

# Uncertain discount rates in climate policy analysis

Richard G. Newell\*, William A. Pizer

*Resources for the Future, 1616 P St NW, Washington, DC 20036, USA*

## Abstract

Consequences in the distant future—such as those from climate change—have little value today when discounted using conventional rates. This result contradicts our “gut feeling” about such problems and often leads to ad hoc application of lower rates for valuations over longer horizons—a step facilitated by confusion and disagreement over the correct rate even over short horizons. We review the theory and intuition behind the choice of discount rates now and, importantly, the impact of likely variation in rates in the future. Correlated changes in future rates imply that the distant future should be discounted at much lower rates than suggested by the current rate, thereby raising the value of future consequences—regardless of opinions concerning the current rate. Using historic data to quantify the likely changes and correlation in changes in future rates, we find that future valuations rise by a factor of many thousands at horizons of 300 years or more, almost doubling the expected present value of climate mitigation benefits relative to constant 4% discounting. Ironically, uncertainty about future rates reduces the ratio of valuations based on alternate choices of the current rate.

© 2003 Elsevier Ltd. All rights reserved.

*Keywords:* Discounting; Uncertainty; Climate change

## 1. Introduction

Most environmental policies involve a trade-off between short-term costs and longer-term benefits. Investments in cleaner technologies and abatement equipment, for example, require up-front expenditures that lead to environmental improvements over time. Climate change presents a dramatic need for balancing costs and benefits over time because the benefits of mitigation measures are linked to the lifespan of greenhouse gases (GHGs), which may remain in the atmosphere for centuries.<sup>1</sup>

How do we compare costs and benefits that are separated by many decades or even centuries? When an individual invests in a new house or saves for retirement, or a business invests in research and new equipment, the market interest rate allows us to convert costs and benefits at different points in time into comparable costs and benefits at a single point in time. This procedure is known as discounting.

When we consider horizons longer than a few decades, however, we run into trouble. Few markets exist for assets with maturities exceeding 30 years, making the interest rate beyond that horizon highly uncertain. This uncertainty can have important consequences for the valuation of distant benefits. As we demonstrate below, our valuation today of benefits 300 years or more in the future rises by a factor of many thousand solely because of this uncertainty in discount rates. Understanding the effect of discount rate uncertainty and quantifying its impact on valuation estimates is the primary purpose of this paper. Note that this is distinct from an analysis of uncertainty in the costs and benefits of climate change mitigation *at the time they occur*, which is a separable issue.

Despite the potential magnitude of the effect of discount rate uncertainty, virtually all climate models—and indeed most economic analyses of long-term problems—ignore it. Only recently have economists taken note of the importance of uncertainty in the interest rate itself, or its capacity to change economic analyses in a meaningful way (Weitzman, 1998, 2001).

Integrated assessment models of climate change can be used to estimate the time profile of *mitigation benefits*—the benefits associated with reducing 1 ton of carbon emissions. Fig. 1 shows one example based on

\*Corresponding author. Tel.: +1-202-328-5111; fax: +1-202-939-3460.

E-mail address: newell@rff.org (R.G. Newell).

<sup>1</sup>The duration may be even longer if climate change leads to a fundamental and irreversible shift in the earth's climate systems.

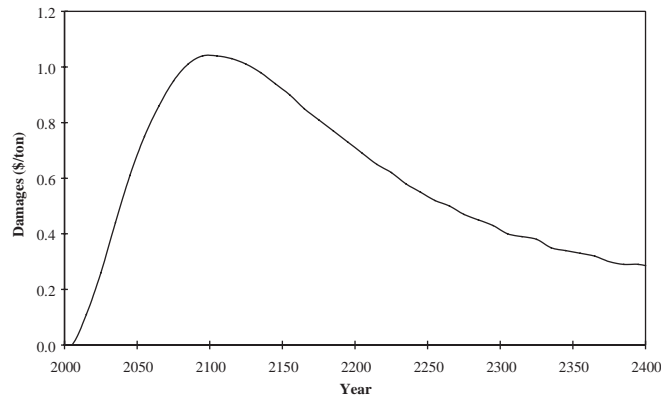


Fig. 1. Time profile of benefits from reducing 1 ton of carbon emissions in 2000. *Note:* Based on the dynamic integrated climate economy (DICE) model (Nordhaus and Boyer, 2000; Nordhaus, 1994). Currency units are 1989 dollars.

Nordhaus' DICE model (Nordhaus and Boyer, 2000; Nordhaus, 1994).<sup>2</sup> Regardless of the *magnitude* of climate consequences, this model depicts a sensible pattern of mitigation benefits having a delayed, then an increasing, and finally a declining effect, as the climate adjusts first to the increase in carbon dioxide (CO<sub>2</sub>) and then to its gradual decay.<sup>3</sup>

The standard approach is to convert the model's path of benefits into equivalent present discounted values based on a single discount rate, and add them up. Applying a discount rate of 4%—the average rate of return to government bonds over the past 200 years—one obtains a discounted value of about \$6 per ton (1989 dollars) using the benefit stream in Fig. 1. This value can be balanced against marginal mitigation costs to determine optimal reductions or directly interpreted as the optimal tax on CO<sub>2</sub> emissions.

Despite the appealing simplicity of that approach, no one knows whether the appropriate discount rate will be 4% for the next 400 years (nor is there universal agreement about using 4% right now). One could instead figure that the discount rate is known in the

<sup>2</sup>We use this particular path of benefits not because we believe it is the "best" estimate of climate damages, but rather because the model is relatively simple and transparent, has been used in a wide range of analyses, and exhibits a time profile of damages that is reasonable. As we describe further below, the quantitative effect of uncertainty on the percentage increase in discounted climate damages is dependent only on the shape of the path of damages, not on its magnitude. This robustness is important because there is little consensus on the consequences of climate change, and many have argued that the DICE model is somewhat conservative in its damage estimates (Repetto and Austin, 1997). For example, one possibility ignored by the DICE model (and most other models) is that GHG emissions may lead to a permanent shift in climatic patterns that will remain even if atmospheric concentrations of these gases eventually decline (Broecker, 1997).

