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Eidgenössische Technische Hochschule Zürich
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Now or never

Environmental protection under hyperbolic discounting

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Abstract: In this paper, we extend the well known result that hyperbolically discounting agents tend to postpone costs into the future. In a simple model we show that, without commitment to the ex ante optimal plan, no investment in environmental protection is undertaken over the whole time horizon, no matter whether the decision makers are naive or sophisticated, although investment seems optimal in the long run from every generations point of view. This result questions the application of hyperbolic discounting in cost-benefit analysis and gives rise to concern, as it is consistent with unsatisfactory policy performance in solving long-term environmental problems.

Keywords: environmental policy, environmental protection, hyperbolic discounting, intertemporal decision theory, procrastination, time-(in)consistency

JEL-Classification: Q53, D90, D61

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1 Introduction

A ubiquitous feature in environmental economics is that welfare costs and benefits of projects undertaken to mitigate environmental problems spread over decades or even centuries (e.g., global climate change, biodiversity loss, depletion of the ozone layer and disposal of radioactive waste). The problem with the standard exponential discounting approach, first introduced by Samuelson (1937) and put on an axiomatic basis by Debreu (1954) and Koopmans (1960), is that outcomes in the far distant future are worth close to nothing for any positive discount rate. In many people's view this is not the way we *do* think or *should* think about the far distant future. Therefore, discounting has been a controversial topic, with proposals ranging from ad-hoc adjustments to alternative axiomatic derivations (e.g., Lind 1982, Rabl 1996, Portney and Weyant 1999, Heal 1998).

One recent approach to deal with the shortcomings of exponential discounting is *hyperbolic discounting*, i.e., the discount rate is not constant but declining over time.¹ It has been advocated for three reasons (for an overview see Pearce et al. 2003, Groom et al. 2005). First, empirical evidence suggests that decision makers use declining rather than constant discount rates (e.g., Gintis 2000, Frederick et al. 2002). Second, uncertainty over the future state of the world leads to declining certainty-equivalent discount rates (e.g., Weitzman 1998, Azfar 1999, Gollier 2002). Third, declining discount rates are consistent with a rule, which balances the welfare of current and future generations (e.g., Chichilnisky 1996, Li and Löfgren 2000).

In this paper, we analyze the optimal investment in environmental protection, given a hyperbolically discounting society, which consists of a series of non overlapping generations, each represented by a unique agent. To capture the common pattern of many environmental problems, we assume that the present generation faces the costs of investment, while the benefits spread over all subsequent generations.

However, as well known from the literature, hyperbolic discounting bears the problem of *time-inconsistency*. As Strotz (1956) has pointed out, this implies that an ex ante optimal decision is not carried out, because a later re-evaluation suggests that it is not optimal anymore. Time-inconsistent behavior can either be overcome by a commitment to future actions or, if no commitment mechanism is available, time-consistent planning is equivalent to solve the non-cooperative sequential investment game all agents play against each other (Phelps and Pollak 1968). Although the time-inconsistency property of hyperbolic discounting has been used to model 'irrational' behavior, such as addiction and procrastination (e.g., Akerlof 1991, O'Donoghue and Rabin 1999, Brocas and Carrillo 2001, Gruber and Koszegi 2001), there is a debate on how serious is the problem of time-inconsistency in long-term and intergenerational decision making (Pearce et al. 2003). Some authors argue that time-consistency is a requirement which cannot be expected to hold for the process of social decision making and, therefore, is not an issue of concern (e.g., Henderson and Bateman 1995, Heal 1998).

Although we agree that time-consistency is hardly met in social decision making, time-

¹ The term stems from the use of generalized hyperbolae to model declining discount rates (e.g., Loewenstein and Prelec 1992). However, nowadays it is used as a generic term to describe declining discount rates, independently of their functional form.

inconsistency can have dramatic consequences. In the model framework described below we show that, in the absence of a commitment mechanism, investment in environmental protection will never be carried out, even though it is optimal from an *ex ante* point of view to invest in the long run. Moreover, this result holds not only for *naïve* decision makers (who are not aware of the time-inconsistency problem), but also for *sophisticated* decision makers (who anticipate future generations' deviation from the *ex ante* optimal plan). In addition, our results are not limited to special functional forms of hyperbolic discounting, like the often used *quasi hyperbolic discount function* (e.g., Laibson 1997, Laibson 1998, Harris and Laibson 2001), but hold in general.

These results challenge the use of hyperbolic discounting in long-term decision making, as the outcome is not only unsatisfactory from the present generation's point of view, but also often inefficient. Moreover, the results give rise to concern, as they are consistent with real world observations of unsatisfactory policy performance.

The paper is organized as follows. In section 2 the model is introduced. The *ex ante* optimal plan is analyzed in section 3, while section 4 is devoted to the *ex post* implemented plan and the welfare analysis. In section 5, we examine some crucial model assumptions with respect to the results, and discuss the implications for environmental policy. Section 6 concludes.

2 Investment in environmental protection under hyperbolic discounting

Consider a project, in which society can invest, that is aimed to decrease the impact of the society's economic activity on the natural environment. In the following, this project is called *environmental protection*. Environmental protection k_t in period t is assumed to be a capital good, i.e., investments i_t in different periods t accumulate over time and decay at the constant rate $\gamma \geq 0$. Thus, the equation of motion for environmental protection is given by:

$$k_{t+1} = (1 - \gamma)k_t + i_t. \quad (1)$$

Investments i_t in environmental protection are assumed to be sunk, i.e., de-investment is not possible and, thus, $i_t \geq 0$ holds for all periods t .

