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More Stringent Cap or Higher Penalty Fee? Dealing with Procrastination in Environmental Protection

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People tend to procrastinate on immediate-cost activities. In environmental protection, resource conservation and pollution control commonly involve substantial immediate costs but long-delayed benefits, giving entrepreneurs an incentive to remain inactive. This paper assumes that procrastination is induced by "present bias," and examines how the government can design policies that promote efficiency in the regulation of procrastinating entrepreneurs. Our main findings are threefold. First, entrepreneurial present bias makes the environmental protection investment increase faster as the compliance deadline approaches. Second, the compliance cost incurred by the entrepreneur increases with the degrees of present bias and entrepreneurial naivete. Third, relative to the traditional policy for rational entrepreneurs without present bias, the optimal policy delivers a more stringent cap for naive entrepreneurs, but a higher penalty fee for sophisticated entrepreneurs.

Key Words: Environmental policy; Time-inconsistent preferences; Present bias; Procrastination; Cap-and-trade; Principal-agent.
JEL Classification Numbers: D01, Q56.

1. INTRODUCTION

Cap-and-trade policy instruments have been applied to mitigate a number of environmental problems such as pollution emissions, fish catch and water diversions (Colby 2000). Beyond the trading mechanism, the specification of the cap and the penalty fee determines policy effectiveness. From a behavioral perspective, if resource-consuming or environmental polluting entrepreneurs tend to procrastinate on making investments in environmen-

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tal protection, how can the government respond? More specifically, relative to the traditional policy for rational entrepreneurs, given a choice between a more stringent cap and a higher penalty fee, which alternative should the government advocate?[1] The answers to these questions are not direct: although both instruments can lead to the same reduction in resource extraction or pollution, they have different effects on entrepreneurs' resource conservation and pollution abatement strategies. In this paper, we build a theoretical model to study the related trade-off and its policy implications.

There are several reasons why entrepreneurial procrastination is important for environmental protection. First, a growing body of evidence from the economics, psychology and neuroscience fields suggests that people tend to procrastinate on activities involving immediate costs and delayed benefits (DellaVigna 2009). Because environmental protection measures such as resource conservation and pollution control commonly involve substantial immediate costs and long-delayed benefits, it is intuitively compelling to assume that entrepreneurs have an incentive to remain inactive in environmental protection. Second, enterprise managers face a finite horizon. They commonly set profit goals for their businesses that need to be achieved within 3 to 5 years. It is thus difficult for them to be interested in long-term benefits which can be realized even in the next century but would decrease their short-term profits (Shleifer and Vishny 1990). Third, the lifetime of a business line is uncertain, and entrepreneurs' aversion to this uncertainty can lead to overemphasis of short-term profits (Bommier 2006). Finally, the debate over the costs and benefits of making regulatory decisions on environmental policy is still going strong, and the social norms related to environmental protection remain absent. This is likely to foster further procrastination (d'Adda 2010).

Existing literature identifies a number of psychological and sociological factors that contribute to procrastination (Burka and Yuen 1983). In terms of individual preference, procrastination is well explained by "present bias": "when evaluating trade-offs between two future events, as the dates of the events become closer, people appear to assign a higher relative weight to the event that takes place earlier" (O' Donoghue and Rabin 1999a). Present bias captures the common tendency of people to succumb to short-run impulses at the expense of long-run interests. In the context of environmental protection, entrepreneurial present bias means that rather than using time-consistent exponential discount rates, entrepreneurs always give extra weight to the immediate cost over any future costs, showing an imperfect altruism toward future generations. The notion of present bias can be con-

[1] To answer this question, we assume implicitly that a more stringent cap is a substitute for a higher penalty fee when the pollution-reduction target is fixed.

cisely modeled by "hyperbolic discounting," which was originally proposed by Strotz (1956) and later developed by Laibson (1997).

Building on the Instantaneous-Gratification model created by by Harris and Laibson (2013), this paper applies hyperbolic discounting in contract design to investigate how the government can design policies that promote the environmental protection efforts of procrastinating entrepreneurs, and formulates a principal-agent problem with a finite horizon. In our framework, the government (principal) determines the cap of the resource use or emissions and the penalty fee per unit of excessive resource use or pollution emissions. The representative entrepreneur (agent) attempts to minimize the total compliance cost with two components: one is the cost of the environmental protection investment, and the other is the penalty incurred at the end of the period. The entrepreneur with hyperbolic discounting encounters a self-control problem. We follow O'Donoghue and Rabin (2001) and discuss three assumptions related to the entrepreneur's awareness of this problem: she is sophisticated, i.e., fully aware of the problem and incorporates it into the decision process ; she is naive, i.e., fully unaware of the problem and makes decisions in a myopic way; and she is partially naive, i.e., aware of the problem but underestimates its magnitude.

Our model intends to capture the entrepreneur's tendency to delay the investment in environmental protection until the deadline, and the government's will to mitigate the cost of procrastination through adjusting the cap and the penalty fee. As our focus is on the cap and the penalty fee, this paper doesn't model the trading mechanism explicitly and just assume that the market price for the resource or emission rights is exogenous. In environmental protection, another reason for entrepreneurs to remain inactive comes from the externality that each single firm has no private incentive to solve (Rezai et al. 2012). We also preclude such externality in this paper and concentrate on the behavioral nature in explaining procrastination. Our main findings are listed below.

First, present bias hampers intertemporal smoothing in the investment in environmental protection. The sophisticated entrepreneur is better than the naive entrepreneur at smoothing the investment, suggesting that an awareness of the self-control problem can alleviate the adverse effect of present bias.

Second, other things being equal, the compliance cost incurred by the entrepreneur increases with the degrees of present bias and entrepreneurial naivete. This suggests that enhancing entrepreneurs' self-control through education, training, behavioral monitoring, product innovation or self-help organizations can help reduce the compliance cost.

Third, we find that different instruments have different effects on entrepreneurs' resource-conservation or pollution abatement strategies. A more stringent cap increases the likelihood of being exceeded and thus increases the penalty of uncovered resource use or pollution emissions, whereas a higher penalty fee hampers intertemporal smoothing in the resource-conservation or pollution abatement strategies and thus increases the cost of the environmental protection investment. Which instrument minimizes the associated cost depends on whether the representative entrepreneur is aware of the associated self-control problem. If she is naive, the cost of intertemporal non-smoothing dominates, and a more stringent cap ought to be advocated; however, if she is sophisticated, the cost of intertemporal non-smoothing becomes negligible and the optimal instrument should switch to a higher penalty fee.

In the choice of regulation versus Pigouvian taxes, Weitzman (1974) shows that uncertainty increases the comparative advantage of quantity regulation. Our paper shows that a pervasive cognitive feature—entrepreneurial naivete—also favors regulation over taxes. When entrepreneurs are time-consistent, the tax mode (a higher penalty fee) is always optimal, irrespective of the discount factor. However, when inconsistency arises, the regulation mode (a more stringent cap) becomes optimal when entrepreneurs are naive.

This paper is closely related to a recent strand of literature aimed at clarifying the implications of hyperbolic discounting on environmental problems.[2] Karp (2005) analyzes the time-consistent Markov perfect equilibrium in a general model with a stock pollutant. Karp and Tsur (2011) examine the implications for climate change policy when the probability of a climate-induced catastrophe depends on the stock of greenhouse gasses. Ekeland et al. (2011) study how the degree of concern for the not-yet born generations influences the equilibrium policy in a classic fishery model. Hepburn et al. (2010) show that if a planner is unable to commit to a policy, the temptation to re-evaluate the policy in the future could lead to an inadvertent collapse in the stocks of a natural resource. Winkler (2009) compares the public investment decisions made under different behavioral patterns and concludes that in the absence of a commitment device, society is stuck in a situation where every agent prefers further investments, yet no agent invests, and awareness of the time-inconsistency problem poses a short-term remedy at best. These studies implement the framework of overlapping generations and focus on the long-run performance of environmental policies. This paper deviates by investigating a short-run incentive problem, with the aim to improve the short-run performance of related policies.

[2]In the literature, hyperbolic discounting has arisen either rationally due to the presence of uncertainty in future events (Weitzman 1998, 2001; Gollier 2002), or irrationally due to the discrepancy between individuals' long- and short-run preferences (Hepburn et al. 2010). For an overview of the declining discounting rate in environmental preservation, see Groom et al. (2005) and Weitzman (2007).

