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Setting Carbon Taxes using Declining Discount Rates: Implications for Investment-Based Mitigation

Chris J. Kennedy[1], Shana M. McDermott[2] and Matthew E. Oliver[3*]

[1]*Environmental Science and Policy, George Mason University, MS 5F2, 4400 University Drive, Fairfax, VA 22030, USA; ckenned7@gmu.edu*
[2]*Department of Economics, Trinity University, One Trinity Place, San Antonio, TX 78212, USA; smcdermo@trinity.edu*
[3]*School of Economics, Georgia Institute of Technology, 221 Bobby Dodd Way, Atlanta, GA 30332, USA; matthew.oliver@econ.gatech.edu*

ABSTRACT

The use of declining discount rates (DDR) to calculate the net present value of damages associated with climate change has important ramifications for climate policy. We examine the behavior of a firm subject to climate-based market interventions, specifically carbon taxes or abatement credits that are indexed to the social cost of carbon (SCC). Recognizing that private abatement investment decisions are financed via capital markets, we show that when the SCC is calculated using a DDR it is impossible for the policymaker to induce a level of investment today that is consistent with the SCC forecast for future periods. This leads to significant under-investment in abatement. We discuss the practical implications of this result for climate policy, with particular focus on climate policies designed to foster investment-based mitigation.

*Corresponding author.

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Introduction

In economic research on global climate change, the discount rate is pivotal in determining the optimal magnitude and trajectory of mitigation investments. The significant temporal gap between outlaid costs and the bulk of avoided damages results in little weight given to even enormous nominal benefits under exponential discounting approaches, a phenomenon described as "the tyranny of discounting" (Pearce *et al.*, 2003). Further complicating the discount rate choice is a high degree of uncertainty over economic and climate projections, again exacerbated by the extended timeline over which damages occur. In response to these and other concerns, economists have promoted a declining discount rate (DDR) schedule for evaluating the costs and benefits of carbon emissions and mitigation investments. Currently, both the UK and France have implemented DDR schedules for evaluating costs and benefits of climate change mitigation policy, and many have called for the US to do the same (Arrow *et al.*, 2014; Arrow *et al.*, 2013; Cropper *et al.*, 2014).[1]

Despite the considerable breadth of economic and policy research on non-exponential discounting approaches, little attention has been paid to the behavior of firms subjected to climate policies designed using DDRs. Our contribution to this literature is to highlight a practical implication of using a DDR for market-based mitigation policies (*e.g.*, carbon taxes or abatement subsidies). We develop a simple model to show that a DDR motivated by uncertainty over future climate change damages[2] blunts the effects of market-based incentives to internalize the social cost of carbon emissions. If the policymaker updates the discount schedule

[1]Recent research also supports the assumption that decision-makers tend to exhibit behavior similar to operating under a DDR rather than a constant discount rate (Gintis, 2000; Frederick and O'Donoghue, 2002).

[2]The analysis presented here is generally applicable under a variety of motivating reasons for using a DDR.

in each successive period, the discount rate applied to costs/benefits in any specific future period increases as that period becomes nearer to the present.[3] Updating the incentive schedule in this way creates the classic problem of "time inconsistency", whereby a government cannot enact a credible policy today when tomorrow's governments must always re-optimize, given a new discounting schedule. The underlying focus of this paper is to illustrate how a profit-maximizing firm investing in abatement will respond to this inconsistency.[4]

We demonstrate that using a DDR to set a carbon tax/subsidy schedule results in under-investment in abatement relative to the policymaker's preferred level, given the forecast of the social cost of carbon (SCC) schedule at $t = 0$. To show this, we model a firm investing in a durable carbon abatement technology in period $t = 0$ to earn a flow of credits (subsidies) in periods $0 - T$. These investments are analogous to other types of capital investments; firms will invest at a level that maximizes the net present value of benefits, equal to the discounted flow of abatement credit payments less investment costs (Graham and Harvey, 2001; Jagannathan *et al.*, 2016; Poterba and Summers, 1995). Nominal abatement credits paid in each period $t \geq 0$ are set based on the SCC, which is calculated contemporaneously using a DDR.[5] Updating the SCC schedule means that, even when future climate damages evolve as expected, the realized SCC in period $t > 0$ will be systematically lower than its forecast at $t = 0$. The firm recognizes this and will rely on expected credit payments when making investment decisions, ultimately leading to under-investment in abatement from the perspective of the policymaker.

[3]To illustrate, the present value of costs/benefits occurring in some future period t when computed in base period $t - s$ will be inconsistent with the present value of the same costs/benefits when computed in base period $t - (s + 1)$.

[4]Note that this time inconsistency need not be due to dynamically inconsistent preferences.

[5]We rely on an assumption that the SCC is an appropriate proxy for future carbon taxes/subsidies. This is a strong assumption, and there are numerous factors that may create a divergence between the SCC and carbon taxes or subsidies; however, to the extent carbon prices are designed to reflect the capitalized damages of carbon emissions, it is reasonable to make a less severe assumption that the *trend* in future expected carbon taxes or subsidies will tend to correspond to that of the SCC schedule, in which case the results of this analysis will hold.

A key feature of our analysis is the explicit recognition that the majority of abatement efforts by private entities are associated with multi-period investment projects that yield payoffs over an extended timeline. For instance, a utility investing in wind generation capacity would look to capital markets for financing and realize benefits (*e.g.*, reduced carbon tax liability) over a period of many years.[6] As a result, when firms make abatement investment decisions that require present value computations, inducing the socially optimal level of investment — as indicated by the calculated SCC at the present — may not be possible.

Declining Discount Rates: A Brief Review

Economists have posited several reasons why a DDR may be preferable to exponential discounting. Beginning with Strotz (1955), but popularly attributed to Thaler (1981), a large literature emerged demonstrating that individuals exhibit hyperbolic time preferences. Early laboratory studies revealed that people systematically discount payoffs occurring in the distant future at lower rates than those occurring in the near future.[7] This launched a foray into the theoretical implications of hyperbolic discounting as a violation of rational choice theory (e.g., Loewenstein and Thaler, 1989), and an investigation of the practical consequences for savings and investment behavior (e.g., Diamond and Köszegi, 2003; Laibson, 1997) and other dynamic decision-making settings.[8]

Theoretical models offer more sophisticated formulations of the DDR, which can be grouped into two general paradigms (Groom *et al.*, 2005). One camp is based on the canonical Ramsey rule for interest- and discount-rate formation (Gollier, 2002). The other, accredited to Martin

[6]In practice, firms may rely on both short-term and long-term financing for different aspects or phases of such projects, but it is long-term investment financing that is most relevant to our argument here. Similarly, when self-financing projects, the calculated internal rate of return will be judged relative to capital markets.

[7]See also: Benzion *et al.* (1989), Pender (1996), and, more recently, Benhabib *et al.* (2010).

[8]Frederick *et al.* (2002) provide a thorough review of the early literature on hyperbolic discounting. A more recent review of hyperbolic discounting in environmental applications is available in Hepburn *et al.* (2010).

Weitzman, uses an expected net present value (ENPV) framework to derive a declining certainty-equivalent social discount rate. One common assumption relates to the role of uncertainty — for instance, uncertainty regarding future interest rates (Drupp *et al.*, 2018; Freeman *et al.*, 2015; Weitzman, 1998), paths of economic growth (Gollier, 2002), or, as depicted in Figure 1, climate outcomes under alternative mitigation scenarios (Gollier, 2013). Subjective uncertainty among economists regarding the appropriate exponential discount rate may also generate a DDR (Weitzman, 2001), and Azfar (1999) has suggested that a DDR may, in fact, be perfectly rational when individuals are uncertain about their own discount factors. In each case, uncertainty tends to grow with the relevant time horizon, providing a strong theoretical case for a DDR, with far-off damages evaluated using a lower discount rate than those used for earlier periods.[9]

DDRs are also justified by the temporal features of climate change itself, reflecting societal preferences for a precautionary approach emphasizing mitigation (Karp, 2005; Weitzman, 2010). Climate change policy solutions typically involve large, up-front abatement investments in exchange for reduced damages in the medium- to long-term.[10] Using a constant discount rate based on empirically- or experimentally-derived primitives of the Ramsey equation may depress climate-related benefits accruing to distant future generations to such a degree that few credible mitigation strategies will pass the traditional cost–benefit analysis test (Arrow *et al.*, 2014), whereas using a DDR addresses concerns by ethicists who object to applying the Ramsey approach to intergenerational discounting.[11]

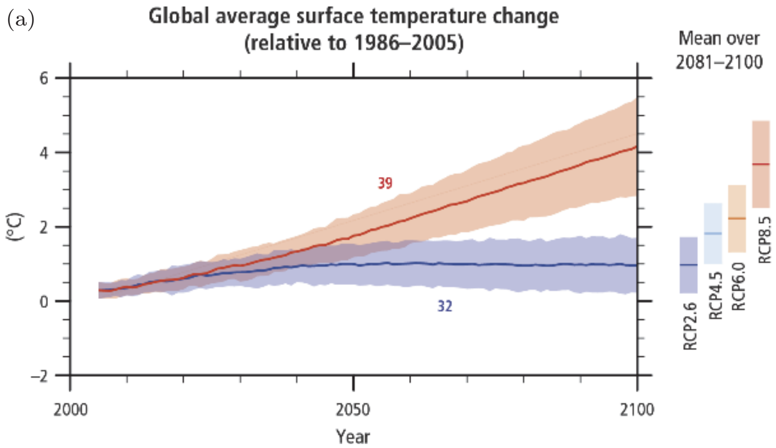
In discussing the merits of a DDR, the issue of time inconsistency invariably arises. The question distills to whether governments are able to enact credible policies when future governments re-optimize

[9]Dasgupta and Maskin (2005) suggest a primal (*i.e.*, evolutionary) link between uncertainty and hyperbolic discounting behavior in both humans and animals.

