

In a session, the 20 participants to the main task faced up to four sequences of interaction. A sequence comprised an indefinite number of rounds, depending on random draws of the computer that were ex-ante unknown to participants and experimenter alike.[16] Within each sequence, participants interacted with the same group (partner protocol). After every sequence, new groups were formed in a way that in following sequences no participant ever interacted again with a person that she had already met (perfect stranger protocol).

Climate change negotiations are performed by professionals and here we employ college students. We aimed at ensuring that agents were well-qualified in the sense of having a good understanding of the rules. To this end: (i) instructions explain the task in a simple way and with an extensive use of figures; (ii) the software has a reader-friendly graphical interface and has built in a simulator tool, where participants can calculate the present and future consequences of hypothetical scenarios of emissions;[17] (iii) everyone completed a comprehension quiz on the

[14]We consider the 2010 average per capita GNIs according to World Bank data. Standard deviations are \$3,273.6 for poor countries, and \$13,340.7 for rich countries. A similar pattern emerges using the median instead of average GNI. We employ the regions of the RICE model.

[15]They received €0.25 for each round of the four sequences plus a show-up fee of €5.

[16] Participants were recruited for a maximum of three hours and a half. If the session was still running after 2 hours and 40 minutes, the experimenter announced that the current sequence was the last one and that the session would have finished within the next 30 minutes. The experimenter told participants that the exact minute at which the sequence was stopped was determined through a 30 faces dice roll, which was immediately rolled and observed by the experimenter but not by the participants.

[17]Four simulations were allowed in every round of each sequence. In Immediate and Persistent treatments, participants used on average 5% of the total simulations available. In the Halving treatment, they simulated slightly more (9%). Some participants never used the simulator (17 in Immediate, 18 in Halving, and 14 in Persistent).

instructions (Appendix D);[18] (iv) those with a poor understanding of the instructions were excluded from the main task: the five participants with the highest number of mistakes and/or missing answers in the quiz were assigned to the prediction task, not the main task; (v) after the quiz, everyone underwent a fifteen-round practice phase playing against robot opponents in order to familiarize with the main task and the software;[19] (vi) we asked participants to write down on paper after every round their own and their group members' emissions in order to make sure that they actively followed the play;[20] (vii) participants experienced four separate sequences with identical rules and, hence, they could have learnt by doing; what we observe are minor changes in average behavior across the sequences (Figure B.7 in Appendix B), which denotes that participants in the initial sequence were already closed to their steady state behavior; (viii) the instructions explicitly stated that when everyone emitted 3, group earnings would be maximized (social optimum).[21]

Table 1 summarizes some statistics of the experimental sessions. Participants in the main task were paid according to the total amount of tokens they earned in all the sequences: they received €0.01 for every 6 tokens plus a show-up fee of €4 in the Persistent treatment, €5 in the Halving treatment, and €6 in the Immediate treatment. Since cumulate earnings could be negative at the end of the experiment because of the damage, we ensured them a minimum payment of €10. Average earnings for those who participated into the main activity were €17.60; overall, 40 participants (20%) earned €10.

Recruitment was done via ORSEE (Greiner, 2015) and participants were involved in at most one session. Instructions were read aloud and participants had a hard copy on their desks. Sessions took place at the BLESS laboratory of the University of Bologna using zTree (Fischbacher, 2007).

5 Results

We report five main results, which concern the degree of overall cooperation achieved in the various treatments (Results 1 and 2) and the strategies used by the representative participant (Results 3–5).[22]

[18] The quiz is implemented on zTree. There is no monetary compensation for correct answers. Whenever a participant selects a wrong answer, the correct one is pointed out. Participants must answer within 50 seconds, else the software automatically moves to the next question; missing answers count as mistakes.

[19] These decisions had no consequences on their earnings. Robots were programmed to choose different levels of emission in every round. Robots decisions were the same for all participants and for all sessions in every treatment.

[20] While past emissions are irrelevant for decisions according to the C-MPE, they can be relevant if participants follow other strategies, such as grim-trigger (Proposition 3).

[21] Similarly, experts participating in climate negotiations are aware of the optimal long-term emissions targets.

[22] The dataset always includes choices under "limited liability", which is the situation where the participant's cumulate earnings over the session *dropped* below €10. The frequency of this situation is as follow: in terms

Result 1 (Cooperation). *Persistence does not hamper cooperation: average emissions are similar with static and dynamic externalities.*

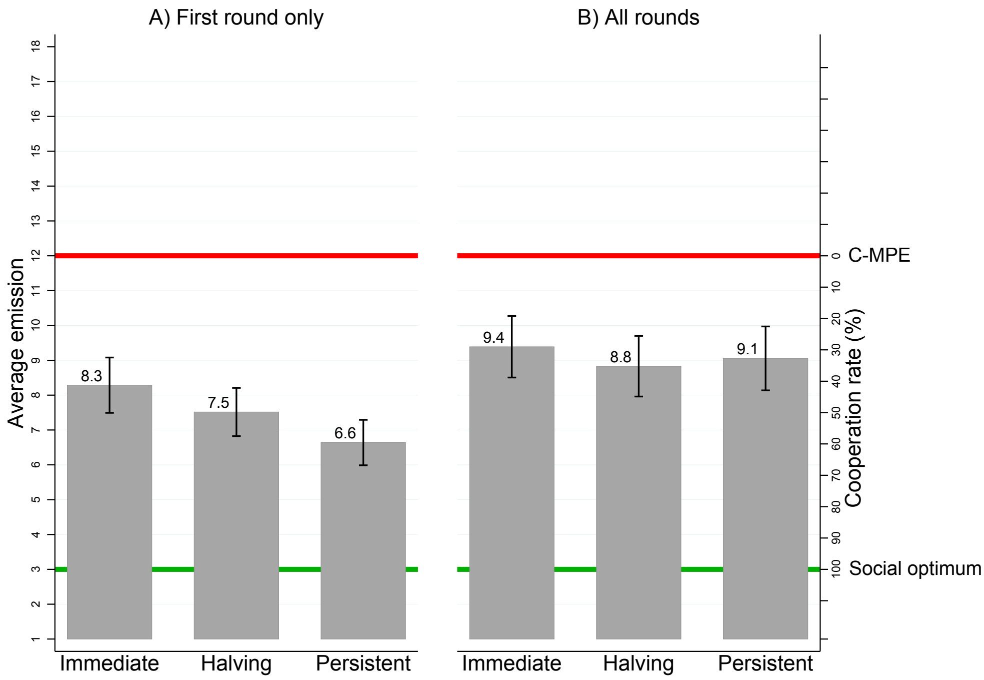
Support for Result 1 is in Figure 2 and Table 2. The social optimum corresponds to a cooperation of 100% and the C-MPE to 0% cooperation. In the experiment, the average cooperation levels were 29.0% in Immediate, 35.2% in Halving, 32.7% in Persistent. There are no statistically significant differences in average emissions across treatments.[23] This result is supported by Tobit regressions, where average emissions under static externalities are not statistically different from those under dynamic externalities with various specifications and when adding controls (Table 2). Average emissions were stable as participants gain experience across sequences (Figure B.7 in Appendix B). Also a non-parametric test over average emission in all rounds reveals no significant monotonic relationship if treatments are ordered by the degree of persistence (Jonckheere-Terpstra test: p-value=0.252, N_I=55, N_H=60, N_P=70).

The reported cooperation levels are in line with those from the dynamic public bad experiments of Sherstyuk et al. (2016) and Pevnitskaya and Ryvkin (2013) in comparable treatments (49% and 10-20%, respectively). Long-run participants in Sherstyuk et al. (2016) achieved average individual emissions of 4.5 in a possible range of 1-11, with a social optimal at 3 and a C-MPE at 6. In Pevnitskaya and Ryvkin (2013) average individual emissions with indefinite horizon were between 8 and 9 in a possible range between 0 (social optimal) and 10 (C-MPE).

of number of choices, 195 (8%) in Immediate 110 (6%) in Halving 0 (0%) in Persistent; in terms of number of participants involved, 4 in Immediate, 8 in the Halving, none in Persistent. None of the participants recovered from limited liability. Appendix B.1 reports robustness checks when excluding these observations. They did not affect any Result 1-5.

[23] We perform a series of Wilcoxon-Mann-Whitney tests on bilateral differences in average emissions for a group in a sequence. The unit of observation is the average emission in each group over all rounds. The test assumes that these observations are independent. We do not detect any significant difference between distributions of average emissions (Persistent vs. Immediate: p-value=0.564, N_P=70, N_I=55; Persistent vs. Halving: p-value=0.817, N_P=70, N_H=60; Immediate vs. Halving: p-value=0.268, N_I=55, N_H=60).

Figure 2: Average Emission by Treatment.



Note: The unit of observation is a group in a sequence (N=55 in Immediate, N=60 in Halving, N=70 in Persistent). Individual emissions can range from 1 through 18. The vertical segments represent the 95% confidence interval. C-MPE and social optimum refer to the perfect foresight model.

Table 2: Static vs. Dynamic Externality (Tobit regressions).