This paper is also related to three other strands of literature. The first explores the comparative advantages of price and quantity instruments. In the pioneering paper by Weitzman (1974), it is clarified that the relative slopes of the marginal benefits and costs of controlling the externality are critical determinants of the efficiency of prices relative to quantities. Pizer (2002) performs simulations based on a stochastic computable general equilibrium model and finds that a hybrid policy is an attractive alternative to either a pure price or quantity system.[3] Kelly (2005) examines quantity regulation and price regulation in a situation where the regulator does not observe firm productivity shocks, and concludes that quantity regulation generates higher welfare regardless of the benefit function. Wirl (2012) considers the strategic implications of price and quantity instruments in a differential game, and shows that both the government and fossil fuel suppliers prefer the price instrument. Karp and Zhang (2012) compare emissions taxes and quotas with asymmetric information related to abatement costs, and find a tax to offer some advantages in their numerical study. We add to the literature by demonstrating that a more stringent cap is more appropriate for naive entrepreneurs, and that a higher penalty fee is more appropriate for sophisticated entrepreneurs.

The second strand of literature related to this paper considers the effects of procrastination on performance and welfare. O'Donoghue and Rabin (1999b, 2001) explored a model of designing a reward scheme to combat procrastination in one-stage projects. O'Donoghue and Rabin (2008) extend their former analysis to long-term projects with multiple stages. Fischer (2001) considers rational procrastination by assuming that a finite work requirement must be completed by a deadline. As the payoff structure considered by these papers is quite different from that in the cap-and-trade policy, the results of these papers cannot be applied directly to our framework.

The third related strand of literature examines the influences of self-control on investment strategies. Grenadier and Wang (2007) provide solutions to the timing problems in real options when entrepreneurs apply hyperbolic discounting to cash flows. Miao (2008) demonstrates that applying the Gul and Pensendorfer self-control utility model to the investment and exit problems can generate the behavior of procrastination and preproperation. Along this line, we are the first to introduce self-control to the dynamic optimization of resource-conservation or pollution abatement strategies.

The layout of this paper is as follows. Section 2 presents the optimization problem of resource-conservation or pollution abatement strategies and

[3]The cap-and-trade system of emissions regulation implemented in the Kyoto Protocol Program is a hybrid policy that combines both the political appeal of quantity controls with the efficiency of prices.

provides solutions when the representative entrepreneur is assumed to be naive, sophisticated and partially naive, respectively. Section 3 formulates the principal-agent problem wherein the government determines the environmental policy and the entrepreneur attempts to minimize the total compliance cost. The properties of the optimal policy are presented in this section. Section 4 concludes the paper. All technical proofs are relegated to the Appendix.

2. THE ABATEMENT PROGRAM

We narrate the story in the context of pollution control. Nevertheless, our analysis is also well-suited to resource extraction, and our policy suggestions apply generally to various cap-and-trade programs in environmental protection.

Imagine that polluting enterprises emit CO_2 during the production process. In a regulatory framework such as the EU ETS, enterprises must pay penalties for their cumulative CO_2 emissions over the compliance period that exceed a pre-specified emission cap.[4] For the representative entrepreneur, the total compliance cost consists of two parts: the cost of pollution-reducing investment, and the penalty incurred at the end of the period. To simplify the analysis, we avoid modeling the trading mechanism explicitly and just assume that purchasing emission allowances in the market is one alternative of pollution-reducing investment whose cost is included in the former part.

We assume that the cumulative emission y_t follows

$$dy_t = (k - u_t)dt, \quad \text{or equivalently,} \quad y_t = kt - \int_0^t u_s ds,$$

where k is the normal rate of emission for productivity. The entrepreneur either employs emission-reduction technologies or purchases emission allowances in the market. When she employs emission-reduction technologies, u_t denotes the rate of abatement. Otherwise, u_t denotes the instantaneous amount of purchased emission allowances. One can easily reinterpret y_t in the context of resource extraction, where y_t denotes the rate of resource consumption, k denotes the normal consumption rate for productivity, and u_t denotes the rate of conservation.

[4]The European Union adopted the European Union Emission Trading Scheme (EU ETS) to decrease the CO_2 emissions of companies from the energy and other carbon-intensive industries. The EU ETS was introduced in 2005, and CO_2 emissions allowances (i.e., CO_2 certificates) have since become available as a new financial instrument.

For the entrepreneur employing emission-reduction technologies, we assume that the marginal abatement cost is an industry-related constant c.[5] For the entrepreneur purchasing emission allowances in the market, c denotes the market price per unit of emission. In Seifert et al. (2008), it is shown that in equilibrium the marginal abatement cost equals the market price per unit of emission. As a result, for both entrepreneurs, the instantaneous cost of pollution-reducing investment is cu_t. In the following, we do not differentiate between the employment of emission-reduction technologies and the purchase of emission allowances again, and term u_t the abatement rate.

At the end of the compliance period, the representative entrepreneur must pay the penalty of uncovered emissions given by $\max[0, p(y_T - e_0)]$, where e_0 is the emission cap and p is the penalty fee per unit of excessive emissions.

For the sake of tractability, we use the power function $U(L) = L^\gamma$ $(\gamma > 1)$ to quantify the disutility of the representative entrepreneur's compliance cost. The convexity of $U(L)$ captures that the marginal disutility is increasing in the cost, reflecting the entrepreneur's aversion to the cost. The case of neutrality arises when $\gamma \to 1$. For a period $[0, T]$ with a finite horizon $T < \infty$, the total compliance cost is thus given by

$$C(e_0, p) \equiv \underbrace{\int_0^T e^{-rt} U(cu_t) dt}_{\text{the cost of pollution-reducing investment}} + \underbrace{e^{-rT} U(\max[0, p(y_T - e_0)])}_{\text{the penalty incurred at the end of the period}}, \tag{1}$$

where r is an exponential discounting factor that can be chosen as the risk-free interest rate. This framework is similar to the one adopted by Seifert et al. (2008).

2.1. The time-consistent benchmark

This subsection outlines the optimal (cost-minimizing) abatement strategy for the time-consistent entrepreneur as a benchmark for later analysis. To simplify the notation, we follow Seifert et al. (2008) in defining $x_t \equiv y_t + k(T - t)$, which satisfies

$$dx_t = -u_t dt, \quad x_0 = kT, \quad x_T = y_T. \tag{2}$$

With a time-consistent preference, the entrepreneur attempts to minimize the total compliance cost given by (1). For the disutility of the

[5] Even if a major breakthrough in emission-reduction technologies may happen anytime, the marginal abatement cost can be considered approximately constant during the period when the effect of the transitory jump diminishes. Our framework is feasible enough to accommodate other kinds of cost functions.

abatement strategy $\{u_s\}_{s\in[t,T]}$ conditional on x_t

$$V(t,x_t) \equiv \min_{u_t}\left[\int_t^T e^{-r(s-t)}U(cu_s)ds + e^{-r(T-t)}U(\max[0,p(x_T-e_0)])\right],$$

the Bellman equation[6] is

$$rV = \min_{u_t}[U(cu_t) + V_t - u_tV_x], \quad V(T,x_T) = \max[0,p^\gamma(x_T-e_0)^\gamma]. \quad (3)$$

Noting that the terminal value $V(T,x_T)$ in (3) is smooth in x_T up to the first order due to $\gamma > 1$, we can easily obtain the closed-form solution.

LEMMA 1. *For the time-consistent entrepreneur, at each time t, the optimal conditional abatement rate for given x_t is $u_t = \frac{(x_t-e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}}$. In the unconditional form, the optimal abatement rate at time t is*

$$u_t = \frac{(kT-e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}},$$

and the optimal cumulative emission at time T is

$$x_T(e_0,p) = e_0 + (kT-e_0)\frac{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}.$$

Further, the minimal total compliance cost in the period $[0,T]$ equals

$$C(e_0,p) = \frac{c^\gamma(kT-e_0)^\gamma}{\left[\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}\right]^{\gamma-1}}.$$

2.2. Entrepreneur's instantaneous gratification

Following Harris and Laibson (2013), we model hyperbolic discounting using a continuous-time formulation. The heuristic behind this formulation is as follows. At each time t, an agent's preferences are divided into a

[6]The derivations of the Bellman equations throughout this paper are relegated to the Appendix.

"present" lasting from t to $t+\tau_t$ and a "future" lasting from $t+\tau_t$ to ∞. Self t controls the decision only in the present, while caring about the utility generated by the decisions of future selves. Thus, the discount function for self t is

$$D_t(s) = \begin{cases} e^{-r(s-t)}, & \text{if } s \in [t, t+\tau_t) \cap [t, T], \\ \beta e^{-r(s-t)}, & \text{if } s \in [t+\tau_t, \infty) \cap [t, T]. \end{cases}$$

The length of the present τ_t is stochastic, and is distributed exponentially with parameter $\lambda \in [0, \infty)$.[7] The hyperbolic discounting factor β ($0 < \beta < 1$) measures the degree of the entrepreneur's time inconsistency. The condition $0 < \beta < 1$ reveals that the individual gives a higher weight to the immediate cost incurred at present over those in the future, undermining her ability to implement a long-run plan. Likewise, when self t's future arrives at time $t+\tau_t$, she is replaced by a new self who takes control of the decision at time $t+\tau_t$.

