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Discounting and Climate Policy

Abstract

The social rate of discount is a crucial driver of the social cost of carbon (*SCC*), i.e. the expected present discounted value of marginal damages resulting from emitting one ton of carbon today. Policy makers should set carbon prices to the *SCC* using a carbon tax or a competitive permits market. The social discount rate is lower and the *SCC* higher if policy makers are more patient and if future generations are less affluent and policy makers care about intergenerational inequality. Uncertainty about the future rate of growth of the economy and emissions and the risk of macroeconomic disasters (tail risks) also depress the social discount rate and boost the *SCC* provided intergenerational inequality aversion is high. Various reasons (e.g. autocorrelation in the economic growth rate or the idea that a decreasing certainty-equivalent discount rate results from a discount rate with a distribution that is constant over time) are discussed for why the social discount rate is likely to decline over time. A declining social discount rate also emerges if account is taken from the relative price effects resulting from different growth rates for ecosystem services and of labour in efficiency units. The market-based asset pricing approach to carbon pricing is contrasted with a more ethical approach to policy making. Some suggestions for further research are offered.

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Keywords: cost-benefit analysis, climate policy, carbon pricing, social discount rate, term structure, Keynes-Ramsey rule, risk and uncertainty, disasters, expert opinions.

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1. Introduction

Climate policy is about making sacrifices now to curb global warming in the distant future. To assess climate policy, it is thus important to assess what the future benefits in terms of less global warming damages are worth today so that they can be compared with the sacrifices that must made today to curb emissions. Instead of looking at what the benefit of curbing emissions today, one could look at the cost of emitting one ton of carbon today. Both require one to know what social discount rates to use to assess what future benefits are worth today. For this purpose, it helps to define the social cost of carbon or *SCC* for short. The *SCC* is defined as the expected present discounted value of all current and present damages to aggregate consumption of emitting one ton of carbon today. It corresponds to a Pigouvian tax.[2] It is of immense practical interest to know what the appropriate social discount rate or *SDR* to use for evaluating climate policy should be both from a theoretical and an empirical point of view. This discount rate depends on ethical and economic considerations and has been subject to huge debate with on one end of the spectrum the *descriptive* market-based approach of Nordhaus (2017) with a relatively high discount rate and a low carbon price, and on the other hand of the spectrum the *prescriptive* ethical approach of the economist Stern (2008) and the philosopher Broome (2012) with a low discount rate and a high carbon price (e.g. Beckerman and Hepburn, 2007; Dietz et al., 2009; Rendall, 2019). It also depends on the uncertainties that affect future economic growth and emissions growth. In particular, the discount rate depends on the volatility and skewness of these growth rates. Most important of all, a strong case can be made for the social discount rate to decline with the length of the horizon of climate policy.

[2] This assumes that there are no other market failures than global warming or, if there are, that all the other market failures are taken care off. For example, there may be learning by doing in the production of renewable energy in which case a renewable energy subsidy is called for. This subsidy must be set to the social benefit of learning, which is defined as the present discounted value of all future marginal reductions in renewable energy cost resulting from installing one extra solar panel today (e.g. Rezai and van der Ploeg, 2017).

The outline of this survey is as follows. Section 2 discusses the celebrated Keynes-Ramsey rule for the *SDR* and a simple relationship between temperature and cumulative carbon emissions. These are then used to derive the *SCC* and interpret its various ethical and economic drivers. Section 3 gives numerical estimates of the *SDR* and the *SCC*. Section 4 derives a related expression for the *SCC* from underlying models of the dynamics of atmospheric carbon and of temperature. Section 5 extends the basic model of the *SDR* and the *SCC* to allow for stochastic shocks to the rate of economic growth and emissions. This allows one to identify the effects of prudence and self-insurance as well as of impatience, affluence, and growing damages on the *SCC*. Section 6 discusses the large upward effects of tail risk in the climate sensitivity and damages, risks of tipping of the climate system and long-run risk about future economic growth on the *SCC*. Section 7 discusses the effects of correlation between damage risks, climatic risks, and economic risks on the *SDR* and the *SCC*. Sections 8 and 9 discuss the effects of macroeconomic disasters on the *SDR* and *SCC* and highlights the connections and differences between the theory of the SCC under uncertainty and asset pricing theory. Section 10 discusses arguments for a declining expected value of the *SDR* and its effect on the *SCC* if the *SDR* is itself uncertain. Section 11 examines the survey and empirical evidence on the appropriate, certainty-equivalent *SDR* to use and by how much it declines. Section 12 reviews evidence from experts on impatience and intra- and intergenerational inequality aversion. Section 13 highlights dual discounting and the endowment approach, and their impact on the *SCC*. Section 14 concludes with a summary of the key insights. Section 15 offers some nuancing comments related to the differences between the social and the private discount rates and intergenerational aspects of climate policy and suggestions for further research.

2. Discounting and the Social Cost of Carbon: Deterministic Case

What is the cost today of one dollar of damages at some future time t? Let this cost be X. To be indifferent in terms of utility units today and in the future, then $U'(C_0)X = U'(C_t)e^{-RTI\times t}$

must hold. Here *RTI* is the constant rate of time impatience (or utility rate of discount), *U*(.) the utility function and C_t consumption at time *t*. Let the utility function be $U(C_t) = \ln C_t$ if $\gamma = 1$ and $U(C_t) = (C_t^{1-\gamma} - 1)/(1-\gamma)$ if $\gamma \neq 1$, where $\gamma > 0$ is the coefficient of intergenerational inequality aversion *IIA* (or inverse of the elasticity of intertemporal substitution) which for this type of utility function also is the coefficient of relative risk aversion.[3] Hence, $0 < X = e^{-SDR \times t} < 1$, where the social discount rate *SDR* is

$$(1) \qquad SDR = RTI + IIA \times GR,$$

where $GR = \ln\left(C(t)/C(0)\right)/t$ denotes the future rate of growth of consumption. This equation is the Keynes-Ramsey rule and can be interpreted as follows. First, the more impatient policy makers are (the higher *RTI*) the higher the social discount rate. Second, the richer future generations (the higher the future rate of economic growth *GR*) and the bigger the aversion to intergenerational inequality (the higher *IIA*) the higher the social discount rate and thus current generations are less willing to make sacrifices today to avoid future global warming damages.

This expression for the *SDR* can be used to evaluate the *SCC*. To do this, two additional assumptions are required. First, the ratio of damages to aggregate production *Y* is a simple linear function of temperature and denote the marginal effect of temperature on the damage ratio by *MDR*. Second, temperature is a linear function of cumulative emissions as suggested by insights from climate science (e.g. Matthews et al., 2009; Allen et al., 2009) and has been applied to derive climate policy (e.g. van der Ploeg, 2018; Dietz and Venmans, 2019a; Dietz et al., 2020). The marginal effect of cumulative emissions on temperature is called the transient climate response to cumulative emissions or the *TCRE*. It is about 1.8 or 2 degrees Celsius per trillion tons of atmospheric carbon. Combining these two assumptions, the marginal effect of

[3] This parameter is also referred to as elasticity of (diminishing) marginal utility. If society is richer in the future, then it values an additional unit in the future less than a unit today. Strictly speaking, the metaphor of different generations across time is not correct.