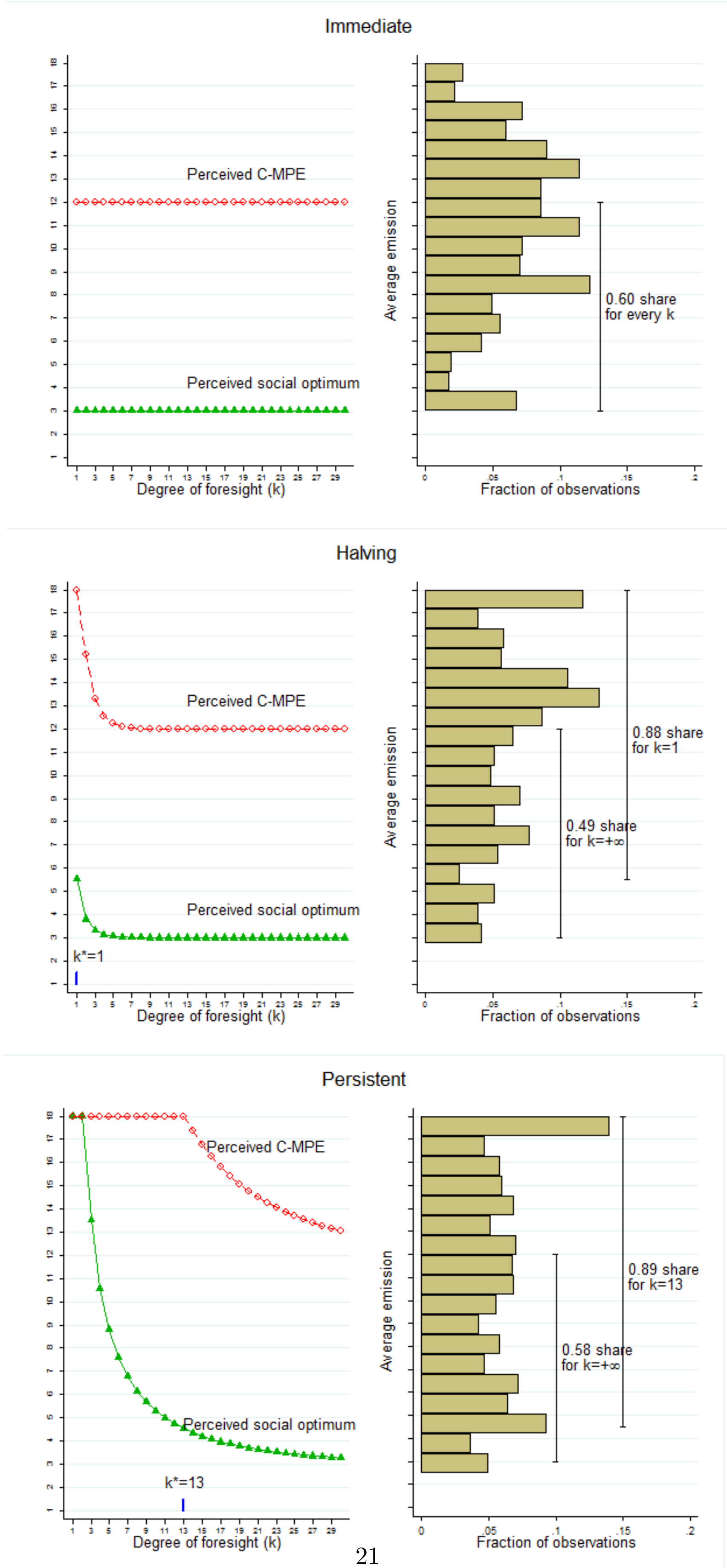
Dependent variable: Average emission over all rounds	(1) All treatments	(2) All treatments	(3) Immediate and Persistent	(4) Immediate and Persistent
Treatment dummies				
Halving or Persistent	–0.439	–0.263		
	(0.563)	(0.504)		
Persistent			–0.336	–0.136
			(0.644)	(0.619)
Sequence dummies				
Sequence 2		1.109*		0.742
		(0.626)		(0.788)
Sequence 3		0.701		0.288
		(0.671)		(0.826)
Sequence 4		0.654		0.003
		(0.656)		(0.888)
Length of current sequence		0.140***		0.122***
		(0.022)		(0.027)
Length of past sequence		–0.013		–0.064
		(0.032)		(0.056)
Constant	9.390***	7.359***	9.390***	8.292***
	(0.472)	(0.683)	(0.482)	(0.915)
Observations	185	185	125	125

Note: The unit of observation is a group in a sequence. Observations are censored at 1 and 18. In columns 3 and 4 observations relative to the Halving treatment are omitted. The variable "Halving or Persistent" is a dummy taking value 1 in the Halving and Persistent treatments and 0 in the Immediate treatment. The variable "Persistent" is a dummy taking value 1 in the Persistent treatment, 0 in the Immediate treatment. The variable "Length of past sequence" counts the number of rounds in the previous sequence; in sequence 1 it is set to 12.5. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The evidence does not support the conjecture that participants' behavior is myopic, that is a systematic underestimation of the long-run consequences of current emissions (Proposition 5). For each treatment, we computed the perceived C-MPE and perceived social optimum for various degrees of myopia. In the Immediate treatment, these theoretical benchmarks are identical for myopic agents and agents with perfect foresight. One can see this because the perceived theoretical benchmarks do not vary with the degree of foresight (k), and appear as flat lines in Figure 3. In the Halving and Persistent treatments, instead, the perceived theoretical benchmarks weakly decline in k (Figure 3). When $k = +\infty$, the agent has perfect foresight. When $k = 1$ the agent perceives only a small fraction of the total damage, because she sees only the damage suffered in the current round.

We perform a simple empirical test of our model of myopic agents. For any given k, all emission levels that lie between the two perceived benchmarks are admissible equilibrium outcomes We proceed by identifying the degree of foresight k^* that can rationalize the widest fraction of emissions observed in each treatment. This exercise shows that our simple model of myopia performs poorly in explaining the data. Consider the empirical distribution of individual emissions over all rounds that is reported on the right-hand side of Figure 3. Under the assumption that all participants are identical in terms of degree of foresight k, the level of myopia that best rationalizes the data is very different for Halving (k^*=1) and Persistent (k^*=13), which is at odd with the random assignment of participants to treatments. Moreover, the myopic model clearly overfits the data in Halving and Persistent in comparison with Immediate, which suggests that the model rationalizes the data for the wrong reason. In Halving, participants with one round of foresight can explain a 0.88 share of the emission choices, while in Persistent participants with 13 rounds of foresight can explain a 0.89 share of choices. In Immediate, neither perfect foresight nor any degree of myopia can explain more than a 0.60 share of choices. In other words, in the situation where myopia plays no role (Immediate), we are able to rationalize a substantially lower share of choices than in the other treatments. Hence, the reason why a myopic model can rationalize more choices in the Halving and Persistent treatments is simply because it widens the range of admissible actions.

Figure 3: Myopic Benchmarks and Empirical Distributions of Emissions.



Note: The unit of observation is the average emission in a group in every round of the sequence (N=595 in Immediate, N=500 in Halving, N=785 in Persistent).

While there are no statically significant differences in emissions when considering all rounds, there are some when focusing on first round emissions, but in the opposite direction of what predicted by myopic behavior. First-round emissions are lower in Persistent than in Immediate treatment, and statistically significant so (Figuer 2A).[24] That suggests the existence of a distinct trend in emissions over the rounds, which we will explore later, after having presented Result 2 below.

Result 2 (Rich vs. poor). *The rich emit 6% to 15% less than the poor depending on treatments. These differences are not always significant.*

The supporting evidence is in Figure 4 and Table 3. While there is no significant difference in average emissions between rich and poor in the Immediate treatment ($p-$value=0.658, $N_I = 55$), the difference is significant in the Halving ($p-$value=0.009, $N_H = 60$) and Persistent treatments ($p-$value=0.003, $N_P = 70$).[25] This result is partially confirmed by Tobit regressions over individual emission choices (Table 3). The Rich dummy takes value 1 if the participant is rich and 0 otherwise, and exhibits a coefficient that is negative and significant only in the Persistent treatment.[26] Thus, the empirical evidence partially diverges from the prediction that emissions are the same for rich and poor countries (Propositions 1 and 2), but to a rather weak extent.

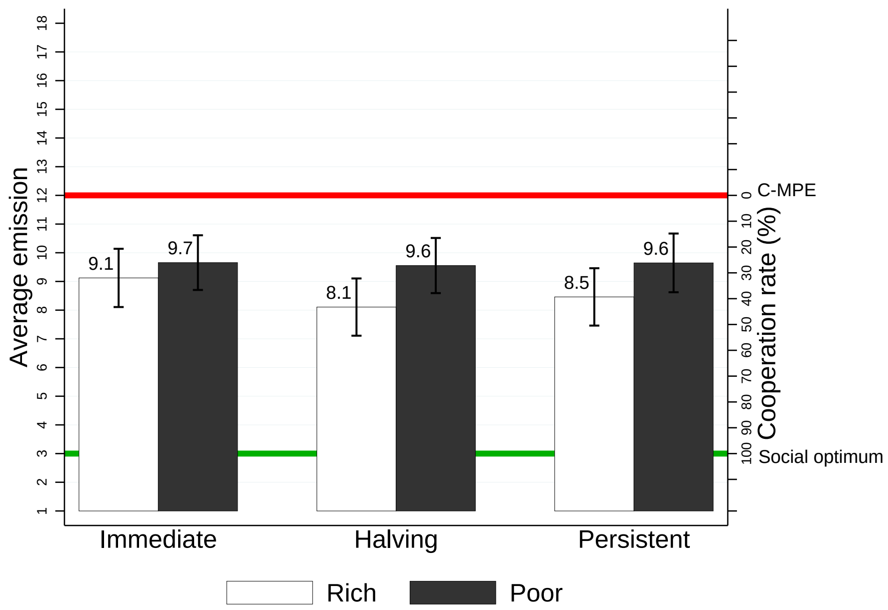
In the experiment, inequality in earnings between rich and poor were sizable, especially in the long run. In Figure 5 we measure the average inequality between rich and poor using a ratio of cumulative earnings. We divide the earnings gap between rich and poor by the earnings of the rich. In round 20, this inequality ratio is 88.6% in the Immediate treatment, 100% in the Halving treatment and 53.6% in the Persistent treatment. By design, inequality is predicted to increase in the dynamic treatments when countries follow a C-MPE strategy. The reason lies in the impact of the cumulative damage over time, which reduces the denominator in the earnings ratio. Empirically, inequality increases over the rounds in all treatments (Figure 5).

[24] Average emissions in the first round of the sequence follow a statistically significant decreasing trend in the degree of persistence (Jonckheere-Terpstra test: p-value=0.000, N_I=55, N_H=60, N_P=70). Tobit regressions confirm this evidence (Table B.4 in Appendix B).

[25] All p-values in parentheses refer to one-sided sign tests, which test whether the median emission of poor participants is higher than the median emission of rich participants. The unit of observation is the median emission of the two rich and the two poor participants of a group over all rounds of the sequence. The test assumes that observations are independent.

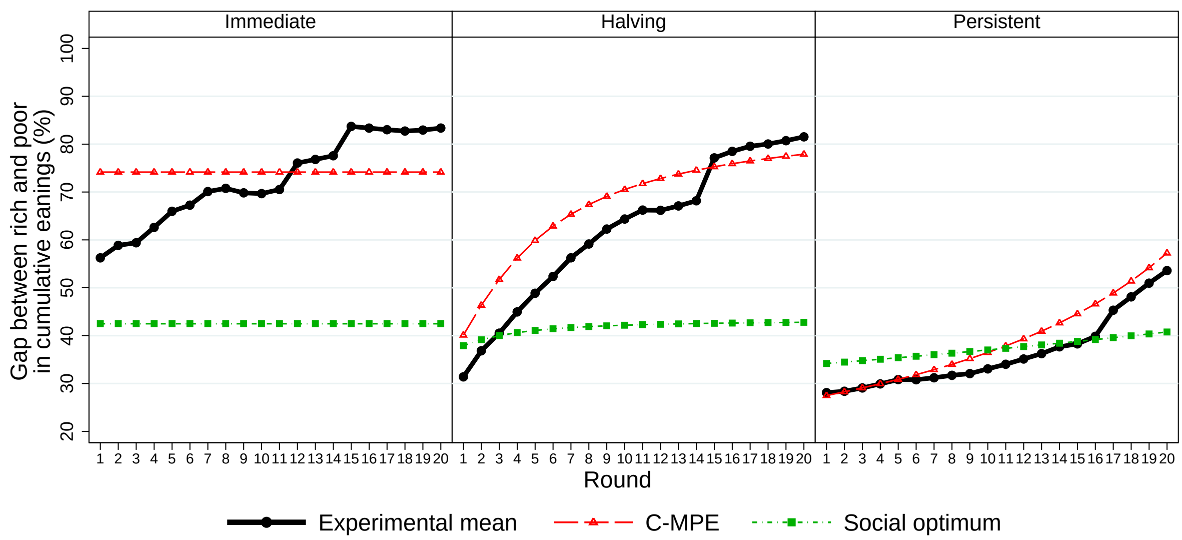
[26] A similar evidence emerges using Tobit regressions with individual random effects instead of clusters (Table B.5 in Appendix B).

