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The social cost of carbon emissions: Seven propositions[☆]

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HIGHLIGHTS

- We emphasize the market failure in the market for carbon emissions for economy-wide CBA.
- Treating the SCC as independent of reference path is vulnerable to the methodological error.
- We gage the effects of uncertainty and ambiguity on the social cost of carbon.
- We review empirical estimates of the SCC.
- We critically discuss recent US policy initiatives placing the SCC at \$77/tC.

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ABSTRACT

Determining the social cost of carbon emissions (SCC) is a crucial step in the economic analysis of climate change policy as the US government's recent decision to use a range of estimates of the SCC centered at \$77/tC (or, equivalently, \$21/tCO$_2$) in cost-benefit analyses of proposed emission-control legislation underlines. This note reviews the welfare economics theory fundamental to the estimation of the SCC in both static and intertemporal contexts, examining the effects of assumptions about the typical agent's pure rate of time preference and elasticity of marginal felicity of consumption, production and mitigation technology, and the magnitude of climate-change damage on estimates of the SCC. We highlight three key conclusions: (i) an estimate of the SCC is conditional on a specific policy scenario, the details of which must be made explicit for the estimate to be meaningful; (ii) the social discount rate relevant to intertemporal allocation decisions also depends on the policy scenario; and (iii) the SCC is uniquely defined only for policy scenarios that lead to an efficient growth path because marginal costs and benefits of emission–mitigation diverge on inefficient growth paths. We illustrate these analytical conclusions with simulations of a growth model calibrated to the world economy.

1. Seven propositions and the economics of climate change

Economic analysis of potential effects of climate change is often based on standard neoclassical welfare economics. This policy note works through the details of this analysis. The discussion begins with a comparative static model at the level of intermediate microeconomic theory and then goes on to consider intertemporal complications. We present our main conclusions in the form of seven propositions in lieu of an introduction. The corresponding analysis is presented in the subsequent sections.

I. In the standard static textbook model of trade-offs between environmental quality and "ordinary" consumption, equilibrium environmental quality at a sub-optimal "business-as-usual" (BAU) point is the result of a negative (emission) externality. A "free lunch" is available in that individuals could increase both conventional consumption and environmental quality.

II. Only at an efficient allocation of environmental quality and consumption is there an unambiguous measure of social marginal cost. The willingness-to-pay for environmental improvement on the part of the typical individual and the social marginal cost of achieving an increased consumption of the good must be equal.

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III. In dynamic analysis of environmental quality and consumption, a typical individual will have a short-term discount rate which is the sum of a pure rate of time preference and the product of the elasticity of her marginal utility of consumption with respect to her level of consumption times the growth rate of her consumption. Consumption growth rates will change as the economy evolves over time so that reasoning in terms of a constant social discount rate is beside the point. Whether the pure rate is a (small) positive number or zero is of secondary importance.

IV. Estimates of costs and benefits of greenhouse gas mitigation must be conditional on a scenario that specifies a reference path of consumption and environmental quality, as well as on the "felicity" function and pure rate of time preference assumed for the typical individual and the technology described by particular production, damage and mitigation functions. The discount rates at which the present value of costs and benefits must be calculated also depend on the reference path of consumption implied by a particular scenario.

V. Numerical simulations suggest that an "optimal" strategy for mitigation of climate change (with the social cost of mitigation equal to present discounted value of damages avoided) could be achieved by reallocating about 10% of current world investment (2.5% of world output) to emission–mitigation. The social discount rate would decline as consumption growth slows. As is typical in dynamic optimization models without complicated constraints on timing, mitigation outlays as a share of output would be higher during early phases of the plan. (A "corollary" is that since mitigation may be less costly in developing countries, it should be "front-loaded" there.)

VI. On an optimal path, a plausible estimate of the marginal cost and benefit of mitigation is about \$200 per tonne of carbon (\$55/tCO_2). On a BAU path the marginal cost would be about \$160/t of carbon (\$44/tCO_2), but the marginal benefit would be about \$1500/t of carbon (\$410/tCO_2).

VII. The costs of mitigation are reasonably well understood. Potential damages from climate change are much harder to evaluate, but could be very high. A key result in the theory of decision-making under uncertainty is that if damages from climate change rise non-linearly with the extent of change, then the avoidance of bad outcomes should be weighed more heavily than the attainment of good ones. Investing 2.5% of GDP in mitigation would be a much less serious mistake than not investing and following a BAU path to climate catastrophe.

In the academic and policy debates a common assertion is that mitigation of climate change will require a sacrifice of current consumption (Karp, 2009). Propositions I and II suggest that this view is misguided.

Many discussions of climate change (Arrow, 2007; Hope, 2006; Nordhaus, 2011; Tol and Anthoff, 2010) reason in terms of a constant rate of discount, ignoring the dynamic "transient" transition from the sub-optimal present resource allocation towards optimal steady growth at a constant rate and also neglecting to take account of the sharp decline in consumption on BAU paths that can lead to very low or even negative social discount rates. Propositions III and IV show the need to correct these presumptions.

Gradually increasing mitigation efforts in an optimal plan is recommended by Nordhaus (1992) and others. Proposition V suggests that complicated assumptions about timing of benefits and costs would be required to support this type of conclusion. Whether there is any evidence to support these assumptions remains to be seen.