<sup>3</sup>Note that while the damages associated with a single ton of emissions declines over time, the cumulative effect of all GHG emissions is not projected to decline over the next several hundred years.

short term but becomes increasingly uncertain in the future. After discussing the general economic rationale behind discounting, we describe both the conceptual and empirical influence of discount rate uncertainty on future valuation. Next we apply our computation of uncertainty-adjusted discount factors to the problem of valuing future climate change consequences. Finally, we summarize and conclude.

We find significant empirical evidence that historical rates are indeed uncertain and persistent. For example, there has been a secular decline in interest rates that goes back at least 200—if not more than 1000—years, overlain with persistent deviations of 1–2% lasting 20–40 years. Using 200 years of data on long-run US government bond yields to predict patterns of future interest rate uncertainty, we find a cumulative effect of uncertainty that raises valuations by a factor of between 130 and 40,000 after 400 years, with the higher value reflecting our preferred model. The wide range depends on whether interest rates are more properly thought of as reverting toward a long-run mean (130) or not (40,000), a determination that is statistically ambiguous over the past 200 years. Nonetheless, we argue that the non-reverting, or random walk, model is more compelling based on both a long-term secular trend and the results of split-sample forecasts over various historical periods. Applied to the real problem of valuing the future damages due to current CO<sub>2</sub> emissions, we find that uncertainty almost doubles the present value of those damages based on the random walk model, while raising the present value a more modest 14% based on the mean-reverting model.

## 2. A plethora of discount rates

The term *discounting* arises in the context of valuing future consequences because individuals typically value future consumption less than present

consumption—they *discount* the future. Over horizons of less than 30 years, discounting is inextricably tied to the interest rate, which reflects the rate at which wealth can be traded across time. For example, investing \$100 at 7% yields \$107 at the end of the year. That \$100 today can be traded for \$107 next year indicates an equivalence between these values—at least from the market's perspective: \$107 next year is valued at only \$100 today. One would say that the future (next year) is *discounted* at 7%.

The traditional investment criterion used in business decisions provides another way of looking at the rationale behind discounting. Let us say private firms can borrow funds at 7% interest. From their perspective, any investment project that returns more than 7% per year is profitable. That is, if \$100 invested in research or equipment yields a net pay-off of more than \$7 every year, they can repay creditors and have something left over. Otherwise, they lose money. This is a statement of the *net present value rule*: if the net benefits from a project discounted at 7% are greater than zero, the project is desirable.

### 2.1. Market rates

In reality, 7% is approximately the real return to investment in large companies over the period 1926–1990<sup>4</sup> and is the rate currently recommended by the US Office of Management and Budget for standard cost–benefit analysis. Nevertheless, there is little consensus on the appropriate discount rate. Part of the problem arises because taxes create a wedge between the observed market return to private investments and the eventual return to consumers after taxes.<sup>5</sup> That is, the investment criterion used by businesses implies a different discount rate than the preferences expressed by consumers.

Corporate income taxes of 35%, for example, imply that the pre-corporate-tax return to private investment

<sup>4</sup>The real return to large company stocks was 8% over the period 1926–1998 (7% over 1926–1990). The real return to corporate bonds was 2.7%, and to government bonds, 2.2% over the same period (Ibbotson Associates, 1999). Based on ex ante survey measures of inflation, such as those discussed in Thomas (1999), rather than the ex post realized rate used by Ibbotson, we find that real *expected* rates of return on government bonds were close to 3% over the same period and closer to 4% over the last 200 years.

<sup>5</sup>Another issue arises when the costs and benefits of a project are measured in *nominal* rather than *real* terms. It is then necessary to use nominal discount rates that are typically several percentage points higher because of inflation. That is, when we talk about \$100 of benefits in 2050, do we imagine that this \$100 can buy a similar basket of goods as it can buy today (a constant-dollar benefit measure), or do we imagine that this \$100 is worth a lot less in 2050 because of inflation (a nominal benefit measure)? Because it is straightforward to establish whether a cost and benefit analysis is based on real or nominal measures, this distinction is relatively uncontroversial. Generally, most analyses utilize real measures.

is closer to 11%. Because individuals pay up to 50% in federal, state, and local income taxes on their 7% pretax return, the return for ordinary people is closer to 4%. This *consumption rate of interest* is taken as a measure of the rate at which people trade-off their spending over time. Individuals face the option of consuming today versus forgoing such consumption, investing the money, and consuming the after-tax proceeds from the investment at some future date. The consumption rate of interest is the rate at which they can perform this shift in consumption over time.

The consumption rate of interest, however, is difficult to pin down. For a particular individual, it depends on one's tax bracket, the use of tax-deferred savings options, and whether one is a net saver or borrower. The types of investment and debt raise another complication, because riskier assets (such as equities) compensate investors by paying a higher rate of return than less risky assets (such as bonds).<sup>6</sup> Thus, while equities have had an average return of about 7%, bonds have had an average return of only 4% before and 2% after taxes. Because the risks involved in social projects may not be comparable to commonly observed market risks, one may want to value that risk differently. It is therefore useful to separate the issue of risk from the issue of discounting.<sup>7</sup>

To separate risk and discounting, we need to identify low-risk investments. Because government bonds are considered very safe, economists point to the return on government bonds as a benchmark for the consumer interest rate absent any risk premium. Using this logic, the government bond rate is the discount rate favored by the US Environmental Protection Agency, the US Congressional Budget Office, and the US General Accounting Office. Still, some economists consider bonds to be unrepresentative assets and prefer to focus on the average return to equity as the appropriate consumption rate of interest.<sup>8</sup> In still other cases, analysts may seek to value forgone investment, and focus on a (pre-corporate tax) private return to investment.

Confronted with the choice between the consumption rate of interest and the rate of return to private investment, we focus on the former. Because climate policy decisions ultimately concern the future welfare of people—not firms—the consumption interest rate is more appropriate. Any effects on firms can be converted into their consumption consequences for individuals and valued along with direct consumption effects at the consumer interest rate. Converting firm effects into

<sup>6</sup>See US EPA (2000, p. 47).

