TIME DISCOUNTING AND OPTIMAL EMISSION REDUCTION: AN APPLICATION OF *FUND*

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Abstract. Time preferences are a dominant influence in cost-benefit analyses of long-term issues such as climate change. *FUND*, a model for optimal emission control, is used to spell out this influence. Classic discounting at various rates is contrasted with Heal discounting where the discount factor depends logarithmically on the time distance (it does linearly in the classic case), and Rabl discounting where the discount rate is set to zero at a certain point in the future. The choice of the discount rate has a strong influence on total and short-term emission reduction. The effect of Rabl and Heal discounting is like lowering the classic discount rate. International cooperation has a larger effect on optimal emission reduction, however, than does the discount rate. Larger still is the influence of explicitly taking up long-term goals for atmospheric concentrations in the welfare function, using a modification of the Chichilnisky criterion.

1. Introduction

A rational climate policy requires that current costs of emission reduction be traded off against future benefits of mitigated climate change. The first step in this trade-off is expressing costs and benefits in a common metric, usually money. This is not the subject of this paper; cf. Pearce et al. (1996). The second step in the trade-off is the comparison of the future to the present. The common approach to this is to use a discount rate, which translates future values into present values. As carbon dioxide remains for a long time in the atmosphere and climate reacts slowly to a change in radiative forcing, the choice of the discount rate is one of the main determinants of the balance between costs and benefits of emission reduction, and subject to dispute (for a recent discussion, see Hasselmann et al. (1997), and the comments by Nordhaus (1997), Brown (1997), and Heal (1997)).

The choice of discount rate is on the one hand empirical and ethical on the other. It is empirical because people, companies and governments make trade-offs between present and future every day. It is ethical because the discount rate determines the allocation of intertemporal goods and services between generations.* In

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* Gerlagh (1997) argues the other way around, letting intertemporal allocations of resources determine the discount rate; the advantage of this approach is a greater intuitive appeal of concrete resource allocations compared to abstract discount rates. d'Arge et al. (1982) let the discount rate be a derivative of an intergenerational welfare function.

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this matter, empirical evidence cannot overrule ethical considerations, because (*i*) the enhanced greenhouse effect is a unique problem and (*ii*) ‘what is’ is not the same as ‘what ought to be’ (the naturalist fallacy). At the same time, ethical considerations cannot overrule empirical evidence either because everyday decisions on intertemporal trade-offs reflect partly the ethics of the decision-makers. Arrow et al. (1996a) give an excellent discussion of current thinking of the issue.

This paper will not try to resolve the appropriate discount rate, not even offer novel arguments for its choice. Instead, I discuss the implications of various discount rates on optimal emission reduction, applying an integrated assessment model known as the *Climate Framework for Uncertainty, Negotiation and Distribution*, Version 1.6 (*FUND*); see Tol (1997a–c) for a description of the model.

FUND applies welfare optimization, a fancy version of cost-benefit analysis, to climate change. The paper is a sensitivity analysis around a crucial assumption in welfare optimization, namely, the discount rate. The paper can also be read as an exploration of the limits of welfare optimization. If the reader believes these limits are passed, the paper becomes a demonstration of the inappropriateness of welfare optimization to such problems as climate change. Tol (1998b) offers a similar approach with regard to uncertainty. Arrow et al. (1996b) and Munasinghe et al. (1996) offer climate-change-specific alternatives to welfare optimization and cost-benefit analysis, and their basic assumptions about consequential rationality.

Section 2 presents four alternative views to look at discounting. Section 3 gives a brief introduction to the *Climate Framework for Uncertainty, Negotiation, and Distribution* (*FUND*). In Section 4, this integrated assessment model is used to analyze the effect of alternative discount rates on optimal greenhouse gas emission control. Section 5 concludes.

2. Various Approaches to Time Discounting

A basic expression for the discount rate r of consumption is

$$r = \rho + \eta g \, , \tag{1}$$

where g is the growth rate of consumption, η is the elasticity of utility in consumption, and ρ is the pure rate of time preference. The discount rate r varies over time, and between goods and services. Some parts of the economy may grow faster than other parts, and preferences for goods and services may change over time. These problems are avoided by using *FUND*. Implicitly, different discount rates are used for different goods and services. The differences follow from the structural changes described by the model. Notably, the discount rate of agricultural products is below average, because this sector is a slow grower (g is low). The discount rate of ecosystem services is below average because people with higher incomes are assumed to value ecosystems higher (η falls over time). Discount rates for other goods and services, and hence the costs of emission reduction, are higher. However, the pure rate of time preference ρ is equal for all goods and services.