Consider further that the payoff of environmental protection in period t is given by $P(i_t, k_t)$, which is a strictly concave function in both arguments (partial derivatives are indicated by subscripts throughout the paper: $P_{ii} < 0$, $P_{kk} < 0$, $P_{ii}P_{kk} - P_{ik}^2 > 0$). A central assumption in this model is that welfare costs and benefits of investments in environmental protection do not accrue at the same time. Without loss of generality, we assume that costs (investments in environmental protection i_t) occur before the benefits (stock of environmental protection k_t).² As a consequence, P is strictly decreasing in i_t ($P_i < 0$) and strictly increasing in k_t ($P_k > 0$). In addition, we assume that the marginal

² As an example think of the abatement of CO₂ to slow down the anthropogenic greenhouse effect. While the costs occur today, the (insecure) benefits spread over several decades or even centuries (IPCC 2001).

costs of investment are non-decreasing with the level of environmental protection, i.e., there are no economies of scale in environmental protection ($P_{ik} \leq 0$). This amounts to the assumption that cheap options to enhance environmental quality are chosen first and, thus, marginal costs increase with the level of environmental protection.

In each period t , there is a decision maker, in the following called *agent t* , who is in charge of the investment decision i_t in environmental protection in period t . Each agent t cares about current and future payoffs, but treats past decisions as bygone. All agents are supposed to exhibit Markov beliefs, i.e., their decisions depend only on the payoff-relevant state variable (environmental protection k_t) and not on the history of past decisions. Thus, agent t 's present value of discounted payoffs V equals

$$V_t = \sum_{s=t}^{\infty} \delta_{s-t} P(i_s, k_s) , \quad (2)$$

where $\delta_n > 0$ with $n \in \mathbb{N}_0$ ³ denotes a strictly decreasing and convergent series of discount factors with $\delta_0 = 1$. Equation (2) implies that all agents apply the same discount factors δ_n , i.e., the discount factors are invariant over time and do not hinge upon past decisions.

If agents discount exponentially, the discount factors are given by $\delta_n = \beta^n$ with $0 < \beta < 1$, which implies that for all $n, m \in \mathbb{N}_0$:

$$\frac{\delta_{n+m}}{\delta_n} = \delta_m . \quad (3)$$

In the case of hyperbolically discounting agents, we do not assume a special functional form, but solely postulate that $\delta_n = \prod_{s=1}^n \beta_s$ for all $n \in \mathbb{N}$, where $0 < \beta_s < 1$ and $\{\beta_s\}_{s=1}^{\infty}$ denotes a weakly increasing series with at least one $s \in \mathbb{N}$ so that $\beta_s < \beta_{s+1}$. As a consequence, the following weak inequality holds for the discount factors δ_n for all $n, m \in \mathbb{N}_0$

$$\frac{\delta_{n+m}}{\delta_n} \geq \delta_m , \quad (4)$$

where the strict inequality holds at least for one $n, m \in \mathbb{N}$.

As Strotz (1956) has shown, there is the potential problem of time-inconsistency for non-stationary intertemporal preferences (including hyperbolic preferences). Accordingly, an *ex ante* optimal investment plan, derived by maximizing the present value of discounted payoffs in period $t = 1$, might be suboptimal if re-evaluated at a later date $t > 1$. Time-inconsistency can lead to different *ex post* outcomes, depending on the degree of awareness of the time-inconsistency problem and the possibility of commitment to future actions.

Following the standard approach, we shall distinguish three different behavioral patterns of the agents t . If the agents are *committed*, they are fully aware of the problem of time-inconsistency and overcome it by agent 1's commitment to the *ex ante* optimal intertemporal consumption and investment plan. In this case, all successors have to stick

³ \mathbb{N} denotes all positive and \mathbb{N}_0 all non-negative integers.

to the ex ante optimal plan, even if they would like to alter it according to future re-evaluations. If the agents do not have the possibility to commit their successors to future actions, but anticipate their successors' departure from the ex ante optimal intertemporal plan, the agents are called *sophisticated*. As recognized by Phelps and Pollak (1968), time-consistent planning is equivalent to a non-cooperative sequential investment game the agents t play against each other. Finally, the agents are called *naive* if they do not recognize that their preferences are non-stationary. In general, they will alter the plan derived by their predecessor in every period t .

In the following, we analyze the optimal investment in environmental protection given that agents are either committed, sophisticated or naive. In particular, we derive conditions under which no investment in environmental protection is carried out *ex post*, although this seemed to be optimal *ex ante*.

3 Ex ante optimal investment plan

First, we derive the ex ante optimal investment plan. This is the plan society achieves by maximizing the intertemporal welfare in period $t = 1$, assuming that all future investment decisions will be carried out according to this plan.

3.1 Intertemporal optimization

Setting the initial level of environmental protection $k_1 = 0$,⁴ the ex ante optimal control problem reads:

$$\begin{aligned} \max_{\{i_t\}_{t=1}^{\infty}} \quad & \sum_{t=1}^{\infty} \delta_{t-1} P(i_t, k_t) \quad \text{s.t.} \\ k_{t+1} \quad &= (1 - \gamma)k_t + i_t, \\ i_t \quad &\geq 0, \\ k_1 \quad &= 0. \end{aligned} \tag{5}$$

As we do not assume Inada conditions to hold for the payoff function P , one has to explicitly consider the corner solutions given by $i_t = 0$. Introducing the shadow price p_t^k for environmental protection and a Kuhn-Tucker variable p_t^i to control for the non-negativity of investment, one obtains the Lagrangian \mathcal{L} :

$$\mathcal{L} = \sum_{t=1}^{\infty} \delta_{t-1} P(i_t, k_t) + \sum_{t=1}^{\infty} p_{t+1}^k [(1 - \gamma)k_t + i_t - k_{t+1}] + \sum_{t=1}^{\infty} p_t^i i_t. \tag{6}$$

Hence, the first order conditions for an optimal intertemporal investment plan read:

$$\delta_{t-1} P_i(i_t, k_t) + p_{t+1}^k + p_t^i = 0, \tag{7}$$

$$\delta_{t-1} P_k(i_t, k_t) + (1 - \gamma)p_{t+1}^k - p_t^k = 0, \tag{8}$$

$$p_t^i \geq 0, \quad p_t^i i_t = 0. \tag{9}$$

⁴ This assumption will be discussed and relaxed in section 5.