Propositions VI and VII suggest that mitigation is feasible at a relatively low cost and that failure to invest in mitigation could lead to disaster. This finding extends the reasoning of Weitzman (2009) to a deterministic setting.

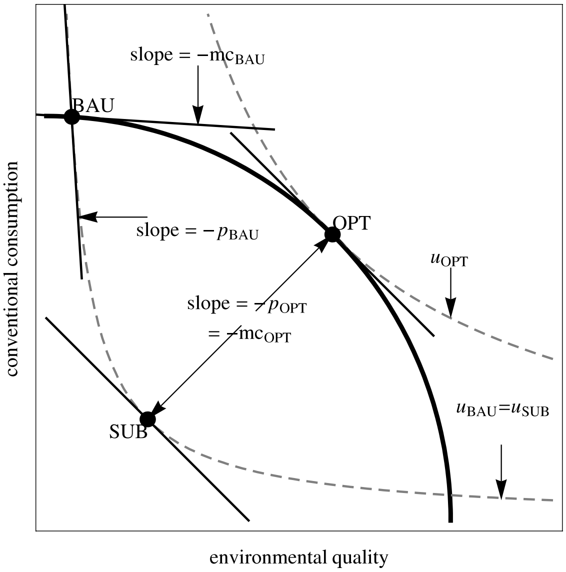

Fig. 1. Static decisions of allocation between consumption and environmental quality in the absence (OPT) and presence (BAU) of a negative externality.

2. Welfare economics revisited

Before tackling the complexities introduced by the inherently intertemporal and intergenerational character of the greenhouse gas problem, it is useful to review these fundamentals in the static context in which they are introduced in intermediate microeconomics courses (Pindyck and Rubinfeld, 2009).

The heavy line concave to the origin in Fig. 1 is a production possibilities frontier between environmental quality (on the horizontal axis) and conventional consumption (on the vertical axis), which it is convenient to measure in dollars. With this convention, the slopes of straight lines in the figure can be interpreted as the negative of money prices for environmental quality. Following a long tradition in welfare economics, we assume that there are social indifference curves representing consistent social preferences over allocations of resources. It is perhaps most convenient in this context to think that there are many members of society who are identical, at least in their preferences over this tradeoff, and that the indifference curves are those of a "typical" or "representative" individual. An efficient (Pareto-optimal) allocation is denoted by the point OPT where the typical individual's indifference curve is tangent to the production possibilities frontier. At this point the typical individual's willingness-to-pay for environmental quality, p_{OPT}, equals the social marginal cost of environmental quality in terms of conventional consumption, mc_{OPT}, thus providing an unambiguous marginal social cost and benefit of environmental quality.

This society, however, finds itself at the sub-optimal point BAU, where the typical individual's indifference curve intersects the production possibilities frontier. At allocations of this kind the typical individual' s willingness-to-pay for environmental quality, p_{BAU}, is higher than the social marginal cost of environmental quality, mc_{BAU}. One reason why a point like BAU might be an equilibrium for this society is that environmental quality is a public good (possibly resulting from open access or a negative externality): the social production possibilities frontier represents what would happen if all the identical members of society contributed more to environmental quality, but each of them believes that if she alone made a larger contribution the others would not reciprocate. As a result, each typical individual perceives the cost of environmental quality as higher than its social cost given coordinated actions.

What is the social cost (or benefit) of environmental quality at a point like BAU? In one sense, environmental quality is free at BAU, because the typical individual can have more of it with no loss, in fact, a gain, in well being, since moving down the production possibilities frontier from BAU towards OPT puts the typical individual on higher and higher indifference curves. The most important message of Fig. 1 is that this free lunch is available, and worth the difference $u_{\text{OPT}} - u_{\text{BAU}}$ to the typical individual. Welfare economists often decompose the movement from BAU to OPT into a "substitution effect", which takes the society from BAU to a point SUB on the same indifference curve as BAU but with a typical individual's willingness-to-pay equal to the social marginal cost at OPT, and an "income effect", which takes the society from SUB to OPT, allowing the typical individual to realize the welfare gains implicit in the inefficiency of BAU through some pattern of increased conventional consumption and environmental quality. To summarize, we present

Proposition I. *In the standard static textbook model of trade-offs between environmental quality and "ordinary" consumption, equilibrium environmental quality at a sub-optimal "business-as-usual" (BAU) point is the result of a negative externality. A "free lunch" is available in that individuals could increase both conventional consumption and environmental quality.*

In the context of climate change, this market failure for GHG emissions has long been understood (for early acknowledgments, see Nordhaus, 1977 and Schelling, 1992; for more recent statements, see Arrow, 2007 and Stern, 2007). Chichilnisky and Heal (1994) are among the first to correctly account for the public good nature of the atmosphere in their economic analysis. Sinn (2007), Foley (2009) and Stern (2010) make the "free lunch" arguments in a dynamic context.

Policy makers in this society might try to reason this out in terms of a "cost-benefit" analysis of making a small move towards higher environmental quality starting from BAU. They would find that the typical individual's willingness-to-pay for environmental quality in terms of conventional consumption (the social benefit of such a move) would exceed the social marginal cost.