That leaves us the pure rate of time preference ρ. Discount rates referred to below are all utility discount rates, or pure rates of time preference. Conventionally, utility at time t is discounted to time 0 by a discount factor DF_t

$$DF_t = (1+\rho)^t \, . \tag{2}$$

Below, ρ assumes the values of 0%, 1% and 3% per year. I refer to this as ‘classic discounting at x%’, even though the chosen discount rates are not necessarily classic. A discount rate of 0% treats utility at any time at par. Ramsey (1928) is an early proponent of this view, which also has advocates today (e.g., Parfit, 1993). A notable feature is that the time horizon of interest equals the time horizon of the disturbance, which is in the case of climate change a far remote future. It takes at least centuries for the effects of today’s greenhouse gas emissions to have faded out. A discount rate of 3% is based on time preferences as observed at long-term risk-free capital markets (Nordhaus, 1994). The enhanced greenhouse effect is not a capital market and it is not free of risk, while the risk premium lowers the discount rate in this case (Tol, 1995). A discount rate of 1% is an arbitrary choice between 0% and 3%.

Heal (1996, 1997) argues that (2) is inappropriate. Using empirical evidence from cognitive psychology, Heal (1996, 1997) concludes that the discount rate depends on the length of the time period considered, in a logarithmic fashion. Thus, (2) is replaced by

$$DF_t = (1+\rho)^{\ln t} \, . \tag{3}$$

Below, ρ assumes the value of 1% per year. I refer to this as ‘Heal discounting’. A distinct advantage of (2) is its attempt to reconcile observed behaviour (and talk) on short and long term issues. Note that Cropper et al. (1992), Henderson and Bateman (1995), and Weitzman (1998) arrive at discount factors with behaviour similar to (3).

Schelling (1995), Rabl (1996) and Lind and Schuler (1996) argue that discounting is inappropriate for intergenerational issues. Schelling (1995) argues that a utility discount rate measures emphatic distance, and that future generations cannot be emphatically distinguished. This is particularly the case for more remote generations, so that Schelling (1995) may share Heal’s (1996, 1997) point of view. Rabl (1996) argues that a discount rate gives improper low weight to the future. Lind and Schuler (1996) argue that discounting implicitly assumes that designated capital transfers between generations are possible, an assumption Lind and Schuler (1996) find incorrect. In fact, Schelling (1995), Rabl (1996) and Lind and Schuler (1996) all argue that discounting is appropriate within a generation but inappropriate for future generations. An extreme interpretation of this, explicitly stated only by Rabl (1996), is

$$DF_t = \begin{cases} (1+\rho)^t & t < T \\ (1+\rho)^T & t \geq T\,, \end{cases} \tag{4}$$

where T is the life-time of a generation. Below, ρ assumes the value of 1% per year; T assumes the value of 10 year, the assumed life-time of a generation of decision-makers. I refer to this as ‘Rabl discounting’.

Long-term discounting reflects our views about intergenerational equity and sustainability. An alternative way of expressing such views is due to Chichilnisky (1996). She argues that sustainability means that the preferences of the current generation do not dominate the preferences of future generations in determining intergenerational distributions of resources. This axiom of ‘non-dictatorship of the present’ combined with one of ‘non-dictatorship of the future’ leads, under some mild regularity conditions, to an intertemporal welfare function that looks like

$$W_{\text{Chichilnisky}} = \alpha \sum_{t=0}^{\infty} W_t DF_t + (1-\alpha) \lim_{t\to\infty} W_t\,, \tag{5}$$

where t denotes time, W welfare and DF some discount factor. Thus, the Chichilnisky criterion is the weighted sum of standard net present welfare and the limiting properties of the system under consideration. This approach may be interpreted as stewardship for future generations’ welfare, as advocated by *inter alia*, Brown (1992). Although theoretically appealing, the Chichilnisky criterion is not readily implemented, partly because the connection between climate change and sustainability is not straightforward (Tol, 1998a).