one unit more cumulative emissions on the damage ratio equals *MDR* x *TCRE*. As damages from global warming are proportional to future aggregate production, the present discounted value of all future damages resulting from emitting one ton of carbon today equals

$$(2) \qquad SCC = \frac{MDR \times TCRE \times Y}{SDR - GR}$$

or equivalently

$$(2') \qquad SCC = \frac{MDR \times TCRE \times Y}{RTI + (IIA - 1) \times GR},$$

where *Y* denotes world GDP. The *SCC* is thus proportional to the marginal effect of temperature on the damage ratio (the *MDR*), the transient climate response to cumulative emissions (the *TCRE*), and the level of economic activity (*Y*). The *SCC* is inversely proportional to the growth-corrected social discount rate (*SDR* – *GR*). The correction for growth internalises that damages grow with the size of the economy. This boosts the *SCC*. Equation (2′) indicates that the *SCC* is determined by ethical considerations (the rate of time impatience and intergenerational inequality aversion), geo-physical considerations (the transient climate response to cumulative emissions) and economic considerations (the level of economic activity and its trend rate of growth) as well as by the marginal effect of temperature on the damage ratio. For logarithmic utility *IIA* = 1, so that the social cost of carbon becomes *SCC* = *MDR* x *TCRE* x *Y* / *RTI*. For this case, the upward effect of more affluent future generations on the *SDR* is exactly offset by the downward effect of higher growth in damages on the growth-corrected *SCC*. As a result, the *SCC* is also unaffected by *IIA* and the rate of growth of the economy.

Variants of these formulae for the *SCC* have been used to advise climate policy. In the absence of any other distortions or market imperfections the first-best optimal response for policy makers is to ensure that carbon emissions are priced at a price equal to the *SCC*. One way of doing this is to have a carbon tax and rebate the revenues in lump-sum manner. Another way is to have a competitive global market for emission permits.

3. Estimates of the Social Cost of Carbon

To assess the order of magnitude of the *SCC* and how sensitive it is to various assumptions, it is helpful to give some illustrative calculations. World GDP in 2017 is about 80 trillion US dollar. A plausible estimate of the climate sensitivity response is 1.8 degrees Celsius per trillion ton of carbon in the atmosphere. Nordhaus (2017) calibrates the damage ratio as 0.236% loss in global income per degree Celsius squared, so the damage ratio is 2.1% and 8.5% of word GDP at, respectively, 3 and 6 degrees Celsius. The marginal damage ratio thus equals 0.472% loss of global income per degree Celsius. At 2 degrees Celsius this gives a *MDR* of 0.944% of global income.[4] Ramsey (1928) argued that discounting the welfare of future generations is ethically indefensible and arises from "the weakness of imagination". Broome (2012) takes a normative stance and arrives at a similar position. It is thus reasonable to set the rate of time impatience to zero, *RTI* = 0. This is close to the 0.1% per year used by the Stern Review to reflect the remote possibility of a meteorite ending the world as we know it (Stern, 2007). The trend rate of growth of the economy is taken to be 2% per year, *GR* = 0.02. Finally, following Gollier (2011, 2012) a coefficient of relative intergenerational inequality aversion of 2 is taken, so that *IIA* = 2. Armed with these assumptions, it follows that *SDR* = 0 + 2 x 0.02 = 4% per year. The growth-corrected discounted rate is thus 2% per year. Equation (2) becomes

(2″) $SCC = (0.00944/^{\circ}\text{C}) \times (1.8\ ^{\circ}\text{C}/\text{TtC}) \times (80\ \text{T\$}) / 0.02 = 68\ \text{\$/tC}$.

Since one ton of carbon is 12/44 tons of CO_2, the *SCC* starts at 18.5 $/t$CO_2$ and grows from then on at a yearly rate of 2%. Each year the *SCC* must also be adjusted for inflation.

[4] Burke et al. (2015) show that overall economic productivity is non-linear in temperature for all countries with productivity peaking at an annual average temperature of 13 ˚C and declining strongly at higher temperatures. They find that expected global losses are approximately linear in global mean temperature, with median losses 2.5-100 times larger than prior estimates for 2 ˚C. It is thus assumed that the damage ratio is linear in temperature.

It is of interest to examine the sensitivity of the *SCC* with respect to various assumptions. Nordhaus (2017) uses a more market-oriented rate of discount and sets *RTI* = 1.5% per year. This implies a higher *SDR* of 5.5% per year, and a lower *SCC* of 39 \$/tC or 10.6 \$/tCO_2. More impatient policy makers thus price carbon less vigorously. Impatience refers to giving less weight to the future benefits of curbing global warming and more weight to current consumption, hence impatient policy makers are less willing to take climate policy action.[5] Less intergenerational inequality aversion, e.g. *IIA* = 1.5, lowers the *SDR* to 3% per year and implies a higher *SCC* of 37 \$/tCO_2. The reason is that current generations are more willing to sacrifice consumption for curbing future temperature and thus pursue a more vigorous climate policy. More pessimistic forecasts of future economic growth, say *GR* equals 1.5% per year, implies a lower *SDR* of 3% per year and thus also a higher *SCC*, i.e. 24.7 \$/tCO_2. Poorer future generations thus make current generations more willing to make sacrifices to fight global warming. The sensitivity of the *SCC* with respect to the transient climate response and the marginal effect of temperature on the damage ratio are straightforward as the *SCC* is proportional to these two parameters.

4. The *SCC* from Models of Temperature and Dynamics of Atmospheric Carbon[6]

Most of the literature uses more complicated models of the dynamics of the stock of carbon in the atmosphere and of temperature to calculate the *SCC*. For example, the linear model of the carbon cycle of Joos et al. (2013) allocates emissions into 4 boxes for atmospheric carbon. The first box contains the 22% of emissions that stays up forever in the atmosphere. The emissions flowing into the other three boxes eventually leave the atmosphere: 22% with mean duration of 399.4 years, 28% with mean duration of 36.5 years and 28% with mean duration of 4.3 years. Climate scientists often use a logarithmic (concave) relationship between temperature and

[5]This should be distinguished from the notion of impatience held my many non-economists, which seems to be that impatience has to do with lots of climate mitigation to head it off as soon as possible.
[6] This section makes the connection with integrated assessment models and can be skipped if necessary.

atmospheric carbon, so the effect of doubling the carbon in the atmosphere on temperature is a constant called the equilibrium climate sensitivity (about 3 degrees Celsius). Combining this with a damage ratio that is quadratic (convex) in temperature, it turns out that concavity of the temperature function and convexity of the damage ratio function roughly cancel out. Hence, the damage ratio can be well described by an exponential function of the atmospheric carbon stock so the marginal effect of an extra trillion ton of atmospheric carbon on damages is about 2.4% of aggregate output (including a factor for tipping risks) (Golosov et al., 2014). It follows that the *SCC* for the Joos et al. (2013) model with world GDP of 80 trillion US dollars is

$$(3)\quad SCC = 0.024 \times 80 \times \left[\frac{0.22}{z} + \frac{0.22}{z + 1/399.4} + \frac{0.28}{z + 1/36.5} + \frac{0.28}{z + 1/4.3} \right] \text{ with } z \equiv SDR - GR.$$

This yields for the base case with *SDR* – *GR* = 2% per year a *SCC* of 53.4 \$/tC or 14.6 \$/tCO_2. This is a bit less than the 68 \$/tC or 18.5 \$/tCO_2 in our base scenario (see equation (2″) above). The bigger the proportions of carbon that stay a short time in the atmosphere, the lower the *SCC*. Analogous expressions can be obtained to evaluate the *SCC* for the linear 2-box model of atmospheric dynamics of Golosov et al. (2014) and the linear 3-box model of Gerlagh and Liski (2018).[7] Most of the models of the carbon cycle and temperature dynamics in the integrated assessment models used by economists have too much temperature inertia and give misleading insights into the magnitude of the *SCC* (Dietz et al., 2020). A more reliable approach is to model temperature as linear function of cumulative emissions as will be done from now on.