This simple example illustrates fundamental points about the concept of "social (marginal) cost". The social marginal cost of a good (or bad) depends on the current allocation of resources. At an inefficient allocation there will be two different measures of social marginal cost and benefit, reflecting the possibility of a Pareto-improving change in allocation. These measures will depend on the allocation itself. The implication is

Proposition II. *Only at an efficient allocation of environmental quality and consumption is there an unambiguous measure of social marginal cost. The willingness-to-pay for environmental improvement on the part of the typical individual and the social marginal cost of achieving an increased consumption of the good must be equal.*

3. The greenhouse gas problem

Carbon dioxide and other greenhouse gases accumulate in he atmosphere in part as the consequence of humans burning fossil fuels, cutting down forests, and grazing ruminant animals. There is strong reason to believe that the accumulation of carbon dioxide in the atmosphere will lead to significant and ultimately catastrophic climate change that on average will have deleterious effects on human well being. Because the half-life of carbon dioxide in the atmosphere is on the order of one to three hundred years, the economic analysis of the trade-offs involved in managing this problem inevitably requires a consideration of the intergenerational distribution of costs and benefits of investment in mitigating emissions.

One simple (perhaps too simple, but illuminating) representation of this problem is to consider as a first approximation a society of identical individuals confronting the tradeoff between conventional consumption and environmental quality (or more specifically greenhouse gas accumulation in the atmosphere) over time. In order to include intergenerational distribution in this setting, it is natural to suppose that the typical individual includes the welfare of future generations in her preferences. (This is only a first step towards a more complete analysis that would take account of other differences among the individuals involved, such as their geographic location and income.)

3.1. Discounting marginal benefits

In this intertemporal setting conventional consumption and environmental quality are paths $c = \{c_1, \ldots, c_T\}, e = \{e_1, \ldots, e_T\}$ specifying the levels of conventional consumption and environmental quality available to the typical individual at each time period starting from the present (year or decade, for example) far into the future. To simplify notation, we will assume that population and employment are constant over time. It is convenient to measure conventional consumption in terms of 2012 dollars, and environmental quality either in terms of the atmospheric concentration of greenhouse gases (parts per million of carbon dioxide by volume) or average planetary temperature. One way to represent the preferences of a typical individual in this setting is through a "discounted felicity" function that depends on total conventional consumption:

$$U[c] \equiv \sum_{t=1}^{T} \frac{u\left[c_t\right]}{(1+\rho)^t}. \tag{1}$$

The function $U[\cdot]$ has as its arguments the whole path of conventional consumption; it is defined to be the sum of *felicity*, $u[\cdot]$, which has as its argument the level of conventional consumption in each period, discounted by the *pure rate of time preference*, ρ. The assumptions that the felicity function and pure rate of time preference are invariant over time are convenient simplifications.

For any given path of consumption, c, we can define a discount rate, $r[c]_t$, for each period by asking how much the representative agent would have to be paid in period $t+1$ to compensate for a small reduction of consumption Δc in period t, which would require the ratio of her utility loss in period t to her utility gain in period $t+1$ to be 1. It is convenient to write $g_t = \frac{c_{t+1}}{c_t} - 1$ for the growth rate of consumption from period t to $t+1$, and $\eta_t = -u''\left[c_t\right] c_t / u'\left[c_t\right]$ for the elasticity of the typical individual's marginal utility of consumption with respect to consumption evaluated at the consumption level in period t. In general, $\eta\left[c_t\right]$ is a function of c_t.[2] Since

$$\begin{aligned} u'[c(1+g)] &\approx u'[c] + u''[c]gc \\ &= u'[c]\left(1 + \frac{u''[c]c}{u'[c]}g\right) = u'[c](1-\eta g) \end{aligned}$$

we can evaluate the discount rate:

$$\begin{aligned} 1 &\approx \left(\frac{u'\left[c_t\right]\Delta c}{(1+\rho)^t} \Big/ \frac{u'\left[c_t\left(1+g_t\right)\right]\left(1+r[c]_t\right)\Delta c}{(1+\rho)^{t+1}}\right) \\ &\approx \frac{1+\rho}{1+r[c]_t} \frac{u'\left[c_t\right]}{u'\left[c_t\right]\left(1-\eta_t g_t\right)} \quad \text{or} \end{aligned}$$

$$\left(1+r[c]_t\right)\left(1-\eta_t g_t\right) \approx 1 + r[c]_t - \eta_t g_t = 1+\rho$$

or

$$r[c]_t \approx \rho + \eta_t g[c]_t \tag{2}$$

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[2] A very common first approximation specification of the felicity function is to assume a constant elasticity of marginal felicity with respect to consumption: $u[c] \equiv \frac{c^{1-\eta}-1}{1-\eta}$ or $\ln[c]$ if $\eta = 1$. With $u'[c] = c^{-\eta}$, and $u''[c] = -\eta c^{-\eta-1}$, this implies $-\frac{u''[c]c}{u'[c]} = \eta$.

with (2) holding with equality for CES utility. The crucial point to remember is that the discount rate in (2) refers to a specific period on a specific path of consumption.

A standard assumption in cost-benefit analysis is that investment projects have marginal effects on a specific consumption path. In such scenarios, the consumption path is invariant to different scenarios. The cost and benefit of climate change mitigation, however, entail reallocations of resources at a non-marginal scale so that the assumption of exogenous consumption paths does not hold (Heal, 2009; Dietz and Hepburn, 2013); discount rates can only be discussed in connection with a specific consumption scenario.