<sup>7</sup>Thus, a standard approach to policy analysis under uncertainty is to convert uncertain cost and benefit flows to certainty equivalents and then discount these flows using a risk-free (or at least low-risk) rate of return (see, e.g., Arrow et al., 1996; Lind, 1982).

<sup>8</sup>See Nordhaus (1994, p. 129).

consumption effects is referred to as the “shadow price of capital” approach because any consequences on firm capitalization are valued in terms of their consequences on consumption—or “shadow value” to consumers.<sup>9</sup>

## 2.2. Intergenerational rates

Plausible consumption discount rates range from 2% to 7% based on our earlier discussion of taxes and asset returns.<sup>10</sup> For a particular choice of asset and tax assumptions, one can turn to the market to observe the current rate.<sup>11</sup> Future rates associated with investment in bonds (at the lower end of the range) can be inferred from bonds with longer maturities, up to about 30 years. Beyond this time horizon, however, two problems arise. First, few bonds exist with maturities of more than 30 years, leaving longer-term interest rates uncertain.<sup>12</sup> Second, at horizons beyond 30 years our decisions affect not only the current generation but future generations as well.

Many economists, dating back to Ramsey (1928), have argued that it is ethically indefensible to discount the *utility* (i.e., well-being) of future generations—although this does not imply a zero discount rate for their *consumption* (e.g., measured in dollars) if con-

sumption is growing over time.<sup>13</sup> Others have argued that at a minimum, the intergenerational discount rate need not equal the observed rate used by individuals within their own generation.<sup>14</sup> These arguments have led to a tendency to simplify the problem by applying lower rates over longer horizons.<sup>15</sup> Long horizons eventually become short, however, and such ad hoc adjustments lead to inconsistent decisions over time.<sup>16</sup> Arbitrarily low intergenerational rates pose an additional problem for our exercise as the use of such rates (e.g., zero) dwarfs the effects of uncertainty.

Our exercise remains focused on the use of market rates between 2% and 7%. Even those who prefer discounting based on intergenerational equity may want to understand the consequences of uncertainty in a more conventional framework. As we will see, our analysis implies that correctly handling uncertainty lowers the effective discount rate in the future such that generations further in the future are increasingly treated the same. In that sense, our findings can be viewed as an argument for intergenerational equity that originates from conventional neoclassical economics.

## 2.3. Choosing a rate

Intergenerational issues aside, the problem of valuing the future consequences of climate change mitigation remains vexing. Looking 400 years into the future, the plausible 2–7% range of discount rates has a corresponding difference in discounted values of 200

<sup>9</sup>See Lind (1982) for a discussion of the shadow price of capital approach. The choice between investment and consumption rates of return is actually a bit more involved than the preceding paragraphs suggest. When public projects directly offset or “crowd out” private investment (e.g., by raising money through bond offerings), it is easy to see why they ought to offer at least as high a return as the forgone private investment. If public projects achieve such a return and the return accrues to firms, firms are clearly better off. When public projects offset consumption (or when costs and benefits are both measured in terms of their consumption consequences), one is no longer measuring improvements in terms of firm profit but in terms of consumer welfare, and the consumption rate of interest is appropriate.

<sup>10</sup>Although the consumption rate of interest measures the rate at which changes in consumption *can* be moved across time, one cannot be sure that it is the return *required* for a welfare improvement unless we assume the existing consumption levels were optimally chosen in response to the consumption interest rate. Although one might take it for granted that businesses regularly maximize profits—and that blindly crowding out private investment will lower profits—there is some evidence that consumers behave irrationally (e.g., forced savings might raise welfare). Nonetheless, when public investment or regulation influences consumption, there are no good alternatives to assume that the consumer rate of interest reflects consumer preferences for trade-offs over time.

<sup>11</sup>In the case of equities, one really observes only *past* rates.

<sup>12</sup>One exception is the British *consols* (first issued in 1749), which are in principle issued in perpetuity—holders can never claim their principal (the debt can be retired at the option of the government, but this is unlikely given the extremely low nominal rate). However, there are several problems with using yields on the consols as a reliable indicator of future interest rates—most importantly, they provide a single summary statistic about all future rates rather than information about specific rates in specific years. Homer and Sylla (1998, p. 160, 443) discusses other problems with using the yield on consols as a reliable measure of the market rate.

<sup>13</sup>Even if the rate of discount on utility is zero, the rate of discount on consumption may be greater than zero because future generations are likely to be richer, and consumption typically becomes less valuable at the margin as this occurs. In other words, an extra \$1 of consumption by the current generation could be more valuable than an extra \$1 of consumption by future generations because the current generation is relatively poor and \$1 is therefore more valuable. This is the distinction between utility discounting and consumption discounting raised by some authors, including Nordhaus (1994).

<sup>14</sup>Arrow et al. (1996) and Cline (1999), among others, discuss this so-called prescriptive approach.

<sup>15</sup>Bazon and Smetters (1999) describe this approach in their survey of “Discounting Inside the Beltway”.

<sup>16</sup>The use of a deterministic declining rate, though perhaps consistent with individual preferences (Ainslie, 1991; Cropper et al., 1994), produces time-inconsistent decisions. For example, suppose one uses a 5% rate for 100 years and 0% afterward. In the year 2000, a choice that trades a \$1 loss in 2150 for a \$2 gain in 2200 is desirable, because there is no discounting between these periods. After 2050, this choice begins to look worse and worse, as the interval between 2150 and 2200 begins to be discounted. Eventually, an optimizing decision maker will want to reverse the initial decision, instead choosing the \$1 in 2150. Recognizing that this will assuredly happen represents a time inconsistency. That is, the mere passage of time will make the decision maker want to change the initial choice. For further discussion, see Cropper and Laibson (1999) and Heal (1998). Arrow (1999) discusses one approach to thinking about this dilemma, viewing it as a game played between generations.