Because of the strict concavity of the Lagrangian (strictly concave objective function and linear restrictions), these necessary conditions are also sufficient if, in addition, the following transversality condition holds:

$$\lim_{t \rightarrow \infty} p_t^k k_t = 0 . \quad (10)$$

The strict concavity of the Lagrangian \mathcal{L} also ensures the uniqueness of the optimal investment path $\{i_t\}_{t=1}^{\infty}$.

Equation (8) is a difference equation, which can be solved unambiguously by taking into account the transversality condition (10):

$$p_t^k = \sum_{s=0}^{\infty} \delta_{t+s-1} (1 - \gamma)^s P_k(i_{t+s}, k_{t+s}) . \quad (11)$$

Thus, in the optimum the shadow price of environmental protection equals the present value of the accumulated future welfare gains of an additional marginal unit of environmental protection. Inserting the shadow price of environmental protection (11) into equation (7), one derives the following necessary and sufficient condition for an ex ante optimal plan, which has to hold for all $t \in \mathbb{N}$:

$$-\delta_{t-1} P_i(i_t, k_t) - p_t^i = \sum_{s=0}^{\infty} \delta_{t+s} (1 - \gamma)^s P_k(i_{t+1+s}, k_{t+1+s}) . \quad (12)$$

Equation (12) states that if positive investment in environmental protection is optimal in period t (i.e., $p_t^i = 0$), investment is undertaken to such an extent that the marginal welfare loss at time t due to the investment in environmental protection (left hand side) equals the present value of the future marginal welfare gains of this investment (right hand side). However, if this condition cannot be met for any positive investment i_t , then no investment in environmental protection is optimal (i.e., $p_t^i \geq 0$).

3.2 Ex ante optimal investment and postponing investment

Now, we turn to the question under which conditions investment in environmental protection is optimal at all, and if so, what is the first period in which investment is undertaken. In fact, we show that if investment is optimal at all, investment starts in the first period for exponentially discounting agents, and may be postponed to later periods in the case of hyperbolically discounting agents. The following proposition elaborates on this result:

Proposition 1 (Ex ante optimal investment and postponing investment)

Given the ex ante optimal control problem (5), investment in the first marginal unit of environmental protection is optimal in period t , if t is the first period for which the following condition holds

$$-\frac{P_i^0}{P_k^0} < \sum_{s=0}^{\infty} \frac{\delta_{t+s}}{\delta_{t-1}} (1 - \gamma)^s , \quad (13)$$

where $P_i^0 = P_i(0, 0)$ and $P_k^0 = P(0, 0)$.

Moreover, if investment in environmental protection is optimal at all, i.e., there exists a period t for which condition (13) holds, then

- (i) exponentially discounting agents will always invest in period $t = 1$, and
- (ii) postponing the first marginal investment into future periods $t > 1$ may be *ex ante* optimal for hyperbolically discounting agents.

Proof: To see condition (13), we start from the necessary and sufficient condition (12) for optimal investment in environmental protection in period t . To derive a condition for which investment in the first marginal unit of environmental protection in period t is optimal, let us first assume that it is *not optimal* to invest at all, i.e., $i_t = 0$ and, thus, also $k_t = 0$ for all t . Recall that the Kuhn-Tucker parameter $p_t^i \geq 0$, if it is *not optimal* to invest in period t . Thus, for the no investment path to be optimal, the following condition has to hold for all periods t :

$$-\delta_{t-1}P_i(0, 0) \geq \sum_{s=0}^{\infty} \delta_{t+s}(1 - \gamma)^s P_k(0, 0) . \quad (14)$$

Denoting $P_i(0, 0)$ by P_i^0 and $P_k(0, 0)$ by P_k^0 , and dividing by $-\delta_{t-1}P_k^0$ yields that the first marginal investment in period t is *optimal*, if investment has not been optimal in any periods prior to period t and, in addition, condition (13) holds for period t .

If agents discount exponentially, then $\delta_n = \beta^n$. Inserting into condition (13) and using the formula for the infinite geometric series yields:

$$-\frac{P_i^0}{P_k^0} < \sum_{s=0}^{\infty} \beta^{s+1}(1 - \gamma)^s = \frac{\beta}{1 - \beta(1 - \gamma)} . \quad (15)$$

Obviously, this condition is independent of the period t . Hence, if investment is not optimal at $t = 1$ then investment is also not optimal for all other periods $t > 0$. As a consequence, if investment is not optimal in period 1, exponentially discounting agents will never invest. Or, the other way round, if investment is optimal at all, exponentially discounting agents always invest in period $t = 1$ (and if $\gamma > 0$ also in all later periods).

Recall that condition (4) holds for hyperbolically discounting agents. Thus, the right hand side of condition (13) increases over time, while the left hand side remains unaltered. As a consequence, it is possible that investment is not optimal in period $t = 1$ but in some later periods $t > 1$.

□

There are three insights to be gained from proposition 1. First, no investment in environmental protection at all may be the *ex ante* optimal plan. This holds, as we do not assume Inada conditions to hold for the payoff function P . If the first marginal unit of investment exhibits only a finite payoff, then the finite costs of this investment may be always higher and, thus, investment is never optimal. This is the case, if condition

(13) is violated for all periods t . Explicitly taking the no investment corner solution into account, allows to scrutinize the question under which conditions there is investment at all, which is often ruled out by assuming Inada conditions to hold.

Second, if agents discount exponentially, it is never optimal to invest in environmental protection in later periods $t > 1$, if it is not optimal to invest in the first period $t = 1$. This holds, as, due to condition (3), the relative weights of costs and benefits of the first marginal unit of investment in environmental protection remain unaltered by a mere transition of the respective investment decision in time. This can be seen from the investment condition (15), which is independent of the time period t .