5. Discounting and the Social Cost of Carbon: Stochastic Case

Returning to the base model that we started with and where cumulative emissions are the driver of temperature, now consider how the *SDR* and the *SCC* are affected if future economic growth

[7] Equation (3) does not allow for lags between changes in the stock of atmospheric carbon and temperature. Gerlagh and Liski (2018) give a formula for the optimal SCC is modified that allows for thermal inertia.

and emissions are stochastic. The *SCC* at time *t* is the expected present discounted value of all current and future damages from time *t* onwards of emitting one of carbon at time *t*. Hence,

$$(4) \qquad SCC_t = E_t\left[\int_t^\infty U'(C_s)\times MDR\times C_s\times TCRE\times e^{-RTI\times(s-t)}ds\right]\frac{1}{U'(C_t)}.$$

This formula converts *future* damages from dollars into utility units by multiplying by the future marginal utilities and then converts the integral back from *current* utility units into dollars by dividing by the marginal utility of consumption at time *t*. To get explicit results, two assumptions are made. First, the power utility function is used with γ denoting both the coefficient of relative risk aversion and the inverse of the elasticity of intertemporal substitution. Upon substitution into equation (4), the *SCC* becomes

$$(4') \qquad SCC_t = MDR\times TCRE\times E_t\left[\int_t^\infty \left(\frac{C_s}{C_t}\right)^{-\gamma}\times C_s\times e^{-RTI\times(s-t)}ds\right].$$

Second, consumption follows a geometric Brownian motion, $dC_t = \mu C_t\times dt + \sigma C_t dW_t,$ where μ denotes the drift of this stochastic process, $\sigma > 0$ is the volatility and W_t is a unit Wiener process. This has solution $C_s = C_t\exp\left(\left(\mu - \frac{1}{2}\sigma^2\right)(s-t) + \sigma W_s\right),$ so $E\left[C_s\right] = \mu(s-t)C_t$ and growth in expected consumption is $E\left[\ln\left(C_s / C_t\right)\right] = GR\times(s-t)$ with $GR \equiv \mu - \frac{1}{2}\sigma^2.$ Using these results in (4′), the social cost of carbon for a power utility function becomes

$$(5) \qquad SCC_t = \frac{MDR\times TCRE\times C_t}{SDR - GR} \quad \text{with} \quad SDR = RTI + IIA\times GR - \frac{1}{2}(IIA-1)\times IIA\times\sigma^2.$$

Power utility functions do not separate intergenerational inequality aversion or *IIA* (the inverse of the elasticity of intertemporal substitution) from risk aversion or *RA*. If recursive preferences are used as put forward by Epstein and Zin (1989) in discrete time and Duffie and Epstein (1992) in continuous time, van den Bremer and van der Ploeg (2019) show that (5) becomes

(6) $$SCC_t = \frac{MDR \times TCRE \times C_t}{SDR - GR} \quad \text{with} \quad SDR = RTI + IIA \times GR - \frac{1}{2}(IIA - 1) \times RA \times \sigma^2.$$

Note that the social discount rate in (6) can be rewritten as

(7) $$SDR = RTI + IIA \times GR - \frac{1}{2}(1 + IIA) \times RA \times \sigma^2 + RA \times \sigma^2.$$

The first term *RTI* is the *impatience* effect: more impatient policy makers use a higher *SDR* and lower *SCC,* so price carbon less vigorously. The second term $IIA \times GR$ is the *affluence* effect: richer future generations and more intergenerational inequality aversion push up the *SDR* and lower the *SCC*. The third term $-\frac{1}{2}(1 + IIA) \times RA \times \sigma^2$ is the *prudence* effect: the more risk-averse policy makers and the bigger their intergenerational inequality aversion and the higher the volatility of economic growth and emissions, the lower the *SDR* and the higher the *SCC*. This term arises if utility has a positive third derivative in which case there is precautionary saving in response to income uncertainty in the consumption-saving problem for the household (cf. Leland, 1968; Kimball, 1990). Also, climate policy makers behave in a prudent fashion by pursuing a more vigorous climate policy if future economic growth is uncertain. The coefficient of relative prudence is 1 + *IIA* for this class of preferences, so the prudence effect is stronger if relative prudence is stronger. The first three terms in (7) can in case *IIA* = *RA* be rewritten as $RTI + IIA \times \mu - \frac{1}{2} IIA^2 \times \sigma^2$ (cf. Gollier, 2011, equation (10); Arrow et al., 2014, equation (2)). The fourth term in (7), $RA \times \sigma^2$, is the *self-insurance* effect: in future states of nature where economic growth is high, damages are high too as damages are proportional to world GDP. Therefore, abatement is a procyclical investment with higher yields in good times. Hence, policy makers can take less climate action, which is reflected in a higher *SDR* and a lower *SCC*. This term is also known as the *risk premium*. In fact, if the elasticity of damages with respect to GDP is β, the risk premium generalises to $\beta \times RA \times \sigma^2$. This premium is thus zero if damages are uncorrelated with the future state of the economy, but positive if they are positively (negatively) correlated with the future state of the economy.

Finally, there is the growth-correction to the *SDR* in the denominator of (6), the term –*GR*, which reflects the *growing damages* effect and calls for a lower *SDR* and a higher *SCC*.

The *SDR* derived from the Keynes-Ramsey rule must be adjusted downwards to allow for the precautionary effect, but this adjustment is small (e.g. Gollier, 2002; Arrow et al., 2014). To see this, set the annual volatility to 3.6% (Kocherlakota, 1996), *IIA* = 2, *RTI* = 0 and *GR* = 2% per year as before. However, we take the coefficient of relative risk aversion to be *RA* = 5 > *IA* = 2 and allow for the self-insurance effect in (7). The prudence effect in (7) is then 0.74% per year (a bit higher than in Arrow et al. (2014) due to the higher *RA*) and the self-insurance effect in (7) is 0.49% per year. These two effects thus depress the *SDR* from 4 to 3.75% year, which boosts the *SCC* from 18.5 to 21.1 $/t$CO_2$. For higher (lower) values of *IIA*, the downward adjustment of the *SDR* and upward adjustment of the *SCC* is bigger (smaller).

6. Effects of Tail Risks, Tipping Risks and Long-Run Risks on the *SCC*

Although uncertainty about future economic activity has a modest effect on the *SDR* and the *SCC*, skewed uncertainty about the climate sensitivity has a substantial upward effect on the *SCC* especially if the damage ratio is a convex function of temperature. More specifically, if shocks to the climate sensitivity are more persistent, more volatile, and more skewed, this pushes up the *SCC* by more (van den Bremer and van der Ploeg, 2019). Uncertainty about shocks to the ratio of damages pushes up the *SCC* but only if the distribution of these shocks is skewed.[8] The effects of these two types of uncertainty on the optimal carbon price can be substantially higher than that of growth uncertainty.

[8] The effect of damage ratio shocks on the *SCC* is different from that of climate sensitivity shocks since the latter affect the damage ratio indirectly via temperature. If the damage ratio is a convex function of temperature (e.g. a quadratic), this would make the climate sensitivity squared a skew distribution (even if the climate sensitivity itself does not have a skew distribution) and thus pushes up the *SCC*.