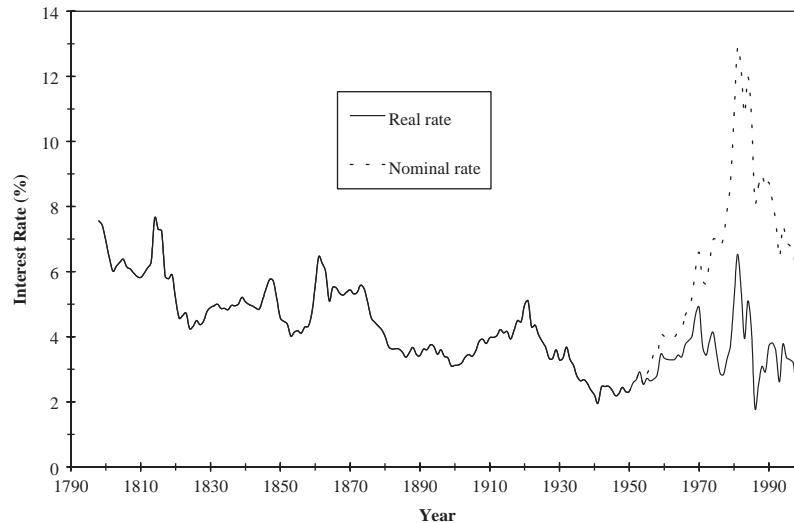


Fig. 2. Market interest rate on US long-term government bonds (1798–1999).

*million-to-1*. And there is little justification for narrowing our range despite a great volume of writing on the topic.<sup>17</sup> On top of this enormous variation based on the underlying rate, we want to consider the further effect of uncertainty about how these rates may change in the future.

Ironically, we find that uncertainty about changes in future interest rates *reduces* the valuation dilemma. Uncertainty about future rates implies that the initial choice of rate is less important because random variation will mix up those choices over time. In the next section we show that the difference in valuation from using a 2% versus a 7% discount rate is only a factor of about 40 to 1 after 400 years, once one considers uncertainty about those rates in the future. Although still significant, it is obviously much smaller than 200 million to 1.

For practical purposes, we first focus on an initial rate of around 4% because this lies in the middle of the 2–7% range and corresponds to the average rate of return for government bonds, the interest rate for which we have the best data. We then explore alternative values of both 2% and 7%. Before turning our attention to the issue of how interest rates may change in the future, it is instructive to consider how rates have changed in the past.

#### 2.4. Changes in interest rates over time

Consider the history of interest rates available on long-term US government bonds, plotted in Fig. 2.

<sup>17</sup>See Lind (1982), a special 1990 issue of the Journal of Environmental Economics and Management (Vol. 18(2)) devoted to discounting, and most recently, Portney and Weyant (1999).

These bonds represent the highest-quality, lowest-risk market investment consistently available in the United States over the past 200 years. Our series consists of rates on Treasury bonds, except for periods where there were no bonds outstanding or when the market was distorted by changes in banking policy.<sup>18</sup> There we substitute rates on high-quality municipal bonds.

As the graph shows, there have been persistent fluctuations in the real interest rate over the past 200 years. Periods of relatively high rates during the 1810s, 1830–40s, 1860–70s, 1910s, and 1970–80s have all been followed by significant declines of 1% or more that remain for a decade or more. Inflation appears in the 1950s, bringing dramatic differences between real and nominal rates beginning in the 1970s.<sup>19</sup> On top of these fluctuations, there is evidence of a secular decline from around 6–7% in 1800 to around 3–4% today. It should therefore not be surprising if interest rates continue to change by 3% or more—up or down—over the next 200 years. Our next objective is to more precisely quantify future interest rate behavior and evaluate the impact of this behavior on future valuations.

<sup>18</sup>See Newell and Pizer (2003) for greater detail on data sources and construction.

<sup>19</sup>To convert nominal to real rates, we use a ten-year moving average of the one-year inflation forecast collected as part of the Livingston Survey since 1945 (Thomas, 1999). Note that prior to 1945, there is little evidence of persistent inflation because the value of money was tied to a gold standard. There were some years of high inflation, usually associated with wars or other temporary disruptions, but they were always offset by subsequent years of deflation. In fact, price levels as measured by the Consumer Price Index were the same in the early 1940s as they were in 1800 (US Bureau of the Census, 1975, p. 211). As a result, financial market participants anticipated that the future rate of inflation would be about zero.

### 3. The effect of discount rate uncertainty on future valuations

Our basic finding is that a model incorporating uncertainty about future rates, calibrated to patterns of historic behavior, leads to a higher valuation of future benefits, regardless of the initial rate that is chosen. Before we explore this effect, however, let us consider the intuition behind it. Suppose we all agree that the current discount rate should be about 4%. Arguably, the rate in the future might decline to as little as 1% over the next 100 years—or rise to 7%. Fig. 3 shows these two alternate future paths, one declining to 1% and one rising to 7%.

These alternative paths have important implications for how much one would value consequences of today's actions 100 years in the future. Using the rates shown in the lower path, \$100 in 2100 is worth \$20.28 in 2000. However, using the rates shown along the higher path, the same \$100 in 2100 is worth only \$0.20 in 2000. Placing equal weight on these two outcomes, the expected value of \$100 in 2100 would be \$10.24.

Now here is the interesting point.<sup>20</sup> Suppose we did the same analysis for the present value of \$100 in 2101—just one year later. Based on the rate of 1% in 2100, the \$20.28 would be worth only \$20.08 ( $\frac{20.28}{1.01} = 20.08$ ). Similarly, based on the higher rate of 7% in 2100, the \$0.20 would decline to \$0.19 ( $\frac{0.20}{1.07} = 0.19$ ). Averaging these results, the expected value of \$100 delivered in the year 2101 would be \$10.13. The expected value thus declines by 1% ( $\frac{10.24}{10.13} = 1.01$ ). That is, with equal probability placed on 1% and 7%, the effective discount rate 100 years hence is very close to the lower value, not the average of the two values, as one might expect. As it turns out, it is discount factors, not discount rates, that one should average—and this distinction makes a big difference, especially for long time horizons.