Below, net present welfare follows from classic discounting with a 1% discount rate; see equation (2). The limit under consideration is the atmospheric concentration of carbon dioxide in the year 2200 (the end of the simulation period). It is translated into welfare as the squared deviation of its desired value (550 ppm). Thus,

$$W_{\text{Chichilnisky}} = \alpha \sum_{t=0}^{2200} \frac{W_t}{(1+\rho)^t} + (1-\alpha)(C_{2200} - 550)^2\,, \tag{6}$$

where C_{2200} denotes the CO_2 concentration in 2200. The weight is such that the business as usual concentration (1793 ppm) takes away half of net present welfare for the first generation of decision makers, that is

$$\alpha_0 = \frac{1/2 \sum_{t=0}^{2200} \frac{W_t^{BaU}}{(1+\rho)^t} - (1793-550)^2}{\sum_{t=0}^{2200} \frac{W_t^{BaU}}{(1+\rho)^t} - (1793-550)^2}\,. \tag{7}$$

For later generations, the weight placed on the limit falls linearly to zero for the 21st and last generation:

$$\alpha_g = \alpha_0(1 - 0.05g)\,, \tag{8}$$

where g denotes the number of the generation, $g = 0, 1, \ldots, 20$. These choices are somewhat arbitrary (as are many above) but serve to illustrate the point.

LeCocq and Hourcade (1997) chose the welfare in the last periods of their model as the limiting factor in (5). Welfare on the long term depends to a substantial extent on how much near-term emission reduction interferes with the economic growth path. The interpretation of LeCocq and Hourcade (1997) may be closer to Chichilnisky's (1996) views. My interpretation is probably closer to Article 2 of the Framework Convention on Climate Change.

3. The Model

FUND is an integrated assessment model of climate change, combining representations of population, economy, greenhouse gas emissions, carbon cycle, climate, and impacts for nine world regions for the period 1950–2200. A detailed model description can be found in Tol (1996–1998). The source code is available upon request.

The period 1950–1990 is used to initialize the climate change impact module, and to give some empirical support to the scenarios used. The period 1990–2100 is used for policy analysis. The period 2100–2200 is used to derive proper final conditions in 2100 (decision makers in *FUND* are forward looking). Hasselmann et al. (1997) argue that climate dynamics are such that one should look beyond 2200. The period beyond 2200 indeed matters for some of the discount rates of the previous section. However, the simplicity of *FUND*'s energy, economy and climate modules does not allow for extrapolation that far in the future.

Essentially, the model revolves around a few driving scenarios (for population, economy, and technology potentials) with all other variables calculated endogenously. The driving scenarios are very close to the EMF Standardised Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). Population is affected by climate change through changed mortality and migration. Economic activity is affected by climate change through damages and adaptation, and by emission reduction through its costs. Technologies are affected by emission reduction.

The modules for greenhouse gas concentrations, climate and sea level rise behave like the simple climate models discussed by the IPCC (Harvey et al., 1997). Greenhouse gases are geometrically depleted in the atmosphere, methane and nitrous oxide in a one-box model with life-times of 9 and 120 years, respectively, and carbon dioxide in a five-box model with life-times varying between 2 years and infinity. Other greenhouse gases are omitted. Radiative forcing is taken from Shine et al. (1990). Climate is represented by the global mean surface air temperature. The equilibrium temperature is linear in radiative forcing, with a climate sensitivity of 2.5 °C. Actual temperatures rise geometrically to their equilibrium level, with a half-time of 50 years, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50}\frac{2.5}{6.3\ln(2)} RF_t\,, \tag{9}$$

where T denotes temperature and RF radiative forcing, both in deviation from pre-industrial times. Sea level rise is modelled similarly, with a sensitivity of 30 cm/°C and a half-time of 50 years.

Climate impacts follow Tol (1996). This module is different in structure from most impact modules in integrated assessment models (cf. Tol and Fankhauser, 1998) but this does not lead to substantially different conclusions (cf. Tol, 1997b). Climate impacts are modelled as second-order polynomials in the change and the rate of change of temperature and sea level. Impacts depending on the rate of change fade geometrically, so as to mimick adaptation. So,

$$D_t = \alpha_{1,t} T_t + \alpha_{2,t} T_t^2 \tag{10a}$$

or

$$D_t = \beta_{1,t} \Delta T_t + \beta_{2,t} \Delta T_t^2 + \beta_{3,t} D_{t-1}\,, \tag{10b}$$

where D denotes impacts of a specific category. Impacts considered are agriculture, sea level rise, malaria, heat stress, cold stress, unmanaged ecosystems, river floods, wind storms, and migration. Impacts are all monetized. The parameters in Equation (10) are time-dependent, so as to indicate that impacts depend also on economy and population, for example, level of urbanization, share of agriculture in economic output, and per capita income. For example, the impact of climate change on malaria is assumed to decrease as people get richer and better health care, although the monetary value of such impacts increases as people attach more value to health if they grow richer. Impacts feed back into economy and population, but are not large enough to substantially affect the base scenarios.