It has also been shown that the risk of climatic tipping (e.g. melting of Ice Sheet or reversal of Gulf Stream) leads to substantial increases in the *SCC* because global warming increases the risk of tipping (e.g. Lemoine and Traeger, 2014, Lontzek et al., 2015; van der Ploeg and de Zeeuw, 2018; Cai and Lontzek, 2019). Furthermore, if one tip raises the likelihood of another tipping point, this domino-effect boosts the *SCC* even more and thus even more vigorous climate action must be undertaken (Cai et al., 2016; Lemoine and Traeger, 2016). Pindyck (2011) gives an excellent survey of the effects of fat-tailed and thin-tailed uncertainty on climate policy and warns that cost-benefit analysis of climate policy is difficult as we do not even know the probability distribution of future temperature impacts. Fat-tailed distributions when combined with power utility functions give rise to the "dismal" theorem, which states that the *SCC* is unbounded and thus that society is prepared to sacrifice all of GDP to curb emissions (Weitzman, 2009, 2011). For utility functions with bounded marginal utility, however, this so-called "dismal" theorem no longer holds. Still, skewed distributions for the climate sensitivity and damage ratio and tipping points call for more stringent climate policies.

7. Correlated Shocks to the Climate, the Damage Ratio, and the Economy

Shocks to the economy, to damages from global warming, and to the climate have often taken to be independent, but these different types of shocks may be correlated. To illustrate this, consider the case *RA* = *IIA* = 1 discussed by Golosov et al. (2014). This implies that *SDR* = *RTI* and thus uncertainty about future aggregate consumption growth and about damages do not affect the *SCC* at all. However, if for this special case, we have a non-unitary instead of unitary elasticity of marginal damages with respect to consumption, say β, so that damages are $MDR \times Temperature_t \times Y_t^{\beta}$, the risk-free social discount rate is $RTI + GR - \sigma^2$ and the risk-adjusted social discount rate becomes (see Dietz et al., 2018, Proposition 1 for an extension)

(8) $$SDR = RTI + (1-\beta) \times GR - \frac{1}{2}(2-\beta)(1-\beta)\sigma^2.$$

For $\beta = 1$, this boils down to $SDR = RTI$ with no effects of uncertainty (i.e. σ) at all. In general, there are two additional effects of a "beta" smaller than one on the *SDR*: (i) as marginal damages grow at a less rapid rate than world GDP, the present discounted value of marginal damages is smaller and this increases the *SDR* (see second term in (8)) and thus lowers the *SCC*; (ii) in future states of nature shocks to future damages are now less than perfect correlated with future world GDP, so self-insurance is less and the risk premium and the *SDR* is pushed down (see third term in (8)) and the *SCC* must increase.[9] The relative magnitudes of these opposing effects can be seen from $\partial SDR / \partial \beta = -GR + (3-2\beta)\sigma^2 / 2.$ With a growth rate of around 2% per annum and an annual volatility of about 3.6% (Kocherlakota, 1996), this expression is negative for all values of β between -1 and 1 so effect (i) dominates effect (ii).

Dietz et al. (2018) argue on basis of theory and integrated assessment modelling with uncertainty about both the growth rate of emissions and about the damage ratio and the climate sensitivity that this climate "beta" is close to unity for maturities up to one hundred years. Effectively, the positive effect on this beta of uncertainty about exogenous, emissions-neutral technical change swamps the negative effect on this beta of uncertainty about the climate sensitivity and the damage ratio. They conclude that mitigating climate change increases aggregate consumption risk, which justifies a higher discount rate on the expected benefits of emission reductions. However, the stream of undiscounted expected benefits also increases in this beta and this dominates the effect on the discount rate, so that on balance the present value of emissions abatement (the *SCC*) increases in this beta (as also indicated by our effect (ii)).

8. Macroeconomic Disasters and the *SCC*: Insights from Asset Pricing Theory

The *SCC* can be viewed as an asset with a *negative* price, since it is the expected present discounted value of all future marginal damages caused by emitting one ton of carbon today.

[9] Effectively, policy makers need to take most climate action when in future states of nature damages are high precisely when economic growth is high. When this correlation is less, more climate action needs to be taken.

In the asset pricing theory put forward by Lucas (1978), the idea is that trees grow fruits each year and that the growth rate in the harvest of fruits is stochastic. The objective is to put a price on these trees. This tree metaphor is used to analyse the idea of an asset, which is like a tree in that it generates a stream of unknown future dividends. The price-dividend ratio, say *V*, is the expected present discounted value of a tree where the dividend is the unleveraged claim on consumption. Asset pricing theory extends the stochastic process for growth of consumption and output for the incidence of rare macroeconomic disasters (wars, great recessions, virus outbreaks, etc.) as well as geometric Brownian motion (Barro, 2016). If disaster shocks occur with instantaneously probability π and destroy $\ln(1–b)Y_t$ of the endowment, the expected endowment growth is $GR = \mu + \frac{1}{2}\sigma^2 - \pi E\left[b\right] < \mu + \frac{1}{2}\sigma^2$ and the dividend-price ratio is

$$(9)\quad \frac{1}{V} = RTI + (1/EIS - 1)\left(GR - \frac{1}{2}RA \times \sigma^2\right) - \pi\frac{1/EIS - 1}{RA - 1}\left(E\left[(1-b)^{1-RA}\right] - 1 - (RA-1)E\left[b\right]\right)$$

where *EIS* (cf. 1/*IIA*) denotes the elasticity of intertemporal substitution which can differ from 1/*RA* for Epstein-Zin preferences (e.g. Barro, 2009). If one accepts that preferences from policy makers correspond to those in financial markets, one could replace 1/*EIS* in (9) by the coefficient of intergenerational inequality aversion *IIA* so instead of (6) the *SCC* becomes

$$(10)\qquad SCC_t = \frac{MDR \times TCRE \times C_t}{1/V} \quad \text{with} \quad \frac{1}{V} = r^e - GR,$$

where $r^e = 1/V + GR$ corresponds to the expected return on unleveraged equity and 1/*V* is akin to *SDR* – *GR* in equation (6). If r^f denotes the risk-free return, the equity premium is

$$(11)\qquad r^e - r^f = RA \times \sigma^2 + \pi\left(E\left[(1-b)^{-RA}\right] - E\left[(1-b)^{1-RA}\right] - E\left[b\right]\right).$$

The asset markets calibration of Barro (2009) aims to explain both the equity-premium puzzle which from (11) requires a high value of the *RA* and the idea that uncertainty depresses the price-dividend ratio which from (9) requires that the EIS exceeds one. Using π = 1.7%/year, E[b] = 0.29%, σ = 2%/√year, μ = 2.5%/year, RA = 4, EIS = 2, RTI = 5.2%/year, $E\left[(1-b)^{-4}\right]=7.69$ and $E\left[(1-b)^{-3}\right]=4.05,$ Barro (2009) finds GR = 2%/year, V = 20.7, r^f = 1%/year, r^e = 6.9%/year and a risk premium of 5.9% per year. An increase in σ by 10% needs an increase of 0.38% in endowment for all years to be compensated for the increase in uncertainty. For a 10% increase in disaster risk, this figure rises to 2.6% each year.