In terms of the hyperbolic discounting, from the perspective of self t, the disutility of the abatement strategy $\{u_s\}_{s\in[t,T]}$ conditional on x_t is given by

$$W(t, x_t) \equiv \min_{u_t} E_t \left[\int_t^T D_t(s) U(cu_s) ds + D_t(T) U(\max[0, p(x_T - e_0)]) \right],$$

where E_t denotes the conditional expectation at time t.[8] To derive the Bellman equation for W, we decompose W into a current disutility and a continuation disutility, the latter of which describes self t's consideration of future selves. The current disutility is $U(cu_t)dt$, but the continuation disutility depends on whether the transition between the present and future occurs. If the transition does not occur, then the continuation disutility is $W(t+dt, x_t+dx_t)$. If the transition occurs, then the continuation disutility changes to be $\beta V^{\text{con}}(t+dt, x_t+dx_t)$. For an infinitesimal time increment dt, the transition probability is $e^{-\lambda dt}$. Taking these elements together, the Bellman system for W and V^{con} is

$$rW = \underbrace{\min_{u_t}[U(cu_t) + W_t - u_t W_x]}_{\text{I}} + \underbrace{\lambda(\beta V^{\text{con}} - W)}_{\text{II}}, \tag{4}$$

$$rV^{\text{con}} = U(cu_t^{\text{con}}) + V_t^{\text{con}} - u_t^{\text{con}} V_x^{\text{con}}, \tag{5}$$

where u_t is the abatement decision controlled by self t, and u_t^{con} is the continuation abatement decision to be controlled by future selves. In (4),

[7] The parameter λ denotes the hazard rate of the transition from the present to future.

[8] This conditional expectation is taken over the stochastic duration of the present τ_t.

term I describes the first-order effect of the decision controlled by self t, which indicates that the optimal abatement choice for self t satisfies

$$cU'(cu_t) = W_x. \tag{6}$$

Term II expresses self t's concern for preference reversals that will occur in the future, where the hyperbolic discounting factor β appears together with the continuation disutility V^{con}. This reflects that when evaluating the future, self t prefers to assign a lower weight.

To improve tractability, Harris and Laibson (2013) establish the notion of "instantaneous gratification," referring to the limiting case $\lambda \to \infty$, in which (4) turns out to be

$$W = \beta V^{\mathrm{con}}.$$

Combining it with (6), it follows that in the Instantaneous-Gratification model, self t chooses her current abatement according to

$$cU'(cu_t) = \beta V_x^{\mathrm{con}}. \tag{7}$$

The left-hand side of (7) is the marginal of the instantaneous disutility, and the right-hand side is the marginal of the perceived continuation disutility. The hyperbolic discounting factor β captures that when making a trade-off between the instantaneous marginal disutility and the perceived future marginal disutility, the current self assigns a lower weight to the future marginal disutility, and thus prefers to make less of an effort at present than in the future. This creates the tendency to procrastinate.

LEMMA 2. *In the Instantaneous-Gratification model, at each time t, we have:*
(i) self t chooses the optimal abatement rate u_t according to (7), believing that her future selves will choose the continuation abatement rate $\{u_s^{con}\}_{s\in(t,T]}$;
(ii) self t's continuation disutility V^{con} evolves in line with (5).

The closed-form solution to the Instantaneous-Gratification model presented in Lemma 2 can be derived by following these steps.

Step 1. Specify u_t^{con} and solve (5) with the terminal condition $V^{\mathrm{con}}(T, x_T) = \max[0, p^\gamma(x_T - e_0)^\gamma]$. This yields the conditional continuation disutility $V^{\mathrm{con}}(t, x_t)$.

Step 2. Insert the conditional continuation disutility $V^{\mathrm{con}}(t, x_t)$ into (7). This yields the actual choice of u_t conditional on x_t.

Step 3. Incorporate the actual choice of u_t conditional on x_t into (2). This leads us to the explicit evolution of u_t and x_t.

The crucial ingredient in these steps is the specification of u_t^{con}, which relies heavily on whether the entrepreneur is aware of the self-control problem to be encountered by her continuation selves. In the next subsection, we specify u_t^{con} according to different assumptions on the awareness of the self-control problem (i.e., different degrees of entrepreneurial naivete) and derive the corresponding closed-form solutions.

2.3. Solutions to the Instantaneous-Gratification model

Case 1: Naivete.

The naive entrepreneur believe falsely that future selves act in the interest of the current self, i.e., that continuation selves will implement the time-consistent preference without present bias. As such, the naive entrepreneur determines $\{u_s^{\text{con}}\}_{s\in(t,T]}$ by maximizing $V^{\text{con}}(t, x_t)$ directly, i.e., she chooses u_t^{con} according to

$$cU'(cu_t^{\text{con}}) = V_x^{\text{con}}, \tag{8}$$

which maximizes the right-hand side of (5). In this case, V^{con} coincides exactly with the time-consistent benchmark V studied in subsection 2.1. It is interesting to compare (8) with (7): (8) characterizes what the naive entrepreneur would like her future selves to prefer, and (7) characterizes what the naive entrepreneur actually chooses when the time for decision arrives. The naive entrepreneur does not recognize that her plan for the future is non-credible because her current self cannot control her subsequent selves. Hence, her actual abatement strategy always differs from those of her earlier selves.

Lemma 3. *When time t is in the future, the naive entrepreneur believes that at that time her future self will take the conditional abatement rate for given x_t as $u_t^{con} = \frac{(x_t-e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}}$. However, when time t arrives, she actually takes $u_t = \beta^{\frac{1}{\gamma-1}}u_t^{con}$. In the unconditional form, the abatement rate adopted by the naive entrepreneur at time t is*

$$u_t = \frac{\beta^{\frac{1}{\gamma-1}}(kT-e_0)e^{\frac{rt}{\gamma-1}}}{\left[\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right]^{\beta^{\frac{1}{\gamma-1}}}\left[\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right]^{1-\beta^{\frac{1}{\gamma-1}}}},$$

and the cumulative emission at time T is

$$x_T(e_0,p) = e_0 + (kT - e_0)\left[\frac{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}\right]^{\beta^{\frac{1}{\gamma-1}}}.$$

Further, the total compliance cost in the period $[0,T]$ equals[9]

$$C(e_0,p) = \frac{c^\gamma (kT-e_0)^\gamma}{\left[\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}\right]^{\gamma\beta^{\frac{1}{\gamma-1}}} \left(\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}\right)^{(\gamma-1)-\gamma\beta^{\frac{1}{\gamma-1}}}}$$
$$\times\left[1 + \frac{\beta^{\frac{\gamma}{\gamma-1}}}{\gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1)}\left(\left(\frac{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}\right)^{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)} - 1\right)\right].$$

Case 2: Sophisticated.

Different from the naive entrepreneur, the sophisticated entrepreneur correctly foresees that her future selves act according to their own preferences, and hence knows that without any commitment device, the abatement strategies that are credible for both the current and subsequent selves should satisfy (7). Therefore, the sophisticated entrepreneur specifies u_t^{con} following

$$cU'(cu_t^{\text{con}}) = \beta V_x^{\text{con}}, \quad \text{or equivalently,} \quad u_t = u_t^{\text{con}}. \tag{9}$$

This equation implies that the sophisticated entrepreneur takes her future selves' preference reversals into account when evaluating the continuation

[9] The expression of $C(e_0,p)$ in this lemma is valid only for $\gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1) \neq 0$. When $\gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1) = 0$, the corresponding expression for $C(e_0,p)$ can be obtained by taking the limit $\lim_{\gamma\beta^{\frac{1}{\gamma-1}}\to(\gamma-1)} \frac{1}{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)}\left(\left(\frac{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}\right)^{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)} - 1\right) = \ln\left(\frac{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}\right)$.

disutility from her current perspective. For this reason, the sophisticated entrepreneur is able to behave in a time-consistent way. In other words, the sophisticated entrepreneur achieves the Markov perfect equilibrium in the non-cooperative sequential game that every self plays against one another.