Why does one effectively use the low rate rather than the average? Intuitively, discounting benefits 100 years hence depends only on the lower rate because the higher rate discounts future benefits to such an extent that they add very little to the expected value. The expected value of \$10.24 almost equals the value when the rate falls to 1%, \$20.28, multiplied by the probability of that outcome, 50%. In fact, the expected value would be virtually the same if the high-value rate were 10%—or 110%—instead of 7%. In this way, the change in value between periods comes to depend solely on the lower rate.<sup>21</sup>

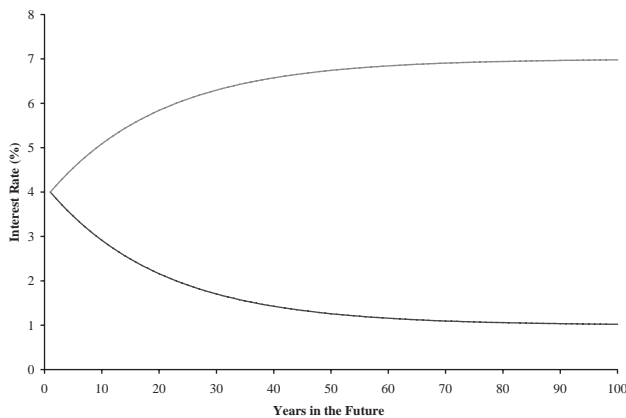


Fig. 3. Future interest rate possibilities.

Most analyses emphasize the enormous difference in discounted values based on discounting at the 2% after-tax return to bonds rather than at the 7% pretax return to equities. If uncertainty about both rates has the same lower bound, namely a zero rate of interest, the uncertainty-adjusted difference in discounted values is more limited, however. As we will show, this difference is still significant, but *much, much* smaller than with simple constant-rate discounting.

#### 3.1. Modeling the long-term behavior of interest rates

The obvious question about the potential impact of discount rate uncertainty is *how much it really matters*. Information about past interest rate fluctuations (Fig. 2) would help us quantify the likely range of interest rate paths in the future. But first we have to make some assumptions about interest rate behavior.

Might interest rates be zero or negative for an extended period of time? Historically, the rates we examine rarely drop below 1%, but some see a downward trend over the past 200 years and even the past millennium and, projecting it, predict that interest rates will eventually decline to zero. But the availability of money, gold, and other durable commodities that retain real value with a zero rate of return suggests that negative investment returns cannot persist because consumers would cease investing in capital, thereby reducing the capital stock and eventually raising the return to investment (see Chapter 7 in Mandler, 1999).

When one considers the interest rate series in Fig. 2, however, it is easy to imagine the rate wandering in such a way that it becomes permanently negative in another 100 years or so. Because we think persistently negative rates are implausible, we construct a model of *logged* (logarithmic) interest rate behavior. Working with forecasts of logged rates, it is impossible for the rates themselves to be negative. As logged rates become

<sup>20</sup>This point, made recently by Weitzman (1998), inspired our work.

<sup>21</sup>Note that although the result that our uncertainty-adjusted discount rate should decline in the future appears similar to the approach of Cline (1999) and others of using lower future discount rates, the basis for the result and the empirical method of applying it are quite different.

lower, the rates themselves simply get infinitesimally closer to zero but remain positive.

We must also decide whether to model the underlying determinants of the interest rate<sup>22</sup>—such as economic productivity and consumer preferences—or simply make predictions based on past values of the interest rate itself. The former, structural approach is appealing because it captures the real workings of the economy, not just the isolated behavior of the interest rate. However, it requires simplifying assumptions about changes in technology and consumer preferences, in addition to having a random, underlying behavior variable to explain interest rate fluctuations.

The alternative is to focus directly on the interest rate itself—to ask how the future interest rate can best be forecast from previous interest rates and how much unpredictable error exists in each period. This approach assumes that past patterns of variation and persistent change in the interest rate will continue. Because it is this variation and persistence that create the uncertainty effect, quantifying these features seems a better strategy than building a more complex and less transparent structural model (Newell and Pizer, 2003).

### 3.2. Random walks versus mean reversion

The final modeling question we confront is whether to model interest rates as following some type of random walk or as reverting to a long-run mean. The term *random walk* is more frequently applied to stock prices because their movement up or down over time is random, and whatever their level at a particular moment, that is usually the best guess about their level in the future (plus some average return). This is analogous to when a drunk meanders down the street: his movement is random and wherever he is now, that is the best guess about where he will be in the future. Two things therefore characterize random walks: random movements and the proposition that the current level is always the best predictor of future level. With *mean reversion*, random movement remains but the future level tends toward some long-run mean.

Unfortunately, statistical analysis of historic data neither confirms nor rejects either model. In fact, if one gives equal confidence to the random walk and mean-reverting models and then uses the data to revise those opinions, one would come out with roughly 60% odds on the random walk model—only a small change in its favor.<sup>23</sup>

<sup>22</sup>In Nordhaus (1994), for example, the interest rate depends on the equilibrium marginal product of capital.

<sup>23</sup>The posterior odds ratio, a measure of the relative likelihood of one model over another based on observed data, is about 1.5 in favor of the random walk model (i.e.,  $\frac{60\%}{40\%} = 1.5$ ). See Schwarz (1978).

Despite the statistical ambiguity, the choice of models makes an enormous difference for forecasting the future effect of uncertainty. Uncertainty about future interest rates has a much smaller effect on future valuation in the mean-reverting model because the mean-reverting model (in contrast to the random walk model) assumes that interest rates cannot remain high or low indefinitely. We emphasize the random walk model results in our application because the random walk model has better prediction interval coverage of actual realized rates in most split samples, something that statistical tests do not reveal (Newell and Pizer, 2003). There is also evidence of a long-term secular trend that is inconsistent with the mean-reverting model. In the end, however, we believe the only convincing way to decide between random walk and mean-reverting models is to introspect and ask whether—having observed unusually low rates for an extended period (say 30–40 years)—one anticipates a return to the longer-run average or a continuation of low rates. We find the latter perspective more compelling.