Third, if agents discount hyperbolically, it is possible that, from an ex ante point of view, investment in the first marginal unit of environmental protection is optimal in later periods $t > 1$, although it is not optimal to invest in the first period $t = 1$. The reason is that, due to condition (4), the costs of the first marginal investment in environmental protection stay constant by postponing investment into the future, while the benefits increase. Thus, eventually the benefits may outweigh the costs, although this was not the case for investment in the first period. In this case, the condition (15) is violated for $t = 1$, at the same time it holds for some later $t > 1$. Thus, postponing investment of the first marginal unit of environmental protection into the future is an ex ante optimal outcome only for hyperbolically discounting agents.⁵

4 Ex post implemented investment

As already mentioned in section 2, hyperbolically discounting agents might not stick to the ex ante optimal plan, if they re-evaluate it in later periods, because of the non-stationarity of their preferences. Hence, depending on the behavioral pattern assumed, the ex post actually implemented plan can differ from the ex ante intertemporal optimal plan. In the following, we show that, if the ex ante optimal plan suggests no investment in the first but positive investment in later periods, only committed agents will actually invest in environmental protection.

4.1 Commitment

If agent 1 has the power to enforce the ex ante optimal plan, she would certainly do so, as this is, by definition, the plan which maximizes her intertemporal welfare. According to the analysis exposed in the former section, investment in environmental protection is ex ante optimal, if the inequality (13) holds for some t . Obviously, in the case of such a commitment, there will be investment in the ex post implemented plan in exactly that amount and at exactly that time as the ex ante optimal plan suggested. The following proposition summarizes this insight.

⁵ Note, however, that postponing investment can also be optimal for exponentially discounting agents within other model frameworks. In particular, this is the case if future outcomes are risky (see, for example, the option value framework developed by Dixit 1992 and Dixit and Pindyck 1994).

Proposition 2 (Commitment)

Consider a society composed of hyperbolically discounting agents. Given the maximization problem (5) and a commitment to the ex ante optimal plan, the society will invest in environmental protection, if and only if condition (13) holds for some $t \in \mathbb{N}$.

4.2 No commitment

If no commitment mechanism is available, the ex post outcome depends on the agents' awareness of the time-inconsistency problem. Following the standard approach, we distinguish two different behavioral patterns.

First, naive agents which are unaware of the fact that future agents might re-evaluate and alter the plan that was optimal from their point of view. In general, the optimal results derived by the re-evaluation do not coincide with the ex ante optimal plan, because the relative weights of marginal welfare gains and losses between different periods have changed, due to condition (4). Second, sophisticated agents which anticipate future agents' deviation from the ex ante optimal plan. Time consistent planning is equivalent to the solution of a non-cooperative sequential game against all other agents. The ex post time consistent investment plan is the Markov perfect equilibrium (MPE) of this game.

Let us turn to the question under which circumstances a society composed of either naive or sophisticated agents will actually invest in environmental protection. We show in the following that the conditions for which investment in environmental protection actually occurs ex post are identical for naive and sophisticated agents. In fact, if agents discount hyperbolically and there is no commitment to the ex ante optimal plan, then investment in environmental protection will never occur, if it was not already optimal in the first period, even if each agent would like future agents to invest. The following proposition elaborates on this result.

Proposition 3 (No commitment)

Consider a society composed of hyperbolically discounting agents. Given the maximization problem (5) and no commitment to the ex ante optimal plan, the society will invest in environmental protection, if and only if:

$$-\frac{P_i^0}{P_k^0} < \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s, \quad (16)$$

where $P_i^0 = P_i(0, 0)$ and $P_k^0 = P(0, 0)$.

In particular, this condition holds no matter whether agents are sophisticated or naive.

Proof: First, consider naive agents. The intertemporal optimization problem the naive agent has to solve in every period t is similar to the ex ante optimization problem (5). Yet, the inherited level of environmental protection k_t is determined by the investment

carried out in the former periods:

$$\begin{aligned}
\max_{\{i_s\}_{s=t}^{\infty}} \sum_{s=t}^{\infty} \delta_{s-t} P(i_s, k_s) \quad & \text{s.t.} \\
k_{s+1} &= (1 - \gamma)k_s + i_s, \\
i_s &\geq 0, \\
k_t &= \sum_{r=1}^{t-1} (1 - \gamma)^{t-1-r} i_r.
\end{aligned} \tag{17}$$

As in the calculation in section 3.1, one derives the following system of equations for every period t , which determines the investment in period t and the putative optimal investments in the later periods ($r = t, \dots, \infty$):

$$-\delta_{r-t} P_i(i_r, k_r) - p_r^i = \sum_{s=r+1}^{\infty} \delta_{s-t} (1 - \gamma)^{s-r-1} P_k(i_s, k_s). \tag{18}$$

Following the same argument as described in detail in the proof of proposition 1 in section 3.2, the first marginal investment in environmental protection in period t is assessed to be optimal by the re-evaluation in period t and, thus, will be carried out, if and only if:

$$-\frac{P_i^0}{P_k^0} < \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s. \tag{19}$$

This condition is independent of the time period t . As a consequence, if investment in environmental protection is not optimal in the first period $t = 1$, then it is also not optimal from the succeeding naive agents' point of view in period $t > 1$, even if the ex ante optimal plan suggested investment at some later time period $t > 1$, as all later agents face (from their point of view) exactly the same investment decision, which is described by condition (16).