LEMMA 4. *For the sophisticated entrepreneur, at each time t, the optimal conditional abatement rate for given x_t is* $u_t = u_t^{con} = \frac{\beta^{\frac{1}{\gamma-1}}(x_t-e_0)e^{\frac{rt}{\gamma-1}}}{\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}}$. *In the unconditional form, the optimal abatement rate at time t is*

$$u_t = \frac{\beta^{\frac{1}{\gamma-1}}(kT-e_0)e^{\frac{rt}{\gamma-1}}}{\left[\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right]^{\frac{\gamma-1}{\gamma-\beta}}\left[\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right]^{\frac{1-\beta}{\gamma-\beta}}},$$

and the optimal cumulative emission at time T is

$$x_T(e_0,p) = e_0 + (kT-e_0)\frac{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-\beta}}e^{\frac{rT}{\gamma-\beta}}}{\left(\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma-\beta}}}.$$

Further, the minimal total compliance cost in the period $[0,T]$ equals

$$C(e_0,p) = \frac{c^{\gamma}(kT-e_0)^{\gamma}}{\left(\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}\right)^{\gamma-1}}.$$

Case 3: Partial Naivete.

It seems plausible that the more realistic case lies between naivete and sophistication. This case is termed "partial naivete." In this case, the entrepreneur foresees the self-control problem to be encountered in the future, but underestimates its magnitude. The entrepreneur believes the degree of time inconsistency in the future to be $\hat{\beta} \in (\beta, 1)$. Hence, she specifies u_t^{con} as

$$cU'(cu_t^{\text{con}}) = \hat{\beta}V_x^{\text{con}}.$$

In this case, one can verify that at each time t the adopted conditional abatement rate for given x_t is

$$u_t = \frac{\beta^{\frac{1}{\gamma-1}}(x_t-e_0)e^{\frac{rt}{\gamma-1}}}{\hat{\beta}^{\frac{1}{\gamma-1}}\frac{\gamma-\hat{\beta}}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}}+\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}},$$

which is a generalization of Lemmas 3 and 4. In the unconditional form, the abatement rate for the partially naive entrepreneur is

$$u_t = \beta^{\frac{1}{\gamma-1}}(kT-e_0)\frac{\left(\hat{\beta}^{\frac{1}{\gamma-1}}\frac{\gamma-\hat{\beta}}{\gamma-1}\frac{e^{\frac{r}{\gamma-1}(T-t)}-1}{\frac{r}{\gamma-1}}+e^{\frac{r}{\gamma-1}(T-t)}\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}\right)^{\frac{1}{\gamma-1}}-1}}{\left(\hat{\beta}^{\frac{1}{\gamma-1}}\frac{\gamma-\hat{\beta}}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}+e^{\frac{rT}{\gamma-1}}\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}\right)^{\frac{1}{\gamma-1}}}}e^{\frac{rt}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}\right)^{\frac{1}{\gamma-1}}}, \tag{10}$$

and the corresponding cumulative emission is

$$x_T = e_0 + (kT-e_0)\frac{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}\right)^{\frac{1}{\gamma-1}}}}{\left(\hat{\beta}^{\frac{1}{\gamma-1}}\frac{\gamma-\hat{\beta}}{\gamma-1}\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}+e^{\frac{rT}{\gamma-1}}\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}\right)^{\frac{1}{\gamma-1}}}}e^{\frac{rT}{\gamma-\hat{\beta}}\left(\frac{\beta}{\hat{\beta}}\right)^{\frac{1}{\gamma-1}}}.$$

3. THE OPTIMAL POLICY

This section incorporates present bias and entrepreneurial naivete into the design of the cap and the penalty fee, and examines how the optimal policy responds to changes in the related behavioral factors. We consider a principal-agent problem, in which the government (principal) determines the emission cap e_0 and the per-unit penalty fee p for the excessive emissions, and the representative entrepreneur (agent) takes an unobservable abatement action to minimize the total compliance cost. To highlight the effects of the behavioral factors, we preclude the adverse selection and cost sharing between entrepreneurs and consumers.[10]

We first characterize the entrepreneur's hidden abatement action. For a given policy (e_0, p), the instantaneous abatement rate, cumulative emission and total compliance cost for the type I entrepreneur are denoted as u_t^I, x_T^I and $C^I(e_0, p)$, respectively.[11] A comparison of the different types is made in the following proposition.[12]

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[10] That is, we assume that the government observes perfectly whether the entrepreneur is naive or sophisticated, and the compliance cost is wholly borne by the entrepreneur.

[11] I = "TC," "Nai," "Sop" and "Par," standing for "time-consistent benchmark," "naive entrepreneur," "sophisticated entrepreneur" and "partially naive entrepreneur," respectively.

[12] Proposition 1 omits the case of partial naivete, as the results for that case would lie between the polar cases of naivete and sophistication.

Proposition 1. *For given $r > 0$, $0 < \beta < 1$, $p > 0$ and $0 \leq e_0 < kT$, we have:*
(i) $u_0^{Nai} < u_0^{Sop} < u_0^{TC}$, $u_T^{Nai} > u_T^{Sop}$;
(ii) if p is large enough relative to c, then $u_T^{Nai} > u_T^{TC}$, $u_T^{Sop} > u_T^{TC}$;
(iii) $x_T^{Nai} > x_T^{Sop} > x_T^{TC}$;
(iv) $C^{Nai} > C^{TC}$, $C^{Sop} > C^{TC}$;
(v) if p is large enough relative to c and $\beta \leq \left(1 - \frac{1}{\gamma}\right)^{\gamma-1}$, then $C^{Nai} > C^{Sop}$.

In the time-consistent benchmark, Lemma 1 shows that with a constant per-unit abatement cost c, the optimal abatement rate increases proportionally with the γ-adjusted inflation rate $e^{\frac{rt}{\gamma-1}}$. In other words, the rational entrepreneur ought to smooth the abatement rate over the compliance period according to r and γ. However, under the assumption that the per-unit penalty fee p is large enough relative to the per-unit abatement cost c, assertions (i) and (ii) in Proposition 1 show that

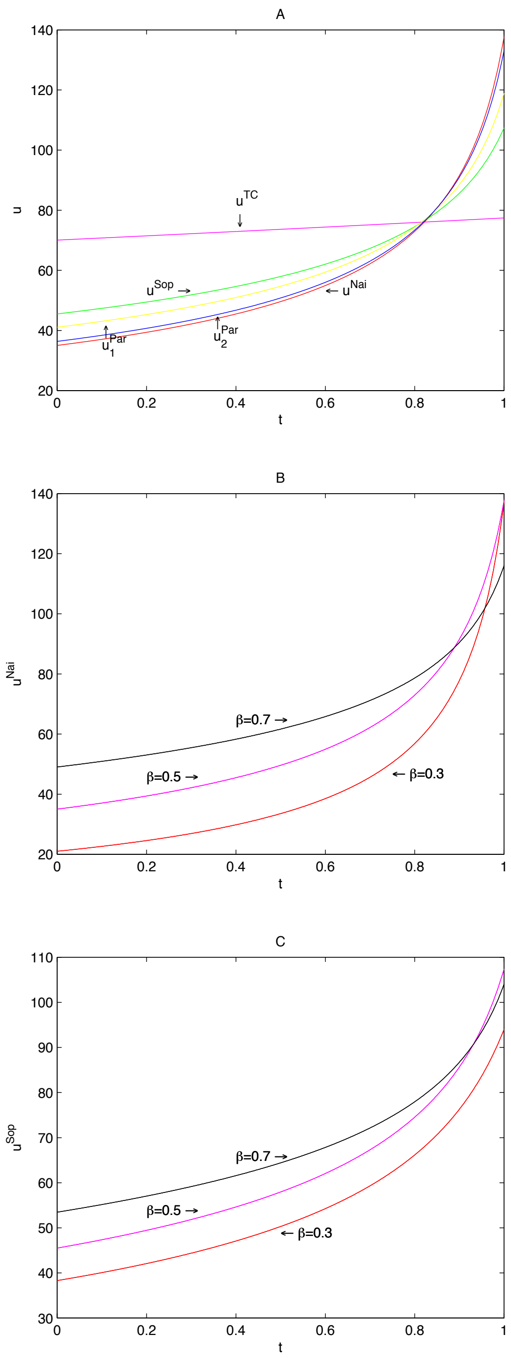
$$u_0^{\mathrm{Nai}} < u_0^{\mathrm{Sop}} < u_0^{\mathrm{TC}}, \quad u_T^{\mathrm{Nai}} > u_T^{\mathrm{Sop}} > u_T^{\mathrm{TC}}, \quad \frac{u_T^{\mathrm{Nai}}}{u_0^{\mathrm{Nai}}} > \frac{u_T^{\mathrm{Sop}}}{u_0^{\mathrm{Sop}}} > \frac{u_T^{\mathrm{TC}}}{u_0^{\mathrm{TC}}} = e^{\frac{rT}{\gamma-1}}.$$

These inequalities have two implications. First, compared with the time-consistent benchmark, present bias hampers intertemporal abatement smoothing regardless of whether the entrepreneur is sophisticated or naive, making the abatement rate lower during the beginning of the compliance period but higher in the end. Second, the sophisticated entrepreneur does better than the naive entrepreneur at smoothing the abatement, suggesting that awareness of the self-control problems can alleviate the adverse effect of present bias. Panel A in Figure 1 visualizes the abatement profiles for different types using a set of artificial parameters. It is clear that a higher degree of naivete leads to a much steeper abatement profile.