Emission reduction is restricted to carbon dioxide from industrial sources. Emission reduction costs are calibrated to the survey of Hourcade et al. (1996). Reduction costs are quadratic in the amount of reduction. Costs differ per region. On average, a reduction of 1% per year (from baseline emissions) costs about 0.02% of economic growth; a 10% reduction would cost 2%.

Emission reduction is determined from optimizing net present welfare. Welfare equals the natural logarithm of average green consumption per capita. Green consumption equals income minus investments minus the monetary value of the non-market losses due to climate change.

The optimal emission reduction of each decade is decided at the start of that decade by optimizing the net present welfare. The net present welfare includes the

TABLE I

Atmospheric concentration of carbon dioxide in 2100. Business as usual concentration: 779.8 ppm

	Classic 1%	Classic 0%	Classic 3%	Heal 1%	Rabl 1%	Chichil.
Non-cooperative	771.3	768.1	775.8	768.1	768.0	517.8
Cooperative	621.1	586.2	679.2	582.3	597.1	464.3

future from the start of the decade until 2200. Carbon dioxide emission reduction is the only instrument available to increase welfare. In the non-cooperative case, each region optimizes its own net present welfare. In doing that, each regions knows the other regions' emission reduction effort. In the cooperative case, the sum of the regional welfares is optimized. In both cases, each generation of decision makers acts in full knowledge of the other generations' actions.

4. Results

Table I displays the atmospheric concentration of carbon dioxide in the year 2100 for the 12 (2×6) policy scenarios. Figure 1 displays a selection. In the non-cooperative cases (with an exception for the Chichilnisky criterion), concentrations remain very close to the business as usual (or no control) scenario. Unsurprisingly, classic discounting at 3% per annum leads to the highest concentration, followed by classic discounting at 1%. Classic discounting at 0%, Heal discounting at 1% and Rabl discounting at 1% are indistinguishable. The Chichilnisky criterion leads to the lowest concentration.

In the cooperative cases, emission reduction is more pronounced than in the non-cooperative cases (except for the non-cooperative Chichilnisky criterion). Classic discounting at 3% and 1% again lead to the highest concentrations, followed by Rabl discounting. The Chichilnisky leads again to the lowest concentration.

Interestingly, Heal discounting leads to lower concentrations than no discounting at all. This is because emission reduction not only leads to reduced climate change impacts, but also to reduced consumption in later years. Economic growth is modelled as an exponential process in time. Climate change impact are modelled to grow less fast over time. In the long-term, therefore, what matters most is the relative influence of climate change impacts and emission abatement on economic growth. Due to the slow workings of the atmosphere, emission abatement affects growth decades before climate change impact does. *FUND* is parameterized such that the long-term effect of emission abatement is greater than the long-term effect of climate change impacts. In the Heal case, the long-term counts less than