Second, consider sophisticated agents, which anticipate later agents deviation from the ex ante optimal plan. Thus, every agent t plays the best investment strategy, anticipating the best investment strategies of all future players and accounting for the investment decisions of past players only in so far as they determine the inherited level of environmental protection k_t . Hence, given the investment strategies of all future agents, each agent t plays the solution of the following optimization problem:

$$\begin{aligned}
\max_{i_t} \sum_{s=t}^{\tau} \delta_{s-t} P(i_s, k_s) \quad & \text{s.t.} \\
k_{s+1} &= (1 - \gamma)k_s + i_s, \\
i_t &\geq 0, \\
k_t &= \sum_{r=1}^{t-1} (1 - \gamma)^{t-r-1} i_r.
\end{aligned} \tag{20}$$

Note that each agent t only maximizes over i_t and considers all other investment decisions i_s ($s \neq t$) as given. Analogously to the calculation in section 3.1, we derive the following necessary and sufficient condition for an optimal investment of agent t :

$$-P_i(i_t, k_t) - p_t^i = \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s P_k(i_{t+1+s}, k_{t+1+s}) . \quad (21)$$

The condition for an MPE is that this equation holds simultaneously for all agents $t \in \mathbb{N}$.

As shown by Karp (2005) in a similar model setting, the MPE is, in general, not unique under hyperbolic discounting. However, it can be shown that if no investment in all periods t is Markov perfect then it is the unique MPE. To see this, suppose that no investment in all periods is Markov perfect. According to equation (21), this implies:

$$-\frac{P_i^0}{P_k^0} \geq \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s . \quad (22)$$

Again, this condition is not contingent on t . Existence is granted, as the no investment MPE (i.e., $i_t = 0$, $\forall t$) is obviously feasible. Uniqueness, however, requires that there is no other set of Markov strategies which satisfies conditions (21) and (22) for all agents t simultaneously. To see this, consider agent t 's best investment decision given the investment decisions of all other agents. The net marginal welfare gain agent t achieves for a marginal investment in environmental protection decreases the more she invests and the more all future agents invest, as $P_{ii} < 0$ and $P_{kk} < 0$. Moreover, because of $P_{ik} \leq 0$ the marginal costs of investment for agent t increase (or stay constant) and because of $P_{kk} < 0$ marginal future gains decrease the more past agents have invested, and thus, the higher is the level of environmental protection agent t inherits from her predecessors. Therefore, if the marginal costs of investment outweigh the discounted sum of all future marginal benefits even in the case of no investment in all periods t (condition 22), this is always the case no matter how much other agents invest. Hence, if no investment in all periods t is Markov perfect, no investment is a dominant strategy for agent t , irrespective of the strategies of all other agents. As this holds for all agents t , the no investment MPE is unique.

Turning it the other way round, a society comprised of sophisticated hyperbolically discounting agents will invest in environmental protection, only if no investment is not an MPE and, thus, the condition (16) holds.

□

A direct consequence of proposition 3 is that, in the absence of a commitment mechanism, society *never* invests in environmental protection if it was not already ex ante optimal to invest in period $t = 1$. Hence, in case of no commitment, an ex ante optimal postponing of investment actually results in an *infinite ex post procrastination*, i.e., agents postpone investment in environmental protection infinitely into the future, even though investment was optimal in the long run from an ex ante point of view.

It might seem odd at first sight that it does not matter whether agents are sophisticated or naive. Note, however, that this only holds if there is *no investment* at all

ex post.⁶ This coincidence hinges upon the assumption of Markov beliefs, in which the other players' actions are only considered in so far as they influence the stock variable environmental protection. Both naive and sophisticated agents consider *past* decisions only in so far as they influence the stock, and the misperception of the naive agents of *future* decisions does not play a crucial role, as no investment is a dominant strategy.

Although there is no difference in the actual outcome, if investment is not optimal in the first period but in the long run from an ex ante point of view, there is a difference between naive and sophisticated agents in the perception of future events. While the sophisticated agents are well aware that not only themselves but also all future agents will not invest in environmental protection, the naive agents stick to the misguided belief that, although they do not invest themselves, some future agents will.

4.3 Welfare analysis

Obviously, in the case of a commitment, society is more likely to invest in environmental protection than in the cases where no commitment mechanism is available. In the latter case, an ex ante optimal investment delay implies infinite ex post procrastination, i.e., ex post no investment will be made over the whole time horizon, even though this was optimal in the long run from an ex ante point of view. In the former case, the infinite ex post procrastination may be overcome by committing all future agents to the ex ante optimal plan. Hence, it is possible that ex post no investment is undertaken in period $t = 1$ but in later periods $t > 1$.

The question arising is whether ex post procrastination leads to inefficient outcomes or not. Applying the Pareto criterion, an ex post implemented plan is efficient if it is not possible to increase the intertemporal welfare of one agent without decreasing the welfare of at least one other agent. Let agent t 's ex post derived welfare be given by equation (2), when inserting the actually implemented ex post plan. Then, the following proposition can be shown to hold.

Proposition 4 (Intertemporal welfare)

Consider a society composed of hyperbolically discounting agents. Given the maximization problem (5), the ex post implemented plan is always Pareto optimal if the ex ante optimal plan is enforced, and may be Pareto inferior in the case of naive and sophisticated agents.

Proof: Obviously, a commitment to the ex ante optimal plan is always Pareto optimal, as the ex ante optimal plan is unique, due to the curvature properties of the Hamiltonian, and, therefore, any deviation from it would decrease agent 1's welfare (otherwise it would not have been optimal in the first place).

We show that the no investment MPE in the case that the ex ante optimal plan suggests to postpone investment to later periods may be inefficient by constructing a simple example. For a more convenient formal presentation, assume that agents discount *quasi-hyperbolically*:

$$\delta_n = \alpha\beta^n, \quad n \in \mathbb{N}. \quad (23)$$

⁶ In general, the ex post implemented plans differ in the case of positive investment.