[10]Another commonly cited environmental application relates to nuclear waste disposal.

[11]There are justifications for the use of a DDR that do not result in a time inconsistency (for instance, declining economic growth or more generally, changes in deep parameters of the Ramsey equation). In those circumstances, so long as those beliefs are commonly held, there is no divergence between private and public future SCC schedules and the use of a DDR does not introduce an inefficiency.

(a)



(b)

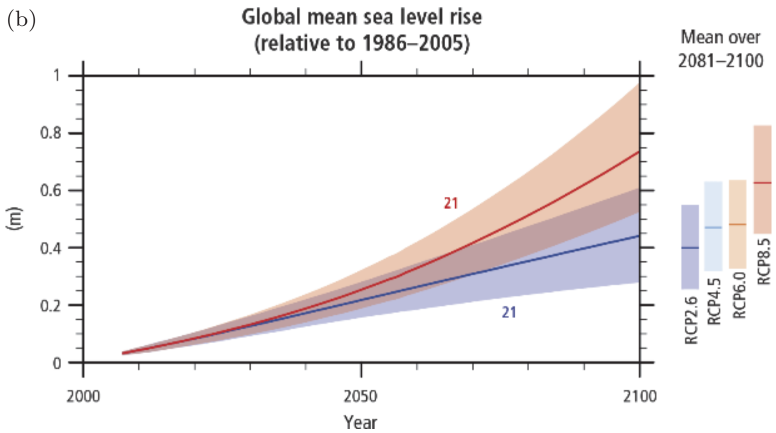


Figure 1: Global average surface temperature change (a) and global mean sea level rise (b) from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars at the right-hand side of each panel. The number of Couple Model Intercomparison Project Phase 5 (CMIP5) models used to calculate the multi-mean is indicated. Figure and caption are taken directly from the 2014 IPCC Climate Change Synthesis Report: Summary for Policymakers (IPCC, 2014).

based on a new discounting schedule.[12] Pearce *et al.* (2003) explain that a government has two choices: to be either *naïve* or *sophisticated*. A naïve government constantly re-optimizes its policy, acting like the much-maligned consumer with hyperbolic time preferences. In contrast, the sophisticated government understands private agents will likely anticipate the time inconsistency in policy resulting from the government's updating of the DDR schedule in each successive period: despite promises at $t = 0$ regarding policies in $t > 0$, reliance on a DDR means those promises are likely to be contradicted in subsequent time periods. At best, this will induce suboptimal behavior on the part of private agents; at worst, it opens the government to arbitrage. Thus, the sophisticated government designs policies that account for this response. This can lead to, as Winkler (2006) puts it, "a clash between economic efficiency and intergenerational equity," such that "the crucial requirement for any improvement is the awareness of time inconsistency." The crudest *sophisticated* policy is thus one of credible commitment, but this is inefficient, as it will fail to incorporate new information in a timely manner, therefore undermining a primary reason for utilizing a DDR in the first place: to appropriately account for the horizon of uncertainty.

Challenging this view, Hansen (2006), in advocating the use of a DDR, offers three reasons why these concerns about time inconsistency with DDRs are mostly overblown. The first is related to the basic message of Weitzman's ENPV framework: uncertainty over future interest rates automatically implies a DDR, and not accounting for this uncertainty necessarily leads to sub-optimal decisions. Second, any policy program that is *sequentially* structured to attain a future goal (an emissions target, for example) will become increasingly attractive within the standard cost–benefit calculus, particularly when prior costs are sunk, implying less incentive to deviate from the program. Third, *no* discounting procedure, with regard to the structuring of long-term policy, is immune to time inconsistency issues, as democratic governments are,

[12] Helm *et al.* (2003) expound on the design of credible, time-consistent carbon policy in the context of changing policy objectives, investment irreversibility, and *ex post* renegotiation of *ex ante* policy commitments.

by nature, prone to turnover, capricious policy reversals, and even total upheaval (see also Pearce *et al.*, 2003).[13]

The existence of multiple discount rates is a related problem that has been also addressed in the context of climate change policy. For instance, Goulder and Wiliams (2012) consider the relationship between discount rates derived from social welfare functions and those determined by capital markets in an effort to develop a coherent approach to considering specific policies in light of the two (often different) discount rate schedules. They do not address the issue of time inconsistency *vis-à-vis* a DDR, or the role of uncertainty in updating SCC schedules. Similarly, Kaplow *et al.* (2010) differentiate private, "behavioral" discount rates from social discount rates. Their purpose is to investigate the efficiency and equity implications of social rates that diverge from private rates, but similar to Goulder and Wiliams (2012), they do not examine DDRs or inefficiency caused by time inconsistencies in policy responses.

While the tension regarding time inconsistency is acknowledged in most research efforts, rarely have specific policy implications of a DDR been addressed. Some researchers have alluded to, but not addressed analytically, the potential for strategic behavior on the part of private agents in the context of the performance of actual policy prescriptions (see, e.g., Gerlagh and Liski, 2018). Others, including Belfiori (2015) and Harstad (2019), examine the challenges a policymaker faces when implementing multiple policies across varying technologies or externalities using a DDR. Harstad (2019) also considers the strategic interaction between current and future policymakers in the context of political turnover. Several authors have also examined how time inconsistency affects achieving certain climate goals, including intergenerational implications (Belfiori, 2015; Iverson and Karp, 2017). All of these efforts are similar in addressing the effects of a DDR on a policymaker choosing an optimal level of abatement or investment, either through direct regulation or market incentives.[14] Crucially, while the policymaker's calculation of the optimal level of abatement in existing models is dynamic in the sense that the SCC represents the capitalized

[13]This is, however, a fundamentally different type of inconsistency in that it is unpredictable.

[14]Note that "optimality" is not necessarily sufficient for dynamic-efficiency or -consistency under a DDR.

avoided damages associated with abatement, there has been no formal consideration of the optimization problem facing firms when abatement investment occurs before the majority of realized abatement and its private benefits, and when such benefits are indexed by a DDR.

Our contribution is focused on this particular issue. Under most implemented and theorized market-based mitigation policies, investments in durable abatement technologies yield a dynamic stream of social benefits in the form of reduced emissions and private benefits in the form of subsidies, credits, or reduced tax liability over the duration of the investment project's lifespan. The policymaker wishes, at any point in time, to encourage a level of periodic abatement investment that will maximize the expected present value of a stream of social benefits. In an environment in which social benefits correspond with the SCC (rather than some other emissions policy), the policymaker consults with a schedule of projected SCC values, and communicates a schedule of taxes, subsidies, or emissions credits corresponding with the optimal path of emissions. Firms, in turn, form expectations over the future SCC and plan investment accordingly so as to maximize the expected present value of private benefits. Importantly, private benefits are exponentially discounted, as the opportunity cost of private investment is determined via private capital markets (Graham and Harvey, 2001; Jagannathan *et al.*, 2016; Poterba and Summers, 1995). When the SCC is calculated using an exponential discounting procedure, the corresponding expected SCC schedule is equivalent for both the policymaker and firms. When the policymaker uses a DDR schedule, firms will expect a lower SCC in future periods than what the DDR schedule projects — and what the policymaker desires *in the current period* — because firms understand that the DDR schedule is repeatedly updated.