Assertion (iii) demonstrates that present bias has a negative effect on the cumulative emission. Regardless of the entrepreneurial type, compared with the time-consistent benchmark, present bias always leads to a greater cumulative emission. As the sophisticated entrepreneur has a stronger incentive to overcome procrastination, she thereby achieves a smaller cumulative emission than the naive entrepreneur.

Assertion (iv) shows that present bias increases the entrepreneur's total compliance cost. As the total compliance cost is calculated in a time-consistent manner with exponential discounting, only the optimal abatement strategy in the time-consistent benchmark minimizes it. If we further ask whether the sophisticated entrepreneur has a smaller total compliance cost than the naive entrepreneur, the answer remains ambiguous. The

FIG. 1. The abatement rates for entrepreneurs of different types.



This figure plots u_t^{TC}, u_t^{Nai}, u_t^{Sop} and u_t^{Par} with varying parameters in the setting $T=1$, $c=20$, $p=20$, $r=0.1$, $\gamma=2$ $x_0=k=20.8$ and $e_0=20$. Panel A depicts the abatement rates for entrepreneurs of different types, where we take $\beta=0.5$, and $\hat{\beta}=0.6$ for u_{1t}^{Par} and $\hat{\beta}=0.8$ for u_{2t}^{Par}. Panels B and C depict the abatement rates for naive and sophisticated entrepreneurs, respectively, with $\beta=0.3, 0.5, 0.7$.

reason is that, although the sophisticated entrepreneur achieves a smaller cumulative emission and in turn incurs a lower penalty, she pays more for a larger investment in abatement. Assertion (v) offers a sufficient condition for a definite answer: when the per-unit penalty fee p is large enough and the present bias is severe, the sophisticated entrepreneur has a Pareto-superior performance: compared with the naive entrepreneur, she achieves a smaller cumulative emission and suffers a lower compliance cost.

PROPOSITION 2. *For given $r > 0$, $p > 0$ and $0 \leq e_0 < kT$, as β becomes smaller,*
(i) $\frac{u_T^{Nai}}{u_0^{Nai}}$ becomes larger, but $\frac{u_T^{Sop}}{u_0^{Sop}}$ may become smaller;
(ii) both x_T^{Nai} and x_T^{Sop} become larger;
(iii) if p is large enough relative to c and $\beta \leq \left(1 - \frac{1}{\gamma}\right)^{\gamma-1}$, then both C^{Nai} and C^{Sop} become larger.

Proposition 2 provides comparative statics in terms of the magnitude of the present bias, which is also illustrated in Figure 1 (see Panels B and C). Assertion (i) indicates that as β becomes smaller, the naive abatement strategy deviates further from rational smoothing. However, the sophisticated strategy may perform better at abatement smoothing. Assertions (ii) and (iii) confirm the intuition that a higher magnitude of present bias would increase the cumulative emission and the total compliance cost.

PROPOSITION 3. *For given $r > 0$, $0 \leq e_0 < kT$, and $0 < \beta < 1$, as p increases, both $\frac{u_T^{Nai}}{u_0^{Nai}}$ and $\frac{u_T^{Sop}}{u_0^{Sop}}$ become larger.*

Recall that in the rational benchmark, $\frac{u_T^{\mathrm{TC}}}{u_0^{\mathrm{TC}}} = e^{\frac{rT}{\gamma-1}}$ is independent of the policy specification (e_0, p). Proposition 3 reveals that a higher penalty fee p makes the abatement strategy deviate further from rational smoothing. The intuition is as follows: irrespective of the entrepreneurial type, the abatement strategy becomes increasingly sensitive to p as time goes by, and as a result, the marginal increase in the abatement due to a higher p will be larger during the latter half of the compliance period than during the former.

In summary, these propositions highlight that the present bias is an important factor deviating the abatement strategy from rational smoothing, leading to greater cumulative emission and a higher total compliance cost. In addition, awareness of the self-control problem alleviates the negative effect, and a higher penalty fee exacerbates it. In the following, we incorporate the effect of present bias into the design of an optimal policy.

Assume that the government sets a target of $\alpha \times 100\%$ reduction in CO_2 emissions within a finite horizon T, and that the representative entrepreneur is of type I, which is observable to the government. A policy (e_0, p) is *compatible* with the target if it satisfies

$$x_T^I(e_0, p) = \alpha kT. \tag{11}$$

Figure 2 visualizes the continuum of compatible policies in the (e_0, p)-coordinate system. It shows that irrespective of the entrepreneurial type, the emission cap e_0 and the per-unit penalty fee p play substitutionary roles in imposing an incentive scheme—when the emission cap is more stringent (e_0 becomes lower), the penalty fee should decrease (p should be lowered), and vice versa. Panel A compares the compatible policies for different types with the same emission target. It is not surprising to see that when p is the same for every type, the emission cap e_0 is smaller for the less-sophisticated entrepreneurs. This implies that to meet the emission target, a more stringent cap should be imposed when the representative entrepreneur is less aware of her self-control problem. Panels B and C compare the compatible policies with different βs for naive and sophisticated entrepreneurs, respectively. They show that for the same p, as β becomes smaller, e_0 also becomes smaller. This implies that a more stringent cap should be imposed when the present bias becomes more severe.

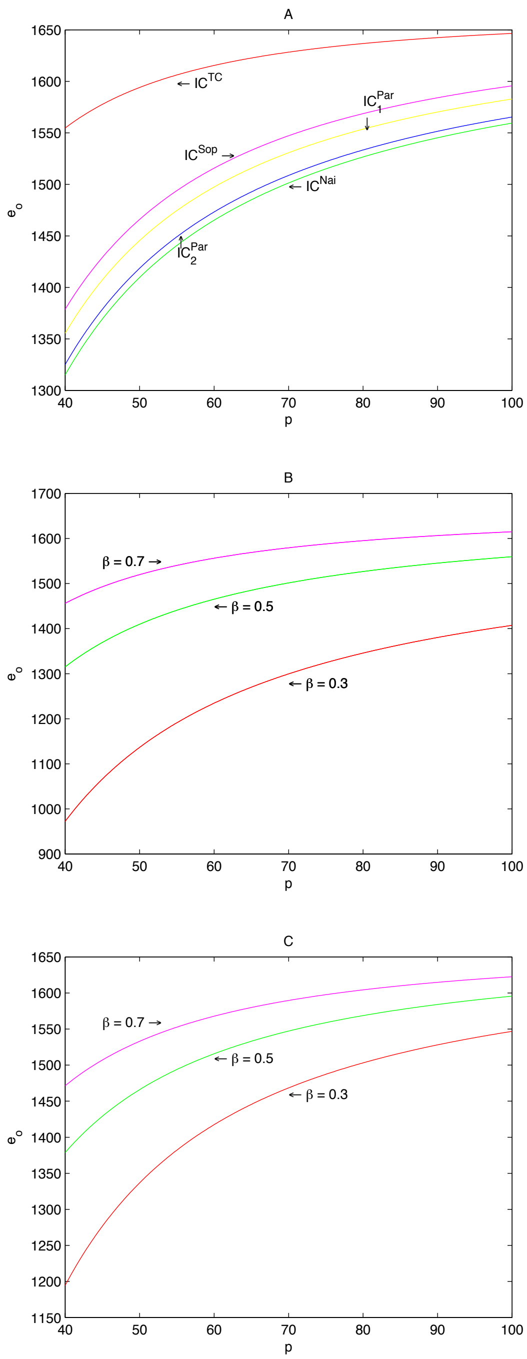
The government's objective is based on paternalism: policies are designed to affect agents' choices for their own good (Sandroni and Squintani 2007). In our setup, the entrepreneur cares about the total compliance cost generated by the abatement process and the penalty. In the same spirit of Harris and Laibson (2013), we measure the entrepreneur's total compliance cost by her time-consistent preference based on her actual abatement strategy, i.e., $C^I(e_0, p)$. The reason is: ex ante, all earlier selves of the entrepreneur evaluate the benefit and cost of their choices based on time-consistent discounting; ex post, the entrepreneur would be grateful if she were forced to take actions as her time-consistent self has planned instead of switching to a different choice halfway.[13] Formally, the problem solved by the government is

$$\begin{aligned} \min_{(e_0,p)} \quad & C^I(e_0, p), \\ s.t. \quad & e_0 \leq \alpha kT, \quad p \geq 0, \quad x_T^I(e_0, p) = \alpha kT. \end{aligned} \tag{12}$$

The solution to (12) is denoted by $(\tilde{e}_0^I, \tilde{p}^I)$. The next proposition presents the main result of this paper.

