ESTIMATES OF THE EXTERNAL AND SUSTAINABILITY COSTS OF CLIMATE CHANGE

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1. Introduction

Climate change is one of the most prominent environmental problems of today. Its impacts are far-reaching in space and in time, while prosperity and fossil fuel use are close entwined. This paper seeks to estimate just how important climate change is using three approaches, denoted as weak, intermediate and strong sustainability.

Weak sustainability is typically defined as non-declining utility, or perhaps non-declining production capacity. Weak sustainability places human welfare at the core, and substituting one source of welfare for another is not an issue (e.g., Pearce and Turner, 1990; Perman *et al.*, 1999). As climate change is unlikely to reverse economic growth (Fankhauser and Tol, 2001; Tol, 1998), it is compatible with weak sustainability. However, climate change does pose an efficiency problem, as greenhouse gas emissions are externalities, and perhaps large ones (Pearce *et al.*, 1996; Smith *et al.*, 2001). Therefore, our first approach to measuring climate change is to estimate the marginal external costs of carbon dioxide emissions.

Strong sustainability typically means maintaining the stock of natural capital. The environment has centre stage, and substitution is problematic (e.g., Pearce and Turner, 1990; Perman *et al.*, 1999). Climate change is a very slow process. It has been set in motion, and it will take centuries to stop, even if no more greenhouse gases were emitted as of today. Sea level rise would continue to eat from the coast for an even longer time. It is thus hard to assess the implications of striving for strong sustainability for climate change (Tol, 1998). However, strong sustainability would imply driving greenhouse gas emissions to zero as fast as we can – although this would not be strongly sustainable, it is as close as we can get. Our third approach is to estimate the costs of emission abatement to achieve that goal; this is operationalised by picking a target that is at the lower end of the range discussed in the literature (concentrations not above 450 ppm) combined with zero emissions at the model horizon (2200).

Intermediate sustainability is somewhere in between weak and strong sustainability. Although weak and strong sustainability have a reasonably clear theoretical interpretation and ethical justification, both notions are unsatisfactory from a pragmatic standpoint. Our second approach seeks the middle ground, where the middle ground is defined as the long-term environmental goals of democratically elected governments. We estimate the costs of achieving such goals. In the European Union, there is something of a consensus that keeping concentrations below 550 ppm would be desirable.

The goals of climate policy are typically expressed in concentrations. We follow that convention. Atmospheric concentrations of greenhouse gases have various advantages that speak for their use as the main indicator. Concentrations are easier to measure and less variable than greenhouse gas emissions, temperature and precipitation; as greenhouse gases mix uniformly in the atmosphere, it is straightforward to measure global concentrations, whereas emissions and climate variables are local. Climate change impacts, the avoidance of which is presumably the goal of climate policy, are exceedingly hard to measure, particularly since impacts are many and diverse and since it is hard to distinguish the effects of climate change from other changes (environmental or social). The aggregation of concentration is the only drawback to their use as an indicator. The logical way of adding concentrations is by weighing them in their contribution to radiative forcing, which is trivial in a static sense but impossible to do correctly dynamically (Smith and Wigley, 2000a,b; see also Manne and Richels, 2001, and Tol *et al.*, 2000). In practice, a set of imperfect *global warming potentials* is used. In this paper, we focus on carbon dioxide, so that this problem is not that important.

2. The model

This paper uses version 2.4 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Parts of the model go back to version 1.6 (see Tol, 1997, 1999a-e, 2001, 2002a). Other parts go back to version 2.0 (Tol, 2000b,c). Relevant for this paper, compared to previous versions, version 2.4 has updated estimates of the impacts of climate change. See Smith *et al.* (2001) and Tol *et al.* (2001) for a discussion of the impacts of climate change.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialise the climate change impact module. In *FUND*, some climate change impacts are assumed to depend on the impact of the year before, so as to reflect the process of adaptation to climate change. Without a proper initialisation, climate change impacts are thus misrepresented in the first decades. Scenarios for the period 1950-1990 are based on historical observation, viz. the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2100 is based on the *FUND* scenario, which lies somewhere in between the IS92a and IS92f scenarios (Leggett *et al.*, 1992). Note that the original IPCC scenarios had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 2100-2200 is based on extrapolation of the population, economic and technological trends in 2050-2100, that is, a gradual shift to a steady state of population, economy and technology. The model and scenarios are for the period 2100-2200 are not to be relied upon. This period is only used to provide the forward-looking agents in *FUND* with a proper perspective.