The naïve policymaker will, as previous efforts have shown, update according to the arrival of new information and systematically overestimate the future SCC. The sophisticated policymaker will recognize this. In her effort to induce a level of investment that maximizes the stream of net social benefits, given the current SCC schedule, she may choose to forgo some of the efficiency gains associated with regular updating and commit to a policy. This can take at least two forms. First, she may choose to capitalize the value of avoided emissions associated with a given investment project and offer a lump sum, up-front payment to private firms in exchange for promised current and future abatement. Second, she may commit to a schedule of payments contemporaneous with investment and contingent on future abatement, corresponding with the initial SCC schedule. Both of these options represent credible commitments, but they have both logistical and, ultimately, fatal drawbacks. In the case of an up-front payment, enforcing compliance on the part of firms following a lump sum payment may be a challenge. The more serious issue associated with both forms of commitment results from the fact that commitments made in different periods implies a regulatory environment with no common SCC in a given period — firms that invest today in projects that yield reduced emissions 20 years from now will be subsidized at a different rate (a higher rate) for that period-specific abatement than firms investing in projects, say, 10 years from now, yielding reduced emissions 20 years from now. This is a key observation of our contribution: when a policymaker relies on a DDR to calculate the projected SCC, any effort to induce the policymaker's optimal level of future-abatement-yielding investment will lead to a new SCC schedule in *every period*, corresponding to (and increasing with) the age of the investment. While this is not a fatal flaw in the context of contemporaneous mitigation, in the presence of market-based approaches (taxes, subsidies, offsets, credits, etc.) and investments in future mitigation, this creates an arbitrage opportunity in which firms with older investments can collect subsidies for their emissions' reductions in excess of the prevailing SCC and purchase credits at the latter rate, thereby allowing them to commit to a higher level of abatement in the initial period than they actually intend to achieve.[15] Thus, neither a naïve or sophisticated policymaker is able to induce the optimal level of abatement investment in the absence of direct regulation. This result is formalized in the next section.

Simple Model of Carbon Abatement Investment at $t = 0$

Consider a price-taking, risk-neutral firm that invests in a durable abatement technology (*e.g.*, solar panels) at year $t = 0$, where the amount of the abatement technology installed, A, is a continuous variable. For simplicity, assume each unit of A produces one unit of abatement per

[15]This applies to both the up-front and committed-schedule options.

year over an infinite time horizon. In other words, the firm makes a one-time, up-front investment that yields A units of abatement each year, in perpetuity. The cost at $t = 0$ of investing in A is $C(A)$, where $C'(A) > 0$ and $C''(A) > 0$, but is zero in each year thereafter.[16]

For each unit of abatement in years $t = 0, 1, \ldots, \infty$ the firm receives a carbon credit payment, hereafter referred to as the "carbon price", $p(t)$. The carbon price in year t is set equal to the per-unit social cost of carbon, $SCC(t)$.

$$p(t) = SCC(t) \tag{1}$$

We assume the SCC is equal to the present value of the flow of expected damages per unit of atmospheric carbon. Let $D(t)$ denote expected damages per unit of carbon in year t.[17] Thus, from the perspective of year $t = 0$, the forecast of the SCC in any given year $s \in t$ is

$$SCC_0(s) = \sum_{t=s}^{\infty} \frac{1}{(1 + \delta(t))^{t-s}} D(t), \tag{2}$$

where $\delta(t)$ is the climate discount rate in year t — which may be declining as t increases — and $1/(1 + \delta(t))^{t-s}$ is the climate discount factor applied to damages in year t. To illustrate, say at year $t = 0$ we wish to compute the SCC in year 0, in which case $s = 0$ and Equation (2) is a simple present value calculation. By contrast, say at year $t = 0$ we wish to forecast the SCC in year $s = 10$, which, using our notation above, is $SCC_0(10)$. Here we compute the present value of the flow of expected damages starting at year $t = 10$, where discounting begins at

[16] Alternatively, $C(A)$ could be interpreted as the net present value of the stream of all future costs associated with the investment made at $t = 0$, including maintenance, interest payments on financed capital, or management labor. These costs would presumably be financed in capital markets, and therefore discounted exponentially at the market interest rate (Graham and Harvey, 2001; Jagannathan *et al.*, 2016; Poterba and Summers, 1995).

[17] $D(t)$ is a simplification of the damage function used in many climate-economy models, in which climate damages are modeled in terms of an economic response to changes in the climate system, which includes adjustment for any adaptive investments (Auffhammer, 2018). To illustrate, let $D(\tau, t) = R(\tau, t)(1 + g)^t$ be damages in period t per unit of carbon emitted in period τ, where $R(\tau, t)$ is the economic response per unit and g is economic growth. We adopt the simplifying assumption — both here and in our numerical illustration—that $R(\tau, t)$ is some constant value $\bar{R}$, such that damages are $D(t) = \bar{R}(1 + g)^t$.

year 10 such that $t - s = 0$ and the climate discount factor for year 10 is therefore equal to unity.

The firm expects to receive a total payment in year s of $A \times p(s)$. As this payment is a purely monetary value, it is discounted at the (constant) market interest rate, r, where $\rho^m(s) = 1/(1+r)^s$ is the *market* discount factor in year s. Thus, the present value of the stream of expected payments to the firm from investing in durable abatement technology amount A in year 0 is

$$V(A) = \sum_{s=0}^{\infty} \rho^m(s)[A \times p(s)]. \tag{3}$$

The firm's expected net present value of investing in A in year 0 is

$$\pi(A) = V(A) - C(A), \tag{4}$$

and its optimal level of abatement investment, A^*, is defined by the first-order condition

$$\frac{d\pi}{dA} = V'(A^*) - C'(A^*) = 0, \tag{5}$$

where, by Equations (1), (2), and (3), it follows that

$$V'(A^*) = \sum_{s=0}^{\infty} \rho^m(s) \left[\sum_{t=s}^{\infty} \frac{1}{(1+\delta(t))^{t-s}} D(t) \right]. \tag{6}$$

Note that $V'(A^*)$ is a fixed value — it is the present value of the stream of expected carbon price payments per unit of the durable abatement technology installed.

For some intuition regarding the firm's decision, consider the simple case in which $D(t)$ is constant and equal to some value $\bar{D} > 0$ and climate discounting is exponential ($\delta(t) = \delta$). By expression (6), $V'(A)$ converges to $\bar{D}(1-\beta)^{-1}(1-\gamma)^{-1}$ where $\beta \equiv 1/(1+\delta)$ and $\gamma \equiv 1/(1+r)$. The firm's optimal investment in the abatement technology is defined by

$$\frac{d\pi}{dA} = \frac{\bar{D}}{(1-\beta)(1-\gamma\beta)} - C'(A^*) = 0. \tag{7}$$

By the implicit function theorem, it is straightforward to show

$$\frac{\partial A^*}{\partial \delta} = -\frac{\bar{D}\beta^2}{C''(A^*)} \left[\frac{(1-\gamma\beta) + \gamma(1-\beta)}{(1-\beta)^2(1-\gamma\beta)^2} \right] < 0. \tag{8}$$

This result is summarized in Lemma 1.

Lemma 1. *Assume Equations* (1)–(5) *characterize a firm's decision to invest in a durable abatement technology in period* $t = 0$*. With exponential discounting and constant damages per unit carbon, the firm's optimal investment,* A^**, decreases as the discount rate applied to future carbon damages increases. That is,* $\frac{\partial A^*}{\partial \delta} < 0$*.*

This result is intuitive. The higher the discount rate, the lower the value placed on future carbon damages, reducing the forecast of the carbon price paid to the firm in every period. The firm thus has less incentive to invest in the abatement technology today.

It follows for the more generalized case where damages are increasing over time and $\delta(t)$ is non-constant (as with a DDR), that an upward revision of the discount rate applied to any given future period lowers the firm's optimal abatement investment in the initial period. To see this, consider the firm's present value calculation of the carbon price it expects to receive in some period s, characterized by Equation (2). Now say the firm expects that when period s arrives the regulator will arbitrarily decide to marginally raise the discount rate applied to some period $s' > s$. Denote the incremental number of periods from s to s' as t', such that $s' = s + t'$. Thus, from the perspective of period s the discount rate applied to damages t' periods in the future is $\delta(t')$. If $V'(A)$ is characterized by Equation (6), then the marginal change in the firm's abatement investment in period 0 resulting from a marginal change in period s of discount rate $\delta(t')$ is

$$\frac{\partial A^*}{\partial[\delta(t')]} = -\frac{1}{C''(A^*)}\sum_{s=0}^{t'} \rho^m(s)\frac{(t'-s)}{(1+\delta(t'))^{t'-(s-1)}}D(t') < 0; \forall(s,t'). \quad (9)$$

This result is summarized by Lemma 2.