Figure 4: Average Emissions of Rich and Poor by Treatment.



Note: The unit of observation is one type of participants of a group in the sequence (N=55 in Immediate, N=60 in Halving, N=70 in Persistent). We consider the average emission of the two rich (poor) participants of a group over all rounds of the sequence. Individual emissions can range from 1 through 18. The vertical segments represent the 95% confidence interval. C-MPE and social optimum refer to the perfect foresight model.

Figure 5: Earnings Inequality between Rich and Poor.



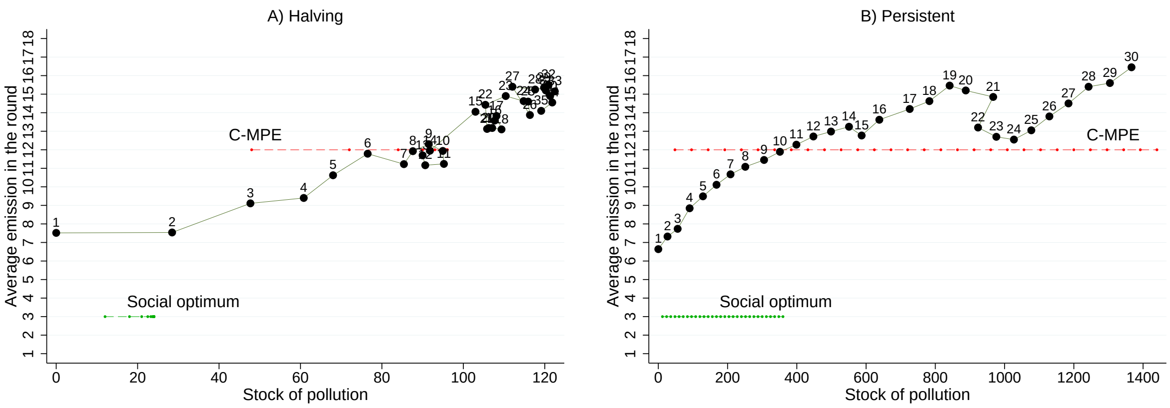
Note: See main text for explanation. Rounds have been truncated to 20. Cumulate earnings of participants under limited liberality are set to the equivalent of €10. C-MPE and social optimum refer to the perfect foresight model.

Table 3: Tobit Regressions of Individual Emission.

	Immediate		Halving		Persistent	
Dependent variable: Individual emission in the current round	(1)	(2)	(3)	(4)	(5)	(6)
Loss in the previous round		2.329***		1.628*		7.819***
		(0.817)		(0.890)		(2.321)
Stock of pollution			0.102***		0.027***	
			(0.010)		(0.002)	
Rich	0.974	1.324*	–0.334	0.331	–1.930***	–1.332**
	(0.730)	(0.779)	(0.805)	(0.918)	(0.696)	(0.676)
Round	–0.008	–0.006	–0.068**	0.197***	–0.566***	0.381***
	(0.036)	(0.035)	(0.028)	(0.042)	(0.095)	(0.108)
Sequence dummies						
Sequence 2	–2.411	–2.322	1.958**	3.311*	–0.241	–1.326
	(1.865)	(1.784)	(0.961)	(1.760)	(0.652)	(1.496)
Sequence 3	0.128	0.147	1.915**	4.010**	0.597	0.289
	(1.616)	(1.557)	(0.965)	(1.936)	(0.759)	(1.367)
Sequence 4	–0.580	–0.570	2.599**	0.894	–0.742	–2.127
	(1.721)	(1.643)	(1.104)	(1.668)	(0.949)	(1.750)
Length of past sequence	–0.135	–0.127	0.006	–0.050	–0.023	–0.093
	(0.154)	(0.149)	(0.054)	(0.108)	(0.051)	(0.113)
Mistakes in the quiz	0.195	0.183	0.476*	0.619*	–0.093	0.074
	(0.436)	(0.435)	(0.278)	(0.342)	(0.231)	(0.282)
Limited liability	3.562**	2.339*	2.589*	3.140		
	(1.625)	(1.331)	(1.406)	(2.439)		
Constant	11.591***	11.160***	2.843***	5.591***	10.060***	10.091***
	(2.123)	(2.024)	(1.095)	(1.709)	(0.952)	(2.274)
Observations	2380	2380	2000	2000	3140	3140

Note: The unit of observation is a participant's emission choice in a round. Observations are censored at 1 and 18. Standard errors are clustered at the level of a group in a sequence. The variable "Loss in the previous round" is a dummy taking value 1 if in participant's earnings in the previous round were negative, and 0 otherwise. The variable "Rich" is a dummy taking value 1 if a participant is of type r and value 0 if is of type p. The variable "Length of past sequence" counts the number of rounds in the previous sequence; in sequence 1 it is set to 12.5. The variable "Mistakes in the quiz" counts the number of mistakes made by the participant in the quiz on the instructions. The variable "Limited liability" is a dummy taking value 1 is the emission decision was made under limited liability, and 0 otherwise. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 6: Participants' Strategies Depend on the Stock of Pollution.



Note: One observation is the average emission of each group in a round of a sequence. Each dot is the average of all groups in a round over all sequences. The number next to each dot indicates the round. The stock of pollution is measured at the beginning of the round. Individual emissions can range from 1 through 18. C-MPE and social optimum refer to the perfect foresight model.

Result 3 (Strategies: Persistent treatment). *In the Persistent treatment, participants' strategies are increasing in the stock of pollution.*

Evidence for Result 3 comes from Figure 6B and Table 3. Figure 6 plots for each round the average emission against the stock of pollution. In the Persistent treatment, the higher the stock and the higher are average emissions, which runs contrary to the theoretical benchmarks of social optimum and C-MPE (Propositions 1 and 2) that are represented by flat lines (Figure 6B).[27] A Tobit regression confirms that emission levels are significantly increasing in the stock of pollution (Table 3, column 5). When controlling for the time trend (Round), the stock of pollution exhibits a positive coefficient, which is statistically significant at 1% level.[28]

Result 4 (Strategies: Halving treatment). *In the Halving treatment, participants' strategies are generally increasing in the stock of pollution. For some levels of the stock, we frequently observe "cycles".*

Evidence for Result 4 comes from Figure 6A and Table 3. In the Halving treatment, a Tobit regression shows that emission levels are significantly increasing in the stock of pollution (Table 3, column 3). When controlling for the time trend (Round), the stock of pollution exhibit a positive coefficient, which is statistically significant at 1% level.

A difference with the Persistent treatment is the presence of cycles at stock levels between 85 and 130 (Figure 6A). Recall that in Halving, unlike in the Persistent treatment, the stock

[27] The stock is lower in round 22 than in round 21 due to the aggregation of the observations, which substantially drop after round 20.

[28] This coefficient remains positive and statistically significant at 1% level in a Tobit regression with individual random effects (Table B.5 in Appendix B).

level can decrease in case of sufficiently low emissions. Consider a situation with a stationary stock. A cycle arises when participants gradually lower emissions and hence the stock declines. In the following rounds participants gradually increase emissions in a way that the stock grows and reaches again the initial level. The effect of these cycles is to keep the average stock of pollution constant. Figure 6, which considers the aggregate behavior, shows three cycles, one of which happening at the stock level around the C-MPE steady state. One can also look at the patterns of cycles in each group in a sequence. In the experiment, the wide majority of groups that interacted for more than 5 rounds displayed at least one cycle (Figure B.9 in Appendix B). What is particularly interesting with these cycles is the fact that when the stock stabilizes reaching the steady state for some emissions, the average group emission tend to decrease. However, the graphical evidence seems to suggest that after observing the consequent reduction of the stock, participants revert towards higher emissions and so the stock begins growing again.

In conclusion, according to Result 3 and 4 individual emissions display an increasing pattern in presence of dynamic externalities (Halving and Persistent treatments). While a clear causal identification is challenging with our design, this pattern seems to be associated with the accumulation of stock of pollution and, hence, of the damage, rather than with a simple time trend.[29] We draw this conclusion by noting that when controlling for the stock of pollution the trend (Round) becomes negative while the stock's coefficient is positive and significant (Table 3, columns 4 and 6). Moreover, Figure 6A shows a stabilization of the average emission when the stock stops growing, because it reached a steady state. In contrast, with static externalities (Immediate treatment), we do not observe any significant trend in the emissions (Table 3, columns 1 and 2), which is quite consistent with the constant-strategies benchmarks (Propositions 1 and 2).

Result 5 (**Impact of losses**). *The individual experience of a loss raised on average the emission in the following round.*

Support for Result 5 comes from Table 3. In a given round, a participant incurs in a loss if the global damage outweighs the benefit from one's emission. The percentage of losses is sizable in all treatments (11.9% in Immediate, 18.7% in Halving, and 11.1% in Persistent).[30] A Tobit regression in Table 3 shows the presence in all treatments of a correlation between experiencing a loss in a given round and increasing emissions in the subsequent round. The coefficient of

[29] Proposition 4 states that no "simple" strategy proportional to the stock of pollution can be a MPE. Nonetheless, there exist MPE with strategies that prescribe increasing emissions when the stock overcomes certain thresholds.

[30] According to a series of Fisher Exact tests there is no significant difference between the fraction of losses in the Immediate treatment and the Persistent treatment (p-value=0.326), while the fraction of losses in the Halving treatment is higher than in both the Immediate and the Persistent treatments at the 1% significance level. The magnitude of the average loss is increasing in the persistence of the externalities (-46 tokens in Immediate, -80.8 in Halving, and -218.1 in Persistent).

Loss is positive and statistically significant at 1% level in the Immediate (column 2) and the Persistent (column 6) treatments, while is positive and significant at 10% level in the Halving treatment (column 4).

6 Conclusions

In order to foster international efforts aimed at avoiding climate change, we need a deep grasp of those factors that hinder or favor cooperation. Here we employ the experimental method to gain an understanding of behavioral factors that are considered crucial in overcoming this special type of social dilemma. In particular, the focus is on a central issue of climate change: the long-term persistence of key greenhouse gases in the atmosphere, which generates irreversibilities. We have developed an experimental platform carefully calibrated on several field specificities to identify the causal effect of different degrees of persistence of pollution on the ability to cooperate in mitigating emissions. We compare settings that cover the full range of possibilities: a static (although repeated) treatment with no persistence, a dynamic treatment where emissions cumulate and last forever, and an intermediate treatment with a decay in pollution at a rate of 50% every round.

We report three main findings. First, the persistence of pollution per sè does not hamper cooperation. One may conjecture that a scenario where today's actions have only immediate consequences would elicit distinct behaviors than a scenario with diluted consequences over time. While an agent with perfect foresight properly considers all types of consequences, a myopic agent may underweight future consequences. We report average levels of cooperation that are similar in these scenarios (Result 1). Moreover, a simple model of myopic behavior does not provide a good fit for the data. This suggests that participants in our experiment, on average, successfully foresee the future impacts of their actions. That is good news for coordinating international efforts to solve the climate change problem as one aspect deemed to negatively influence cooperation seems to have minor effects.