The exogenous scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonisation of the energy use, nitrous oxide emissions, and methane emissions.

Incomes and population are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions. Economic impacts of climate change are modelled as deadweight losses to disposable income. Scenarios are only slightly perturbed by climate change impacts, however, so that income and population are largely exogenous.

The endogenous parts of *FUND* consist of carbon dioxide emissions, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture and forestry, energy consumption, water resources, natural ecosystems and human health. The impact module is described in more detail in the next section. *FUND* uses simple models for representing all these components; each simple model is calibrate to either more complex models or to data; *FUND* as a whole has no match, either model or observations.

Carbon dioxide emissions are calculated on the basis of the Kaya identity:

$$(1) \qquad M_{r,t} = \frac{M_{r,t}}{E_{r,t}} \frac{E_{r,t}}{Y_{r,t}} \frac{Y_{r,t}}{P_{r,t}} P_{r,t} := \psi_{r,t} \varphi_{r,t} Y_{r,t}$$

The carbon intensity of energy use, and the energy intensity of production follow from:

$$(2) \qquad \psi_{r,t} = g^{\psi}_{r,t-1} \psi_{r,t-1} - \alpha \tau^{\psi}_{r,t-1}$$

and

$$(3) \qquad \varphi_{r,t} = g^{\varphi}_{r,t-1} \varphi_{r,t-1} - \alpha \tau^{\varphi}_{r,t-1}$$

where τ is policy intervention. Policy affects emissions via

$$(1') \qquad M_{r,t} = \left(\psi_{r,t} - \chi^{\psi}_{r,t}\right)\left(\varphi_{r,t} - \chi^{\varphi}_{r,t}\right) Y_{r,t}$$

$$(4) \qquad \chi^{\psi}_{r,t} = \kappa_{\psi} \chi_{r,t-1} + (1-\alpha) \tau^{\psi}_{r,t-1}$$

and

$$(5) \qquad \chi^{\varphi}_{r,t} = \kappa_{\varphi} \chi_{r,t-1} + (1-\alpha) \tau^{\varphi}_{r,t-1}$$

Thus, the parameter $0 < \alpha < 1$ governs which part of emission reduction is *permanent* (reducing carbon and energy intensities) and which part of emission reduction is *temporary* (reducing energy consumptions and carbon emissions), fading at a rate of $0 < \kappa < 1$. Alternatively, one can interpret the difference between permanent and temporary emission reduction as affecting commercial technologies and capital stocks, respectively. The behaviour of the emission reduction module is similar as the models of Grubb *et al.* (1995), Ha-Duong *et al.* (1997) and Hasselmann *et al.* (1997).

The costs of emission reduction are given by

$$(6) \qquad \frac{C_{r,t}}{Y_{r,t}} = \frac{\beta_{r,t} \tau^2_{r,t}}{H_{r,t} H^g_t}$$

The parameter β follows from

$$(7) \qquad \beta_{r,t} = \beta_{Max} - \beta_{Diff} \sqrt{\frac{M_{r,t}}{Y_{r,t}} - \min_s \frac{M_{s,t}}{Y_{s,t}}}$$

That is, emission reduction is relatively expensive for the region that has the lowest emission intensity. The calibration is such that a 10% emission reduction cut would cost 2.24% of GDP in this case ($\beta_{Max} = 2.24$). Emission reduction is relatively cheap for regions with high emission intensities ($\beta_{Diff} = 0.24$). The thought is that emission reduction is cheap in countries that use a lot of energy and rely heavily on fossil fuels, while other countries use less energy and less fossil fuels. The model has been calibrated to the results reported in Hourcade *et al.* (1996).

The regional and global knowledge stocks follow from

(8) $$H_{r,t} = H_{r,t-1}\sqrt{1+\gamma_R \tau_{r,t-1}}$$

and

(9) $$H_t^G = H_{t-1}^G \sqrt{1+\gamma_G \tau_{r,t}}$$

Knowledge accumulates with emission abatement. The parameters γ determines which part of the knowledge is kept within the region, and which part spills over to other regions as well. In the base case, γ_R=0.9 and γ_G=0.1. The model is similar in structure and numbers to that of Goulder and Schneider (1999) and Goulder and Mathai (2000).