Lemma 2. *Assume Equations* (1)–(6) *characterize a firm's decision to invest in a durable abatement technology in period* $s = 0$*. With a non-constant discount rate and damages per unit carbon that increase over time, the firm's optimal investment,* A^**, decreases as the discount rate applied to future carbon damages in any period* $t' \in (s, \infty)$ *increases. That is,* $\frac{\partial A^*}{\partial[\delta(t')]} < 0$*,* $\forall(s,t')$*.*

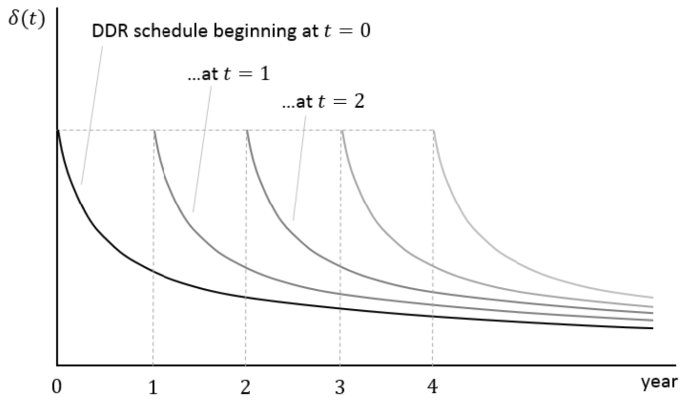


Figure 2: Stylized representation of DDR updating process.

Now consider a naïve policymaker that uses a DDR and revises the DDR schedule each year. Figure 2 is a stylized representation of the annual updating process. Notice that the discount rate applied in, say, year 3 increases depending on whether the DDR schedule begins in year 0, 1, or 2, respectively.

The key intuition is that from the perspective of year t a carbon price schedule based on a DDR schedule starting in year t is considered by the policymaker to be efficient. Time inconsistency emerges as a result of updating, however, because as time moves forward the DDR schedule is revised. The carbon price schedule that is efficient in year t will no longer be efficient in year $t+1$; the carbon price schedule that is efficient in year $t+1$ will no longer be efficient in year $t+2$, and so on.

This brings us to the crux of the problem inherent in naïve updating. In year 0, the government's forecast of the carbon price paid to the firm in any future year $t > 0$ is defined by Equations (1) and (2). The policymaker considers the firm's *efficient* level of investment in year 0 to be that defined by Equations (4) and (5), which follows the expected SCC schedule defined by Equation (2). This level of investment, A^*, serves as the benchmark against which to compare the firm's actual — *i.e.*, privately optimal — investment.

From the firm's point of view in year 0, if it is aware of the government's updating process, it will be aware that in any given future period the discount rate actually used to compute the present value of the flow of carbon damages will be higher than what is announced in year 0. By the logic of Lemma 2, this implies that the firm's investment in year 0 in the durable abatement technology will be lower than what is considered by the policymaker to be the efficient amount. This is our main analytical result, summarized in Proposition 1.

Proposition 1. *Assume Equations* (1)–(6) *characterize a firm's efficient investment in a durable abatement technology in period* $t = 0$, *based on a DDR schedule starting in period* $t = 0$. *Denote this value as* A^*. *If the firm is aware that a naïve policymaker updates the DDR schedule each year*, *the firm's actual investment*, A^{**}, *will be lower than the efficient amount. That is*, $A^{**} < A^*$.

The proof of Proposition 1 is straightforward. Because the firm is aware of the policymaker's time inconsistency, its forecast of the carbon price in any year $s > 0$ will be different than what is announced by the policymaker in year 0. In other words, when year s arrives the DDR schedule will be revised to start anew in year s — the implication being that even if carbon damages have evolved as expected between year 0 and year s, the carbon price the firm will receive in year s will be inconsistent with the government's year 0 forecast of the year s carbon price.

To see this, consider the firm's privately optimal investment in year 0 under the assumption of an annually revised DDR schedule. In year $s > 0$, the actual carbon price will be

$$\bar{p}(s) = \overline{SCC}_s(s) = \sum_{t=s}^{\infty} \frac{1}{(1+\delta(t-s))^{t-s}} D(t), \tag{10}$$

assuming realized damages evolve according to expectations. Comparing Equation (9) with Equation (2), it should be clear that $\overline{SCC}_s(s) < SCC_0(s)$ because the discount rate applied in year s to all subsequent expected damages will be higher than what it was forecast to be when looking ahead from year 0 — *i.e.*, because $\delta(t) < \delta(t-s)$ for all $t, s > 0$. We refer to the resulting difference in the SCC as the *inconsistency gap*.

Moreover, because the firm's privately optimal abatement investment depends on the carbon price schedule defined by Equation (9), the intuition laid out in Lemma 2 indicates a lower level of investment than that defined by Equations (5) and (6). Denote the firm's value function under the annually updated DDR schedule as $\bar{V}(A)$. Its privately optimal abatement level, A^{**}, solves the first-order condition

$$\frac{d\pi}{dA} = \bar{V}'(A^{**}) - C'(A^{**}) = 0, \tag{11}$$

where

$$\bar{V}'(A^{**}) = \sum_{s=0}^{\infty} \rho^m(s) \left[\sum_{t=s}^{\infty} \frac{1}{(1+\delta(t-s))^{t-s}} D(t) \right]. \tag{12}$$

Because $\delta(t) < \delta(t-s)$ for all $ts > 0$, by Lemma 2 it follows that $A^{**} < A^*$.

The implication is that under naïve updating, a price-based policy using a DDR to compute the flow of carbon damages and set compensation schedules for future abatement resulting from current investment in the durable abatement technology cannot induce the firm to select the efficient investment level.

Can the Regulator Be More Sophisticated?

One might be tempted to suggest that the policymaker should simply be less naïve and more sophisticated, in the sense posited by Pearce *et al.* (2003); if this issue arises because the policymaker is unaware of the effects of time inconsistency on firm behavior, why not adopt a more sophisticated carbon tax/subsidy program that incorporates an awareness of this time inconsistency? As Pearce *et al.* argue, however, this does not solve the problem. The sophisticated policymaker accounts for the firm's knowledge of the procedure whereby the DDR is updated each period, and must therefore adjust the carbon tax/subsidy policy accordingly. "In other words," Pearce *et al.* explain that "the government makes policy, which is the best response to successive governments' best responses." Optimality in the first-best sense is elusive in a DDR regime.

In our simple model, there are two ways for the policymaker to induce a firm to invest in the preferred level of abatement in year 0. As shown below, one method is inherently inefficient. The other is likely to be fiscally infeasible and may open the government up to arbitrage.

Consider a case in which the policymaker anticipates the firm's knowledge of the time inconsistency and offers in year 0 an additional per-unit payment, τ, such that

$$\tau = \sum_{s=0}^{\infty} \rho^m(s)[SCC_0(s) - SCC_s(s)]. \tag{13}$$

The per-unit transfer equals the present value of the stream of all future inconsistency gaps, which from the firm's perspective makes up for the shortfall of future payments relative to the regulator's year-0 forecast. The firm's problem is now to choose A that maximizes

$$\pi(A) = \bar{V}(A) - C(A) + \tau A. \tag{14}$$

Its optimal level of abatement is $\bar{A}$, as defined by the first-order condition

$$\frac{d\pi}{dA} = \bar{V}'(\bar{A}) - C'(\bar{A}) + \tau = 0. \tag{15}$$

and

$$\bar{V}'(\bar{A}) + \tau = \sum_{s=0}^{\infty} \rho^m(s) \left[\sum_{t=s}^{\infty} \frac{1}{(1+\delta(t))^{t-s}} D(t)\right], \tag{16}$$

which implies $\bar{A} = A^*$. The additional transfer in year 0 induces the firm to invest in the regulator's preferred level of abatement.

However, it is easy to show this is inefficient. The regulator is already paying the firm $SCC_0(0)$ in year 0 for its abatement — the efficient payment. In paying an additional amount τ per unit A, the total payment in year 0 exceeds the social value of abatement. The regulator thus faces a choice between two costs: (i) a lower abatement investment by the firm due to the time inconsistency of the SCC (valued at $SCC_0(0)$ in year 0), or (ii) the net social cost of having to offer the additional payment τ in year 0. A numerical illustration below suggests option (i) is the lower-cost alternative.

Alternatively, it would be possible for the policymaker to (i) pay the firm in year 0 the full present value of the stream of SCC credits defined by Equation (5) and nothing thereafter, or (ii) commit to a schedule of payments based on the projected SCC schedule at the time of investment. Both of these approaches would eliminate the time inconsistency problem, and would theoretically induce firms to invest in the preferred abatement level. However, there are drawbacks. First, a full payment in year 0 may be infeasible when the policymaker faces a fiscal constraint. Second, in the absence of direct regulation, both the up-front in-full payment and the committed schedule of payments open the policymaker up to intertemporal arbitrage. To illustrate, consider a firm that commits in period 0 to purchase a carbon offset in some future period s in exchange for a payment in year 0 from the regulator equal to $\rho^m(s) \times SCC_0(s)$. The firm could then place that payment into an interest-bearing account, and by year s its value would increase to $SCC_0(s)$. But when the DDR is updated in each year, the actual SCC in year s, $SCC_s(s)$, will be lower than this amount, and the firm's purchase of the committed carbon offset will yield a capital gain to the firm equal to the difference, $SCC_0(s) - SCC_s(s)$. In essence, pre-commitment by the regulator and regulated firms creates an environment in which there is no single SCC. Instead, there is a market SCC that is based on current calculations, and a different (higher) SCC that applies to abatement from firms that engaged in contracts in prior periods. Direct regulation (*i.e.*, no trading, offsets, or price-based regulation) is the only way to avoid the possibility of arbitrage in this environment.