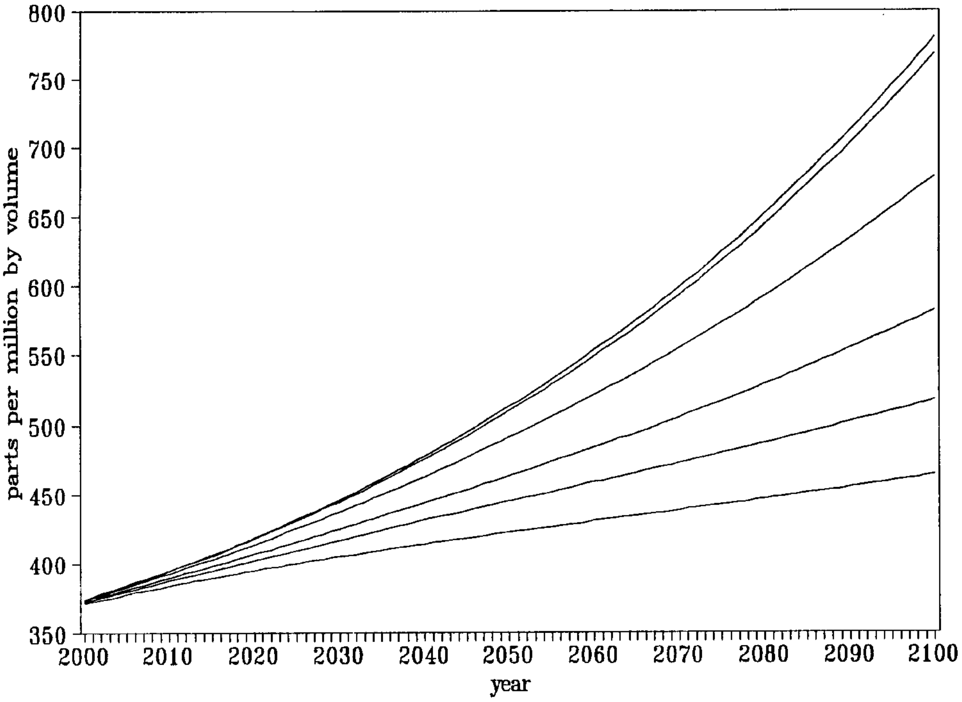

Figure 1. The atmospheric concentration of carbon dioxide in the period 2000–2100 for six alternative scenarios, from top to bottom: business as usual, non-cooperative Rabl discounting (the strictest non-cooperative control), cooperative classic discounting at 3% (the least strict cooperative control), cooperative Heal discounting (the strictest cooperative control), non-cooperative Chichilnisky criterion, and cooperative Chichilnisky criterion. See the text for a description of the scenarios. See Tables I and II for additional details and additional scenarios.

in the no-discounting case. Therefore, Heal discounting leads to higher emission abatement.

Table II displays the annual emission reduction in the 1990s for the 12 scenarios for the OECD, Central and Eastern Europe and the former Soviet Union, less developed countries and the world. The pattern is the same as for 2100 concentrations. Depending on the discount rate chosen, optimal emission reduction can be 50% higher or lower than the ‘base case’ of classic discounting at 1% per year. This effect is dominated by the question whether or not the regions of the world cooperate. In *FUND*, cooperation is not ensured, even unstable (cf. Tol, 1997b,d).

The Chichilnisky criterion leads to emission reductions which lie substantially above optimal control based on discounted welfare, particularly in the non-cooperative case. This is partly because the Chichilnisky criterion induces a form of cooperation (the atmospheric concentration of carbon dioxide in 2200 is the same for all regions and all generations), and partly because the chosen target-concentration of 550 ppm falls below the desired concentration based on discounted welfare optimization, regardless of the discount rate. 550 ppm as a target-

TABLE II

Optimal annual emission reduction effort in the period 1990–1999 (% reduction from baseline per year)[a]

	Classic 1%	Classic 0%	Classic 3%	Heal 1%	Rabl 1%	Chichil.
Non-cooperative						
OECD	0.05	0.07	0.02	0.06	0.07	1.34
CE&fSU	0.00	0.00	0.00	0.00	0.00	1.91
LDCs	0.05	0.07	0.02	0.07	0.07	1.26
World	0.04	0.06	0.02	0.06	0.06	1.43
Cooperative						
OECD	0.75	0.97	0.41	0.97	0.99	2.16
CEE&fSU	1.02	1.39	0.52	1.44	1.31	2.85
LDCs	0.55	0.83	0.26	0.85	0.73	2.06
World	0.75	1.01	0.38	1.03	0.98	2.26

[a] For example, with classic discounting at 1%, OECD emissions lie 0.05% below business as usual in 1990, approximately 0.10% in 1991, and approximately 0.5% in 1999.

concentration is widely accepted for reasons of sustainability. At least one of the two lines of reasoning – welfare optimization or sustainability – must be flawed.

5. Conclusions

The analysis shows that the optimal control of greenhouse gas emissions is sensitive to the choice of the discount rate – hardly a surprising conclusion – and that alternative representations of time preferences (Heal and Rabl discounting) have the same effect numerically on optimal control as lowering the pure rate of time preference in classic discounting. The size of discounting effect is dominated, however, by the question whether or not countries cooperate. According to *FUND*, the non-cooperative optimal concentration in 2100 is 99% of the no control concentration with a classic discount rate of 1%, and 98% in case of Heal discounting. In the cooperative case, these figures are 87% and 75%, respectively.

For comparison, a similar exercise with *DICE* (Nordhaus, 1994) yields optimal 2100 concentrations of 93% (classic at 3%) and 73% (Heal at 14%) of the business as usual concentration. *FUND* and *DICE* are not really comparable, however. In *DICE*, the discount rate also controls investment (but see Tol, 1994). With Heal discounting, it is hard to reproduce *DICE*'s business as usual scenario and the period 1965–1995.

Emission reduction is substantially higher if a target concentration is explicitly taken up in the welfare function by means of a modification of the Chichilnisky criterion. One interpretation of this result is that welfare maximization is inconsistent with substainability. Another interpretation is that the chosen, sustainable target cannot be justified on grounds of welfare maximization.

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