## 4. Valuing future climate change consequences

Based on statistical estimation of historical interest rate patterns we simulate future interest rate paths.<sup>24</sup> We repeat this process tens of thousands of times, each time drawing a different random path from a fixed initial rate. For each path and each period, we compute a discount factor that makes future benefits (from climate change mitigation) comparable with current costs (of mitigation). From the simulations, we have tens of thousands of equally plausible values for the discount factor at a particular point in the future. Common sense—and indeed economic theory—tells us to *average them*.<sup>25</sup> Doing this delivers an expected discount factor and, multiplied by a valuation in the future, an expected present value.<sup>26</sup>

### 4.1. Expected discount factors

Table 1 presents our estimates of discount factors over the next 400 years based on a 4% rate of return in 2000 and using our historical data on long-term government bonds to quantify discount rate

<sup>24</sup>See Newell and Pizer (2003) for greater technical detail on the estimation results and simulation approach.

<sup>25</sup>The idea that the value associated with an uncertain outcome—in this case the path of interest rates—equals the average or expected value is described by expected utility theory. See Chapter 6 of Mas-Colell et al. (1995).

<sup>26</sup>If the valuation in the future itself is uncertain, the calculation may not be valid if the uncertainty about the discount factor is correlated with the uncertainty about the future valuation.

Table 1  
Value today of \$100 in the future

Years in future	Discount rate model			Value relative to constant discounting	
	Constant 4%	Mean reverting	Random walk	Mean reverting	Random walk
0	\$100.00	\$100.00	\$100.00	1	1
20	45.64	46.17	46.24	1	1
40	20.83	21.90	22.88	1	1
60	9.51	10.61	12.54	1	1
80	4.34	5.23	7.63	1	2
100	1.98	2.61	5.09	1	3
120	0.90	1.33	3.64	1	4
140	0.41	0.68	2.77	2	7
160	0.19	0.36	2.20	2	12
180	0.09	0.19	1.81	2	21
200	0.04	0.10	1.54	3	39
220	0.02	0.06	1.33	3	75
240	0.01	0.03	1.18	4	145
260	0.00	0.02	1.06	5	285
280	0.00	0.01	0.97	7	568
300	0.00	0.01	0.89	11	1147
320	0.00	0.01	0.83	16	2336
340	0.00	0.00	0.78	26	4796
360	0.00	0.00	0.73	43	9915
380	0.00	0.00	0.69	74	20,618
400	0.00	0.00	0.66	131	43,102

uncertainty.<sup>27</sup> We report results for both the random walk and the mean-reverting models. For comparison we present discount factors associated with a *constant* rate of 4%. Discount factors are expressed in terms of the value today of \$100 provided at various points in the future—that is, the discount factor multiplied by 100.

After only 100 years, conventional discounting at a constant 4% undervalues the future by a factor of 3 based on the random walk model of interest rate behavior. After 200 years, the future is undervalued by a factor of about 40. That is, although conventional discounting values \$100 in the year 2200 at 4 cents, the random walk model values the same \$100 at \$1.54—about 40 times higher. Going further into the future, conventional discounting is off by a factor of more than 40,000 after 400 years. The mean-reverting model produces less dramatic yet still significant results, raising the discount factor by a multiple of about 130 after 400 years.

Table 2 presents an alternative comparison using the random walk model with initial discount rates of 2% and 7%—our upper and lower bounds on the consumer rate of interest. We use the same assumptions about random disturbances estimated from data on government bond rates but start the simulations at a different

rate.<sup>28</sup> Again, we compute discount factors based on the corresponding constant rate as a benchmark. When we compare the ratio of random-walk to constant-rate discount factors, these valuations show that the *relative* effect of discount rate uncertainty (measured by this ratio) rises as the initial rate rises. For example, the effect of uncertainty at a horizon of 400 years raises the valuation by a factor of 530 million relative to a constant 7% rate. Meanwhile, the effect over a similar horizon is a factor of a little over 100 based on a 2% rate (from the bottom line of Table 2). Intuitively, the effect must be smaller for low discount rates (e.g., 2%) because the range of possible lower rates (0–2%) is narrower. It is the possibility of these lower rates that raises the valuation.

These effects imply that the ratio between valuations using different initial rates is *smaller* when uncertainty about future rates is incorporated. Note that the ratio of discount factors using a 2% versus a 7% initial rate (based on the random walk model) is a factor of about 40 after 400 years (see bottom line of Table 2:  $\frac{3.83}{0.09} \approx 40$ ). Though a factor of 40 is still substantial, it compares favorably with a factor of 200 million based on constant discount

<sup>27</sup> A rate of 4% reflects the approximate 200-year average as well as the average over the past 20 years. It also falls close to the middle of the range of defensible consumption rates of interest (2–7%).

<sup>28</sup> Note that because the logged interest rate follows a random walk, disturbances to the (unlogged) interest rate are scaled by the magnitude of the interest rate—larger rates lead experience larger disturbances, and vice-versa for smaller initial rates. Casual observation of historic fluctuations supports such an assumption (see figures on pages 369, 394 and 424 of Homer and Sylla, 1998).