Numerical Illustration

We explore the implications of the above model with a numerical illustration that involves several steps. Our simulation begins with a comparison of an exponential discount rate versus a DDR, demonstrating how the two discount rates impact the present value of damages per ton of CO_2 emitted. We then take the present value of damages per ton of CO_2 to illustrate the time inconsistency that exists when calculating the SCC under a naïve updating regime. Finally, using the calculated SCC for each discount regime, we compute and compare the optimal abatement investment levels of the firm and the policymaker. Our simulations illustrate that firms will underinvest in abatement under a naïve regulator that uses a DDR. Moreover, a sophisticated regulator will find that it is not cost-effective to correct the firm's underinvestment.

DDR versus Exponential Discounting

Our DDR schedule is based on Weitzman's (2001) "gamma discounting" formulation. The key intuition is as follows: (1) Imagine a sufficiently large sample of economists (indexed by j) is surveyed, each being asked to provide his or her expert opinion regarding the appropriate *exponential* discount rate, x_j, to be used in computing the present values of expected costs and benefits of climate change mitigation projects; (2) The resulting data for x_j comprises a random variable — with mean μ and variance σ^2 — that is assumed to follow the gamma distribution.[18]

For brevity, we do not recount the full analytical derivation here. However, Weitzman demonstrates the gamma-distributed expert opinions regarding the appropriate exponential discount rate yield an implied effective discount rate in any period t of

$$\delta(t) = \frac{\mu}{1 + t\sigma^2/\mu}. \tag{17}$$

This formulation implies that (i) the effective discount rate starts out at time $t = 0$ at its mean value, μ, and (ii) exponential discounting represents the limiting case in which σ approaches zero (that is, perfect agreement).

Weitzman parameterized the distribution by eliciting from over 2,100 economists a "professionally considered gut feeling" about the correct exponential discount rate. This resulted in parameters of approximately $\mu = 0.04$ and $\sigma = 0.03$. Figure 3 plots the time path of the resulting DDR schedule alongside the benchmark, constant discount rate of 4%.

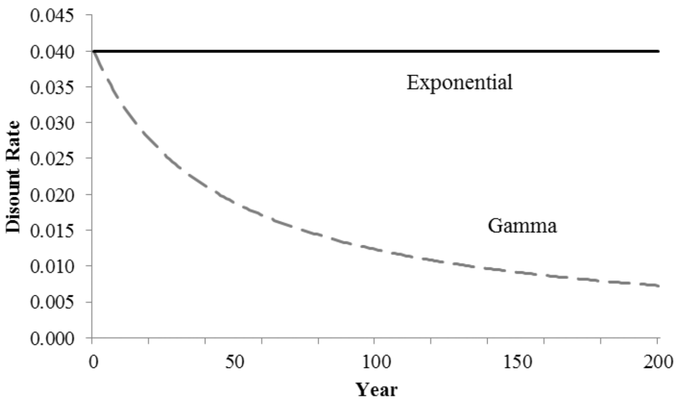


Figure 3: Discount rate comparison: exponential versus declining (gamma).

[18]The gamma distribution has the density function $f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}$ where α is the "shape" parameter and β is the "inverse scale" parameter. The mean and variance are, respectively, $\mu = \alpha/\beta$ and $\sigma^2 = \alpha/\beta^2$.

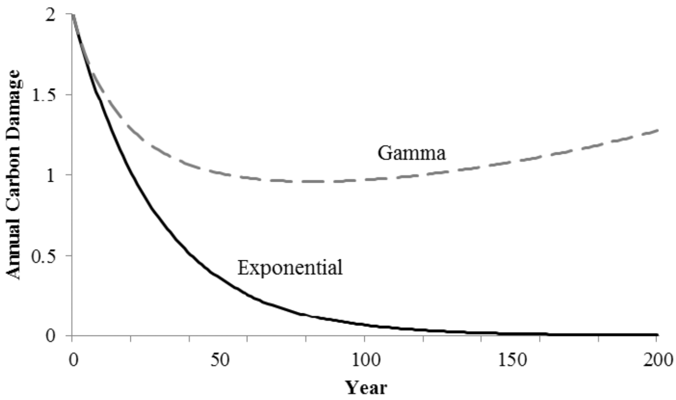


Figure 4: Comparison of discounted present value of damages per ton, assuming damages of $2 per ton in year 0, rising 0.5% per year thereafter.

We now consider a scenario in which the SCC reflects a net present value calculation by policymakers looking 200 years into the future.[19] We assume marginal annual climate damages rise by 0.5% a year, starting conservatively at $2 per year per ton of CO_2 (tCO_2), to produce an SCC roughly in line with the range of U.S. EPA estimates.[20] Figure 4 plots the resulting present value of future climate damages per ton using the exponential and gamma discounting schedules.

SCC and Time Inconsistency

To calculate the SCC, we compute the discounted sum of damages across the 200-year time horizon under the three discounting scenarios. Figure 5 plots (i) the time path of the SCC under exponential discounting (depicted by the black, dashed plot), (ii) the realized time path of the SCC using a DDR that is revised to begin anew each year (gray, solid), and (iii) the policymaker's forecast in year 0 of the time path of the expected SCC using a DDR that begins in year 0 (black, solid). Each assumes that the evolution of climate damages unfolds over time in

[19]The restriction of the time horizon to 200 years is for the purpose of computational simplification, although the analysis could be extended to the case of an infinite stream.

[20]That is, prior to the newest guidance released by the Trump Administration, which we address in the sensitivity analysis.

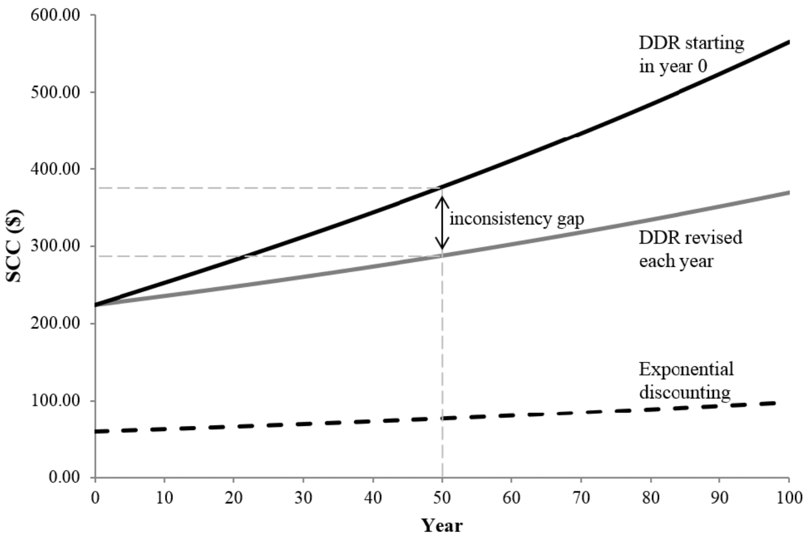


Figure 5: Time inconsistency of the SCC.

a manner consistent with prior expectations. By expression (2), and as visualized in Figure 5, the SCC in year 0 is approximately \$59 per tCO_2 under exponential discounting and \$224 per tCO_2 under gamma discounting, which is immediately indicative of the significant difference in the two approaches and why exponential is often referred to as the "tyranny of discounting."

More importantly, Figure 5 illustrates the *inconsistency gap* that emerges over time with a DDR. Consider the calculation of the realized SCC in year 50 when a naïve policymaker has updated the DDR schedule to begin anew in year 50. If prior expectations regarding the path of climate damages are realized (and there are no updates to future projections), the SCC in year 50 is roughly \$288 per tCO_2 under gamma discounting and \$76 per tCO_2 under exponential discounting. In each case, the SCC has grown at a rate of precisely 0.5% per year, and cumulatively by 28.3%. This difference reflects the increased marginal damages in the base year (\$2.57 in year 50 versus \$2 in year 0) and subsequent compounding effects.