Even if we assume that the elasticity of marginal felicity with respect to consumption is invariant over time, the typical individual's discount rate varies over time if the growth rate of consumption varies over time. This case is particularly relevant to evaluating investments in mitigation that would vary the typical individual's consumption around a BAU path, because BAU paths are prone to climate catastrophes in which the growth rate of consumption becomes negative for significant periods of time.

Many thoughtful welfare economists and economic philosophers argue that there are no good reasons for individuals to discount the felicity of future generations at all, that the pure rate of time preference ought to be taken as $\rho = 0$. But Eq. (2) warns us that this emphatically does not mean that the relevant discount rate for consumption on a particular growth path is zero (Heal, 2009). In fact, this case underlines the important point that the relevant discount rate for consumption itself may be negative in periods where consumption is shrinking on a BAU path due to climate damage. In summary, we present

Proposition III. *In dynamic analysis of environmental quality and consumption, a typical individual will have a short-term discount rate which is the sum of a pure rate of time preference and the product of the elasticity of her marginal utility of consumption with respect to her level of consumption times the growth rate of her consumption. Consumption growth rates will change as the economy evolves over time so that reasoning in terms of a constant social discount rate is beside the point. Whether the pure rate is a (small) positive number or zero is of secondary importance.*

Given a path of consumption for the typical individual $c = \{c_1, \ldots, c_T\}$, the present discounted value of a small variation in consumption in period t, Δc_t, which might be the result of a reduction in greenhouse gas emissions is

$$\left(\prod_{\tau=1}^{t} \frac{1}{1 + r[c]_\tau}\right) \Delta c_t$$

where each r_τ is given by (2). In periods where $r[c]_t$ is negative, which can occur if $g[c]_t$ is negative, the discount factor will actually be greater than unity. On paths with sustained declines in the consumption of the typical individual, the present value may be comparable to or a multiple of the consumption benefit associated with an investment in reducing greenhouse gas emissions.

This is equivalent to discounting the path of consumption at a sequence of average discount rates $R[c] = \{R[c]_1, \ldots, R[c]_T\}$ where

$$\left(\frac{1}{1 + R[c]_t}\right)^t = \prod_{\tau=1}^{t} \frac{1}{1 + r[c]_\tau} \quad \text{or}$$
$$\frac{1}{1 + R[c]_t} = \left(\prod_{\tau=1}^{t} \frac{1}{1 + r[c]_\tau}\right)^{1/t}. \tag{3}$$

The present discounted value of a stream of consumption $\Delta c = \{\Delta c_1, \ldots, \Delta c_T\}$, given a reference consumption path c is thus

$$\sum_{t-1}^{T} \frac{\Delta c_t}{1 + R[c]_t}. \tag{4}$$

3.2. Marginal cost of environmental quality

Technology constrains the possible paths of conventional consumption and environmental quality achievable given currently and prospectively available resources. One widely adopted approach to the economic analysis of climate change assumes that potential output in each period depends on the conventional capital stock available in that period, but that the level of environmental quality determines the proportion of this potential output that survives the damage associated with climate change in usable form. This usable output then has to be divided between conventional consumption, conventional investment, and investment in mitigating greenhouse gas emissions. These assumptions are represented mathematically as *constraints*:

$$\begin{aligned} k_{t+1} &= (1 - \delta)k_t + z\,[e_t] f\,[k_t] - m_t - c_t \\ e_{t+1} &= (1 + \epsilon)e_t - \beta f\,[k_t] \\ &\quad + g\left[\frac{m_t}{z\,[e_t] f\,[k_t]}\right] z\,[e_t] f\,[k_t], \quad \text{or} \end{aligned} \tag{5}$$

$$F[c, e, k, m] = 0. \tag{6}$$

In this formalism, k_t represents the conventional stock of capital, $y = f\,[k_t]$ represents potential output, $z\,[e_t]$ is the proportion of potential output that survives climate damage, m_t is investment in mitigation of greenhouse gas emissions, δ is the proportion of the existing conventional capital stock that is lost in each period to depreciation, β is the rate of emissions of greenhouse gases from (potential) production, $g[\cdot]$ is the rate of mitigation, and ϵ is the spontaneous improvement in environmental quality due to natural decay of greenhouse gases. The functional $F[\cdot]$ in (6) summarizes the constraints in (5) and therefore depends on the complete paths of consumption, environmental quality, conventional capital, and mitigation investment through the technological constraints (5). It is a representation of the intertemporal production possibilities set.

Since this technology includes the damage of climate change in the survival function, $z[\cdot]$, it is consistent with the assumption that the felicity function depends only on consumption per capita (or, for simplicity, per employed worker), as we worked out above.

What is the marginal cost of a change in the path of environment quality? Suppose, given reference paths of mitigation investment, consumption, and conventional capital, m, c, k, (sometimes referred to as a *scenario*) that lead under the constraints (5) to a path of environmental quality $e[c, k, m]$ ($F[c, e[c, k, m], k, m] = 0$), we want to achieve a change in the path of environmental quality $\Delta e = e[m + \Delta m, c + \Delta c, k + \Delta k] - e[m, c, k]$ also consistent with the technological constraints (5) (so that $F[c + \Delta c, e + \Delta e, m + \Delta m, k + \Delta k] = 0$). If the reference path is not optimal, it will be possible to find technologically feasible alternate paths for which $\Delta U = U[c + \Delta c] - U[c] > 0$. Thus unless the reference path is optimal, the marginal cost in terms of the typical agent's utility of environmental quality is negative, as in the static example of the first section of this note.