What does this market-based calibration imply for the optimal risk-adjusted SCC? Using 1/V = 4.83% per year, C_t = 80 \$T, MDR = 2.4% and $TCRE$ = 1.8 °C/TtC, the SCC from equations (9)-(10) becomes 72 \$/tC or 19.5 \$/tCO_2. The corresponding carbon price with $\mu = \sigma$ = 0.02, π = 0.017 and E[b] = 0.29, and the ethical preferences RTI = 0 and RRA = IIA = 1/EIS = 2 from Gollier (2011) gives a "dividend-price" ratio (i.e. $SDR - GR$) of 1/V = 0.72% per year and thus a carbon price of 131 \$/tCO_2. With no disaster risk and with no economic growth uncertainty whatsoever, the carbon price is only 48 \$/tCO_2 and 47 \$/tCO_2, respectively.

Bansal and Yaron (2004) explain the equity premium by shocks to the long-run economic growth rate with time-varying variance instead of disaster risk, but this requires a very high RA of 10. Cai and Lontzek (2020) analyse a complex and frontier numerical integrated assessment model with a market-based calibration with EIS = 1.5 > 1, RA = 10, long-run risks as in Bansal and Yaron (2004) and a wide variety of tipping points. Their Figure 2, Panel B and Figure 3, Panel D confirm that more growth uncertainty indeed depresses the SCC, whereas their Figure 6 indicates that climate tipping substantially raises the SCC. Bansal et al. (2017, 2019) use forward-looking information in capital markets to demonstrate empirically that equity valuations are significantly negatively affected by long-run impacts of temperature on the economy and that long-run temperature fluctuations carry a positive risk premium in equity markets that rises with temperature. The resulting SCC implied by market expectations and temperature-induced tail risks is large. Bansal et al. (2017, 2019) conclude that temperature is a source of long-run economic risks and shows that it is important to allow for forward-looking capital markets for understanding the cost and impact of climate change.

9. What can one learn from the asset pricing interpretation of climate policy?

First, whereas the dividend-price ratio increases and thus the *SCC* decreases in uncertainty for the market-based calibration, the ethics-based growth-corrected social discount rate decreases and consequently the carbon price increases in uncertainty. The reason is that Barro (2009) has $EIS = 2 > 1$ whilst Gollier (2011) has $IIA = 2$ which corresponds to $EIS = 0.5 < 1$. Growth rate uncertainty thus demands more vigorous climate action if $IIA > 1$ as in Nordhaus (2007), Gollier (2011, 2012) and van den Bremer and van der Ploeg (2019) but requires less strong carbon pricing if $EIS > 1$ or equivalently $IIA < 1$.

Second, allowing for macroeconomic disasters substantially depresses the dividend-price ratio and thus the growth-corrected social discount rate by much more than normal growth uncertainty (i.e. geometric Brownian motion). This means that disaster uncertainty has substantially larger positive or negative effects on the *SCC* than normal growth uncertainty depending on whether the *IIA* is above or below one.

Third, as pointed out by Epstein et al. (2014), Epstein-Zin preferences are too restrictive as they only have two parameters to capture three aspects of preferences, i.e. aversion to risk, aversion to intergenerational inequality and preference for early resolution of uncertainty. What is needed is general enough preferences, so one can separate calibration of all three aspects.

Fourth, some argue that it is important to use the market rate of interest to discount returns from social investments (or damages from global warming) thus respecting private preferences, Caplin and Leahy (2014) argue that this is only justified if preferences over all choices including past ones are time invariant. Under reasonable conditions policy makers should be more patient than private citizens, whose choice define the most short-sighted Pareto optimum.

Finally, future work needs to face the challenge of private versus social preferences head-on. Barrage (2018) and Belfiori (2017) show in a deterministic setting with more patient policy makers than private agents that the optimal policy is to have a carbon price equal to the SCC and a capital subsidy to correct for the excessive impatience of private agents. If the capital subsidy is not implemented, climate policy will be time inconsistent. Future research needs to combine the ethical calibration of climate policy put in place by relatively patient policy makers with *IIA* > 1 and combine this with market-based consumers and investors with *EIS* > 1.

10. Discounting the Far Future with Uncertain Discount Rates

So far, the analysis has assumed a constant *SDR*, irrespective of the horizon of the intended policy. The rate to discount a project in year 101 to year 100 is thus the same as the rate used to discount a project in year 11 to year 10. If more distant discount rates are smaller (larger), there is a downward- (upward-sloping) term structure for the discount rate. In fact, it has been argued that a declining term structure for the *SDR* is more appropriate (e.g. Arrow et al., 2014). The reason for this is that, if shocks to interest rates and thus to consumption growth rates are persistent, the resulting schedule of efficient discount rates must decline for longer horizons. France and the United Kingdom indeed employ declining *SDR*s.

A declining *SDR* occurs if shocks to the consumption growth rate are not independently and identically distributed, but positive correlated over time. The *SDR* is then no longer constant and the downward adjustment to allow for the uncertain growth rate is not necessarily small anymore. Furthermore, the downward adjustment of the *SDR* becomes more substantial for long horizons as discussed in the excellent survey of Gollier (2012). The point is that, due to positive correlation, positive shocks to consumption make future consumption riskier, which magnifies the prudence term in equation (7) for distant horizons. Gollier (2008) shows that, if the growth in consumption, $\ln(C_t / C_{t-1}) \equiv x_t$ follows an AR(1) process, the *SDR* is lower for longer horizons provided the autocorrelation coefficient of the process, φ, is between zero and one. In fact, the prudence effect is multiplied by $(1-\varphi)^{-2} > 1$ as the horizon tends to infinity. Hence, the more autocorrelation in shocks to consumption growth (higher φ), the bigger the amplification of the prudence effect at very long horizons.

Vasicek (1977) had shown much earlier that, if the spot interest rate follows an Ornstein-Uhlenbeck process with positive serial correlation as proposed by Merton (1971) and the initial interest rate is high enough, the conditional expectation of the interest rate declines over time towards its long-term mean, the term structure slopes downwards. If the initial interest rate is low enough, the term structure slopes upwards. For intermediate values, it is a humped curve.

It turns out that estimated models with autocorrelation in consumption growth only imply modest declines in the *SDR*. However, Weitzman (2007) and Gollier (2008) show that subjective uncertainty about the trend and volatility of the growth rate of aggregate consumption can lead to a declining *SDR* too. Gollier (2008) gives an example where the mean growth rate of aggregate consumption takes the values 1% and 3% per year with equal probability and shows that this implies that with *IIA* = *RRA* = 2 the *SDR* excluding the self-insurance term falls from 3.5% today to 2% per year in three centuries.[10] This is not that different from the 4% per year for the first three decades and 2% per year thereafter that the French government uses for project appraisal. Arrow et al. (2014) argue that it need not make sense to have a higher *RRA* then *IIA*, since recursive preferences have been used to explain saving decisions in financial markets. Hence, it is more appropriate to use (5) than (6).

[10] With *IIA* = *RRA* = 2 and *RTI* = 0, the *SDR* takes on 6% and 2% with equal probability so the certainty-equivalent value is $0 < -\ln\left(0.5e^{-0.06t} + 0.5e^{-0.02t}\right)/t < 0.01.$ The mean instantaneous rate is 0.5 x 0.06 + 0.5 x 0.02 or 4% but for a horizon *t* of 300 years it is 2.23% and as the horizon tends to infinity it tapers off to 2% per year.

Weitzman (1998, 2001, 2007) takes a different tack by demonstrating that calculating expected net present values with an uncertain but constant social discount rate *SDR* is equivalent to calculating net present values with a certain but decreasing certainty-equivalent (CE) value of the *SDR*, where the CE value of the *SDR* equals $-\ln\left(E\left[e^{-SDR\times t}\right]\right)/t$ and the instantaneous certainty-equivalent *SDR* is the forward rate. Jensen's inequality gives $E\left[e^{-SDR\times t}\right] > e^{-E[SDR]t}$, so that the CE value of the *SDR* is less than $E\left[SDR\right]$ and this difference rises with time.