Second, when pollution reaches critical levels, cooperation declines rather than increasing. In all treatments, the experience of a loss in a given round triggers, on average, a higher individual emission in the next round (Result 5). Moreover, with dynamic externalities, emissions exhibit an increasing trend. One may conjecture that the use of conditionally cooperative strategies may explain such trend. However, in the setting most closely related to the experimental literature on social dilemmas (Immediate treatment), no increasing trend appears in the data. Furthermore, in the Halving treatment, when the stock reaches its steady state and stops growing, average emissions tend to stabilize as well. Taken together, these considerations suggest that the increasing trend in emissions emerging in the Halving and Persistent treatments is linked to the stock of pollution rather than time or experience (Results 3-4). One possible behavioral mechanism is that participants may attempt to maintain positive earnings in each round. As the damage is proportional to the stock, participants may increase their emissions over the rounds in order to overcome the effects of a higher stock. If this interpretation is correct, it implies that climate change calls for urgent interventions. Policy-makers should not delay mitigation actions until the situation gets dangerous, as the experimental evidence suggests that cooperation becomes harder than early on.

Third, behavioral differences in emissions between rich and poor are of second-order importance (Result 2). In our setting, equilibrium emissions are identical for rich and poor countries. By design, however, the same level of emissions will generate a lower per capita output in poor than rich countries with a rather wide gap in terms of welfare (from 41% to 78% depending on the treatment). Moreover, by design there is no intrinsic conflict between concerns for efficiency and equality, as both motivations will induce participants to increase cooperation levels toward the social optimum level (in the Persistent treatment, this is true only in the long run). In the experiment, rich participants emit less than poor participants, at least with dynamic externalities. However, the extent to which the rich emit less than poor participants is rather small (on average, between 6% and 15%). This suggests that rich participants are not willing to contribute much more than poor participants in the mitigation efforts, even if mitigation is more demanding for the poors in terms of welfare.

Any economic experiment on climate change is necessarily a study in a highly simplified setting. This is true also in our case. Take for example the damage function: in the lab, impacts are immediate and deterministic instead of delayed and stochastic. Uncertainty or limited perception of the actual environment may impair countries' ability to cooperate. Future work can remove these and other limitations of our approach. Nevertheless, we believe that experiments are yet an additional tool that can further our understanding of how to foster international cooperation for tackling climate change.

This study brings a novel contribution on the behavioral components of cooperation to solve the climate change problem by addressing the issue of pollution persistence. Carbon is forever but the good news is that, at least in the short-term, this will not condemn us to suffer from lack of cooperation any more than in the usual static social dilemmas. Still, policy interventions are urgent and must kick in as soon as possible.

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Appendices

A Proofs

Proof of Proposition 1 (Social optimum). At any round t, let E be any initial value of emission and $V(E)$ the associated value function, i.e. the solution of the dynamic programming problem (Hamilton Jacobi Bellman equation):

$$V(E) = \max_{e_r,e_p}\{\frac{N}{2}\gamma\left[ln(a_r e_r) + ln(a_p e_p)\right] - c \times \left(E + \frac{N}{2}e_r + \frac{N}{2}e_p\right)] + \delta V(E + \frac{N}{2}e_r + \frac{N}{2}e_p)\},$$

where for a simpler notation E is the stock of emissions inherited from the past. Let $e_p(E), e_r(E)$ be solutions to the previous maximization. Plugging these into the previous equation we obtain a functional equation in $V(E)$. We guess that $V(E)$ takes the following form:

$$V(E) = \frac{N}{2}\left(w_p + w_r\right) - \frac{N}{2}(k_p + k_r)E.$$

We now have to verify if these four parameters w_i and k_r exist that satisfy the HJB equation and to identify them. From the HJB equation, applying our guess for the value function we obtain

$$\begin{aligned}\frac{N}{2}\left(w_p + w_r\right) - \frac{N}{2}(k_p + k_r)E \quad &= \quad \max_{e_r,e_p}\{\frac{N}{2}\gamma\left[ln(a_r e_r) + ln(a_p e_p)\right] - c \times \left(E + \frac{N}{2}e_r + \frac{N}{2}e_p\right) + \\ &\quad +\delta[\frac{N}{2}\left(w_p + w_r\right) - \frac{N}{2}(k_p + k_r)\sigma(E + \frac{N}{2}e_r + \frac{N}{2}e_p)]\}\end{aligned}$$

The necessary conditions on e_r, e_p are

$$\frac{\gamma}{e_i} = c + \delta\sigma(k_p + k_r)\frac{N}{2}$$

or

$$\bar{e}_i = \frac{\gamma}{c + \sigma\delta(k_p + k_r)\frac{N}{2}}$$

which is independent of E. Plugging into the HJB Equation, we have

$$\begin{aligned}\frac{N}{2}\left(w_p + w_r\right) - \frac{N}{2}(k_p + k_r)E \quad &= \quad \frac{N}{2}\gamma\left[ln(a_r \bar{e}_r) + ln(a_p \bar{e}_p)\right] - c \times \left(E + \frac{N}{2}\bar{e}_r + \frac{N}{2}\bar{e}_p\right) + \\ &\quad +\delta[\frac{N}{2}\left(w_p + w_r\right) - \frac{N}{2}(k_p + k_r)\sigma(E + \frac{N}{2}\bar{e}_r + \frac{N}{2}\bar{e}_p)]\end{aligned}$$

Solving for $w_p + w_r$

$$
\begin{aligned}
(w_p + w_r) \quad &= \quad \frac{1}{1-\delta}\Bigg\{(k_p + k_r)E + \gamma\left[ln(a_r\bar{e}_r) + ln(a_p\bar{e}_p)\right] - c \times \left(E\frac{2}{N} + \bar{e}_r + \bar{e}_p\right) + \\
&+\delta[-(k_p + k_r)\sigma(E + \frac{N}{2}\bar{e}_r + \frac{N}{2}\bar{e}_p)]\Bigg\}
\end{aligned}
$$

and in order for $w_p + w_r$ to be independent of E it must be

$$(k_p + k_r) - c\frac{2}{N} - \delta(k_p + k_r)\sigma = 0$$

that is

$$k_p + k_r = \frac{2c}{N(1-\delta\sigma)}$$

which shows $\bar{e}_i = e^*$. We also notice that

$$V(E) = \frac{1}{1-\delta}\left[\frac{N}{2}\gamma\left[ln(a_r e^*) + ln(a_p e^*)\right] - \frac{c}{1-\sigma\delta}Ne^*\right] - \frac{c}{1-\sigma\delta}E.$$

QED

Proof of Proposition 2 (Constant MPE). We show that if all countries $j \neq i$ play the constant action e^F then the best response for country i is $e_i = e^F$ which leads to a value function of the type

$$V_i(E) = w - kE.$$

With this guess on the value function we can write

$$w - kE = \max_{e_i}\{\gamma ln(a_i e_i) - \frac{c}{N} \times \left(E + e_i + (N-1)e^F\right) + \delta\left[w - k\sigma(E + e_i + (N-1)e^F)\right]\}$$

where for a simpler notation E is the stock of emissions inherited from the past. The maximizer must satisfy

$$\frac{\gamma}{e_i} = \frac{c}{N} + \delta\sigma k \Longleftrightarrow e_i = \frac{N\gamma}{c + N\delta\sigma k}$$

Subsisting, the previous HJB equation does not depend on E iff,

$$-k = -\frac{c}{N} - \delta\sigma k.$$

or, equivalently

$$k = \frac{c}{N\left(1-\delta\sigma\right)}.$$

It then follows that the best response is indeed

$$e_i = \frac{N\gamma}{c + N\delta\sigma k} = \frac{N\gamma}{c + \delta\sigma\frac{c}{(1-\delta\sigma)}} = \frac{N\gamma\,(1-\delta\sigma)}{c} = e^F.$$

It is also useful to notice that with this result we can write

$$w = \frac{1}{1-\delta}\left[\gamma ln(a_i e^F) - c\frac{1}{1-\delta\sigma}e^F\right]$$

so that

$$V_i(E) = \frac{1}{1-\delta}\left[\gamma ln(a_i e^F) - c\frac{1}{1-\delta\sigma}e^F\right] - \frac{c}{N\,(1-\delta\sigma)}E.$$

QED

Proof of Proposition 3 (Constant Trigger Equilibrium). For any E, the incentive compatibility constraint for any country i with a (candidate) constant equilibrium with actions $\hat{e}_i$ is

$$\begin{aligned} & \gamma ln(a_i\ \hat{e}_i) - \frac{c}{N}\times\left(E + \frac{N}{2}\hat{e}_r + \frac{N}{2}\hat{e}_p\right) + \delta\left\{\hat{U}_i - \frac{c}{N(1-\delta\sigma)}\sigma\left(E + \frac{N}{2}\hat{e}_r + \frac{N}{2}\hat{e}_p\right)\right\} \\ \geq\ & \gamma ln(a_i\ \tilde{e}_i) - \frac{c}{N}\times\left(E + \tilde{e}_i + \frac{N-1}{2}\hat{e}_{i'} + \frac{N}{2}\hat{e}_j\right) + \delta\left\{U_i^F - \frac{c}{N(1-\delta\sigma)}\sigma\left(E + \tilde{e}_i + \frac{N-1}{2}\hat{e}_{i'} + \frac{N}{2}\hat{e}_j\right)\right\} \end{aligned}$$

Clearly, for an optimal deviation $\tilde{e}_i$

$$\tilde{e}_i = e^F$$

and the constraint becomes

$$\begin{aligned} & \gamma ln(a_i\ \hat{e}_i) - \frac{c}{N}\times\hat{e}_i + \delta\left\{\hat{U}_i - \frac{c}{N(1-\delta\sigma)}\sigma\hat{e}_i\right\} \\ \geq\ & \gamma ln(a_i\ e^F) - \frac{c}{N}\times e^F + \delta\left\{U_i^F - \frac{c}{N(1-\delta\sigma)}\sigma e^F\right\} \end{aligned}$$

Using the definition of

$$\hat{U}_i = \frac{1}{1-\delta}\left[\gamma ln(a_i\ \hat{e}_i) - \frac{c}{N(1-\delta\sigma)}(\frac{N}{2}\hat{e}_r + \frac{N}{2}\hat{e}_p)\right]$$

and of

$$U_i^F = \frac{1}{1-\delta}\left[\gamma ln(a_i\ e^F) - \frac{c}{1-\delta\sigma}e^F\right]$$

(the w in the proof of Proposition 2) the constraint can be finally rewritten as (using $\hat{e}_i = \hat{e}_r = \hat{e}_p$)

$$\begin{aligned} & \gamma ln(a_i\ \hat{e}_i) - \frac{c}{N} \times \hat{e}_i + \delta \left\{ \frac{1}{1-\delta} \left[\gamma ln(a_i\ \hat{e}_i) - \frac{c}{1-\delta\sigma} \hat{e}_i \right] - \frac{c}{N(1-\delta\sigma)} \sigma \hat{e}_i \right\} \\ \geq\ & \gamma ln(a_i\ e^F) - \frac{c}{N} \times e^F + \delta \left\{ \frac{1}{1-\delta} \left[\gamma ln(a_i\ e^F) - \frac{c}{1-\delta\sigma} e^F \right] - \frac{c}{N(1-\delta\sigma)} \sigma e^F \right\} \end{aligned}$$

which becomes

$$c\left(e^F - \hat{e}_i\right) \left[\frac{1}{N} + \delta \frac{N + \sigma(1-\delta)}{(1-\delta)N(1-\delta\sigma)} \right] \geq \frac{1}{1-\delta} \gamma \left[ln(a_i\ e^F) - ln(a_i\ \hat{e}_i) \right].$$