Now, consider the naïve policymaker's forecast of the SCC in year 50 from the perspective of year 0. The base year for aggregating damages is again year 50 (as in the previous example). However, the discount rates applied to damages incurred in years 50–250 are based on the discounting schedule starting at year 0, and are therefore *lower* than (*i.e.*, inconsistent with) those applied to the same years in the previous calculation. The policymaker's forecast of the SCC in year 50 is \$376 instead of \$288 per tCO_2. By contrast, with exponential discounting the forecast and realized values are consistent (\$76 per ton). Moreover, the further out the forecast, the greater the inconsistency between the realized and forecast values of the SCC under a DDR regime. By year 100, these values are, respectively, \$369 and \$535 per tCO_2. This numerical simulation illustrates the theoretical results emerging from updating the discount rate schedule in a manner similar to that depicted in Figure 2.

Firm Abatement Investment under Time Inconsistency

To get a sense of how this time inconsistency affects the firm's investment in abatement, we now solve the firm's first-order condition for each of the three SCC time paths depicted in Figure 5, where marginal cost per tCO_2 abated is characterized by the following linear form, $C'(A) = 1.9212 \times A$, which we borrow from Karp (2005).[21] As a simplification, assume the useful life of one ton of CO_2 abatement capital is 50 years.[22] Our choice of a 50-year horizon roughly corresponds to the lifespans of several different carbon-reducing baseload electricity generation technologies, e.g., nuclear, combined-cycle coal gasification, biomass, and others (Tidball *et al.*, 2010).

Figure 6 illustrates the firm's optimal abatement investment decision for each alternative time path of the SCC. The firm's marginal benefit from investing in one unit of abatement is $V'(A)$, which, as noted earlier, is a constant value and depends on the time path of the SCC. Using the numbers generated above, we calculate $V'(A) = \$1{,}446$ per tCO_2 abated under exponential discounting, $V'(A) = \$5{,}455$ per tCO_2 abated under a DDR revised annually, and $V'(A) = \$6{,}103$ per tCO_2 abated

[21] Karp (2005) models total abatement cost as $\frac{b}{2}A^2$, using the parameter value $b = 1.9212$, which implies the linear marginal abatement cost curve above. This general functional form or shape is consistent with previous Integrated Assessment Models MAC estimates (Ellerman and Decaux, 1998).

[22] For an investment made in year 0, the firm is paid the SCC annually from year 0 to year 49.

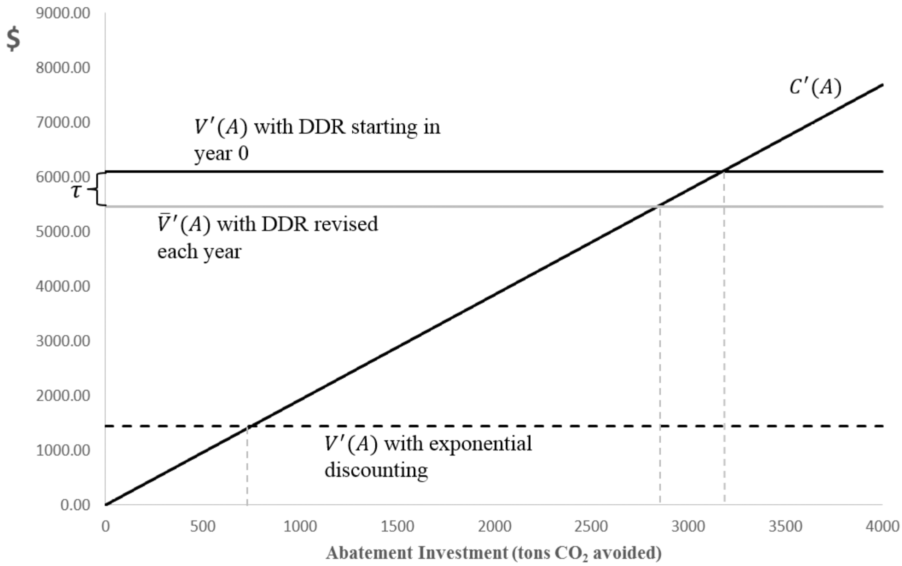


Figure 6: Firm's optimal abatement investment under alternative time paths of SCC.

under a DDR starting in year 0. Optimal abatement investment is found by equating the marginal abatement cost with these values as illustrated in Figure 6.

Under exponential discounting, the firm's optimal abatement investment yields a reduction of 752 tons of CO_2 per year and there is no gap between the firm's and the regulator's optimal level of abatement. However, under a DDR the firm's abatement investment is markedly higher, irrespective of whether the firm abides by the policymaker's preference that it makes its investment based on the DDR schedule beginning in year 0. In the case we have defined as the policymaker's preferred (*i.e.*, efficient) investment level, the firm's optimal abatement investment would yield a reduction of 3,177 tons of CO_2 per year. The firm's optimal abatement level under the annually revised, time-inconsistent DDR schedule, however, is a reduction of 2,840 tons of CO_2.

This example suggests even a time-inconsistent DDR schedule results in a significant increase in abatement relative to exponential discounting, and would seem to support Hansen's (2006) dismissal of concerns about the implications of any time inconsistency. However, the difference in the regulator's preferred abatement level and the firm's privately optimal level is not trivial. Table 1 summarizes this difference in terms of the SCC itself. Valued at the SCC in year 0 (\$224/tCO_2), the additional 337-ton reduction in CO_2 is worth \$75,524 — roughly a 10.6% reduction relative to the value of the regulator's preferred level.[23] Extrapolating this result beyond a single firm to some conception of aggregate abatement implies a considerable underinvestment in absolute terms.[24]

Finally, notice that the vertical distance between $V'(A)$ and $\bar{V}'(A)$ in Figure 6 is equal to τ, or \$648, the additional per-ton payment that the "sophisticated" regulator would have to offer the firm in year 0 to incentivize the preferred abatement investment. The cost of the transfer for the additional 337 tCO_2-reduction would be roughly \$218,376. But as seen from Table 1, the social value of the incremental abatement is \$75,524, which means that the regulator faces a net loss of roughly \$142,852. This result means that the policymaker is better off tolerating the firm's exploitation of the time inconsistency.

To further explore and understand how the individual components of the model affect this result, we allow most of the parameters to

Table 1: Policymaker's preferred investment in year 0 versus firm's optimal investment under time-inconsistent DDR.

	Abatement level (tons CO_2)	Valued at SCC in year 0 (\$224.05/ton)
Preferred by policymaker	3,176.64	\$711,725.64
Firm's optimal	2,839.55	\$636,202.11
Difference	337.09	\$75,523.53

[23] Our \$75,524 valuation accounts for discounting the 337-ton reduction over the 50-year period.

[24] An important insight that is beyond the scope of this paper is that even though the naïve regulator underperforms the sophisticated regulator in terms of abatement reduction, the naïve outcome does perform better in terms of reducing emissions more than the constant discount rate. Future research would benefit from conducting a thorough welfare analysis, which will help illustrate the best outcome for both the firm and regulator.

Table 2: Sensitivity analysis: How each parameter affects the gap between the policymaker's and the firm's optimal levels of abatement investment.

Parameter	Parameter values	Policymaker's preferred investment level based on DDR schedule beginning in year 0	Firm's optimal abatement level under an annually revised, time-inconsistent DDR schedule	% Difference
Baseline model*		3,176.63	2,839.55	−10.61
Growth in annual climate damage	0.0045	2,999.25	2,682.69	−10.55
	0.0055	3,367.69	3,008.47	−10.66
Initial climate damage	2.2	3,494.30	3,123.51	−10.61
	1.8	2,858.97	2,555.60	−10.61
μ	0.02**	4,045.89	3831.27	−5.30
	0.044	2,695.00	2,461.83	−8.65
σ	0.027	2,740.05	2509.81	−8.40
	0.033	3,603.43	3,169.57	−12.04

*Growth in annual climate damage = 0.005, initial climate damage = 2, $\mu = 0.04$, $\sigma = 0.03$.
**$\sigma = 0.01$ to keep the discount rate from falling below zero.

vary +/−10% (see Table 2).[25] Of note, we find that underinvestment in abatement by the firm is exacerbated as a result of an increase in the growth of annual climate damages. These results are particularly concerning, given the IPCC's report from 2018 that says that climate damages are increasing faster than expected. By contrast, other research argues for giving more consideration to future generations — *i.e.*, lowering the discount rate — which may result in reducing the inconsistency gap (Chichilnisky, 1996; Li and Löfgren, 2000) by firms closer to −5%. Additionally, narrowing the uncertainty around the mean discount rate leads to a smaller gap of −8.4% between the policymaker's and the firm's optimal levels of investment. Regardless of the

[25]We allow the discount rate to vary by more than 10% given that Drupp *et al.* (2018) and Pindyck (2019) suggest a discount rate closer to 2% as compared to Weitzman's survey responses that yield an average discount rate of 4%.

parameter changes, our results are consistent in that a regulator using a continuously updating DDR will result in an underinvestment from firms absent any additional financial incentive.