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

(10) $$C_t = C_{t-1} + \alpha E_t - \beta (C_{t-1} - C_{pre})$$

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table 1 displays the parameters for both gases. Equation (10) is a simplified representation of the relevant atmospheric chemistry. Particularly, the atmospheric life-time is not constant, but depends on the concentrations and emissions of other chemical species.

Table 1. Parameters of Equation (10).

Gas	α^a	β^b	Pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; 1/β is the atmospheric life-time (in years) of the gases.

Source: Shine *et al.* (1990) .

The carbon cycle is a five-box model[1]:

(11a) $$Box_{i,t} = \rho_i\, Box_{i,t-1} + 0.000471 \alpha_i E_t$$

with

(11b) $$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmospheric, while 10% is – on average – removed in two years. The model is due to Maier-Reimer and Hasselmann (1987), its parameters to Hammitt *et al.* (1992). It assumes, incorrectly, that the carbon cycle is independent of climate change. Carbon dioxide concentrations are measured in parts per million by volume.

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[1] The boxes have no physical representation. Rather, the model is a Green's function approximation to a complex ocean carbon-cycle model, with five characteristic life-times.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing RF), with a life-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t \tag{12}$$

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

3. An Update

The basis of the climate impact module is fully described in Tol (2002b,c). The impact module has two units of measurement: people and money. People can die prematurely and migrate. These effects, like all other impacts, are monetised. Damage can be due to either the rate of change or the level of change. Benchmark estimates can be found in Table 2.

Table 2. Estimated impacts of a 1°C increase in the global mean temperature. Standard deviations are given in brackets.

	Billion dollar		percent of GDP	
OECD-A	175	(107)	3.4	(2.1)
OECD-E	203	(118)	3.7	(2.2)
OECD-P	32	(35)	1.0	(1.1)
CEE&fSU	57	(108)	2.0	(3.8)
ME	4	(8)	1.1	(2.2)
LA	-1	(5)	-0.1	(0.6)
S&SEA	-14	(9)	-1.7	(1.1)
CPA	9	(22)	2.1	(5.0)
AFR	-17	(9)	-4.1	(2.2)

Source: Tol (2002b).

Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. The climate optimum is determined by a mix of factors, including physiology and behaviour. Impacts are positive or negative depending on whether climate is moving to or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative. See Tol (2002c).

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, but do not change sign. See Tol (2002c).

Vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector-borne diseases (with improved health care). See Tol (2002c).

Below, we discuss the changes introduced to *FUND*, version 2.4.

Agriculture

Tol (2002b,c) presents results for the impact of climate change on agriculture, based on the studies of Darwin *et al.* (1995), Kane *et al.* (1992), Reilly *et al.* (1994), Rosenzweig and Parry (1994), and Tsigas *et al.* (1996). In this paper, we add results from the AIM model (Morita *et al.,* 1994) as presented in Audus (1998) and IEA GHG (1999). Each of these studies combines estimates of changes in crop yield or land productivity with a model of national and international trade in agricultural products. Some of the studies report results without CO_2 fertilisation, some with, and some do both. This allows us to separate out the effects of CO_2 fertilisation. This is important, particularly for multiple gas studies (nitrous oxide, for example, contributes to warming but not to carbon dioxide concentrations). Table 3 reports the results for a 2.5°C increase in the global mean temperature, a rate of 0.04°C/year, and a doubling of the atmospheric concentration of carbon dioxide.

Table 3. Impacts of climate change on agriculture.

Region	rate of change (%GAP/0.04°)		level of change (%GAP/2.5°C)		optimal temperature (°C)		CO_2 fertilisation (%GAP/2xCO_2)	
OECD-A	-.030	(.033)	0.77	(0.84)	1.73	(2.55)	0.32	(1.99)
OECD-E	-.034	(.028)	0.63	(0.60)	1.70	(2.49)	1.82	(1.65)
OECD-P	-.018	(.036)	-0.17	(1.51)	1.23	(4.10)	1.07	(1.65)
CEE&fSU	-.041	(.024)	0.54	(0.90)	1.69	(2.36)	2.45	(1.64)
ME	-.030	(.012)	-0.40	(0.32)	1.51	(2.79)	0.90	(0.68)
LA	-.040	(.017)	-0.85	(0.48)	1.44	(3.58)	1.29	(0.99)
S&SEA	-.038	(.010)	-0.86	(0.43)	1.44	(3.23)	1.38	(0.51)
CPA	-.043	(.026)	0.29	(1.11)	1.68	(2.00)	2.52	(1.13)
AFR	-.020	(.007)	-0.31	(0.21)	0.51	(2.30)	0.67	(0.40)

Source: Own calculations based on references in main text.