[13] See also O'Donoghue and Rabin (1999, 2001) and DellaVigna and Malmendier (2004) for a similar argument.

FIG. 2. The compatible policies for entrepreneurs of different types.



This figure plots the set of the compatible policies (e_0, p) satisfying (11). We take $T = 1$, $c = 20$, $r = 0.1$, $\gamma = 2$ $x_0 = k = 20.8$ and $\alpha = 0.8$. Panel A depicts the compatible policies for entrepreneurs of different types, where we take $\beta = 0.5$, and $\hat{\beta} = 0.6$ for IC_1^{Par} and $\hat{\beta} = 0.8$ for IC_2^{Par}. Panels B and C depict the compatible policies for naive and sophisticated entrepreneurs, respectively, with $\beta = 0.3, 0.5, 0.7$.

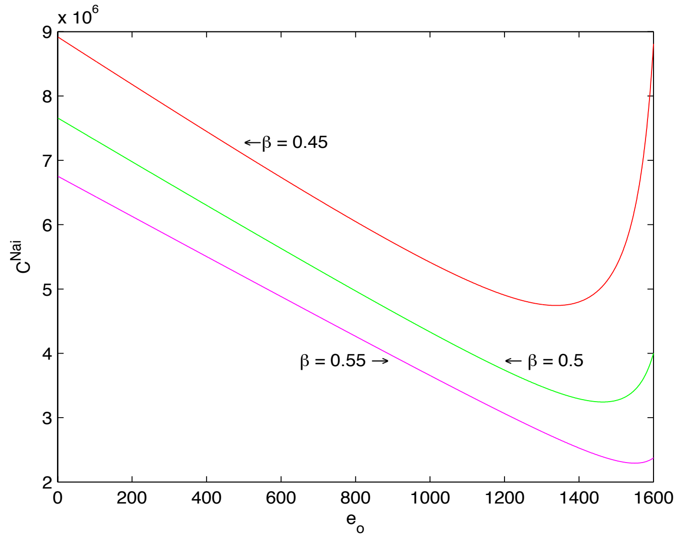
PROPOSITION 4. *For the solution to (12), we have:*
(i) for I = "TC" and "Sop", $\tilde{e}_0^I$ approximates αkT and $\tilde{p}^I$ approximates infinity;
(ii) for I = "Nai", if $\beta > \left(1-\frac{1}{\gamma}\right)^{\gamma-1}$, then $\tilde{e}_0^I$ approximates αkT and $\tilde{p}^I$ approximates infinity; if $\beta \leq \left(1-\frac{1}{\gamma}\right)^{\gamma-1}$, then $\tilde{e}_0^I$ is strictly smaller than αkT and $\tilde{p}^I$ is bounded from above.

As seen in Figure 2, among the compatible policies, the government can choose either a high e_0 together with a high p or a low e_0 together with a low p. In the time-consistent benchmark, the optimal emission cap $\tilde{e}_0^{\mathrm{TC}}$ should be as high as possible for the following reason. In the proof of Proposition 4, one can check that the total compliance cost has the same order of magnitude as the penalty incurred at the end of the compliance period. With the same emission target, when e_0 increases such that the excessive emission $\alpha kT - e_0$ decreases by an infinitesimal portion of δ, the associated p increases by a portion of $(1-\frac{1}{\gamma})\delta$, a magnitude smaller than δ. The resulting penalty decreases by a portion of $\frac{1}{\gamma}\delta$.[14] This argument provides a theoretical justification for the usage of a high emission cap in practice.

Accounting for present bias in policy design, Proposition 4 demonstrates that the choice of $\tilde{e}_0^I$ and $\tilde{p}^I$ relies heavily on whether the representative entrepreneur is aware of the self-control problem. Recall that a decrease in $\tilde{e}_0^I$ has two conflicting effects. The beneficial effect is that a lower $\tilde{e}_0^I$ is accompanied by a smaller $\tilde{p}^I$, which helps the entrepreneur behave more rationally and decreases the cost of irrationality (see Proposition 3). The adverse effect is that a lower $\tilde{e}_0^I$ increases the likelihood of being exceeded, which in turn increases the penalty of uncovered emissions. When the representative entrepreneur is sophisticated, the adverse effect dominates and the government ought to set $\tilde{e}_0^{\mathrm{Sop}}$ and $\tilde{p}^{\mathrm{Sop}}$ in a pattern similar to the time-consistent benchmark, i.e., it is optimal to set $\tilde{e}_0^{\mathrm{Sop}}$ as high as possible. When the representative entrepreneur is naive, a high emission cap is applicable only when the present bias is slight. When the present bias becomes severe, i.e., $\beta \leq \left(1-\frac{1}{\gamma}\right)^{\gamma-1}$, the beneficial effect dominates and the optimal policy ought to decrease both the emission cap and per-unit penalty fee. Figure 3 illustrates further that for the naive entrepreneur, the

[14]When e_0 changes such that $(\alpha kT - e_0)$ decreases to $(1-\delta)(\alpha kT - e_0)$ $(0<\delta<1)$, the associated p increases to $\frac{p}{(1-\delta)^{\frac{\gamma-1}{\gamma}}} \approx \left[1+\frac{\gamma-1}{\gamma}\delta + O(\delta^2)\right]p$, and the resulting penalty changes from $p(\alpha kT - e_0)$ to $(1-\delta)^{\frac{1}{\gamma}}p(\alpha kT - e_0) \approx \left[1-\frac{1}{\gamma}\delta + O(\delta^2)\right]p(\alpha kT - e_0)$.

FIG. 3. The optimal policy for the naive entrepreneur.



This figure plots $C^{\mathrm{Nai}}(e_0, p)$ when e_0 is varying and p is chosen as a function of e_0 through (11). The optimal policy attains the lowest point on the curve. Here, $T = 1$, $c = 20$, $r = 0.1$, $\gamma = 1.5$ $x_0 = k = 20.8$, and $\alpha = 0.8$.

optimal emission cap $\tilde{e}_0^{\mathrm{Nai}}$ should be lowered as the present bias becomes more severe.

A particularly interesting case arises when entrepreneurs are neutral, i.e., $\gamma \to 1$. In this case, the threshold value $\left(1 - \frac{1}{\gamma}\right)^{\gamma - 1}$ approaches 1, which suggests that a lower emission cap is always optimal, as long as the representative entrepreneur is nave.

We conclude this section by discussing two limitations of our analysis. First, our policy implications are drawn from the behavior of the representative entrepreneur who faces present bias at the aggregate level. Discriminating among entrepreneurs at the individual level using categorical labels such as "naive" and "sophisticated" based on past abatement histories and introducing discriminatory penalty fees may also help improve regulatory efficiency. Second, our model assumes that the government has perfect information on the types of representative entrepreneur. This assumption enables us to focus on investigating behavioral bias, but is not very realistic. Introducing information asymmetry and screening into the policy design may bring the theory into closer accord with reality. We will expand our model to ease these restrictions in future studies.

4. CONCLUSION

This paper explores the effects of present bias and entrepreneurial naivete on environmental protection investment, and examines how the government can design policy to improve regulatory efficiency. Our findings highlight the present bias as an important factor that deviates the environmental protection investment from rational smoothing, which leads to underinvestment in environmental protection and high compliance cost. With present bias, awareness of the resulting self-control problem can alleviate these negative effects. In terms of policy guidance, our study suggests that a more stringent cap is more appropriate for naive entrepreneurs, whereas a looser cap together with a higher penalty fee is more appropriate for sophisticated entrepreneurs. At the same time, enhancing entrepreneurs' self-control through education, training, behavioral monitoring, product innovation or self-help organizations can help reduce the compliance cost.

As a first step toward an understanding of the effects of entrepreneurial present bias on environmental policymaking, our model precludes the adverse selection and cost sharing between entrepreneurs and consumers. Future studies may consider introducing screening or consumer strategies into the policy design to create new insights. Examining empirically whether entrepreneurial naivete is a driving force of observed procrastination in environmental protection is also a promising future research avenue.

Another limitation of our analysis is that the technology in environmental protection in our model is assumed to be deterministic. While this simplistic assumption is useful for us to focus exclusively on the effects of inconsistency in time preferences, a more realistic assumption is that there is uncertainty about the environmental technology (Heal and Millner 2013). Intuitively, an increase in technological uncertainty may reduce the likelihood of the long-term benefit, accelerate the pace of procrastination in the investment in environmental technologies, and induce a greater difference between naive entrepreneurs and sophisticated entrepreneurs. Thereby, technological uncertainty may reinforce the importance of the choice between stringent caps and penalty fees in the regulation of procrastinating entrepreneurs. The current framework can be modified in order to predict when a more stringent cap is more efficient with technological uncertainty. Since a complete characterization of entrepreneurial decisions and policymaking under uncertainty may obscure the direct effects of present bias and naivete on entrepreneurs' effort making, we think of our study as a starting stage and leave the study based on a full-fledged setting involving uncertainty to future research.