Discussion

Our model is simple but intuitive. When climate-based investments in any period t yield mitigation benefits over the course of $T > 1$ periods, we show that a policymaker relying on a DDR to forecast an SCC — and thus carbon price — schedule cannot induce the optimal level of current investment in a durable abatement technology. When the policymaker employs exponential discounting, the firm and the policymaker automatically have the same projected SCC schedule at $t = 0$, and the firm will therefore invest in the abatement technology at the policymaker's preferred level. If, however, the naïve policymaker employs a DDR — which implicitly presumes updating, time inconsistency, and therefore "myopia" in the sense that the policymaker does not anticipate the firm's incentive to incorporate this knowledge into its present value calculations of the stream of abatement credit payments — the policymaker's and firm's projections at $t = 0$ will diverge. The risk-neutral firm will take this year's SCC as given and, knowing that the SCC in period $t > 0$ will be revised, will expect the realized carbon price schedule based on the SCC in future periods to be lower than what was originally projected by the policymaker in $t = 0$. Therefore, the firm will not invest in as much of the durable abatement technology as is considered by the policymaker to be efficient in $t = 0$.

The alternative is for the policymaker to commit to an SCC schedule in $t = 0$, which might be operationalized in three ways. In one possible approach, as we showed above, the regulatory authority makes payments in $t = 0$ that are equal to the (exponentially) discounted stream of inconsistency gaps over time. We showed this approach to be inefficient. In the second approach, the regulatory authority makes payments in $t = 0$ that are equal to the (exponentially) discounted stream of mitigation credit payments over the expected life of the investment.[26]

[26] This is common in solar markets, for example, where a private owner of solar panels can sell the rights to the associated renewable energy credits (or similar market instrument) for the expected life of the system.

We showed that this approach could be infeasible if the regulator faces financial constraints. Further, both of these approaches will result in an environment where there is no common SCC associated with abatement in any given period, opening the government up to arbitrage opportunities and incentivizing firms to rely on offsets or other market mechanisms instead of abatement investments.

This analysis would seem to suggest a fatal flaw in relying on a DDR for the development of market-based incentives for private mitigation investment. However, even persistent inefficiencies do not necessarily preclude the use of specific policy approaches so long as they are welfare improving, and it may be that the net benefits to relying on a DDR outweigh the inconsistency gap identified here — or simply that the reliance on a DDR is a non-negotiable result of a policy-making process based on ethical considerations or otherwise exogenous to the choice of policy instrument.[27] Generalizing to the real world, there are other considerations that may allow policymakers to proactively manage this inefficiency. For instance, declining discount rate schedules currently in use by the UK and other countries tend to be moderate and non-linear in their rate of decline. In general, the more rapid the decline in a DDR, the greater the inefficiencies caused by a DDR-based policy. Further, in the case of nonlinear schedules, which tend to rely on a constant rate for discreet, forward-looking intervals (*e.g.*, in 20 years, the rate for SCC calculation falls from 3% to 2%), the policymaker is time consistent save for those "threshold" periods. A policymaker could therefore structure payment schedules to correspond with thresholds, still incentivizing much of the investment in mitigation without opening up arbitrage opportunities around those break points. Further, while we assume firms are profit maximizers and risk neutral, it is also true that the potential gains from attempting to arbitrage an inconsistent policy may simply not be worth the costs, and especially when those gains are based on speculative assumptions about the future SCC and financed via capital markets. In effect, the same uncertainty that drives the adoption of a DDR will make speculative financing more expensive for firms.

Although our model reveals an important implication for the design of climate policy using a DDR, some key opportunities remain for

[27] In this case, every policy would be evaluated as a second-best, including command-and-control.

continuing research. We discuss two possibilities below: (i) allowing the firm to delay investment until some future period, $t > 0$, and (ii) the implications of a DDR in an emissions trading system (ETS) in which permits may or may not be bankable. Although rigorous analysis of these cases is beyond the scope of this paper, we can at least say a few things about how each might be affected when climate policy is designed under a DDR regime.

We adopted the simplifying assumption that the firm makes an investment in mitigation in period $t = 0$. However, because the evolution of climate damages is inherently uncertain, the firm may find it optimal to delay the investment until some future period. Real options analysis holds that there is value in waiting; the opportunity cost of investing today is the forgone value of preserving the option to invest in the future. In standard benefit-cost analysis (BCA), the firm should invest if the ENPV of the investment is positive. Accounting for option values alters the cost–benefit calculus; projects that pass the BCA criterion without consideration of option values may fail when option values are included (Dixit *et al.*, 1994).

Time inconsistency with respect to climate policy instruments like carbon taxes or subsidies would alter the BCA calculus further for firms considering investment-based mitigation projects. Similar to the "inconsistency gap" shown in Figure 5, option values (and thus investment schedules) calculated in period $t = 0$ and based on the expected path of the SCC when the DDR schedule commences in period $t = 0$ would likely diverge from those calculated based on a continually updated DDR schedule. The optimal timing of mitigation investments would therefore differ from the perspectives of the policymaker versus the firm.

Emissions trading systems (ETSs) are a crucial tool in the current and future carbon policy landscape. It is therefore imperative to understand any interactions that may arise when ETS and DDR policies are used in tandem. One possibility is to employ a dynamic optimal control model of a socially optimal tradable permit system similar to that of Biglaiser *et al.* (1995) and incorporate some of our model's critical features — a DDR and increasing marginal climate damages. This would allow one to solve for the optimal time path of the permit price, which would presumably be different under the alternative time paths of the discount rate and result in divergent signals to the firm about the optimal abatement level over time. Presumably, under a naïvely updated DDR, an emission cap based on a time-inconsistent SCC computation would be continually revised upward, which might have similar implications to those outlined in the model above. Such an exercise may also provide some insight into the widely-known price versus quantity debate (Weitzman, 1974).

Conclusion

The debate over the appropriate manner in which to discount future damages associated with climate change is robust and ongoing and remains a highly controversial topic in climate economics. Indeed, real-world practitioners of benefit–cost analyses may resort to the imploring sentiment of Moore *et al.* (2004) — "Just give me a number!" In practice, the complications arising from such normative policies may prove difficult to overcome.

We have explored one such complication here — namely, carbon taxes or abatement subsidies predicated on a DDR are incapable of inducing the policymaker's desired investment in a durable abatement technology in period $t = 0$. The tendency of the policymaker to update the DDR schedule in each period generates a time-inconsistent carbon tax/subsidy schedule. The risk-neutral firm, recognizing this "inconsistency gap" between forecast and actual levels of the tax/subsidy in every future period, will adjust abatement investments accordingly, resulting in under-investment.[28] Our analysis is an important step in developing a broader understanding of the potential interactions between climate policy and the use of DDRs. Given the high stakes associated with global climate change, economists, policymakers, and other stakeholders cannot afford to compartmentalize analyses such that models of alternative regulatory instruments do not account for the effects of different discounting regimes, or *vice versa*. This is particularly important since it is already well known that computations of the benefits and costs of policy changes to distant future generations can be extremely sensitive to discount rates. It is imperative that we take a

[28]Future research will benefit by considering how risk aversion affects our results. For example, it may be likely that a risk-averse firm, potentially operating with a lower discount rate, would close the 'inconsistency gap' while a risk-loving firm who is willing to accept a higher discount rate may exacerbate the gap.

more holistic view when discussing DDR policy in the context of climate or other intergenerational considerations, so that any complementarities or countervailing effects are fully understood.[29]

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References

Arrow, K. J., M. L. Cropper, C. Gollier, B. Groom, G. M. Heal, R. G. Newell, W. D. Nordhaus, and *et al.* (2014), "Should Governments Use a Declining Discount Rate in Project Analysis?", *Review of Environmental Economics and Policy*, 8, 145–63, doi:10.1093/reep/reu008.

Arrow, K., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, and *et al.* (2013), "Environmental Economics. Determining Benefits and Costs for Future Generations", *Science (New York, N.Y.)* 341, 349–50, doi:10.1126/science.1235665.

Auffhammer, M. (2018), "Quantifying Economic Damages from Climate Change", *Journal of Economic Perspectives*, 32(4), 33–52.

[29] Future research would also benefit from a thorough econometric analysis of whether there are abatement investment differences across countries that have DDR as compared to those that do not.

Azfar, O. (1999), "Rationalizing Hyperbolic Discounting.", *Journal of Economic Behavior & Organization*, 38, 245–52, doi:10.1016/S0167-2681(99)00009-8.

Belfiori, M. E. (2015), "Time-Consistent Climate Policies", *Political Economy and Instruments of Environmental Politics*, 251.

Benhabib, J., A. Bisin, and A. Schotter (2010), "Present-Bias, Quasi-hyperbolic Discounting, and Fixed Costs", *Games and Economic Behavior*, 69, 205–23, doi:10.1016/j.geb.2009.11.003.