Then, an ex ante optimal investment delay implies:

$$-P_i^0 > P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)}, \quad (24)$$

$$-\alpha\beta P_i^0 < P_k^0 \frac{\alpha\beta^2}{1 - \beta(1 - \gamma)}. \quad (25)$$

To assess, if a Pareto improvement is possible, consider the welfare effect of a marginal investment Δi_1 of agent 1. In return, all other agents t compensate agent 1 by investment Δi_t in period t . Agent 1's net welfare effect ΔW_1 yields:

$$\begin{aligned} \Delta W_1 = & \Delta i_1 \left[P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)} + P_i^0 \right] + \\ & + \sum_{s=2}^{\infty} \Delta i_s \left[P_k^0 \frac{\alpha\beta^s}{1 - \beta(1 - \gamma)} + \alpha\beta^{s-1} P_i^0 \right]. \end{aligned} \quad (26)$$

According to inequalities (24) and (25), the first term is negative and each term of the sum is positive. Agent t 's net welfare effect is given by:

$$\begin{aligned} \Delta W_t = & \Delta i_t \left[P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)} + P_i^0 \right] + \\ & + \sum_{s=1}^{t-1} \Delta i_s (1 - \gamma)^{t-s-1} P_k^0 \left[1 + \frac{\alpha\beta}{1 - \beta(1 - \gamma)} \right] + \\ & + \sum_{s=t+1}^{\infty} \Delta i_s \left[P_k^0 \frac{\alpha\beta^{s-t-1}}{1 - \beta(1 - \gamma)} + \alpha\beta^{s-t} P_i^0 \right]. \end{aligned} \quad (27)$$

Again, the welfare gain due to agent t 's own investment is negative, while the welfare gain due to all other agents s ($s \neq t$) is positive. If all agents $t \neq 1$ invest to such an extent that the net welfare gain $\Delta W_t = 0$, then a Pareto improvement is possible, if ΔW_1 is positive.

To see that cases exist, where Pareto improvement is possible and, therefore, the no investment MPE is Pareto inefficient, assume that only agent 1 and agent 2 invest. In this case, it is obvious from equation (27) that $\Delta W_t > 0$ for $t > 2$. Assuming that agent 2 invests to such an amount that her net welfare gain is zero, yields for the maximal investment Δi_2 :

$$\Delta i_2 = -\Delta i_1 \frac{P_k^0 \left[1 + \frac{\alpha\beta}{1 - \beta(1 - \gamma)} \right]}{P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)} + P_i^0}. \quad (28)$$

Inserting in equation (26) and dividing by Δi_1 yields:

$$\begin{aligned} \frac{\Delta W_1}{\Delta i_1} = & P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)} + P_i^0 - \\ & - \frac{P_k^0 \left[1 + \frac{\alpha\beta}{1 - \beta(1 - \gamma)} \right] \left[P_k^0 \frac{\alpha^2\beta}{1 - \beta(1 - \gamma)} + \alpha\beta P_i^0 \right]}{P_k^0 \frac{\alpha\beta}{1 - \beta(1 - \gamma)} + P_i^0}. \end{aligned} \quad (29)$$

For an example, set $P_i^0 = -5$, $P_k^0 = 1$, $\alpha = 0.7$, $\beta = 0.95$ and $\gamma = 0.1$. Given these numbers $\Delta i_2 = 0.694$, indicating that agent 2's welfare gain equals zero if she invests 69.4% of agent 1's marginal investment. Furthermore $\Delta W_1 / \Delta i_1 > 0$ and, therefore, a Pareto improvement can be achieved if both agents 1 and 2 depart from the no investment MPE.

□

Proposition 4 states that, if the ex ante optimal plan suggests to postpone investment to later periods and is not enforceable, the ex post implemented plan may be inefficient. If it is so, however, hinges upon the possibility of future agents to compensate earlier agents for a deviation from the no investment MPE, which is determined by the marginal cost of investment P_i^0 , the marginal benefit of investment P_k^0 , the deterioration rate γ and the series of discount factors δ_n .

If the no investment MPE is inefficient, society faces the standard Prisoners' Dilemma: The MPE is not Pareto efficient, while the Pareto efficient outcome is not Markov perfect and, therefore, unlikely to be implemented ex post. Even if agent 1 decides to deviate from the no investment MPE and invests in environmental protection in the first period, there are no incentives for agent 2 to deviate from the no investment strategy, as no investment is the dominant strategy irrespective of the investment decisions of all other agents.

Moreover, due to the sequential nature of the problem, standard coordination mechanisms like enforcement or agreement do not work. First, it is difficult to think of a mechanism to ensure the enforcement of the ex ante optimal or any other Pareto optimal plan. By definition, investment in period t is under control of agent t . Why should future generations obey a plan which is suboptimal from their point of view and how could past generations force them to do so? Second, the different generations cannot agree on a Pareto optimal strategy as they do not live at the same time. Moreover, implicit agreement is also unlikely as there are no means for earlier generations to monitor later generations' investment decisions and punish them for deviation from the implicitly agreed plan.

5 Discussion

It is well known from the literature that hyperbolically discounting agents tend to postpone actions into the future from an ex ante point of view, as declining discount rates imply a change of the relative weight of benefits and losses. It is also well known that naive agents tend to further procrastinate actions from an ex post point of view, as they are not aware of the time-inconsistency problem and that this outcome may be inefficient (e.g., Akerlof 1991, O'Donoghue and Rabin 1999). Yet, the interesting result derived from the exposition so far is that, no matter whether agents are sophisticated or naive, they will never invest in environmental protection if agent 1 does not invest. In this section, we show which assumptions drive these results and discuss the implications for the design of environmental policies.

5.1 Model assumptions

The infinite ex post procrastination results from the assumption that the payoff function P depends only on investment i_t and the stock k_t of environmental protection and that the initial stock of environmental protection $k_1 = 0$. In the following, we briefly consider how the results change, if we allow for an initial capital stock $k_1 > 0$ or an explicit time-dependence of the payoff function $P = P(i_t, k_t, t)$.