Forestry

Tol (2002b,c) is based on one single forestry study only (Perez-Garcia *et al*., 1996). Since then, Sohngen *et al*. (1996) published their results for the impact of climate change on the global timber market. The results here – see Table 4 – are based on the average of the two studies. Note that the results of Perez-Garcia dominate the average, as they show less variation between scenarios. The estimates of the two studies are the means of the normalised scenarios and cases reported; the standard deviation is the variation between the scenarios and cases.

Table 4. Estimates of the impact of a 1°C global warming on forestry.

	Sohngen		Perez-Garcia		Combined	
OECD-A	510	(535)	218	(36)	219	(36)
OECD-E	595	(190)	134	(24)	141	(24)
OECD-P	267	(235)	93	(57)	103	(55)
CEE&fSU	360	(360)	-136	(148)	-65	(137)
ME	0	(185)	0	(10)	0	(10)

LA	392	(143)	10	(5)	10	(5)
S&SEA	102	(29)	14	(52)	81	(25)
CPA	248	(36)	0	(2)	1	(2)
AFR	142	(61)	0	(5)	1	(5)

Source: Own calculations, based on Perez-Garcia *et al.* (1996) and Sohngen *et al.* (1996).

Biodiversity

Climate change is expected to impact heavily on species, ecosystems and landscapes. Yet, this aspect has been paid relatively little attention to by economists, primarily so because the physical impact is still to a large extent unknown (Watson *et al.*, 1996), but also because the value of an ecosystem or a species cannot be easily estimated (Bjornstad and Kahn, 1996; Braden and Kolstad, 1991; Freeman, 1993; Hausman, 1993; Mitchell and Carson, 1989; Pearce and Moran, 1994). Climate economists therefore face a double problem, i.e., how to derive a value of something which is unknown in quantity and price.

Tol (2002b) uses a valuation procedure that is based on the "warm-glow" effect, described in the valuation literature (e.g., Andreoni, 1988, 1990). This effect suggests that people contribute to good causes; the amount is unrelated to the nature of the good cause. The underlying assumptions are that people perceive the impacts of climate change on ecosystems as bad, but that such impacts cannot readily be measured or attributed.

The problem with Tol's (2002b,c) formulation is that it is unrelated to climate change. Therefore, we add the assumption that more people would be aware of climate change and its impacts on ecosystems, if climate change is faster and its impacts more pronounced. For this, we use a logistic relationship, calibrated such that half the people would sense ecosystems losses if the globe warms by 0.025°C a year.

Another problem is that Tol (2002b,c) neglects the scarcity value of biodiversity. Weitzman (1998) argues that, for practical purposes, one should rank biodiversity conservation practices according to

$$R_{species} = \left(D_{species} + U_{species}\right)\frac{\Delta P_{species}}{C_{species}} \tag{13}$$

where *R* is the index used for ranking, the expression between brackets is the value of the species, and the ratio is the "cost-effectiveness" (change in the chance of survival over the cost of the intervention that brings about that change).

The value of the species consists of two components, i.e., its contribution to biodiversity (*D*) and its own total economic value (*U*). Weitzman (1992, 1993) argues that half the Shannon index (*H*) is a reasonable way of measuring biodiversity. Weitzman's index (*W*) is defined as

$$W = \frac{H}{2} = -\frac{1}{2}\sum_{species} P_{species}\log_2 P_{species} = -\frac{1}{2\ln 2}\sum_{species} P_{species}\ln P_{species} \tag{14}$$

where *P* is the contribution of a species to all living beings. One way of thinking about *P* is the fraction of a species' biomass in total biomass.