Benzion, U., A. Rapoport, and J. Yagil (1989), "Discount Rates Inferred from Decisions: An Experimental Study", *Management Science*, 35, INFORMS 270–284. doi:10.1287/mnsc.35.3.270.

Biglaiser, G., J. K. Horowitz, and J. Quiggin (1995), "Dynamic Pollution Regulation", *Journal of Regulatory Economics*, 8, Kluwer Academic Publishers: 33–44. doi:10.1007/BF01066598.

Chichilnisky, G. (1996), "An Axiomatic Approach to Sustainable Development", *Social Choice and Welfare*, 13(2), 231–57.

Cropper, M. L., M. C. Freeman, B. Groom, and W. A. Pizer (2014), "Declining Discount Rates", *American Economic Review*, 104, American Economic Association: 538–43.

Dasgupta, P. and E. Maskin (2005), "Uncertainty and Hyperbolic Discounting", *American Economic Review*, 95, 1290–9, doi:10.1257/0002828054825637.

Diamond, P. and B. Köszegi (2003), "Quasi-hyperbolic Discounting and Retirement", *Journal of Public Economics*, 87, 1839–72, doi:10.1016/S0047-2727(02)00041-5.

Dixit, A. K., R. K. Dixit, and R. S. Pindyck (1994), *Investment under Uncertainty*, Princeton, NJ: Princeton University Press.

Drupp, M. A., M. C. Freeman, B. Groom, and F. Nesje (2018), "Discounting Disentangled", *American Economic Journal: Economic Policy*, 10(4), 109–34.

Ellerman, A. D. and A. Decaux (1998), "Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves", MIT Joint Program on the Science and Policy of Global Change Report 40.

Frederick, S., G. Loewenstein, and T. O'Donoghue (2002), "Time Discounting and Time Preference: A Critical Review", *Journal of Economic Literature*, 40, 351–401, doi:10.1257/002205102320161311.

Freeman, M. C., B. Groom, E. Panopoulou, and T. Pantelidis (2015), "Declining Discount Rates and the Fisher Effect: Inflated Past, Discounted Future?", *Journal of Environmental Economics and Management*, 73, 32–49, doi:10.1016/j.jeem.2015.06.003.

Gerlagh, R. and M. Liski (2018), "Consistent Climate Policies", *Journal of the European Economic Association*, 16(1), 1–44, doi:101093/jeea/jvx010.

Gintis, H. (2000), "Beyond *Homo economicus*: Evidence from Experimental Economics", *Ecological Economics*, 35, 311–22.

Gollier, C. (2013), *Pricing the Planet's Future*, Princeton, NJ: Princeton University Press.

Gollier, C. (2002), "Discounting an Uncertain Future", *Journal of Public Economics*, 85, 149–66, doi:10.1016/S0047-2727(01)00079-2.

Goulder, L. H. and R. C. Wiliams (2012), "The Choice of Discount Rate for Climate Change Policy", *Climate Change Economics*, 3(4), 1–18.

Graham, J. R. and C. R. Harvey (2001), "The Theory and Practice of Corporate Finance: Evidence from the Field", *Journal of Financial Economics*, 60(2–3), 187–243.

Groom, B., C. Hepburn, P. Koundouri, and D. Pearce (2005), "Declining Discount Rates: The Long and the Short of It", *Environmental & Resource Economics*, 32, Kluwer Academic Publishers: 445–493. doi:10.1007/s10640-005-4681-y.

Hansen, A. C. (2006), "Do Declining Discount Rates Lead to Time Inconsistent Economic Advice?", *Ecological Economics*, 60, 138–44, doi:10.1016/j.ecolecon.2006.03.007.

Harstad, B. (2019), "Technology and Time Inconsistency", *Journal of Political Economy*, Conditional acceptance (May 15, 2019).

Helm, D., C. Hepburn, and R. Mash (2003), "Credible Carbon Policy", *Oxford Review of Economic Policy*, 19, Oxford University Press: 438–450. doi:10.1093/oxrep/19.3.438.

Hepburn, C., S. Duncan, and A. Papachristodoulou (2010), "Behavioural Economics, Hyperbolic Discounting and Environmental Policy", *Environmental and Resource Economics*, 46, Springer Netherlands: 189–206. doi:10.1007/s10640-010-9354-9.

IPCC (2014), *Climate Change 2014 Synthesis Report Summary Chapter for Policymakers*, *Ipcc*. doi:10.1017/CBO9781107415324.

IPCC (2018), "Global warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty [V. Masson-Delmotte and P. Zhai and H. O. Pörtner and D. Roberts and J. Skea and P. R. Shukla and A. Pirani and W. Moufouma-Okia and C. Péan and R. Pidcock and S. Connors and J. B. R. Matthews and Y. Chen and X. Zhou and M. I. Gomis and E. Lonnoy and T. Maycock and M. Tignor and T. Waterfield (eds.)]. In Press".

Iverson, T. and L. Karp (2017), "Carbon Taxes and Climate Commitment with Non-constant Time Preference", Working Paper.

Jagannathan, R., D. A. Matsa, I. Meier, and V. Tarhan (2016), "Why Do Firms Use High Discount Rates?", *Journal of Financial Economics*, 120(3), 445–63.

Kaplow, L., E. Moyer, and D. A. Weisbach (2010), "The Social Evaluation of Intergenerational Policies and Its Application to Integrated Assessment Models", *The B.E. Journal of Economic Analysis and Policy*, 10(2), 1–34.

Karp, L. (2005), "Global Warming and Hyperbolic Discounting", *Journal of Public Economics*, 89, 261–82, doi:10.1016/j.jpubeco.2004.02.005.

Laibson, D. (1997), "Golden Eggs and Hyperbolic Discounting", *The Quarterly Journal of Economics*, 112, Oxford University Press: 443–478. doi:10.1162/003355397555253.

Li, C. Z. and K. G. Löfgren (2000), "Renewable Resources and Economic Sustainability: A Dynamic Analysis with Heterogeneous Time Preferences", *Journal of Environmental Economics and Management*, 40(3), 236–50.

Loewenstein, G. and R. H. Thaler (1989), "Anomalies: Intertemporal Choice", *The Journal of Economic Perspectives*, 3, American Economic Association: 181–193.

Moore, M. A., A. E. Boardman, A. R. Vining, D. L. Weimer, and D. H. Greenberg (2004), ""Just Give Me a Number!" Practical Values for the Social Discount Rate", *Journal of Policy Analysis and Management*, 23, Wiley Subscription Services, Inc., A Wiley Company: 789–812. doi:10.1002/pam.20047.

Pearce, D. W., B. Groom, C. J. Hepburn, and P. Koundouri (2003), "Valuing the Future", *World Economics*, 4, World Economics, Economic & Financial Publishing, 1 Ivory Square, Plantation Wharf, London, United Kingdom, SW11 3UE: 121–141.

Pender, J. L. (1996), "Discount Rates and Credit Markets: Theory and Evidence from Rural India", *Journal of Development Economics*, 50, 257–96, doi:10.1016/S0304-3878(96)00400-2.

Pindyck, R. S. (2019), "The Social Cost of Carbon Revisited", *Journal of Environmental Economics and Management*, 94, 140–60.

Poterba, J. M. and L. H. Summers (1995), "A CEO Survey of US Companies' Time Horizons and Hurdle Rates", *MIT Sloan Management Review*, 37(1), 43.

Strotz, R. H. (1955), "Myopia and Inconsistency in Dynamic Utility Maximization", *The Review of Economic Studies*, 23, 165, doi:10.2307/2295722.

Thaler, R. (1981), "Some Empirical Evidence on Dynamic Inconsistency", *Economics Letters*, 8, 201–7, doi:10.1016/0165-1765(81)90067-7.

Tidball, R., J. Bluestein, N. Rodriguez, and S. Knoke (2010), *Cost and Performance Assumptions for Modeling Electricity Generation Technologies*.

Weitzman, M. L. (1974), "Prices vs. Quantities", *The Review of Economic Studies*, 41(4), 477–91.

Weitzman, M. L. (1998), "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate", *Journal of Environmental Economics and Management*, 36, Elsevier: 201–208.

Weitzman, M. L. (2001), "Gamma Discounting", *American Economic Review*, 91, 260–71, doi:10.1257/aer.91.1.260.

Weitzman, M. L. (2010), "Risk-Adjusted Gamma Discounting", *Journal of Environmental Economics and Management*, 60, 1–13, doi:10.1016/j.jeem.2010.03.002.

Winkler, R. (2006), "Does "Better" Discounting Lead to "Worse" Outcomes in Long-Run Decisions? The Dilemma of Hyperbolic Discounting", *Ecological Economics*, 57, 573–82, doi:10.1016/j.ecolecon.2005.05.013.