Substituting $\hat{e}_i = \frac{\gamma(1-\delta\sigma)}{c}$ and $e^F = N\frac{\gamma(1-\delta\sigma)}{c}$ this becomes,

$$c\left(N\frac{\gamma(1-\delta\sigma)}{c} - \frac{\gamma(1-\delta\sigma)}{c} \right) \frac{(1-\delta)(1-\delta\sigma) + \delta\left[N + \sigma(1-\delta)\right]}{N(1-\delta\sigma)} \geq \gamma \left[ln(N\frac{\gamma(1-\delta\sigma)}{c}) - ln(\frac{\gamma(1-\delta\sigma)}{c}) \right]$$

from which finally

$$\delta \geq \frac{1}{N-1} \left[ln(N) \frac{N}{N-1} - 1 \right].$$

QED

Referring to the case $N = 4$ as in our experiments, the constraints becomes

$$\delta \geq \frac{1}{3} \left[ln(4) \frac{4}{3} - 1 \right] = \frac{1}{9} \left[8ln(2) - 3 \right] \simeq 0.28.$$

Proof of Proposition 4 (Non-Constant "simple" strategies). The proof is in two steps.

Step 1. At any round t and for any stock of pollution E, the value function in any subgame perfect equilibrium has the following affine representation for any country i, $V_i(E) = w - kE$ where w and k are parameters. The proof of this first step is in Dutta and Radner (2009) for a similar dynamic game and it is thus only sketched here. Applying a generalization of the Dynamic Programming Bellman equation proposed by Abreu et al. (1990), the set of the payoffs of all subgame perfect equilibria in repeated games can be characterized by means of their B-operator and its fixed points. Although Abreu et al. (1990) provided their operator for repeated games, the fact that a country' strategy can depend on the entire history in their analysis simply allows to extend their approach to dynamic games like ours. The linearity of the damage of emissions and the accumulation dynamics in our model imply that starting with a conjectured expression as the $V_i(E)$ above and applying the B-operator of Abreu et al. (1990), the resulting value function has the same affine structure as $V_i(E)$. Hence, recursive application of this idea implies $V_i(E)$ must be affine.

Step 2. Consider now any non-constant Markov strategy of the simple form where the emission strategy $\hat{e}(E)$ is some continuous and continuously differentiable combination of "simple" functions, i.e. (non constant) polynomial, logarithms and exponential functions. Let this $\hat{e}(E)$ be an equilibrium (symmetric, to simplify the argument). Using the HJB equation, the associated equilibrium payoff can be written as

$$\begin{aligned} V_i(E) &= \gamma ln(a_i\hat{e}(E)) - c \times (E + \hat{e}(E)) + \delta V_i\left[\sigma\left(E + N\hat{e}(E)\right)\right] \\ &= \gamma ln(a_i\hat{e}_i(E)) - c \times (E + \hat{e}(E)) + \delta\left[w - k\sigma\left(E + N\hat{e}(E)\right)\right]. \end{aligned}$$

Substituting in the previous any combination of "simple" functions leads to a $V_i(E)$ which is not affine, unless $\hat{e}_i(E)$ is the "simple" constant function.

QED

Proof of Proposition 5 (Myopic MPE). With $k \geq 1$ and finite, exploiting the separability of $u_i(t)$ and the linearity in E, the emission choice at any round t can be seen as a different decision process for the country who chooses $e_i(t)$ to maximize

$$v_i^k = \gamma ln\left(a_i e_i(t)\right) - \frac{c}{N}\sum_{t=0}^{k-1}(\sigma\delta)^t \times e_i(t). \tag{4}$$

From the first order condition

$$\frac{\gamma}{e_i(t)} = \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}$$

we immediately obtain

$$e_k^M = e^F \times \frac{1}{1-(\sigma\delta)^k}.$$

QED

Proof of Proposition 6 (Constant Trigger Equilibrium Myopic). The proof follows the same steps as that of Proposition 3, except for the fact that the perceived marginal cost of emission is now

$$\frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}.$$

Country i will not deviate from $\hat{e}_{ik}$ if the following is satisfied

$$\begin{aligned} &\gamma ln(a_i\ \hat{e}_{ik}) - \frac{c}{N} \times \hat{e}_{ik} + \delta\left\{\hat{U}_{ik} - \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}\sigma\hat{e}_{ik}\right\} \\ \geq\ &\gamma ln(a_i\ e_k^M) - \frac{c}{N} \times e_k^M + \delta\left\{U_{ik}^M - \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}\sigma e_k^M\right\} \end{aligned}$$

where

$$\hat{U}_{ik} = \frac{1}{1-\delta}\left[\gamma ln(a_i\ \hat{e}_{ik}) - \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}(\frac{N}{2}\hat{e}_{rk} + \frac{N}{2}\hat{e}_{pk})\right]$$

and

$$U_{ik}^{M} = \frac{1}{1-\delta}\left[\gamma ln(a_i\ e_k^M) - c\frac{1-(\sigma\delta)^k}{1-\sigma\delta}e_k^M\right]$$

The constraint can be finally rewritten as

$$\begin{aligned} &\gamma ln(a_i\ \hat{e}_{ik}) - \frac{c}{N}\times\hat{e}_{ik} + \delta\left\{\frac{1}{1-\delta}\left[\gamma ln(a_i\ \hat{e}_{ik}) - c\frac{1-(\sigma\delta)^k}{1-\sigma\delta}\hat{e}_{ik}\right] - \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}\sigma\hat{e}_{ik}\right\} \\ \geq\ &\gamma ln(a_i\ e_k^M) - \frac{c}{N}\times e_k^M + \delta\left\{\frac{1}{1-\delta}\left[\gamma ln(a_i\ e_k^M) - c\frac{1-(\sigma\delta)^k}{1-\sigma\delta}e_k^M\right] - \frac{c}{N}\frac{1-(\sigma\delta)^k}{1-\sigma\delta}\sigma e_k^M\right\} \end{aligned}$$

which becomes

$$c\left(e_k^M - \hat{e}_{ik}\right)\left[\frac{1}{N} + \delta\frac{\left(1-(\sigma\delta)^k\right)[N+\sigma(1-\delta)]}{(1-\sigma\delta)(1-\delta)N}\right] \geq \frac{1}{1-\delta}\gamma\left[ln(a_i\ e_k^M) - ln(a_i\ \hat{e}_{ik})\right].$$

Substituting e_k^M and $\hat{e}_{ik}$,

$$c\left(N\frac{\gamma(1-\delta\sigma)}{c} - \frac{\gamma(1-\delta\sigma)}{c}\right)\frac{(1-\delta)(1-\delta\sigma)+\delta[N+\sigma(1-\delta)]}{N(1-\delta\sigma)} \geq \gamma\left[ln(N\frac{\gamma(1-\delta\sigma)}{c}) - ln(\frac{\gamma(1-\delta\sigma)}{c})\right]$$

from which finally

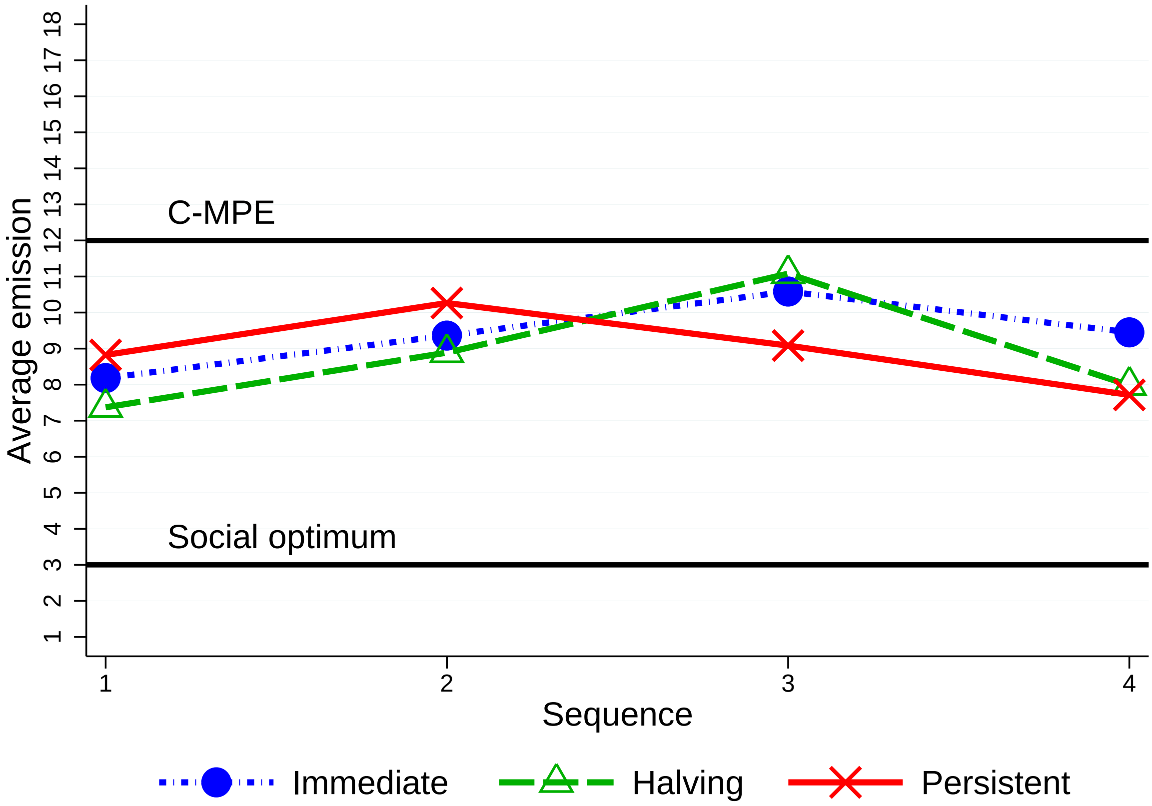
$$\frac{1-\delta+\delta N-\delta\left(\sigma\delta\right)^k[N+\sigma(1-\delta)]}{1-(\sigma\delta)^k} \geq ln(N)\frac{N}{N-1}$$

This inequality cannot be explicitly solved for any k. However, the l.h.s. is decreasing in k so that it is more demanding for $k\to\infty$ which is the case of perfect foresight. Hence, it is certainly satisfied if $\delta \geq \bar{\delta}$.