Estimates of the marginal cost of environmental quality (for example, reduced atmospheric GHG concentrations) must implicitly hold one of the dimensions of the reference path constant, for example the path of conventional capital. Using (4), we see that the path $\Delta m[\Delta e, \Delta k = 0]$ satisfies

$$\begin{aligned} \Delta e_{t+1} &= \epsilon \Delta e_t + g'_t \left(\frac{\Delta m_t}{z\,[e_t] f\,[k_t]} - \frac{z'_t \Delta e_t m_t}{z\,[e_t]^2 f\,[k_t]}\right) \\ &\qquad \times z\,[e_t] f\,[k_t] + g\left[\frac{m_t}{z\,[e_t] f\,[k_t]}\right] f\,[k_t]\, z'_t \Delta e_t \quad \text{or} \\ \Delta m_t &= \left(-\epsilon e_t - m_t \frac{z'_t e_t}{z_t}\left(1 + \frac{g_t}{g'_t}\frac{z_t f\,[k_t]}{m_t}\right)\right)\frac{\Delta e_t}{e_t} \\ &\qquad + \frac{\Delta e_{t+1}}{g'_t} \quad \text{and} \end{aligned}$$

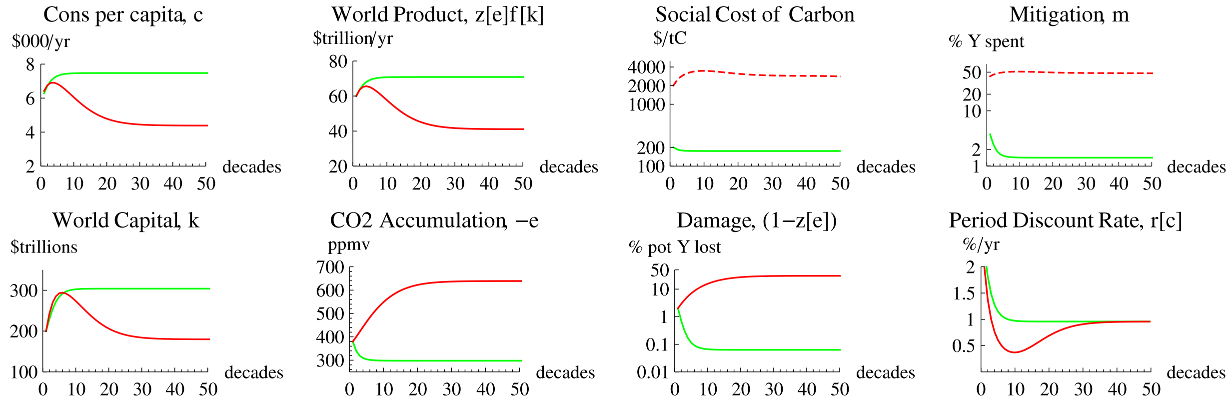

Fig. 2. Model simulations for the world economy in the absence (OPT, light) and presence (BAU, dark) of the negative emission externality.

$$\Delta c_t = \frac{z'_t e_t}{z_t} z\left[e_t\right] f\left[k_t\right] \frac{\Delta e_t}{e_t} - \Delta m_t .$$

The marginal cost of the Δe path then can be calculated as the present discounted value of the corresponding Δc path at the discount rate path $R[c]$ defined in the last section.

3.3. Costs and benefits are conditional on reference paths

We summarize these conclusions in

Proposition IV. *Estimates of costs and benefits of greenhouse gas mitigation must be conditional on a scenario that specifies a reference path of consumption and environmental quality, as well as on the "felicity" function and pure rate of time preference assumed for the typical individual and the technology described by particular production, damage and mitigation functions. The discount rates at which the present value of costs and benefits must be calculated also depend on the reference path of consumption implied by a particular scenario.*

4. An example

As an example of the working out of these ideas concretely, consider the model of Rezai et al. (2012). This model assumes a typical individual with an isoelastic utility of consumption per capita, and a technology for conventional capital accumulation of the same type as (5). This typical individual is assumed, in line with much of the existing literature (Nordhaus, 2008), to have a pure rate of time preference of 1% per year, and an elasticity of marginal utility with respect to consumption of −2. The environmental quality variable in that paper is atmospheric concentration of carbon dioxide (which is treated as a "bad", requiring suitable changes of sign in (5)). All other parameter values are taken from Rezai et al. (2012) who calibrate the model to match data for the world economy in 2009.