APPENDIX

Derivation of equation (3). The dynamic of $V(t, x_t)$ satisfies

$$V(t, x_t) = U(cu_t)dt + e^{-rdt}V(t + dt, x_t + dx_t).$$

Multiplying through by e^{rdt} and subtracting $V(t, x_t)$ from both sides, we obtain

$$(e^{rdt} - 1)V(t, x_t) = e^{rdt}U(cu_t)dt + V(t + dt, x_t + dx_t) - V(t, x_t).$$

Substituting

$$e^{rdt} = 1 + rdt + O(dt^2), \quad V(t + dt, x_t + dx_t) - V(t, x_t) = (V_t - u_t V_x)dt + O(dt^2)$$

into the preceding equation, we are led to (3). $\square$

Proof of Lemma 1. With the power disutility, u_t on the right-hand side of (3) satisfies

$$cU'(cu_t) = V_x \Leftrightarrow \gamma c^\gamma u_t^{\gamma-1} = V_x \Leftrightarrow u_t = \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} V_x^{\frac{1}{\gamma-1}}.$$

Thus, (3) can be simplified to be

$$rV = V_t - \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} (1 - \gamma^{-1}) V_x^{\frac{\gamma}{\gamma-1}}, \quad V(T, x_T) = \max[0, p^\gamma (x_T - e_0)^\gamma].$$

Due to $\gamma > 1$, $V(T, x_T)$ is in fact smooth in x_T up to the first order. Fitting the solution in the form $V(t, x) \equiv h(t)g(x) \equiv h(t)\max[0, (x - e_0)^\gamma]$, we obtain

$$h(t) = \left[\frac{1}{e^{\frac{r}{\gamma-1}(T-t)} p^{-\frac{\gamma}{\gamma-1}} + c^{-\frac{\gamma}{\gamma-1}} \frac{e^{\frac{r}{\gamma-1}(T-t)} - 1}{\frac{r}{\gamma-1}}} \right]^{\gamma-1},$$

which yields the conditional abatement rate

$$u_t = \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} V_x^{\frac{1}{\gamma-1}} = c^{-\frac{\gamma}{\gamma-1}} h^{\frac{1}{\gamma-1}}(t)(x_t - e_0) = \frac{(x_t - e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}} - e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}.$$

Solving $dx_t = -u_t dt$ with the preceding equation, we get the unconditional form of u_t and x_t presented in the lemma. Moreover, $C(e_0, p; T) = V(0, kT) = h(0)(kT - e_0)^\gamma$ due to $kT > e_0$. $\square$

Remark A. It should be highlighted that because $h(t)$ obtained in the preceding proof is smooth in t in every order, and because $g(x) \equiv \max[0, (x -$

$e_0)^\gamma]$ is smooth in x up to the first order, the solution $V(t,x) = h(t)g(x)$ is differentiable in terms of x and t. The explicit solution of x_t shows that as long as $kT > e_0$, then $x_T > e_0$. Lemma 1 can also be proved via the Lagrange approach. As a cross validation, we derive

$$\begin{aligned}
&\min_{\{u_t\}_{t\in[0,T]}} \int_0^T e^{-rt}c^\gamma u_t^\gamma dt + e^{-rT}p^\gamma(x_T-e_0)^\gamma \quad s.t. \int_0^T u_t dt + x_T = x_0\\
\Leftrightarrow &\min_{\{u_t,x_T\}} \int_0^T \left(e^{-rt}c^\gamma u_t^\gamma - \lambda u_t\right)dt + \left[e^{-rT}p^\gamma(x_T-e_0)^\gamma - \lambda x_T\right]\\
\Rightarrow &\gamma e^{-rt}c^\gamma u_t^{\gamma-1} = \lambda, \quad \gamma e^{-rT}p^\gamma(x_T-e_0)^{\gamma-1} = \lambda\\
\Rightarrow &u_t = \left(\frac{\lambda}{\gamma c^\gamma}\right)^{\frac{1}{\gamma-1}} e^{\frac{rt}{\gamma-1}}, \quad x_T = \left(\frac{\lambda}{\gamma p^\gamma}\right)^{\frac{1}{\gamma-1}} e^{\frac{rT}{\gamma-1}} + e_0.
\end{aligned}$$

The budget constraint

$$\Rightarrow \lambda^{\frac{1}{\gamma-1}} \left[\left(\frac{1}{\gamma c^\gamma}\right)^{\frac{1}{\gamma-1}} \frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{1}{\gamma p^\gamma}\right)^{\frac{1}{\gamma-1}} e^{\frac{rT}{\gamma-1}}\right] = x_0 - e_0$$

yields $\lambda^{\frac{1}{\gamma-1}} = \frac{x_0-e_0}{\left(\frac{1}{\gamma c^\gamma}\right)^{\frac{1}{\gamma-1}} \frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}} + \left(\frac{1}{\gamma p^\gamma}\right)^{\frac{1}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}$, which leads us to the desired x_T.

Derivation of systems (4)-(5). The dynamic of W and V^{con} satisfies

$$\begin{aligned}
W(t,x_t) =& U(cu_t)dt + e^{-\lambda dt}e^{-rdt}E_tW(t+dt, x_t+dx_t)\\
&+ (1-e^{-\lambda dt})e^{-rdt}\beta E_t V^{\text{con}}(t+dt, x_t+dx_t),\\
V^{\text{con}}(t,x_t) =& U(cu_t^{\text{con}})dt + e^{-rdt}E_tV^{\text{con}}(t+dt, x_t+dx_t),
\end{aligned}$$

where u_t is the abatement decision controlled by self t and u_t^{con} is the continuation abatement decision to be controlled by future selves. Following the derivation for (3), we can easily obtain (4) and (5). □

Proof of Lemma 3. When the entrepreneur is naive, she believes she will behave as the time-consistent benchmark in the future, which amounts to her belief that

$$u_t^{\text{con}} = \frac{(x_t-e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}} - e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}.$$

However, when time t arrives, the naive entrepreneur succumbs to the short-run impulse and switches to (7):

$$u_t = \beta^{\frac{1}{\gamma-1}} u_t^{\text{con}} = \frac{\beta^{\frac{1}{\gamma-1}}(x_t - e_0)e^{\frac{rt}{\gamma-1}}}{\frac{e^{\frac{rT}{\gamma-1}} - e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}.$$

Solving $dx_t = -u_t dt$ with the preceding equation, we obtain the unconditional form of u_t and x_t presented in the lemma. For the naive entrepreneur, $C(e_0, p; T)$ is no longer equal to $V^{\text{con}}(0, kT)$, and can be calculated in line with the definition of $C(e_0, p; T)$ given in (1). □

Proof of Lemma 4. The sophisticated entrepreneur correctly foresees that her future selves will act according to their own preferences. Hence, she incorporates

$$u_t^{\text{con}} = u_t = \beta^{\frac{1}{\gamma-1}} \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} (V_x^{\text{con}})^{\frac{1}{\gamma-1}}$$

into (5), and we obtain

$$\begin{aligned} rV^{\text{con}} =& V_t^{\text{con}} - \beta^{\frac{1}{\gamma-1}} \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} \left(1 - \frac{\beta}{\gamma}\right) (V^{\text{con}})_x^{\frac{\gamma}{\gamma-1}}, \\ V^{\text{con}}(T, x_T) =& \max[0, p^\gamma (x_T - e_0)^\gamma]. \end{aligned}$$

Fitting the solution in the form $V^{\text{con}}(t, x) = h(t) \max[0, (x - e_0)^\gamma]$, we obtain

$$h(t) = \left[\frac{1}{e^{\frac{r}{\gamma-1}(T-t)} p^{-\frac{\gamma}{\gamma-1}} + \beta^{\frac{1}{\gamma-1}} \frac{\gamma-\beta}{\gamma-1} c^{-\frac{\gamma}{\gamma-1}} \frac{e^{\frac{r}{\gamma-1}(T-t)} - 1}{\frac{r}{\gamma-1}}} \right]^{\gamma-1},$$

which yields the conditional abatement rate

$$\begin{aligned} u_t =& \beta^{\frac{1}{\gamma-1}} \gamma^{-\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} V_x^{\frac{1}{\gamma-1}} = \beta^{\frac{1}{\gamma-1}} c^{-\frac{\gamma}{\gamma-1}} h^{\frac{1}{\gamma-1}}(t)(x_t - e_0) \\ =& \frac{\beta^{\frac{1}{\gamma-1}}(x_t - e_0)e^{\frac{rt}{\gamma-1}}}{\beta^{\frac{1}{\gamma-1}} \frac{\gamma-\beta}{\gamma-1} \frac{e^{\frac{rT}{\gamma-1}} - e^{\frac{rt}{\gamma-1}}}{\frac{r}{\gamma-1}} + \left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}} e^{\frac{rT}{\gamma-1}}}. \end{aligned}$$