QED

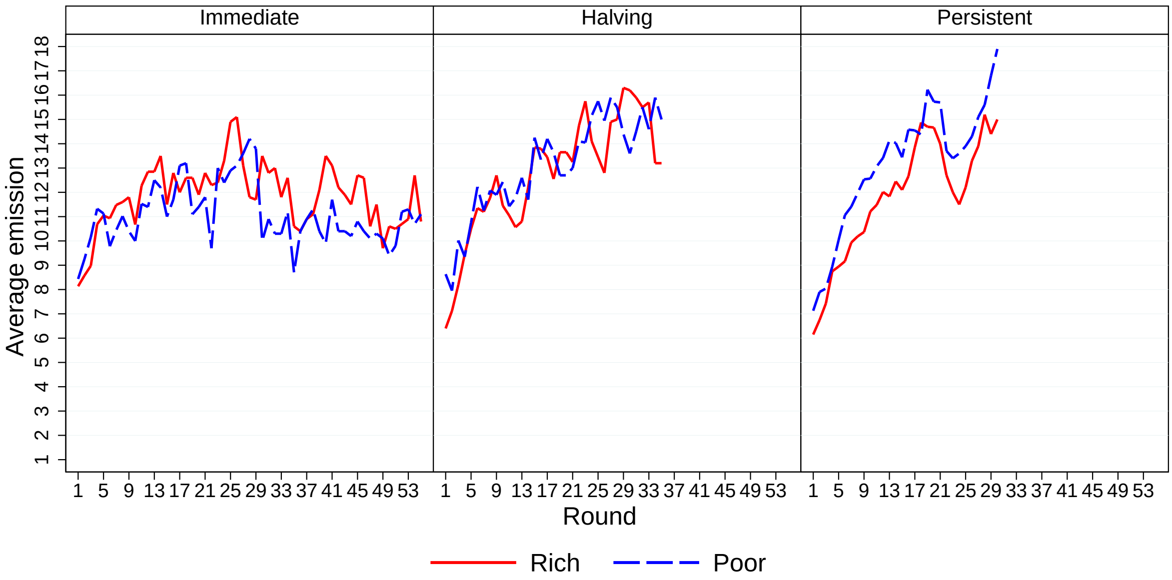
B Additional Figures and Tables

Figure B.7: Average Emissions across Sequences by Treatment.



Note: The unit of observation is a group in a sequence. We consider the average emission over all rounds.

Figure B.8: Average Emissions of Rich and Poor by Treatment.



Note: The unit of observation is a type of participants of a group in a sequence. We consider the average emission of the two rich (poor) participants of a group in a sequence.

Table B.4: Static vs. Dynamic Externality (Tobit regression; First rounds only).

Dependent variable: Average emission in first round	(1) All treatments	(2) All treatments	(3) Immediate and Persistent	(4) Immediate and Persistent
Treatment dummies				
Halving or Persistent	–1.242***	–1.246***		
	(0.447)	(0.447)		
Persistent			–1.647***	–1.647***
			(0.505)	(0.530)
Sequence dummies				
Sequence 2		0.878		0.802
		(0.554)		(0.677)
Sequence 3		1.617***		1.189*
		(0.572)		(0.700)
Sequence 4		1.390**		1.240
		(0.575)		(0.755)
Length of past sequence		0.002		0.005
		(0.028)		(0.047)
Constant	8.286***	7.337***	8.286***	7.478***
	(0.375)	(0.570)	(0.378)	(0.734)
Observations	185	185	125	125

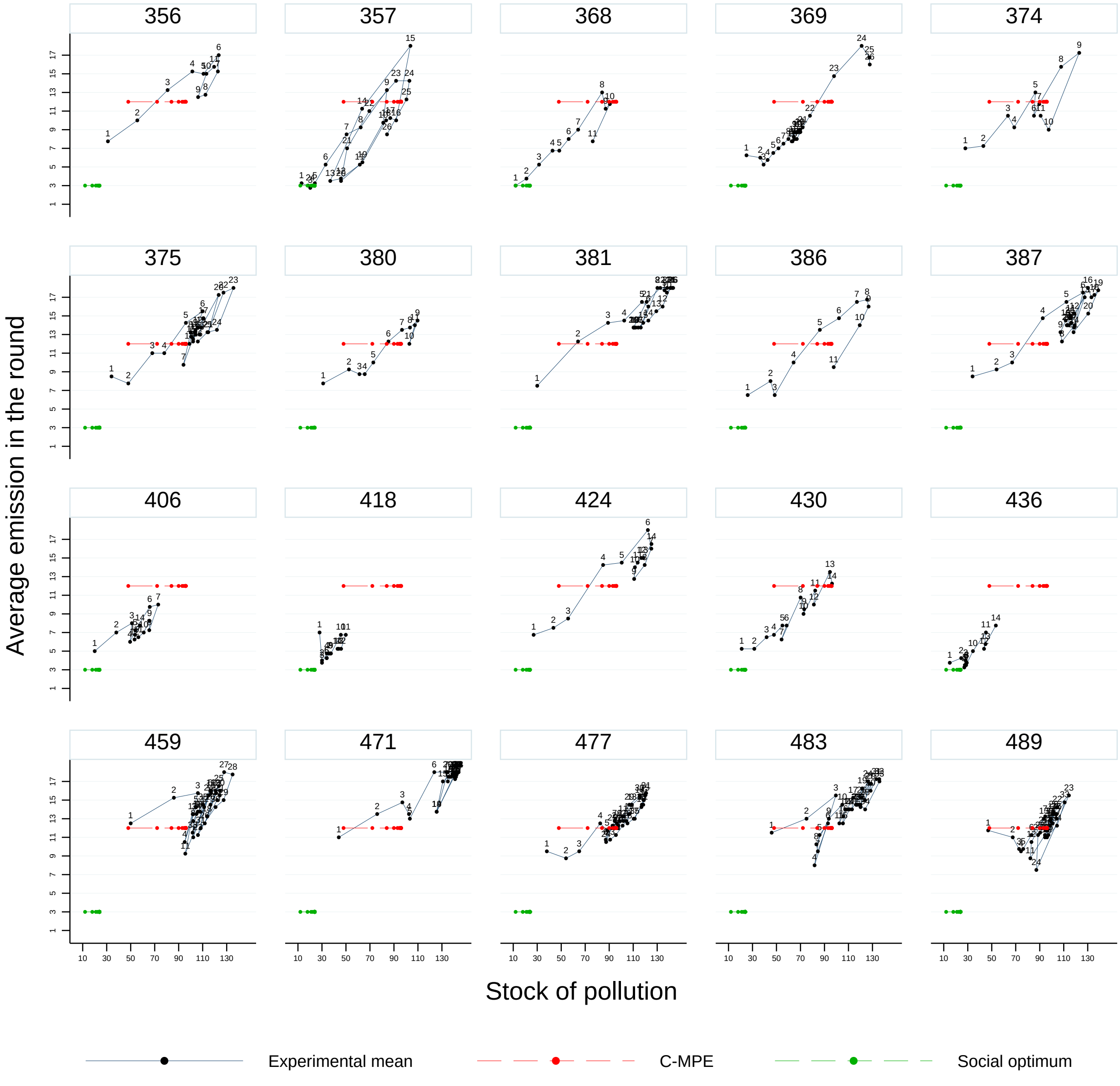
Note: The unit of observation is a group in a sequence. Observations are censored at 1 and 18. In columns 3 and 4 observations relative to the Halving treatment are omitted. The variable "Halving or Persistent" is a dummy taking value 1 in the Halving and Persistent treatments and 0 in the Immediate treatment. The variable "Persistent" is a dummy taking value 1 in the Persistent treatment, 0 in the Immediate treatment. The variable "Length of past sequence" counts the number of rounds in the previous sequence; in sequence 1 it is set to 12.5. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table B.5: Tobit Regressions of Individual Emission with Participants Random Effects.

	Immediate		Halving		Persistent	
Dependent variable: Individual emission in the current round	(1)	(2)	(3)	(4)	(5)	(6)
Loss in the previous round		2.128***		0.798*		3.724***
		(0.395)		(0.479)		(0.486)
Stock of pollution			0.074***		0.018***	
			(0.005)		(0.001)	
Rich	0.245	0.548	–0.670	–0.474	–1.952**	–1.650
	(1.148)	(1.143)	(0.910)	(1.115)	(0.948)	(1.153)
Round	–0.011	–0.009	0.011	0.214***	–0.236***	0.421***
	(0.009)	(0.009)	(0.021)	(0.018)	(0.036)	(0.019)
Sequence dummies						
Sequence 2	0.296	0.275	2.752***	2.734***	0.007	–0.678***
	(0.723)	(0.718)	(0.651)	(0.706)	(0.244)	(0.256)
Sequence 3	1.449***	1.421***	2.406***	3.168***	1.057***	1.071***
	(0.543)	(0.539)	(0.496)	(0.535)	(0.293)	(0.313)
Sequence 4	0.489	0.463	1.750***	0.530	0.066	–0.418
	(0.481)	(0.479)	(0.603)	(0.640)	(0.367)	(0.391)
Length of past sequence	–0.055	–0.051	0.042	–0.031	–0.122***	–0.214***
	(0.051)	(0.051)	(0.030)	(0.032)	(0.018)	(0.019)
Mistakes in the quiz	0.256	0.247	0.504	0.582	–0.101	0.008
	(0.501)	(0.498)	(0.343)	(0.417)	(0.385)	(0.469)
Limited liability	0.026	–1.114	1.627**	1.116		
	(0.795)	(0.818)	(0.764)	(0.827)		
Constant	10.021***	9.702***	3.619***	6.495***	10.575***	11.001***
	(1.152)	(1.147)	(1.218)	(1.434)	(1.027)	(1.237)
Random effects	YES	YES	YES	YES	YES	YES
Observations	2380	2380	2000	2000	3140	3140

Note: The unit of observation is a participant's emission choice in a round. Observations are censored at 1 and 18. The variable "Loss in the previous round" is a dummy taking value 1 if in participant's earnings in the previous round were negative, and 0 otherwise. The variable "Rich" is a dummy taking value 1 if a participant is of type r and value 0 if is of type p. The variable "Length of past sequence" counts the number of rounds in the previous sequence; in sequence 1 it is set to 12.5. The variable "Mistakes in the quiz" counts the number of mistakes made by the participant in the quiz on the instructions. The variable "Limited liability" is a dummy taking value 1 is the emission decision was made under limited liability, and 0 otherwise. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure B.9: Current Emission over Current Emissions' Stock across Groups in Halving.



Note: One observation is a group in a sequence. Only groups which interacted for at least 5 rounds are reported.

B.1 Regressions without Choices under Limited Liability

Table B.6: Regressions on The Effect of Static vs. Dynamic Externalities.

Dependent variable: Average emission over all rounds	(1) All treatments	(2) All treatments	(3) Immediate and Persistent	(4) Immediate and Persistent
Treatment dummies				
Halving or Persistent	–0.492	–0.282		
	(0.563)	(0.500)		
Persistent			–0.357	–0.160
			(0.647)	(0.619)
Sequence dummies				
Sequence 2		1.072*		0.733
		(0.621)		(0.788)
Sequence 3		0.663		0.307
		(0.666)		(0.826)
Sequence 4		0.574		0.016
		(0.650)		(0.888)
Length of current sequence		0.142***		0.125***
		(0.022)		(0.027)
Length of past sequence		–0.021		–0.063
		(0.032)		(0.056)
Constant	9.411***	7.460***	9.411***	8.273***
	(0.472)	(0.677)	(0.484)	(0.915)
Observations	185	185	125	125

Note: see notes to Table 2.