Following an analogous approach as outlined in the proof of proposition 1, the first marginal investment in environmental protection is optimal for a positive initial stock of capital $k_1 > 0$, if:

$$-P_i(0, k_t) < \sum_{s=0}^{\infty} \frac{\delta_{t+s}}{\delta_{t-1}} (1 - \gamma)^s P_k(0, k_{t+1+s}) , \quad (30)$$

where $k_t = (1 - \gamma)^{t-1} k_1$ denotes the exponentially decaying initial stock of environmental protection. As $\partial P_k(0, k_t) / \partial t > 0$, it may even happen for exponentially discounting agents that the ex ante optimal plan suggests not to invest in environmental protection in the first but a later period. However, what happens if agents discount hyperbolically and no commitment to the ex ante optimal plan is possible? Following an analogous approach as outlined in the proof to proposition 3, ex post investment is only optimal for agent t , if

$$-P_i(0, k_t) < \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s P_k(0, k_{t+1+s}) . \quad (31)$$

Because of condition (4), the right hand side of condition (31) is smaller than the right hand side of condition (30). As a consequence, ex post the agents are, in general, not investing at the period the ex ante optimal plan suggests, but do so, if at all, later.⁷ Again, it may happen that no investment is actually carried out for the whole time horizon, although the ex ante optimal plan suggested to do so. Also, the condition for the first marginal investment to be optimal are identical for naive and sophisticated agents and given by condition (31).

We now turn to the assumption of a time-invariant payoff function P . For example, this neglects problems where doing nothing worsens the environmental problem and, therefore, increases marginal benefits of investments in environmental protection over time. This is the case when the environmental problem is caused by a stock pollutant with increasing marginal damage. Then, no investment in the beginning would lead to an accumulation of the pollution stock and, therefore, would only be optimal until the marginal costs of investment are eventually outweighed by the marginal damage of an additional unit of pollutant. Another example, which is not covered by the assumptions made about the payoff function P , is technical progress in environmental protection. Technological change or learning-by-doing would decrease the marginal costs

⁷ Due to the discrete model setup, the case might happen that hyperbolically discounting agents actually *do invest* in the period suggested by the ex ante optimal plan, but not in the proposed amount.

of investment over time and might eventually reach a level, where the marginal benefits of investment in environmental protection outweigh the marginal costs.

Let us now assume that the payoff function P is explicitly time dependent, i.e., $P = P(i_t, k_t, t)$. Then, the first marginal investment in environmental protection is optimal from an ex ante point of view, if

$$-P_i(0, 0, t) < \sum_{s=0}^{\infty} \frac{\delta_{t+s}}{\delta_{t-1}} (1 - \gamma)^s P_k(0, 0, t+1+s) , \quad (32)$$

and ex post actually carried out by uncommitted hyperbolically discounting agents, if

$$-P_i(0, 0, t) < \sum_{s=0}^{\infty} \delta_{s+1} (1 - \gamma)^s P_k(0, 0, t+1+s) . \quad (33)$$

In the following, we investigate two interesting cases for the time dependence of P , the first corresponding to stock pollutants with increasing marginal damage, i.e., $\partial P_k / \partial t > 0$, and the second to decreasing investment costs due to technical progress, i.e., $\partial P_i / \partial t > 0$. The first case is analogously to the case of an initial stock of environmental protection. As the marginal benefit of environmental protection increases over time, the right hand side of conditions (32) and (33) increase over time. If the costs of investment due to technological progress decrease, then the left hand side of conditions (32) and (33) decrease over time. In both cases, it may be optimal from an ex ante point of view, not to invest in the first but in a later period (even if agents discount exponentially). However, if agents discount hyperbolically and no commitment to the ex ante optimal plan is possible, it might happen that no investment is actually carried out over the whole time horizon, although the ex ante optimal plan suggested to do so. Moreover, if investment is actually carried out, it is, in general, postponed to later periods than the ex ante optimal plan suggests. Again, the condition for the first marginal unit of investment to be optimal is identical for naive and sophisticated agents.

In summary, the assumptions of no explicit time-dependence of the payoff function and the absence of an initial stock of environmental protection lead to the clear cut result that uncommitted hyperbolically discounting agents will never invest, if they do not invest in the first period, no matter whether they are naive or sophisticated. Yet, the result is *qualitatively* robust if time-dependence of the payoff function and initial capital stocks are considered, as it is still the case that the conditions for investment to be optimal are stricter ex post than ex ante and, thus, procrastination of investment is likely (although not necessarily infinite). Moreover, the conditions for the first marginal unit of investment to be optimal are identical for both naive and sophisticated agents.

A crucial assumption for the ex ante optimal plan to suggest no investment in the first but in later periods is that the payoff function does not satisfy the Inada conditions, as the Inada conditions rule out corner solutions. No investment is a corner solution in the sense that the non-negativity constraint for investment is binding for some periods t . It is also the non-negativity constraint which guarantees, together with the assumption that $P_{ik} \leq 0$, that the no-investment MPE is unique. As shown by Karp (2005)

in a similar model setting, the MPE is in general not unique. In fact, analyzing the unconstrained optimization problem would lead to multiple MPE with a continuum of *negative* stationary state levels of environmental protection, which are condensed by the feasibility constraint to the unique no-investment MPE. However, even if $P_{ik} > 0$ and ex ante procrastination leads to multiple MPE,⁸ the no-investment MPE is still Markov perfect and, therefore, a credible ex post outcome.

5.2 Policy implications

Although our results have been derived from a stylized theoretical model, there are some immediate policy implications to be drawn. First, our result that without a commitment mechanism hyperbolic discounting can lead to an infinite ex post procrastination questions the application of hyperbolic discounting in long-term cost-benefit analysis. Yet, HM Treasury (2003) requires hyperbolic discounting in the evaluation of the UK Governments investment decisions for projects exceeding a 30 year time horizon. In light of our results, the UK government is well advised to reconsider this policy or at least investigate the possibility of commitment mechanisms.