To illustrate this, Table 1 gives different CE values of the *SDR* at different horizons where the *SDR* is either 2%, 4% or 6%, each with equal probability. The CE value of the *SDR* equals the mean value of the *SDR* (4%) at infinitesimally small horizons and goes to the minimum value of the *SDR* (2%) as the horizon becomes infinitely large. For long enough horizons the payoff with the lowest *SDR* completely dominates the pay-off under the other *SDR*'s. Alternatively, if the *SDR* follows a gamma distribution with scale parameter $E\left[SDR\right]/CV$ and shape parameter 1/*CV*, where *CV* is the coefficient of variation of the *SDR* (standard deviation divided by mean), the CE value of the *SDR*, $\ln\left(1+E\left[SDR\right]\times CV^2\times t\right)/(CV^2\times t) < E\left[SDR\right]$, decreases in the coefficient of variation and the length of the horizon *t*. Uncertainty about future discount rates thus calls for a decreasing term structure of the certainty-equivalent value of the *SDR*.[11]

Table 1: Declining certainty-equivalence of the SDR

Horizon (years)	Low *SDR* 2%/year	Middle *SDR* 4%/year	High *SDR* 6%/year	Mean outcome	CE value of *SDR* (%/year)
1	980	961	942	961	3.99
10	819	670	549	679	3.87
50	368	135	50	184	3.34
100	135	18	2	52	2.96
200	18	0.33	0.006	6.2	2.54

Key: Columns 2-5 give present value today in millions of 1 billion in the future

[11] The astute reader may ask why the *SCC* in (5) or (6) uses a *constant SDR* in (7). The reason is that the growing variance of consumption growth demands a *rising SDR*, which offsets the declining *SDR* highlighted here.

Groom and Hepburn (2009) examine the result of Gollier (2004) that as the evaluation date moves further into the future, the discount rate at a given point in time will increase. They show, however, that for a given evaluation date the schedule of discount rates will decline in line with the seminal paper of Weitzman (2001). Gollier and Weitzman (2010) attempt to reconcile the positively correlation consumption growth and the expected net present value approaches for a declining *SDR* by showing that the latter approach is equivalent to utility maximisation with a logarithmic utility function. Groom and Hepburn (2019) survey the various approaches to the *SDR* and the mechanisms for why it might decline with the horizon.

Differences in opinions do not necessarily reflect uncertainty in the statistical sense but may reflect differences in ethical judgements. In fact, Gollier and Zeckhauser (2005) offer theoretical arguments why heterogeneity in rates of time impatience can lead to a declining utility discount rate and possibly also to a social discount rate that declines for longer horizons.[12] They show that this requires that all individual agents have a constant discount rate and display decreasing absolute risk aversion. They also discuss the possibility that the discount rate decreases with GDP per capita. Millner and Heal (2018) consider a dynamic social choice problem where a sequence of committees decides on how to consume a public asset and each committee takes account of the behaviour of future committees. Furthermore, each committee member has a different view of the pure rate of time preference. They show that deciding by majoritarian vote in each period is superior to aggregating preferences in utilitarian manner, since the latter leads to time inconsistent and inefficient decision making.

[12] Millner (2020) offers a theoretical framework of non-dogmatic policy makers where agents differ in their normative rates of time impatience. Policy makers admit that they might change their views, but refrain from imposing their current normative judgements on their future selves. Still, all non-dogmatic theories yield the same value of the long-run discount rate. Jaakkola and Millner (2018) show that admitting the possibility of a change in views once every forty years leads to a 4.6-fold reduction in the range of recommended carbon prices.

11. Survey and Empirical Evidence on Declining Discount Rates

Using responses from a couple of thousand professional economists about the constant discount rate giving a mean of 4% and a standard deviation of 3%, Weitzman (2001) modelled uncertainty about this rate with a gamma distribution and found that the immediate future (1-5 years), near future (6-25 years), medium future (26-75 years), distant future (76-300 years) and far-distant future (more than 300 years) future should be discounted at 4%, 3%, 2%, 1% and 0% per year, respectively. Freeman and Groom (2015a) warn against this interpretation of survey evidence. If the variation in opinions about discount rates is due to irreducible differences in ethical judgements, then as Weitzman (2001) has shown the term structure of the *SDR* declines rapidly. However, if this variation is due to respondents forecasting future rates under uncertainty, Freeman and Groom (2015a) show that the term structure of the *SDR* is much flatter as opinions from additional experts provide new information and can be used to cut forecasting errors, especially if forecasts by experts are not much correlated. This leads to a much lower *SCC* than the one suggested by a rapidly declining term structure. When interpreting survey evidence, it is thus important to distinguish heterogeneity and uncertainty.

Newell and Pizer (2003), Groom et al. (2007), Hepburn et al. (2009) and Freeman and Groom (2015b) have estimated certainty-equivalent interest rates from historical data series. For example, Newell and Pizer (2003) find that the certainty-equivalent value of the social discount rate falls from 4% today to 2% in a century if a random walk for interest rates is assumed, but falls from 4% to 2% in more than three centuries if a mean-reverting auto-regressive model for interest rates is used. Groom et al. (2007) find that these declining patterns also occur for autoregressive models with conditional heteroscedasticity and for regime-switching and state-space models, especially if returns to capital are uncertain and persistent. Hepburn et al. (2009) also find that the regime-switching model is a better model of past interest rates and that this implies a faster decline in certainty-equivalent discount rates than Newell and Pizer (2003).

Freeman and Groom (2015b) obtain a declining *SDR* by using real rather than nominal interest rates and estimating a co-integration model of inflation and nominal interest rates.

12. Expert and Other Evidence on Preferences of Policy Makers

Since market data cannot be relied on to estimate preferences needed to formulate climate policy, scholars have turned to other methods. Grijalva et al. (2014) use a laboratory experiment to elicit discount rates over a 20-year horizon when government bonds can be used for payment. Using exponential discounting, they find an implied average discount rate of 4.9% per year, much lower than in previous experimental studies that used horizons of days or months. They also find strong support for discount rates that decline with longer horizons (falling to 0.5% in a century). There is also evidence that more optimistic people with more optimistic views about technological progress have higher discount rates, which is in line with the Keynes-Ramsey rule (1). However, Drupp et al. (2018) surveyed 200 experts to disentangle the various effects on the *SDR* but found that most experts when recommending which *SDR* to use did not follow the Keynes-Ramsey rule. Despite disagreements, they found that three-quarters of the experts found a median risk-free social discount rate of 2% per year acceptable. This is much lower than the figure of 4.9% per year found in Grijalva et al. (2004).

Pindyck (2019) elicits expert opinions about the probabilities of alternative economic outcomes of climate change, including extreme outcomes such as a 20% or greater drop in GDP and the reduction in emissions required to avert an extreme outcome. He then estimates the *SCC* as the ratio of the present value of damages from an extreme outcome to the total emission reduction needed to avert such an outcome. This transparent approach gives an estimate for the *SCC* of at least 200 $ per ton of carbon, If outliers are dropped and only experts with a high degree of confidence in their answers are used, this figure drops to 80 to 100 $ per ton of carbon.