The center of this paper is the calculation of paths for consumption, conventional capital, environmental quality, climate change damage, and mitigation under two sets of assumptions. The optimal path (OPT) is calculated by maximizing the typical individual's utility under the full technological constraints (5), thus assuming that the GHG emission externality is completely internalized through some combination of policies, which might take the form of cap-and-trade markets, carbon taxes, or direct controls on emissions. This path implies a path of shadow prices (Lagrange multipliers) for carbon emissions, which governs consumption, conventional investment, and mitigation expenditures (see Chichilnisky and Sheeran (2009) for an interpretation of these shadow prices as the market prices for emissions in a cap-and-trade system). On the optimal path the marginal cost of mitigation is equal in each period to the marginal benefit from avoiding climate damage. On this path (see Fig. 2), given today's technology and population size, per capita consumption rises smoothly from about \$6000 (measured in current US dollars) to about \$7500 over next 100 years of the simulation. The carbon price declines from about \$200/t of carbon (\$55/tCO$_2$) to a steady level of around \$175/tC (\$48/tCO$_2$). This carbon price induces the expenditure of around 3% of world output on mitigation in the early periods, declining to 1.5% in the steady state, and investment in mitigation which is sufficient to return atmospheric concentrations of carbon dioxide to pre-industrial levels and reduce climate damage to negligible levels. Our SCC estimates are within the usual (wide) range of numbers (Kuik et al., 2009; McKinsey & Company, 2009). If we modify mitigation technology to preclude negative emissions, the SCC would rise. On this optimal path the implied real interest rate (as defined by (2) above) declines from above 2% in early periods to the pure rate of time preference 1% in the steady state. This path corresponds to the OPT type of allocation pictured in Fig. 1.

Proposition V. *Numerical simulations suggest that an "optimal" strategy for mitigation of climate change (with the social cost of mitigation equal to present discounted value of damages avoided) could be achieved by reallocating about 10% of current world investment (2.5% of world output) to emission–mitigation. The social discount rate would decline as consumption growth slows. As is typical in dynamic optimization models without complicated constraints on timing, mitigation outlays as a share of output would be higher during early phases of the plan. (A "corollary" is that since mitigation may be less costly in developing countries, it should be "frontloaded" there.)*

The business-as-usual (BAU) path makes the same assumptions about the preferences of the typical individual and the technology of world production and greenhouse-gas emission and accumulation as on the OPT path. The difference is that the costs of greenhouse-gas emission remain external and are not taken into account, i.e. the shadow price of greenhouse gas emissions is set to zero on the BAU path, and the typical individual chooses consumption, conventional investment, and mitigation levels to maximize utility subject to the resulting budget constraint, correctly anticipating the actual atmospheric accumulation of greenhouse gases that results. The mathematical assumption that the shadow price of greenhouse gas emissions is zero, like the BAU point in Fig. 1, implies that although the typical agent correctly forecasts the accumulation of greenhouse gases and the resulting climate damage to economic production, she does not adjust her individual consumption, investment, and mitigation spending to take account of their actual impact on emissions and climate change. With a zero shadow (or market) price of carbon, the typical individual makes no mitigation investment at all.

The BAU path in these simulations follows the OPT path closely for several decades, but then diverges sharply due to a "climate catastrophe'', rapidly rising economic damages attributable to high greenhouse gas concentrations in the atmosphere. These damages reduce the effective productivity of labor and conventional capital and force per capita consumption to drastically lower levels, which fall significantly below current levels and stabilize at around \$4500 per capita. On this BAU path, as we might expect, GHG concentrations rise steadily, which ultimately imposes a loss of about 30% of potential output to climate damage. The implied real interest rate on the BAU path starts somewhat lower than on the OPT path, at around 2% per annum, and then fall below the pure rate of time preference 1% after the ''climate catastrophe'', which per capita consumption levels are falling steadily. Rezai et al. (2012) assume exogenous technological progress and population growth. Higher productive capacity increases income levels and lowers the cost of mitigation. It also worsens the externality, leading to steeper falls in consumption per capita and interest rates. These low real interest rates reflect the strong desire of the typical individual to shift consumption from the periods preceding the climate catastrophe to the periods of the climate catastrophe. Because she anticipates high levels of consumption before the climate catastrophe relative to the low levels of consumption during and after the climate catastrophe, the typical individual will make investments with real rates of return below the pure rate of time preference under these circumstances. While there is no effective shadow or market price for greenhouse gas emissions on the BAU path, it is possible to calculate the implied price of carbon on this path using the methods developed in the previous sections of this note. In contrast to the OPT path, where the carbon price starts at around \$200/tC (\$55/tCO_2) and declines steadily over time, on the BAU path the implied carbon price starts at about \$2000/tC (\$550/tCO_2) and soars to a peak of around \$3500/tC (\$950/tCO_2) at the height of the climate catastrophe. It is important to note that this is owed not only to high damage levels, but also to low discount rates implied by falling consumption possibilities while technology and preferences are kept unchanged. Ackerman and Stanton (2012) derive similar social carbon prices for optimal paths by changing climate, damage, and preference parameters.

4.1. What is the social cost of carbon in this model?

This question can be answered only in relation to some particular scenario that defines a reference path. If the scenario is the OPT scenario, which envisions the effective internalization of the greenhouse gas emission externality in the near future, the social cost of carbon can be measured either by the discounted present value of the damages imposed on the economy by the emissions from a tonne of carbon, or by the marginal cost of mitigating those emissions, since on an optimal path these measures must be equal. With the damage, production, and mitigation technologies assumed in the model, the social cost of a tonne of carbon at present is around \$200 (\$55/tCO_2). This estimate is significantly higher than estimates of a social cost of carbon dioxide on the order of \$77/tC or, equivalently, \$21/tCO_2 (Interagency Working Group, 2010), which are the basis of current and future US climate policy according to Ackerman and Stanton (2012).