In a climate change context, we do not know which species gets lost, so we set *P*=1/*N*, where *N* is the total number of species. The biodiversity value of a species getting lost is then proportional to

$$D = \frac{\partial W}{\partial N} = -\frac{\partial}{\partial N}\left(\frac{1}{2\ln 2}\sum_{species} P_{species}\ln P_{species}\right) = -\frac{1}{2\ln 2}\frac{\partial}{\partial N}\left(\sum_{N}\frac{1}{N}\ln\frac{1}{N}\right) = \frac{1}{2\ln 2}\frac{1}{N} \tag{15}$$

The current number of species is estimated to be about 14 million, with an uncertainty range of 2-100 million. At the moment, the diversity value of a species getting lost is in the order of one in ten million. However, a more and more species are going extinct, the diversity value will increase. In addition, climate change will enhance the rate of extinction. REFS

We assume that, of the current amount people are willing to pay for nature protection, 5% has to do with preserving biodiversity (with a standard deviation of 5%); the rest has to do with recreation, aesthetics, the species intrinsic value, and so on. The biodiversity part of the value increase with N_0/N_t . The expected rate of species extinction is about 0.4% a year. We assume that 0.3% (with a standard deviation of 0.3%) is autonomous; 0.1% (with a standard deviation of 0.1%) is due to an annual temperature increase of 0.025°C; this relationship is quadratic.

Wetlands

Biodiversity is not the only thing that will get scarcer. Coastal wetlands are also in decline. Sea level rise and coastal protection measures are assumed to be the sole causes of wetland loss. In analogy to the biodiversity losses, other 95% of the value people currently assign to wetland loss (some $5 million per square kilometre in the OECD; Tol, 2002b,c) are due to more generic, and therefore substitutable, recreation, nature conservation and extraction activities; the remaining 5% is due to the general scarcity of coastal wetlands This value increases proportionally to the ratio of current wetland and remaining wetlands, but no more than 20 times. In some regions, almost all wetlands disappear before 2200. The total wetland value thus increases not more than 100%.

Morbidity

Tol (2002b,c) estimates the impacts of climate change on human mortality through 6 pathways: malaria, schistosomiasis, dengue fever, cold-related cardiovascular diseases, heat-related cardiovascular diseases, and heat-related respiratory disorders, based on EUROWINTER Group (1997), Martens (1996, 1997, 1998), Martens *et al.* (1995, 1997), Martin and Lefebvre (1995), Matsuoko and Kai (1995). Estimates of the changes in the disease burden due to climate change were overlaid with data on the mortality burden (Murray and Lopez, 1996a,b). Here, we follow the same procedure for data on the morbidity burden.

Table 5. Number of additional years of life disabled (1000s) for 1°C global warming.

	Malaria	Schisto[a]	Dengue	C-Heat[b]	C-Cold[c]	Resp.[d]	Total
OECD-A	0.0	0.0	0.0	11.0	-61.9	26.3	-24.6
	(0.0)	(0.0)	(0.0)	(5.7)	(4.2)	(85.0)	
OECD-E	0.0	0.0	0.0	11.2	-95.9	-24.5	-109.2
	(0.0)	(0.0)	(0.0)	(3.8)	(2.5)	(50.0)	
OECD-P	0.0	0.0	0.0	3.4	-12.6	8.8	-0.5
	(0.0)	(0.0)	(0.0)	(2.7)	(2.1)	(42.1)	
CEE&fSU	0.0	0.0	0.0	9.6	-78.6	53.1	-15.9
	(0.0)	(0.0)	(0.0)	(4.0)	(4.7)	(129.9)	
ME	5.0	-5.2	0.0	3.4	-12.0	215.9	207.1
	(2.5)	(0.0)	(0.0)	(0.5)	(1.7)	(56.7)	

LA	5.0	-6.9	0.0	10.2	-25.1	245.9	229.1
	(3.7)	(0.0)	(0.0)	(2.3)	(4.4)	(155.1)	
S&SEA	53.9	-0.6	2.1	24.2	-88.2	2509.9	2501.3
	(38.7)	(0.0)	(0.4)	(4.0)	(23.4)	(606.1)	
CPA	0.0	-1.1	0.0	30.1	-128.2	521.7	422.5
	(0.0)	(0.0)	(0.0)	(5.7)	(26.9)	(368.8)	
AFR	211.6	-133.1	0.0	6.3	-24.3	536.2	596.7
	(153.2)	(26.6)	(0.0)	(0.7)	(8.0)	(129.7)	

[a] Schistosomiasis.
[b] Heat-related, cardiovascular mortality.
[c] Cold-related, cardiovascular mortality.
[d] Heat-related, respiratory mortality.

Source: Own calculations based on references in the main text.

Morbidity is valued at 80% of per capita income per year of illness, with a standard deviation of 1.2, based on the assumptions of Navrud (2001).