Table B.7: Regressions of Individual Emission.

	Immediate		Halving		Persistent	
Dependent variable: Individual emission in the current round	(1)	(2)	(3)	(4)	(5)	(6)
Loss in the previous round		3.063***		1.550*		7.819***
		(0.870)		(0.912)		(2.321)
Stock of pollution			0.100***		0.027***	
			(0.010)		(0.002)	
Rich	0.958	1.411*	–0.365	0.256	–1.930***	–1.332**
	(0.745)	(0.835)	(0.798)	(0.911)	(0.696)	(0.676)
Round	–0.010	–0.008	–0.065**	0.204***	–0.566***	0.381***
	(0.040)	(0.038)	(0.032)	(0.043)	(0.095)	(0.108)
Sequence dummies						
Sequence 2	–2.423	–2.304	1.900**	3.240*	–0.241	–1.326
	(1.872)	(1.764)	(0.958)	(1.778)	(0.652)	(1.496)
Sequence 3	0.152	0.166	1.865*	3.852**	0.597	0.289
	(1.637)	(1.558)	(0.965)	(1.951)	(0.759)	(1.367)
Sequence 4	–0.580	–0.566	2.730***	1.095	–0.742	–2.127
	(1.726)	(1.622)	(1.037)	(1.604)	(0.949)	(1.750)
Length of past sequence	–0.135	–0.125	0.001	–0.052	–0.023	–0.093
	(0.155)	(0.147)	(0.054)	(0.111)	(0.051)	(0.113)
Mistakes in the quiz	0.225	0.217	0.400	0.506	–0.093	0.074
	(0.496)	(0.503)	(0.254)	(0.332)	(0.231)	(0.282)
Constant	11.592***	11.013***	3.154***	5.892***	10.060***	10.091***
	(2.158)	(2.057)	(1.060)	(1.764)	(0.952)	(2.274)
Observations	2185	2185	1890	1890	3140	3140

Note: See notes to Table 3.

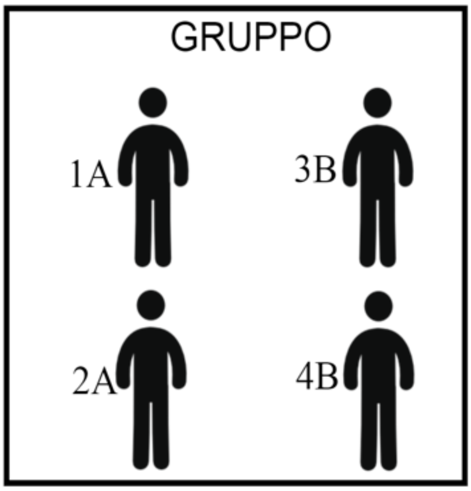
C Experimental Instructions (Persistent Treatment)

Welcome!

You are going to participate in a study on economic decision-making funded by the Italian Ministry of Instruction and Scientific Research.
Your earnings depend on yours and others' decisions. Payment will be made in private at the end of this study.
We ask you to follow these instructions carefully. It is not allowed to talk with other participants. Please turn off you phone. If you have questions, raise your hand at any time and an assistant will answer in private.

SEQUENCES AND GROUPS

This study consists of four independent parts - if there will be enough time - which we call "sequences". The instructions are the same for all sequences. Every sequence includes multiple rounds of interaction.



- Before every sequence, participants are matched in **groups** of 4 members, two of type **A** and two of type **B**.
- Every type has different earnings. The type is randomly assigned at the beginning of the study and remains fixed throughout the study.
- Your group is fixed for the length of a sequence.
- Your group changes in the subsequent sequences. You will never be matched with the same person in more than one sequence.

EARNINGS

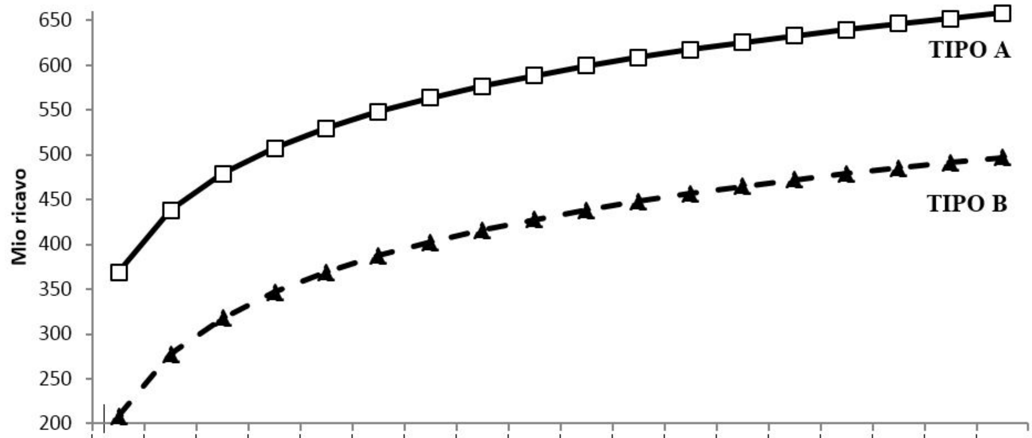
In every round, every participant chooses how much to **produce** from 1 through 18.
Your production has two effects:

1. It generates a **revenue** for you.
2. It creates a **damage** both for you and for the other members of your group.

Your earnings are determined by your revenue minus your damage and will be expressed in tokens. For every 6 tokens you will earn 1 cent (€0.01). In addition you will receive €4 for your participation. Your production in the round generates a revenue limited to the current round. However, it creates a damage both in the current round and in the subsequent rounds.
Let us look at these effects in detail.

REVENUE

The more you produce, the more your revenue increases.
For every level of your production, you can see the generated revenue below:



Mia produzione	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Mio ricavo se sono tipo A	369	438	479	508	530	548	564	577	589	599	609	618	626	633	640	646	652	658
Mio ricavo se sono tipo B	208	277	318	347	369	387	403	416	428	438	448	457	465	472	479	485	491	497

As you can see from the table, for the same production, a type B participant has always a lower revenue than a type A. For example:

- A type A who produces 5 has a revenue of 530 tokens
- A type B who produces 5 has a revenue of 369 tokens

The revenue depends only on your production in the current round.
If you want to know it, the mathematical formula is the following:

Type A: My revenue = $100\times logarithm(40\times$My current production)

Type B: My revenue = $100\times logarithm(8\ \times$My current production)

Are there questions about the revenue?

DAMAGE

The more you produces, the more the damage increases.
The production affects both the revenue and the damage, but in different ways

- On the one hand, the revenue is only yours, while the created damage is **equally split among all group's members**.
- On the other hand, the revenue is immediately obtained in the round, while the damage hits immediately **but persists also in all the subsequent rounds**.

Let us see the first feature of the damage. Every unit you produce in a round generates a damage that reduces your earnings of 0.67 tokens. Moreover, it reduces in the same way also the earnings of every member of the group and hence it generates a damage in the round to the group equal to 2.68 tokens (=0.67×4).

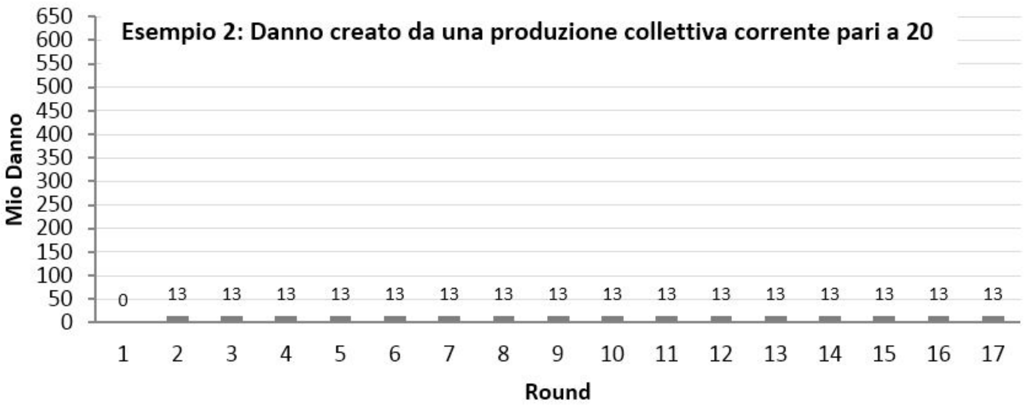
Thus, to compute your damage from production, it is not enough that you only look at what you produce. Instead, you have also to consider the sum of the productions of all the members of your group in the round, namely the current "collective production":

My damage from the current production = 0.67 × Current collective production

Example 1: We are in round 2 and everyone produces 3. The collective production of the group is hence equal to 12 and creates a damage to you of 8 tokens in the current round (=0.67×12). Moreover, it creates a damage of 8 tokens in the current round to every member of the group. How much is your damage if instead you produce 1 and everyone else produces 5? The collective production will be 16 and it will create a damage to you of 11 tokens in the current round (=0.67×16).

It does not matter whether you are type A or type B: the damage is equally split among all.
Let us now look at the second feature of the damage: the persistence. Every unit you produce causes a damage in the current round, in the next one and all the subsequent rounds until the end of the sequence. Earnings will reduce of 0.67 tokens for you and the other members of your group **in every round**.

Example 2: We are in round 2 and the current collective production is equal to 20. Look the graph below: your damage is 13 tokens in round 2 (=0.67×20), 13 tokens in round 3, and so on in every subsequent round.



An important consequence of the persistence is that your total damage in a round depends both on the current production and the **past production**.
My total damage in the round=

= My damage inherited from past production + My damage from current production
=(0.67×Sum of all past collective productions)+(0.67×Collective current production)

Example 3: In round 1, the collective production was equal to 27. We are in round 2 and the collective production is 15. How much is your total damage in round 2? We must sum the damage inherited from round 1 to the damage from the collective production in round 2. The total damage is 28 tokens, 18 ow which inherited (=0.67×27) and 10 created by the current production (=0.67×15). We can see this from the computation and the graph below.

My total damage in round 2	=	Inherited damage	+	Damage from production in round 2
	=	(0.67×27)	+	(0.67×15)=18+10=28

Because of the damage, your earnings in the round could be negative. In this case, the loss in the round will be subtracted from the tokens accumulated in the previous rounds.