If the scenario defining the reference path for consumption is the BAU scenario, however, the question of the social cost of carbon becomes more complicated. In this type of non-optimal (second-best) scenario, there are two possible meaningful answers. One is the discounted present value of future damages imposed by the emissions from burning 1 t of carbon, which, given the model's assumptions, is about \$1500/t, 7 times the value on the OPT path. The other is the marginal cost of mitigating the emissions from 1 t of carbon, which are actually somewhat lower than the OPT path, about \$160/t. (The reason the BAU marginal cost of mitigation is lower than the OPT marginal cost is that the model assumes diminishing returns to mitigation investment, and the BAU level of mitigation, zero, is smaller than the OPT level of mitigation of about 1.5% of world output.) To summarize, we present

Proposition VI. *On an optimal path, a plausible estimate of the marginal cost and benefit of mitigation is about* \$200 *per tonne of carbon (*\$55/tCO_2*). On a BAU path the marginal cost would be about* \$160/t *of carbon (*\$44/tCO_2*), but the marginal benefit would be about* \$1500/t *of carbon (*\$410/tCO_2*).*

5. Methodological fallacies in GHG cost-benefit analysis

Because estimates of costs of GHG emissions, benefits of emission–mitigation, and the rates at which it makes sense to discount these costs and benefits are logically conditioned on a scenario that specifies reference paths for consumption and environmental quality, analysts who treat any of these concepts as independent of reference path assumptions are vulnerable to methodological error.

It does not make sense, for example, to compare the average of estimated present discounted benefits of GHG emission mitigation under various scenarios to the average of estimated present discounted costs *even if these averages refer to the same set of scenarios*. Unfortunately this type of comparison is frequently the content of studies of the social cost of carbon intended to inform policy makers.

The results of the Interagency Working Group (2010) are subject to two errors pointed out in this note. First, the study assumed fixed interest rates for its scenarios (5%, 3%, and 2.5% per year). The SCC was then calculated by discounting future damages from carbon emissions using one of these interest rate parameters. In conventional cost-benefit analysis, interest rates are taken to be given as investment projects are assumed to be ''small'', i.e. not large enough to affect the overall allocation of resources. We argue that this is not the case when considering the problem of climate change. Climate change is happening on very large geographical and temporal scales and, if left unchecked, can easily alter the allocation of resources and with it the trajectory of the interest rate. Second, the study used three prominent climate–economy models for its assessment of the SCC: FUND (Tol and Anthoff, 2010), PAGE (Hope, 2006; Stern, 2006) and DICE (Nordhaus, 2008). Each model was used to assess the costs of pre-determined emission scenarios. To boil the three differing SCC time profile down to a single one, averages were taken.

The three models used in the study are themselves subject to some of the fallacies discussed in this note. FUND and PAGE rely on assumptions of exogenous growth paths of output and consumption. Through the adoption of (2), their discount rate is fixed by exogenous changes in consumption. The assumption of the rule in (2), which is based on optimal saving behavior, is, however, dubious in light of exogenous investment, consumption, and output trajectories. The guiding principles in building FUND and PAGE were not general equilibrium considerations, but the aspirations of creating comprehensive accounts of the effects and costs of climate change. Omitting the possibility that climate change can alter the allocation of resources, through e.g. inducing significant reductions in future consumption possibilities, these models either implicitly assume that either climate change is not a serious problem or base their welfare analysis on weak economic footing.

The third model used in the interagency study, DICE, is the only model which is based on the kind of intertemporal optimization outlined above; optimal saving behavior guarantees that general equilibrium considerations are taken into account and that (2) holds with equality. Nordhaus (2007) has been adamant about pointing out its implication for the estimation of discount rates and argues that the pure rate of time preference has to be chosen "descriptively", i.e. in a way to reproduce interest rates observed in actual markets (Arrow et al., 1996). In the view of the "descriptionists", mitigation investment has to yield at least the same return as the capital investment it displaces. However, their arguments usually implicitly assume a first-best world in which resources are allocated optimally and price signals represent accurate measures of scarcity (Stiglitz, 1982; Heal, 2009). Most importantly, Nordhaus (2008, 2011) and other proponents do not take into account the failure in the market for GHG emissions (Rezai, 2011). The externality induces market participants to overvalue conventional and undervalue "climate" capital (Foley, 2009). As a result, the observable market interest rate is distorted and the market interest rate corresponding to an economy with an internalized externality would be lower. One implication of this is that SCC is underestimated due to the assumption of a too high pure rate of time preference. The imposition of the assumption of an optimal world additionally lowers SCC estimates because on optimal paths the SCC is limited by the marginal cost and benefit of mitigation. Such scenarios do not report the current of SCC, the social cost of carbon emissions in a world in which they pose an uncorrected externality.

6. Risks

There are important uncertainties inherent in the greenhouse gas mitigation problem. As compared with other problems of projecting economic growth over long time horizons, which must also make assumptions about the productivity of labor and other inputs to production, the most salient of these uncertainties concern the damages from climate change and the costs of mitigation.

The cost of mitigation is the more straightforward and tractable of these problems. There already exists a spectrum of emission–mitigation technologies, ranging from the substitution of sustainable energy sources such as solar power for burning of fossil fuels to remediations like carbon sequestration either at the point of combustion, or directly from the atmosphere. These mitigation technologies exist at various stages of maturity, from systems currently available on the market, through systems at various stages of technical development. Behind these technologies we have a very well-developed understanding of the science relevant to mitigation. The existing technologies serve to put credible upper bounds on the initial marginal cost of mitigation. The rate at which returns to these technologies will diminish as they are scaled up in size is less well-established, though educated assessments informed by the underlying science can reduce these uncertainties to levels comparable to those encountered in other public-policy decisions. (There is also a strong presumption that if vigorous and large-scale markets for these technologies were established by policies to control the greenhouse gas emission externality, economies of scale and learning-by-doing would to some degree offset these diminishing returns.) Thus the costs of doing something about mitigation are fairly well understood.