Table 2  
Sensitivity of valuation to initial interest rate

Years in future	2% initial rate			7% initial rate		
	Random walk	Constant rate	Ratio	Random walk	Constant rate	Ratio
0	100.00	100.00	1	100.00	100.00	1
20	67.54	67.30	1	26.89	25.84	1
40	46.48	45.29	1	8.67	6.68	1
60	33.05	30.48	1	3.52	1.73	2
80	24.42	20.51	1	1.75	0.45	4
100	18.76	13.80	1	1.02	0.12	9
120	14.93	9.29	2	0.67	0.03	22
140	12.25	6.25	2	0.47	0.01	62
160	10.32	4.21	2	0.36	0.00	181
180	8.89	2.83	3	0.29	0.00	557
200	7.81	1.91	4	0.24	0.00	1778
220	6.97	1.28	5	0.20	0.00	5851
240	6.30	0.86	7	0.17	0.00	19,726
260	5.77	0.58	10	0.16	0.00	67,829
280	5.33	0.39	14	0.14	0.00	236,788
300	4.97	0.26	19	0.13	0.00	837,153
320	4.66	0.18	26	0.12	0.00	2,992,921
340	4.40	0.12	37	0.11	0.00	10,804,932
360	4.18	0.08	52	0.10	0.00	39,298,213
380	3.99	0.05	74	0.10	0.00	143,866,569
400	3.83	0.04	105	0.09	0.00	529,656,724

rates.<sup>29</sup> In other words, the choice of discount rate noted earlier is rendered less important when one considers the effect of uncertainty.

#### 4.2. Valuing future climate change consequences

We can now apply our appropriately adjusted discount factors to the consequences of climate change caused by CO<sub>2</sub> emissions. Starting with the time profile of mitigation benefits in Fig. 1, we can value those benefits using the discount factor series shown in Tables 1 and 2. That is, we take the estimated gain in global output every year in the future due to a 1-ton reduction in CO<sub>2</sub> emissions in the year 2000, multiply by the discount factor for that year, and add them up. The results are shown in Table 3. For each rate—the 4% rate that reflects the historic return to government bonds, as well as our high and low sensitivity calculations—we report the valuation based on both the random walk and the mean-reverting models, as well as for the conventional constant rate model, and indicate the relative effect of uncertainty—the ratio of the valuation under the two uncertainty models to the corresponding valuation with constant rates.<sup>30</sup>

Based on our analysis, uncertainty about future interest rates raises the estimated present value of

reducing carbon emissions from about \$6 per ton to \$10 (1989 dollars)—an increase of more than 80%. This assumes that interest rates follow a random walk. If we instead assume they always revert to their long-run average (about 4%), we find a more modest effect of about 14%.

The relative effect of uncertainty on the present value of expected mitigation benefits is larger when the initial rate and average future rate are higher. This reflects the greater opportunity for uncertainty to lower rates when the initial rate is higher (versus a low initial rate that simply cannot go much lower). The effect of uncertainty is a 56% increase in discounted mitigation benefits with a 2% rate, and a 95% increase with a 7% rate, based on the random walk model. The mean reverting model again yields a more modest 7% increase using the 2% rate, and a 21% increase using the 7% initial rate. These results imply that the ratio of valuations using a 2% versus 7% rate decline from 15 without consideration of future interest rate uncertainty to 12 with such consideration.

Although the dollar value of discounted climate benefits is sensitive to the magnitude of the benefits, the proportional increase due to uncertainty depends only on the general shape of the profile. In addition, because we focus on a 400-year horizon, our results are conservative; extending the horizon further introduces damages that are counted more heavily in the presence of uncertainty.<sup>31</sup> Applying the uncertainty-adjusted

<sup>29</sup> Discounting at a constant rate of 7%, \$100 delivered 400 years in the future would be valued at  $2 \times 10^{-10}$  today, a fact obscured because of rounding in the bottom line of Table 2, column 6. Note that  $0.04 / (2 \times 10^{-10}) = 2 \times 10^8$  or 200 million.

<sup>30</sup> For brevity, we did not report the mean-reverting discount factors based on initial rates of 2% and 7% in Table 2.

<sup>31</sup> We have estimated that this understatement might be as much as 4% based on the rate of decline in discounted carbon benefits at the end of our 400-year horizon.

Table 3  
Expected discounted value of climate mitigation benefits (per ton carbon)

		Benefits from 1 ton of carbon mitigation (1989 dollars)	Relative to constant rate
Government bond rate (4%)	Constant 4% rate	\$5.74	—
	Random walk model	\$10.44	+ 82%
	Mean-reverting model	\$6.52	+ 14%
2% rate	Constant 2% rate	\$21.73	—
	Random walk model	\$33.84	+ 56%
	Mean-reverting model	\$23.32	+ 7%
7% rate	Constant 7% rate	\$1.48	—
	Random walk model	\$2.88	+ 95%
	Mean-reverting model	\$1.79	+ 21%

discount factors to GHGs with longer atmospheric residence (e.g., perfluorocarbons or sulfur hexafluoride) or including catastrophic or permanent events (e.g., species loss) would also generate larger increases in discounted climate damages because the consequences would be more heavily concentrated in the future. In general, the greater the proportion of benefit flows occurring in the distant future, the greater the error introduced through discounting that ignores uncertainty in the discount rate itself.

## 5. Summary and conclusions

The evaluation of environmental policies frequently requires balancing near-term mitigation costs against long-term environmental benefits. To make these costs and benefits comparable, conventional economic theory suggests discounting future consequences based on the market rate of return to investment. In this way, one gains assurance that environmental policies provide welfare improvements that are at least as good as other productive activities.

Several practical issues complicate the application of this straightforward concept. No consensus exists on the appropriate rate to use for discounting. And in the case of policies to mitigate climate change, the time horizons involve centuries—horizons for which there are no comparable market investments that establish future rates of return.

Here, we have considered the effect of uncertain future discount rates on the valuation of future benefits, distinct from any uncertainty about the magnitude of the benefits themselves. Because the effect of changes in the discount rate is not symmetric—unexpectedly low rates raise valuations by a much larger amount than unexpectedly high rates reduce them—this uncertainty raises future valuations relative to analyses that maintain a fixed discount rate forever.

The behavior of long-term government bond rates in the United States leads us to believe that changes in

interest rates are likely to continue. After estimating the uncertainty surrounding interest rates in the past, simulating uncertain rates in the future, and computing the appropriate discount factors for various time horizons and alternative base rates, we have found that the effect of uncertainty is larger for higher discount rates. Intuitively, higher discount rates have more room to decline and therefore raise valuations compared to low discount rates. This implies that the valuation of benefits occurring in the future is less sensitive to the choice of the current discount rate when the effect of uncertainty is taken into account. That is, not only do valuations rise when one considers uncertainty, but they become less sensitive to whether the analysis is based on the after-tax return on bonds or the pretax return on equities.