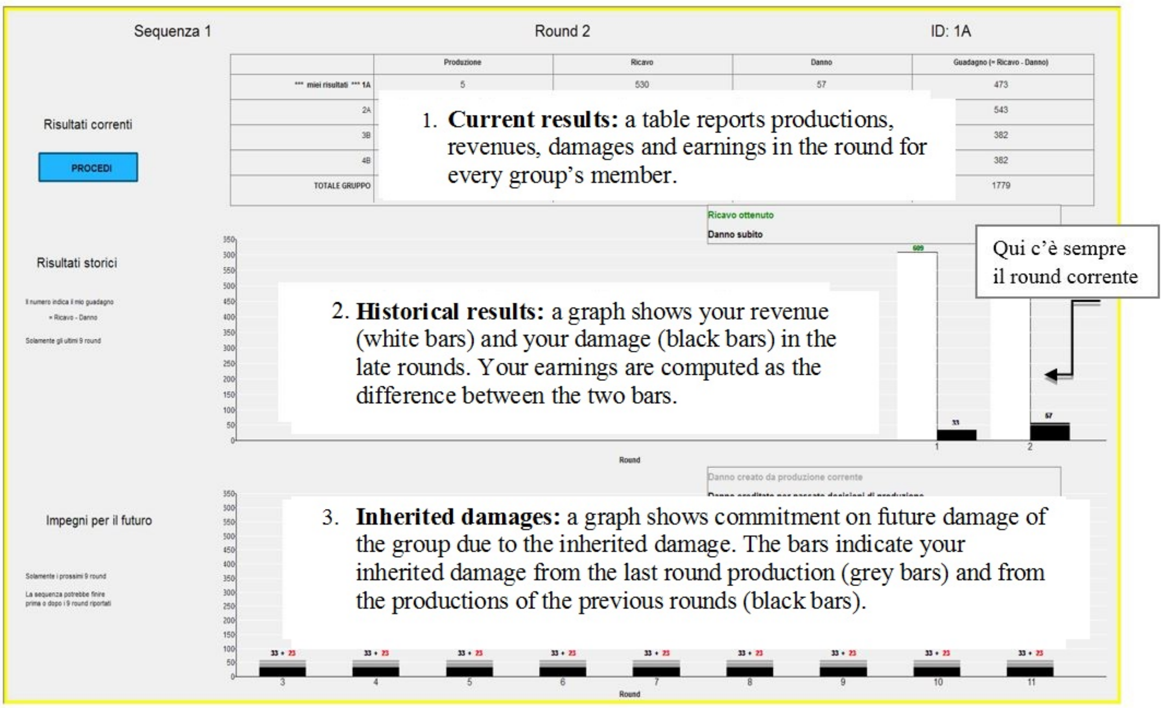
Every sequence is independent from the previous one: you will start every sequence without any commitment on future damage due to the heritage of the past.
Are there questions about the calculation of the damage?

HOW MUCH TO PRODUCE

Let us see how one can think about how much to produce. **Should I increase the production of one unit?** To answer, you can compare the additional revenue from a one unit increase in production with the additional damage.
Focus for a moment **only on your earnings**. For example, if you produce 5 units instead of 4, your revenue increases of **22** tokens, as you can see from the revenues table. Moreover, producing an additional unit increases your damage of 0.67 tokens. However, it is not enough that you consider this damage in the current round only: you must weight the damages that you create to yourself in all the subsequent rounds. For example, if you expect that there are 13 rounds, producing an additional unit in the current round increases your damage of **8.71** tokens (=0.67×13).
Consider now the **effects on all the members of your group**. For example, if you produce 5 units instead of 4, your revenue increases of **22** tokens but no one else in the group benefits from it. Instead the damage that you create is of 0.67 tokens for you and every member of the group, namely it is multiplied by four (2,68 = 0.67×4). For example, when we consider damages over 13 current and future rounds, the damage to the group increases of **34.84** tokens (=2,68×13). Following this reasoning, we can compute that – **if everyone chooses the same level of production** throughout the sequence – the earnings of the group are maximized when each one produces **3 units** in every round.

RESULTS

At the end of each round, results will be displayed with a screen as the one below:



DURATION OF A SEQUENCE

The duration of a sequence is variable and ex-ante unknown. The duration is determined as follows. At the end of every round, the computer randomly draws a number from an urn which contains the integer numbers from 1 to 100. Every number has the same probability of being drawn.

- If the number is less or equal to 92, the sequence continues with a new round.
- If the number is greater or equal to 93, the sequence ends.

So: after every round, there is 92% chances that there is another round in the sequence, and 8% chances that the sequence ends. Following this procedure of random draws:

- It is never possible to know in advance which will be the last round of the sequence.
- One can calculate that a sequence will have an **average duration of 13 rounds**. However, you can expect that some sequences will last much longer than 13 rounds and other much less.

QUIZ AND PRACTICE ROUNDS

We now ask you to answer 11 questions to verify your understanding of the instructions. **Those who do not answer satisfactorily will have a different task from that described above.**
After the quiz, you will participate in a practice sequence. **Unlike the subsequent sequences**, in the practice sequence: (a) you will not be paid for your decisions; (b) the sequence will last exactly 15 rounds; (c) the other members of your group will be robots who are programmed to choose a different production level in every round.
Are there questions before proceeding?

Before starting the four sequences, let us look at two final things.

RECORD SHEET

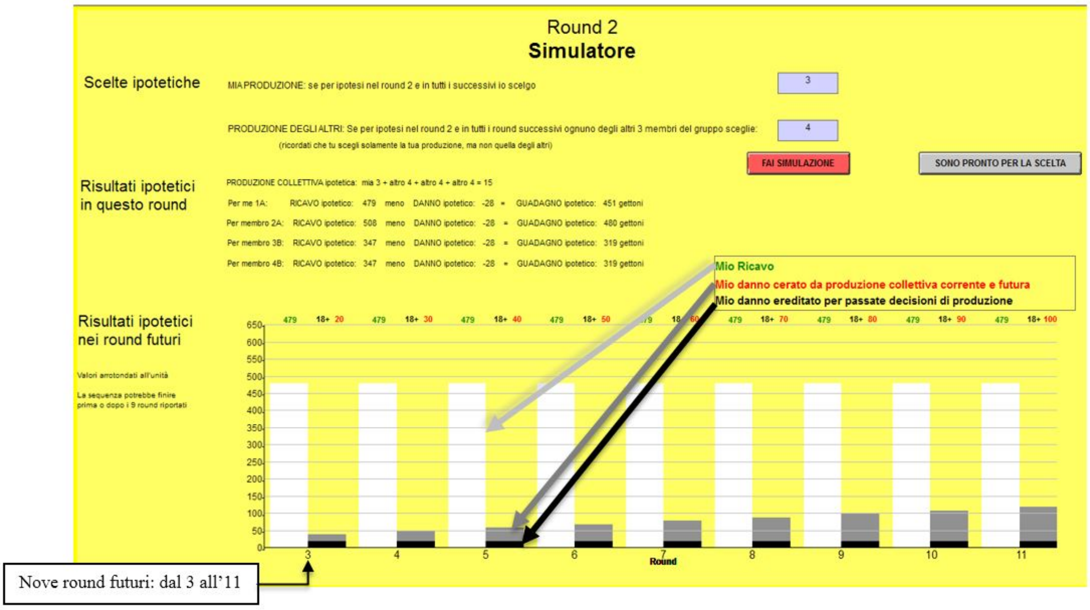
At the end of each round, we ask you to write down on paper the results in the round. In particular,

- **Sequence** and **Round**, that you will see on top of the screen,
- **Your production** and the **production of everyone else** that you see in the final screen of the round in table (see screen at page 5). You can fill the production of everyone after having marked down the ID of the participant to which the column refers.

SIMULATION TOOL

You can use a simulator to understand how the result changes as production choices vary. You can make trials with the simulator without any consequence on your earnings. You can insert in the simulator an hypothetical production for you and an hypothetical production for the other group members. Hypothetical productions do not influence the outcome of the round.
By clicking the button "Simulate" the hypothetical results of these choices will appear with numbers and graphs. Look at the picture below.

- You can see the "Hypothetical results in this round" in the table: revenues, damages, and earnings of everyone
- You can see the "Hypothetical results in future rounds" on the graph
  - Your earnings (white bars)
  - Your damage created by the simulated collective production (gray bars)
  - Your damage inherited from past decisions (black bars)



An important note on how to read the "Hypothetical results in the future rounds". In the example screen above, your simulated production is 3 units and the simulated production of the others is 4 units. The hypothetical results illustrate the **consequences when these levels of production is maintained constant also for all the subsequent rounds**. As you can see:

- Your revenue is constant in all rounds (white bar)
- Your damage created by the simulated production (gray bar) **increases over the future rounds** because the damage is persistent and so, with a constant production, the damage cumulates.

<u>Example 4</u>: Let us consider again Example 3 where the collective production in round 1 was of 27 units. Now we are in round 2 and we use the simulator to compute the consequences of a collective production of 15 units:

- Your revenue is equal to 479 tokens **in every round** (as you see in the revenues table when you produce 3 units)
- The inherited damage is equal to 18 tokens **in every round**, as we have already seen in Example 3 (=0.67×27)
- Your total damage in **round 2** amounts to 28 tokens, see in "Hypothetical results in the current round": 18 are inherited and 10 are created by the production in round 2 (=0,67×15). So in round 2 you earn 479–28 = 451 tokens
- Your total damage in **round 3** amounts to 38 tokens, which corresponds to 18 inherited (black bar), plus 10 created by the production in round 2, plus 10 created by the production in round 3 (gray bar). So in round 3 you earn 479–38 = 441 tokens.
- Your total damage in **round 4** amounts to 48 tokens, which corresponds to 18 inherited (black bar), plus 10 created by the production in rounds 2, 3, and 4 (gray bar). So in round 4 you earn 479–48 = 431 tokens. And so on.

Let us perform one last practice round (round 16), in which you have 3 minutes to try the simulator.

D Quiz (Persistent Treatment)

1. How many independent sequences are there in this study? 1–10
2. You are at round 1 of a certain sequence. How many rounds do you expect there will be in the sequence on average? 1–20
3. You are at round 13 of a certain sequence. With which probability do you expect that there will be an additional round in the sequence? 0–100
4. TRUE OR FALSE? In every new sequence it is possible to meet again a participant that was in my group in a previous sequence.
5. How much is the revenue of a type B who produces 4?
6. TRUE OR FALSE? For the same production level, type B participants always obtain a lower revenue than type A participants.
7. COMPLETE THE SENTENCE: The collective production is computed. . .
   (A) . . . by summing the production of the other group's members in all rounds of the sequence.
   (B) . . . by summing the production of all four group's members (me included) in all rounds in the sequence.
   (C) . . . by summing the production of all four group's members (me included) in a round.
8. COMPLETE THE SENTENCE: If I increase my production of one unit. . .
   (A) . . . I create a damage to the group of 0.67 in the current round and in all the subsequent rounds, which is equally split among the group's members.
   (B) . . . I create a damage to the group of 2.68 in the current round and in all the subsequent rounds, which is equally split among the group's members.
   (C) . . . I damage to myself of 0.67 in the current round and in all the subsequent rounds.
9. COMPLETE THE SENTENCE: The more the other group's members produce. . .
   (A) . . . the less damages I suffer.
   (B) . . . the more damages me and the other group's members suffer.
   (C) . . . the more damages the other group's members suffer.
10. TRUE OR FALSE? The damage generated by the production reduces the earnings of types A and B of different amounts.
11. COMPLETE THE SENTENCE: The damage I suffer in every round depends. . .
    (A) . . . both on the collective production in the previous rounds and on the collective production in the current round.
    (B) . . . only on the collective production in the previous rounds.
    (C) . . . only on the collective production in the current round.

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