The damages to be anticipated from climate change are subject to much greater uncertainties, arising from our imperfect understanding of the non-linearities of climate interactions that will become increasingly important at higher atmospheric concentrations of greenhouse gases, and the complexities of assessing the economic damage to be attributed to climate change. From a practical point of view, however, these uncertainties may not be a severe obstacle to the establishment of responsible and prudent public policy.

The most important point is that on paths in which we make a significant effort to mitigate greenhouse gas emissions, greenhouse gas concentrations will not rise much beyond present levels (and may over time fall back closer to pre-industrial levels). In these scenarios the speculative question of just how severe a climate catastrophe will be or at what levels of atmospheric accumulation of greenhouse gases would precipitate it become irrelevant to policy because they will never eventuate.

The other side of this coin is that on BAU-type paths with very low levels of mitigation investment, it is quite certain that greenhouse gas accumulations will rise effectively without any limit. Thus even if a model makes very large errors in associating particular levels of greenhouse gas accumulation with particular levels of economic damage through adopting some particular damage function, *sooner or later* on BAU paths catastrophic levels of economic damage are highly likely. The exact timing of a climate catastrophe may be quite uncertain, but the eventual occurrence of one is much more likely. From the cost-benefit point of view taken in this note, the key point is when a climate catastrophe imposes sharp reductions in economic welfare on the world population, the implicit real interest rate will fall sharply and in some scenarios can become negative. Whether this occurs in 200 or 400 years it has the effect of greatly increasing the present discounted value of emissions damage, and hence the marginal benefit of avoiding that damage through mitigation of emissions, through the negative discount rate effect. A similar argument was made by Weitzman (2009) in the context of fat-tailed structural uncertainty.

The general conclusion of statistical decision theory, which analyzes rational policy making under uncertainty, is that when loss is a convex function of a state variable like environmental quality the avoidance of bad outcomes must be weighed more heavily than the chance of good outcomes in choosing policy. At this point the relevant favorable possibilities in greenhouse gas emission policy are the eventualities either that we will discover that greenhouse gas accumulations will not lead to climate change through average temperature rise, or that large temperature increases will turn out not to impose major economic costs. Neither of these eventualities seems very probable given current scientific evidence and knowledge. But the mistake our species would make in investing 2.5% of current output in mitigation of greenhouse gas emissions if it turned out to be unnecessary is much less serious than the mistake we would make in following a BAU scenario up to a climate catastrophe (see Heal, 2009, for numerical examples; Lemoine and Traeger, forthcoming; Millner et al., 2013, for the effects of such reasoning on optimal abatement strategies). In summary, we present

Proposition VII. *The costs of mitigation are reasonably well understood. Potential damages from climate change are much harder to evaluate, but could be very high. A key result in the theory of decision-making under uncertainty is that if damages from climate change rise non-linearly with the extent of change, then the avoidance of bad outcomes should be weighed more heavily than the attainment of good ones. Investing* 2.5% *of GDP in mitigation would be a much less serious mistake than not investing and following a BAU path to climate catastrophe.*

7. Conclusion—the social cost of carbon

The social cost of carbon can be meaningfully estimated only in the context of concrete scenarios of future consumption and environmental quality. Even subject to the considerable uncertainties in current scientific and economic analysis, some conclusions seem highly probable.

On a close-to-optimal mitigation path, the social cost of carbon will be limited by the marginal cost of mitigation, which seems to be unlikely to be higher than \$200/tC (\$55/tCO_2). If the burning of fossil fuels were priced at this level, it is likely that about 2.5% of world output might be diverted to mitigation, with the prospect of a decline in this proportion over time as greenhouse gas accumulations recede and lower-cost mitigation technologies come on line. Since world investment is about 23% of world output, such climate policy would induce a redirecting of about 10% of world investment to mitigation, which is far from trivial. However, the uncertainties surrounding this scenario are fairly limited; especially the concentration of atmospheric carbon and its damage, for which we know least for unprecedented levels, would be limited to a historical or reliably projectable range.

On a business-as-usual path where mitigation remains very low, greenhouse gas accumulation will inexorably rise, with a high probability of triggering a climate catastrophe at some point and imposing severe economic costs. With this scenario and reference path, the present discounted value of carbon emission is likely to be several multiples of the level on an optimal path, on the order of \$2000–\$3500/tC (\$550–\$950/tCO_2). This is owed to higher damage levels, but also to lower discount rates implied by falling consumption possibilities. The marginal cost of mitigation on these paths will be very close to and somewhat lower than the marginal cost on the close-to-optimal paths.

Our conclusions support rapid implementation of policies which impose the social cost of carbon on individual decision makers. The underlying welfare economics suggest that such a shift towards optimal policy makes available efficiency gains. The costs of a transformation of the energy base, while not trivial, are reasonably well understood and manageable. A continuation of the current near-zero mitigation policies will increase the concentration of atmospheric carbon to levels whose implications are unpredictable but potentially disastrous for the world economy.

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