We find that after 400 years, the cumulative effect of discount rate uncertainty is to raise valuations by a factor of between 130 and 40,000, where we find the random walk model supporting the higher factor more compelling. Applied to one estimate of the consequences of climate change, the effect of uncertainty is large: using a rate of 4%, the expected present value of damages from current CO<sub>2</sub> emissions increases by more than 80% when we incorporate the effect of future interest rate uncertainty (under the random walk model). An initial rate of 7% yields a 95% increase, and an initial rate of 2% yields an increase of about 55%. Viewed another way, uncertainty reduces the ratio of present value estimates associated with 2% versus 7% from 15 to 12.

Using conventional discounting techniques to value benefits over hundreds of years renders future benefits insignificant, and to many people, that somehow seems “wrong.” Our results show that constant discount rates do in fact undervalue the benefits of GHG abatement measures. Moreover, they suggest that this concern is at least partially addressed—without abandoning conventional economic theory—by viewing future interest rates as uncertain. Although this will not yield the same dramatic effects as the decision to arbitrarily apply a

lower discount rate, uncertainty does have a large effect on consequences valued at horizons of 70 years or more in the future.

### Acknowledgements

We thank Michael Batz for research assistance. The research was supported in part by the Pew Center on Global Climate Change, although such support does not imply agreement with the views expressed in the paper. Additional technical detail on the approach and results described in this paper are given in Newell and Pizer (2001, 2003).

### References

- Ainslie, G., 1991. Derivation of 'rational' economic behavior from hyperbolic discount curves. *American Economic Review* 81, 334–340.
- Arrow, K.J., 1999. Discounting, morality, and gaming. In: Portney, P.R., Weyant, J.P. (Eds.), *Discounting and Intergenerational Equity*. Resources for the Future, Washington, DC.
- Arrow, K.J., Cline, W.R., Maler, K.G., Munasinghe, M., Squitieri, R., Stiglitz, J.E., 1996. Intertemporal equity, discounting and economic efficiency. In: Bruce, J.P., Lee, H., Haites, E.F. (Eds.), *Climate Change 1995—Economic and Social Dimensions of Climate Change*. Cambridge University Press, Cambridge, UK.
- Bazelon, C., Smetters, K., 1999. Discounting inside the beltway. *Journal of Economic Perspectives* 13 (4), 213–228.
- Broecker, W.S., 1997. Thermohaline circulation, the Achilles heel of our climate system: will man-made CO<sub>2</sub> upset the current balance? *Science* 278, 1582–1588.
- Cline, W.R., 1999. Discounting for the very long term. In: Portney, P.R., Weyant, J.P. (Eds.), *Discounting and Intergenerational Equity*. Resources for the Future, Washington, DC.
- Cropper, M.L., Laibson, D., 1999. The implications of hyperbolic discounting for project evaluation. In: Portney, P.R., Weyant, J.P. (Eds.), *Discounting and Intergenerational Equity*. Resources for the Future, Washington, DC.
- Cropper, M.L., Aydede, S.K., Portney, P.R., 1994. Preferences for life saving programs: how the public discounts time and age. *Journal of Risk and Uncertainty* 8, 243–265.
- Heal, G.M., 1998. Valuing the future: economic theory and sustainability. In: Chichilnisky, G., Heal, G. (Eds.), *Economics for a Sustainable Earth*. Columbia University Press, New York.
- Homer, S., Sylla, R., 1998. *A History of Interest Rates*, 3rd Edition. Rutgers University Press, New Brunswick, NJ.
- Ibbotson Associates, 1999. *Stocks, Bonds, Bills and Inflation*. Year-end Summary Report. Ibbotson Associates, Chicago, IL.
- Lind, R.C. (Ed.), 1982. *Discounting for Time and Risk in Energy Policy*. Johns Hopkins University Press for Resources for the Future, Baltimore.
- Mandler, M., 1999. *Dilemmas in Economic Theory: Persisting Foundational Problems of Microeconomics*. Oxford University Press, New York, NY.
- Mas-Colell, A., Whinston, M.D., Green, J.R., 1995. *Microeconomic Theory*. Oxford University Press, New York, NY.
- Newell, R.G., Pizer, W.A., 2001. *Discounting the Benefits of Climate Change Mitigation: How Much do Uncertain Rates Increase Valuations?* Economics Technical Series, Pew Center on Global Climate Change, Washington, DC.
- Newell, R.G., Pizer, W.A., 2003. Discounting the distant future: how much do uncertain rates increase valuations? *Journal of Environmental Economics and Management* 46 (1), 52–71.
- Nordhaus, W.D., 1994. *Managing the Global Commons*. MIT Press, Cambridge.
- Nordhaus, W.D., Boyer, J., 2000. *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.
- Portney, P.R., Weyant, J.P. (Eds.), 1999. *Discounting and Intergenerational Equity*. Resources for the Future, Washington.
- Ramsey, F.P., 1928. A mathematical theory of saving. *The Economic Journal* 38 (152), 543–559.
- Repetto, R., Austin, D., 1997. *The Costs of Climate Protection: A Guide for the Perplexed*. World Resources Institute, Washington, DC.
- Schwarz, G., 1978. Estimating the dimension of a model. *Annals of Statistics* 6 (2), 461–464.
- Thomas, L.B., 1999. Survey measures of expected US inflation. *Journal of Economic Perspectives* 13 (4), 125–144.
- US Bureau of the Census, 1975. *Historical Statistics of the United States*. US Department of Commerce, Washington, DC.
- US Environmental Protection Agency (US EPA), 2000. *Guidelines for Preparing Economic Analyses*. US GPO, Washington, DC.
- Weitzman, M.L., 1998. Why the far-distant future should be discounted at its lowest possible rate. *Journal of Environmental Economics and Management* 36 (3), 201–208.
- Weitzman, M.L., 2001. Gamma discounting. *American Economic Review* 91 (1), 260–271.