It is also important to have solid experimental or survey evidence on what intergenerational inequality aversion might be. Gollier (2012) gives various arguments based on surveys and introspection for why *IIA* of 2 is plausible. Weitzman (2007) and Nordhaus (2016) also use *IIA* = 2, Arrow (2007) uses an *IIA* of 2 to 3, and the Intergovernmental Panel on Climate Change uses a range of 1.5 to 2 for the *IIA*. Stern (2007) uses *IIA* = 1, but Dasgupta (2007, 2008) criticises this for being much too low implying too much indifference between welfare of current and future generations. Dasgupta (2007) finds it absurd that the current generation literally must starve itself so that future generations can enjoy ever-increasing consumption levels and argues that a value for *IIA* of 2 to 4 is much more reasonable. The point is that none of these studies recommend a value of *IIA* less than one (corresponding to *EIS* > 1) and thus take a radically different view than taken in the asset pricing literature.

To assess the appropriate *SDR*, it is thus not only necessary to form an opinion or have evidence on the value of the rate of time impatience but also to have survey or other empirical evidence on intergenerational inequality aversion. Inequality aversion can be estimated across individuals from progressive taxation or across countries from development aid to be 0.7 (Tol, 2010), but this offers no guidance on inequality aversion across generations. Evans (2005) uses evidence on the structure of personal income taxes for OECD countries that the average elasticity of marginal utility is 1.4, but this is more like an estimate of intra-generational than intergenerational aversion. Groom and Maddison (2019) use the same method (the equal-sacrifice income tax method) and three other methods (the Euler equation approach, the Frisch additive preference approach, and risk aversion in insurance markets) to come up with an estimate of the elasticity of marginal utility of 1.5. The same value then captures intra-generational and intergenerational inequality aversion and risk aversion, but that is a big leap.

Dennig et al. (2015) put forward an integrated assessment model with different measures for both intra-regional and intergenerational inequality aversion. They show that Thomas

Schelling's conjecture that the inequality parameter can have the opposite effect on the intensity of climate policy to what is suggested by the Keynes-Ramsey rule (Budolfson, et al., 2017). Hence, despite that higher *IIA* implies a higher *SDR* and thus a lower *SCC*, when inequalities are properly accounted for, it is possible that climate policy should become more ambitious under higher (intergenerational and intra-regional) inequality aversion.

Others have tried to estimate *RTI* and *IIA* from stated preferences, but this suffers from both methodological and conceptual issues as people have different values for these parameters. Yet another alternative is to derive *RTI*, *IIA* and *RA* from financial market data, but as discussed in section 8 it is not clear that this has much to do with preferences of climate policy makers. This explains why some researchers have turned to survey evidence from experts.

13. Dual Discount Rates, Relative Scarcity and The Endowment Effect

A classic paper highlights that over time the relative benefits of preservation increase as there may be limited substitution with economic development, technical progress in economic development, and demand for environmental quality might rise more than proportionally with wealth (Fisher and Krutilla, 1975). This leads to dual discount rates, where the discount rate for future benefits from preservation is smaller than that for future benefits and costs of developing a project. This makes environmental policy more ambitious. More generally, if the consumption of environmental quality is a driver of household satisfaction, its relative price is likely to change over time. To value an environmental project, future environmental gains are thus converted at current relative prices and an "environmental" discount rate equal to the *SDR* minus the rate at which the relative price of environmental goods in terms of consumption goods is used. An alternative way to value such a project is to convert future environmental gains into consumption units using the future relative price and use the consumption discount rate. When thinking about discounting it is thus important to focus at the relative scarcity of the natural environment in the provision of ecosystem services (e.g. Hoel and Sterner, 2007;

Sterner and Persson, 2008; Gollier, 2010; Traeger, 2011; Zhu et al., 2019). Because the growth rates of the economy and ecosystem services differ, relative prices change over time and this affects the *SDR*. Empirical work suggests that the discount rate for ecosystem services is about 1%-point smaller than that for consumption (e.g. Drupp, 2018).

Zhu et al. (2019) use a Ramsey growth framework with different growth rates for the economy and ecosystem services, so that valuation of environmental benefits relative to consumption goods changes over time and relative prices are not constant over time. Discount rates for consumption and for ecosystem services thus differ. Economic growth is curbed if ecosystem services in production do not grow and cannot easily be substituted in production. With CES production and exogenous growth rates in ecosystem services and labour (measured in efficiency units), if the elasticity of substitution is less (greater) than one, growth of the composite of ecosystem services and labour converges to growth of ecosystem services (the growth rate of labour in efficiency units). If manmade inputs cannot easily substitute for ecosystem services, the low growth of ecosystem services eventually drives and curbs economic growth. This then implies that the consumption discount rate declines towards a low value that is given by the standard Keynes-Ramsey rule with a low growth rate. If ecosystem services can be easily substituted, this effect does not occur. The effect on the discount rate of limited substitutability of ecosystem services in production is much stronger than the relative price effect that results from limited substitutability of ecosystem services in utility.

Hoel and Sterner (2007), Traeger (2011) and Zhu et al. (2019) also investigate the effects of ecosystem services in the utility function on the time pattern of the discount rate. They conclude that even for a given growth of consumption the discount rate is not constant due to the time-varying value share of ecosystem services. If the elasticity of intra-temporal substitution between consumption and ecosystem services exceeds one but is less than the elasticity of intertemporal substitution, the discount rate declines with time. This also occurs if the elasticity of intra-temporal substitution is less than one but greater than the elasticity of intertemporal substitution (see Figure 7 in Zhu et al., 2019). This effect appears to be relatively small.

Dietz and Venmans (2019b) also find a declining discount rate, but here the mechanism is due to habit persistence or reference dependence and loss aversion. They show that loss aversion affects the discount rate via an instantaneous endowment effect and via a reference-updating effect, which reduces the incentive to smooth consumption. On a path of rising material consumption, this reduced incentive tends to lower the discount rate, but on a declining path of environmental quality it leads to a higher discount rate.

Venmans and Groom (2019) have elicited higher measures of intra-temporal aversion to inequality in environmental outcomes (about 3) than of intertemporal inequality aversion (either –2 or 1.4 for, respectively, negative or positive growth in environmental quality) using assessment of social projects in the presence of environmental inequalities across space and time and allowing for different contextual framings. They find that differences across different environmental domains (e.g. air pollution, recreational forests) are not very strong. Their results also cast doubt on the classical utilitarian formulation of intertemporal social welfare.

Finally, in a very impressive extension of Nordhaus's DICE model to allow for the relative scarcity of non-market goods, Drupp and Hänsel (2020) show that for their core calibration accounting for relative prices is equivalent to a decreasing pure rate of time preference by 0.6%-points and leads to a more than 50% higher *SCC*.

14. Conclusion

The appropriate choice and term structure of the *SDR* to be used for climate policy matters enormously and is hotly debated. One billion dollars of damages a century from now is worth today only 7.6 million dollars if the discount rate is 5% but 370 million dollars if the discount rate is 1% per annum. In the latter case, the *SCC* is much higher. Alternatively, climate investments to abate future damages can have almost fifty times higher costs and still be worth it if the discount rate is 1% instead of 45%v per year. Hence, the discount rate matters hugely for climate policy and that is why better understanding is needed.

The *SDR* is high and the carbon price is low, if policy makers are impatient and future generations are wealthier than current ones, especially if intergenerational inequality aversion is large. Normal uncertainty about future economic growth hardly affects the *SDR* and the carbon price. Provided intergenerational inequality aversion exceeds one, the risk of macroeconomic or of climate-related disasters depresses the *SDR* substantially and thus pushes up the carbon price significantly. Carbon pricing becomes even more vigorous if the risk of (multiple) climatic tipping points is taken account of. Various arguments have been put forward why the social discount rate used to discount future damages from global warming should decline with time. A constant discount rate can lead to very misleading conclusions in the analysis of climate policy, since long-run damages are hardly taken account of.