Solving $dx_t = -u_t dt$ with the preceding equation, we obtain the unconditional forms of u_t and x_t presented in the lemma. Moreover, because the sophisticated entrepreneur behaves in the time-consistent way, we have $C(e_0, p; T) = V^{\text{con}}(0, kT) = h(0)(kT - e_0)^\gamma$. □

Proof of Proposition 1. To prove this proposition, we first note that for $\gamma > 1$, $0 < \beta < 1$ and $t > 0$, there is

$$(1+t) > \left(1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}t\right)^{\frac{\gamma-1}{\gamma-\beta}} > (1+t)^{\beta^{\frac{1}{\gamma-1}}}, \tag{A1}$$

which follows straightforwardly from $\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1} < 1$ and $1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}t > (1+t)^{\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}}$. To prove Proposition 1, let $a = \frac{kT-e_0}{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}}$, $b = \frac{\frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}}{\left(\frac{c}{p}\right)^{\frac{\gamma}{\gamma-1}}e^{\frac{rT}{\gamma-1}}}$. By Lemmas 1, 3 and 4, we get

$$u_0^{\mathrm{TC}} = \frac{a}{1+b},\quad u_0^{\mathrm{Nai}} = \frac{\beta^{\frac{1}{\gamma-1}}a}{1+b},\quad u_0^{\mathrm{Sop}} = \frac{\beta^{\frac{1}{\gamma-1}}a}{1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}b};$$
$$u_T^{\mathrm{TC}} = \frac{ae^{\frac{rT}{\gamma-1}}}{1+b},\quad u_T^{\mathrm{Nai}} = \frac{\beta^{\frac{1}{\gamma-1}}ae^{\frac{rT}{\gamma-1}}}{(1+b)^{\beta^{\frac{1}{\gamma-1}}}},\quad u_T^{\mathrm{Sop}} = \frac{\beta^{\frac{1}{\gamma-1}}ae^{\frac{rT}{\gamma-1}}}{\left(1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}b\right)^{\frac{\gamma-1}{\gamma-\beta}}}.$$

Then, (i) follows directly from (A1) and (ii) follows from $\beta^{\frac{1}{\gamma-1}}(1+b) > (1+b)^{\beta^{\frac{1}{\gamma-1}}}$ and $\beta^{\frac{1}{\gamma-1}}(1+b) > \left(1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}b\right)^{\frac{\gamma-1}{\gamma-\beta}}$ for a large enough b. Similarly,

$$\begin{aligned}
x_T^{\mathrm{TC}} &= e_0 + \frac{kT-e_0}{1+b},\\
x_T^{\mathrm{Nai}} &= e_0 + \frac{kT-e_0}{(1+b)^{\beta^{\frac{1}{\gamma-1}}}},\\
x_T^{\mathrm{Sop}} &= e_0 + \frac{kT-e_0}{\left(1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}b\right)^{\frac{\gamma-1}{\gamma-\beta}}},
\end{aligned}$$

which implies (iii) through (A1). Finally,

$$\begin{aligned}
C^{\mathrm{TC}} &= \frac{c^{\gamma}(kT-e_0)a^{\gamma-1}}{(1+b)^{\gamma-1}},\\
C^{\mathrm{Nai}} &= \frac{c^{\gamma}(kT-e_0)a^{\gamma-1}}{(1+b)^{\gamma\beta^{\frac{1}{\gamma-1}}} \Big/ \left[1+\frac{\beta^{\frac{\gamma}{\gamma-1}}}{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)}\left((1+b)^{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)}-1\right)\right]},\\
C^{\mathrm{Sop}} &= \frac{c^{\gamma}(kT-e_0)a^{\gamma-1}}{\left(1+\beta^{\frac{1}{\gamma-1}}\frac{\gamma-\beta}{\gamma-1}b\right)^{\gamma-1}},
\end{aligned}$$

which yields (iv) through $\beta^{\frac{\gamma}{\gamma-1}} > \gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1)$ and

$$1 + \frac{\beta^{\frac{\gamma}{\gamma-1}}}{\gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1)} \left((1+b)^{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)} - 1 \right) > (1+b)^{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)}.$$

(v) follows because when $\beta \leq \left(1 - \frac{1}{\gamma}\right)^{\gamma-1}$, $\lim_{b\to\infty} \frac{C^{\text{Sop}}}{C^{\text{Nai}}} = 0$. □

Proof of Proposition 2. The expressions for x_T^{Nai}, x_T^{Sop}, C_T^{Nai} and C_T^{Sop} can be found in the proof of Proposition 1. For the slope of the abatement strategy,

$$\frac{u_T^{\text{Nai}} - u_0^{\text{Nai}}}{u_0^{\text{Nai}}} = e^{\frac{rT}{\gamma-1}} (1+b)^{1-\beta^{\frac{1}{\gamma-1}}} - 1, \tag{A2}$$

$$\frac{u_T^{\text{Sop}} - u_0^{\text{Sop}}}{u_0^{\text{Sop}}} = e^{\frac{rT}{\gamma-1}} \left(1 + \beta^{\frac{1}{\gamma-1}} \frac{\gamma-\beta}{\gamma-1} b \right)^{1-\frac{\gamma-1}{\gamma-\beta}} - 1. \tag{A3}$$

The comparative statics then follow straightforwardly from simple manipulations. □

Proof of Proposition 3. The results follow from that (A2) and (A3) increase with b. □

Proof of Proposition 4. To simplify the notation, denote $f = \frac{e^{\frac{rT}{\gamma-1}}-1}{\frac{r}{\gamma-1}}$. For type I, we derive p as a function of e_0 from $x_T^I(e_0, p) = \alpha kT$, insert it into $C^I(e_0, p)$, and obtain

$$\begin{aligned}
C^{\text{TC}} =& \frac{c^\gamma}{f^{\gamma-1}} (kT - e_0) \left[(1-\alpha)kT \right]^{\gamma-1}, \\
C^{\text{Sop}} =& \frac{c^\gamma}{\left(\beta^{\frac{1}{\gamma-1}} \frac{\gamma-\beta}{\gamma-1} f \right)^{\gamma-1}} \left[(kT-e_0)^{\frac{\gamma}{\gamma-1}} - (\alpha kT - e_0)^{\frac{\gamma-\beta}{\gamma-1}} (kT-e_0)^{\frac{\beta}{\gamma-1}} \right]^{\gamma-1}. \\
C^{\text{Nai}} =& \frac{c^\gamma}{f^{\gamma-1}} \left[(\alpha kT - e_0)^{\frac{\gamma}{\gamma-1} - \frac{1}{\beta^{\frac{1}{\gamma-1}}}} (kT-e_0)^{\frac{1}{\beta^{\frac{1}{\gamma-1}}}} - (\alpha kT - e_0)^{\frac{\gamma}{\gamma-1}} \right]^{\gamma-1} \\
&+ \frac{c^\gamma}{f^{\gamma-1}} \frac{\beta^{\frac{\gamma}{\gamma-1}}}{\gamma\beta^{\frac{1}{\gamma-1}} - (\gamma-1)} \left[(kT-e_0)^{\frac{1}{\beta^{\frac{1}{\gamma-1}}}} - (\alpha kT - e_0)^{\frac{1}{\beta^{\frac{1}{\gamma-1}}}} \right]^{\gamma-1} \\
&\times \left[(kT-e_0)^{\frac{\gamma\beta^{\frac{1}{\gamma-1}}-(\gamma-1)}{\beta^{\frac{1}{\gamma-1}}}} - (\alpha kT - e_0)^{\gamma - \frac{\gamma-1}{\beta^{\frac{1}{\gamma-1}}}} \right].
\end{aligned}$$

Both C^{TC} and C^{Sop} are decreasing in $e_0 \in [0, \alpha kT]$, implying (i). For (ii), if $\gamma\beta^{\frac{1}{\gamma-1}} > \gamma - 1$, C^{Nai} is decreasing in $e_0 \in [0, \alpha kT]$; if $\gamma\beta^{\frac{1}{\gamma-1}} \leq \gamma - 1$, then $\lim_{e_0\to\alpha kT} C^{\text{Nai}} = +\infty$. □

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