Second, our theoretical results are consistent with real world observations. In fact, hyperbolic discounting offers a new explanation for unsatisfactory policy performance in the context of long-run environmental problems. Take as an example the stabilization of greenhouse gases to prevent, or at least reduce, anthropogenic climate change.⁹ The Framework Convention on Climate Change, which was open to signature in Rio de Janeiro in June 1992 and at the UN headquarters thereafter, received the signatures of 186 states. The signatory developed countries agreed as a first step to stabilize their greenhouse gas emissions at their 1990 levels by 2000. Despite their sincere intention at the date of signature, most countries have failed to do so. Similar outcomes can be observed with the subsequent Kyoto protocol which was signed in December 1997. In this treaty the developed countries agreed to reduce their greenhouse gas emissions to 95 % of their 1990 levels by 2008–2012. Some countries which signed the protocol now refuse to ratify it (e.g., USA and Australia). Also many countries which ratified Kyoto are still far from their promised emission targets. Moreover, the countries which already met, or are likely to meet, their targets by 2008 have done so more by accident than by deliberate action (Pearce 2003).

These facts fit perfectly with the behavior we would expect if governments make decisions on the basis of hyperbolic discounting (although they might be not aware of it) and the ex ante optimal plan suggests to postpone investment to later periods. Although the governments intended to act in the future at the time they signed the treaties, they failed to do so because of ex post procrastination.

Although hyperbolic discounting is clearly not the sole possible explanation for the

⁸ Note that the assumption $P_{ik} \leq 0$ is a *sufficient* but not *necessary* condition for the uniqueness of the no-investment MPE.

⁹ Although anthropogenic climate change is a *stock* pollutant problem which is likely to exhibit increasing marginal damage, the case is applicable to the results of the model presented as the Framework Convention on Climate Change and the Kyoto protocol only limit *emissions*.

unsatisfactory performance of the Kyoto protocol (e.g., Nordhaus and Boyer 1999, Victor 2001, Böhringer 2003), it should not be dismissed, for three reasons. First, other examples also support the observation that governments might discount hyperbolically rather than exponentially. Hepburn (2003) shows that the discrepancies between the forecast and actual development of the northern Atlantic cod population is consistent with naive hyperbolically discounting agents. Another example is the ongoing procrastination in solving the final nuclear waste disposal problem. Although Proops (2001) argues from a political discourse perspective, the observations are also consistent with hyperbolically discounting governments.

Second, if the hyperbolic discounting explanation plays a role, this gives rise to severe concerns about the future, as *ex ante* optimal investment delays lead inevitably to (infinite) *ex post* procrastination. Moreover, even awareness of the problem does not help, as sophisticated agents perform as badly as naive agents.

Third, in the case of sophisticated agents, hyperbolic discounting introduces a second strategic dimension to the problem of the long-run mitigation of anthropogenic climate change which hinders its solution. The first strategic dimension is *spatial*, as climate change is a global environmental problem and, thus, the question of “burden sharing” arises, i.e., which country cuts emissions of greenhouse gases by how much (e.g., Endres and Finus 1999, 2002, Rubio and Casino 2005, Yang 2003). The second strategic dimension is the *intertemporal nature* of the investment game the sophisticated agents play against each other. Thus, we might face a “two-dimensional Prisoner’s Dilemma” in the solution of global (environmental) problems.

6 Conclusion

In this paper we have analyzed optimal intertemporal investment in environmental protection for a society consisting of hyperbolically discounting agents. Because of the non-stationarity of hyperbolic preferences, the *ex post* observed outcome crucially depends on additional behavioral constraints. As prime examples we have discussed the committed, the naive and the sophisticated agents. The well known result that naive agents tend to (infinitely) postpone actions into the future has been extended by the result that sophisticated agents perform as badly as naive agents if the *ex ante* optimal plan suggests investment in the long-run but not in the present.

In the model framework analyzed we have shown that, no matter whether the agents are naive or sophisticated, an *ex ante* optimal investment delay implies an infinite *ex post* procrastination, i.e., there is no investment in environmental protection in all periods, although this has been optimal from an *ex ante* point of view. This infinite *ex post* delay is the result of the assumption that the payoff function does only depend on the investment and the level of environmental protection and that marginal costs of investment do not decrease with the level of environmental protection. Nevertheless, even if infinite *ex post* procrastination is overcome by increasing marginal benefits or decreasing marginal costs of investment the qualitative results are fairly robust.

Furthermore, we have shown that, in the absence of a commitment mechanism, the *ex*

post implemented plan may lead to a Pareto inefficient intertemporal outcome. However, inefficiency is not guaranteed in general, but hinges upon the set of exogenously given parameters on the discount factors δ_n , and the marginal costs P_i^0 of investment and the marginal benefits P_k^0 of environmental protection. On the one hand, the results question the application of hyperbolic discounting in the cost-benefit analysis of long-term environmental projects. On the other hand, they give rise to concern as they are consistent with real world observations of unsatisfactory policy performance. In a sense, it might be that the crucial question is not whether to adopt hyperbolic discounting in long-term decision making or not, but, given that decision makers discount hyperbolically, how can we design environmental policies to exclude the (from every generation's point of view) unsatisfactory and often also inefficient outcome of an infinite ex post procrastination.

Clearly, a commitment mechanism would solve the problem. Cropper and Laibson (1999), for example, suggest to Pareto improve the outcome by subsidizing the interest rate. Their crucial assumption is that the effect of implemented policies occur with a time-lag, which is in fact a commitment for the next period. Another possible commitment device is a supra-national organization such as the European Union, which enforces environmental legislation to be adopted by member states and also has the power to punish in the case of non-compliance. However, especially in a long-term and intergenerational setting, the enforcement power of the present generation is very limited (and also questionable on ethical grounds as this implies a dictatorship of the present over the future generations). Hence, the solution of this problem is open to future research.

Finally, it is worth noting that, although our model was primarily designed to address long-run environmental problems, the results extend to other investment decisions of a long-run and intergenerational nature, such as education, health insurance and pension schemes.

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