The stochastic discount factors that arise naturally in asset pricing with Epstein-Zin preferences and long-run risks[13] have been used to derive the optimal carbon price, where the latter corresponds to the expected value in terms of less future global warming damages of reducing emissions by one ton of carbon today. Since the asset pricing literature assumes that uncertainty depresses the price-dividend ratio, it assumes that the elasticity of intertemporal substitution exceeds one (and calibrates risk aversion to explain the equity premium puzzle). However, if this is applied to climate policy, this implies that normal growth uncertainty and the risk of macroeconomic disasters lead to *lower* carbon prices. Although the insights from asset pricing regarding discount rates are invaluable, it is important to realise that impatience and attitudes

[13] Long-run risks have been analysed by Bansal and Yaron (2004). Weitzman (2012) employs an evolving hidden-state stochastic process to allow for projections of future growth rates that are fuzzier for longer horizons and show that a declining discount rate emerges. The underlying growth rate is only recoverable as a probability distribution via Bayesian updating.

to risk and intergenerational inequality of policy makers cannot be deduced from savings and investment decisions in financial markets. Ethics-based preferences of policy makers typically have much lower rates of impatience and higher degrees of intergenerational inequality aversion. Such preferences may allow risk aversion to exceed intergenerational inequality aversion as this would also allow for a preference for early resolution of uncertainty.

15. Further Research

There are many promising avenues for further research into how to use discounting and asset pricing in the formulation of climate policy. First, the decisions to undertaken abatement projects require long-run climate investments and a careful application of cost-benefit analysis. For example, Gollier (2020b) stresses that policy makers should use *project-specific* risk-adjusted discount rates. In practice, due to financial illiteracy, the dogma that the government in contrast to the private sector can pool all risks[14], or the misguide use of using a single discount rate corresponding the weighted average cost of capital[15], many public (and private) decision makers use an all-purpose discount rate that does not depend on the risk profile of their investment projects. The welfare loss of using a single discount rate rather than different discount rates for different projects with different risk profiles leads to a welfare loss corresponding reduction in permanent consumption of 15 to 45%, depending on which discount rate is used. Policy makers should reform the way to discount and evaluate investment projects to abate emissions in line with the well-known principles of asset pricing theory. This also has crucial implications for the *SDR* to be used for different climate investment projects. Projects with a negative correlation with the future state of the economy (e.g. dikes) should be evaluated using a lower *SDR* than projects with a positive correlation.

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[14] This goes back to Arrow and Lind (1976), who argued that the pooling argument implies that all public investment projects should be invested at the risk-free rate. But from the consumption capital asset pricing model, it is well known that this proposition is only true for projects with a *zero* beta. Using a single discount rate thus means that projects with a positive beta (e.g. railroads, highways) get implemented more easily.

[15] This implies there is too much investment in risky and not enough in safe projects (Krueger et al., 2015).

Second, asset pricing can also be used to better understand how best to implement caps on temperature as required by the Paris Agreement on climate policy. A temperature cap implies a cap on cumulative emissions as temperature is a simple function of cumulative emissions. Intertemporal efficient arbitrage then requires that the carbon price must grow at a rate equal to the rate of interest, because only then is society indifferent between emitting one ton less today (thus saving the carbon tax which can yield a rate of return equal to the interest rate) or emitting one ton less next year (thus facing an expected increase in the carbon price). Gollier (2020a) uses an intertemporal asset pricing approach with both conventional and uncertainty and disaster risks about the rate of economic growth and with uncertainty about future abatement technologies to show that the appropriate risk-adjusted interest to use is about 3.75% per year, which is higher than the risk-free rate implying a positive carbon risk premium (provided marginal abatement costs and aggregate consumption are positively correlated) but a lot lower than the return on risky assets. The 7% per year or even higher rate of growth of the carbon price typically used in integrated assessment models thus leads to intertemporally inefficient outcomes, grossly under-estimating the efficient carbon price that is needed today.

Third, more thinking and sound empirical work is needed on the appropriate term structure. A recent macro-finance study uses tools from the fixed-income literature on government yields to specify and estimate a Bayesian time-series model to show that the equilibrium real interest rate is a crucial anchor for the term structure of discount rates and that empirically this anchor has fallen by about 1%-point per year and has thus roughly doubled the estimated present value of the economic loss from climate change, the *SCC*, since the 1990s (Bauer and Rudebusch, 2020). An exciting other recent study estimates a downward-sloping term structure for real estate with an average return of 6% and a discount rate for a century ahead of about 2.6% per year (Giglio et al., 2020). It also shows that real estate performs badly during consumption disasters and is thus a risky asset and that real estate is exposed to climate change risk (proxied by rising sea levels, hurricanes). It combines these findings with asset pricing insights to come up with a social discount rate for climate policy appraisal which has similar horizons as real estate but a different risk profile. Their key assumptions are that disasters are more likely when growth is high, and that economic growth picks up temporarily after a disaster. These assumptions imply that the appropriate discount rate to use for climate appraisal starts off very low and then rises, i.e. an upward-sloping, not downward-sloping term structure of the social discount rate. The point is that hedging against the adverse effect of disasters on short-term cash flows is more valuable than hedging long-term cash flows as these are affected less due to adaptation. The discount rate is below the risk-free rate of 1-2% per year at all horizons.

Fourth, as this survey's discussion of the application of asset pricing to climate policy has highlighted, it is crucial to allow for integrated assessments of the economy and the climate that allow for different preferences for policy makers and private agents. If the government uses a lower (ethically based) social discount rate for climate change than for investments in other domains, the government policy is not Pareto-efficient. Higher welfare can be obtained by transferring part of the investments for climate with a low internal rate of return to the other sectors with higher hurdle rate. This requires an analysis of second-best optimal climate policies. Barrage (2018) shows that, if patient policy makers that are more patient (farsighted) than the private sector, a capital subsidy as well as a carbon price is needed. In the absence of such a subsidy, climate policy is time inconsistent. Others use the hyperbolic discounting framework put forward by Laibson (1977) and Krusell and Smith (2003) to analyse climate policy (e.g. Karp, 2005; Karp and Tsur, 2011; Iverson and Karp, 2017; Gerlagh and Liski, 2018). For example, Iverson and Karp (2017) study the Markov-perfect equilibrium to a dynamic game where private agents choose savings and policy makers decide on climate policy. They show that with hyperbolic discounting, convex damages give rise to significant strategic interactions across generations of planners. Being able to commit for over a century significantly boosts welfare of the first generation but being able to commit for only a few decades has hardly any benefit. Gerlagh and Liski (2018) show that with a declining discount rate the delay and persistence of climate impacts act as a commitment device to policy makers. They also focus at the Markov-perfect equilibrium and find that the returns on capital and climate investments are no longer leading, which implies a substantial boost to the carbon price. The commitment value increases the carbon price by a factor of 20.

Finally, future research should deal with the problem of different generations in a realistic fashion. For example, Kotlikoff et al. (2019) use an overlapping generations model to design Pareto-improving green tax reforms by taxing future generations to give transfers to current generations in a way that makes all generations better off. The challenge is thus to study the drivers of the social discount rate and climate policy in second-best frameworks where private agents and governments have diverging preferences, commitment matters, and both the economic and climate system are subject to both normal uncertainties and tipping risks.

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