Urban Population

In earlier versions of *FUND*, an exogenous scenario specified the fraction of the population living in the city. In the current version, we assume that urbanisation is a function of per capita income and population density:

$$U_t = \frac{\alpha\sqrt{y_t} + \beta\sqrt{PD_t}}{1 + \alpha\sqrt{y_t} + \beta\sqrt{PD_t}} \tag{16}$$

where U is the fraction of people living in cities, y is per capita income, PD is population density and t is time; α and β are parameters, estimated from national data for the year 1995; α=0.031 (0.002) and β=-0.011 (0.005); R^2=0.66.

Water

Earlier versions of *FUND* incorrectly assumed that water technologies are constant. *FUND*'s impact estimates are based on Downing *et al.* (1995, 1996), and they also assume that there is no technological change in water. In reality, however, there are considerable improvements, both for water supply (e.g., desalinisation) and water demand (e.g., drip irrigation). In the revised impacts module, we assume that water technology progress by 0.5% a year, with a standard deviation of 0.5%. This manifests itself in that the sensitivity of the water sector to climate change falls by 0.5% a year.

Energy consumption

FUND's impact estimates for energy consumption are based on Downing *et al.* (1995, 1996). As Downing *et al.* do not provide details on the functional form, earlier versions of FUND assume that the demand for heating decreases linearly with temperature, while the demand for cooling increases linearly. There is obviously a limit to the savings on heating, whereas the additional demand for cooling may actually rise faster than linearly. Therefore, cooling energy demand is assumed to rise with temperature to the power 1.5, and heating energy demand is assumed to fall with the square root of temperature.

Marginal Cost Estimates

Marginal costs of carbon dioxide are estimated as follows. First, a base run is made with the model. Second, a perturbed run is made in which one million metric tonnes of carbon are added to the atmosphere for the period 2000-2009. In both runs, relative impacts, GDP and population are saved. Marginal costs are estimated using:

$$\frac{\sum_{r=1}^{9}\sum_{t=0}^{150}\left(\frac{D_{r,t}^{P}}{Y_{r,t}^{P}}-\frac{D_{r,t}^{B}}{Y_{r,t}^{B}}\right)\frac{Y_{r,t}^{B}}{(1+\rho+g_{r,t}^{B})^{t}}(\$)}{10000000(tC)} \tag{17}$$

where *D* is monetised damage; *Y* is GDP, *g* is the growth rate of per capita income; *ρ* is the pure rate of time preference; the subscript *t* is time; and the superscript denotes base (*B*) or perturbed (*P*) run. That is, the change in *relative* impacts is evaluated against the baseline economic growth – this is to avoid the complications of differential effects on the economic growth path (see Fankhauser and Tol, 2001, for a discussion). Impact are discounted using the standard neo-classical discount rate, viz., the sum of the pure rate of time preference and the growth rate of per capita consumption.

Figure 1 displays the effect of the changes described abore on the marginal costs of carbon dioxide emissions. For reference, the marginal damages according to *FUND*1.6 and *FUND*2.0 are given. Starting from *FUND*2.0, incremental changes are made, in the same order as above, to arrive at the marginal cost estimates of *FUND*2.4. The updated agriculture impact estimates slightly reduce the marginal costs. This is because the *AIM* model, newly added, is quite optimistic about the impacts of climate change on agriculture. The new forestry estimates leave the marginal costs largely unchanged, which is no surprise as the Perez-Garcia estimates dominate the Sohngen estimates, and forestry is a tiny economic sector. The new "detection" formulation for ecosystem impacts drives up the marginal costs (recall they were zero – at the margin – before). Adding the increasing scarcity of biodiversity and wetlands does not change much, as this effect is small. Adding morbidity increases the marginal costs, but only by a little bit. This is because there are positive as well as negative morbidity effects, and although the total number of life years disabled is clearly negative, the positive effects are concentrated in the richer countries. The new urbanisation scenario works to reduce marginal impacts. In the new scenario, urbanisation is somewhat lower worldwide, but particularly so in Latin America. Less people in hot cities implies less heat-related cardiovascular and respiratory disorders. Adding technological progress to the water sector decreases the marginal costs, but changing the curvature of energy consumption increases the marginal costs. Overall, *FUND*2.4 has somewhat higher marginal cost estimates than does *FUND*2.0.

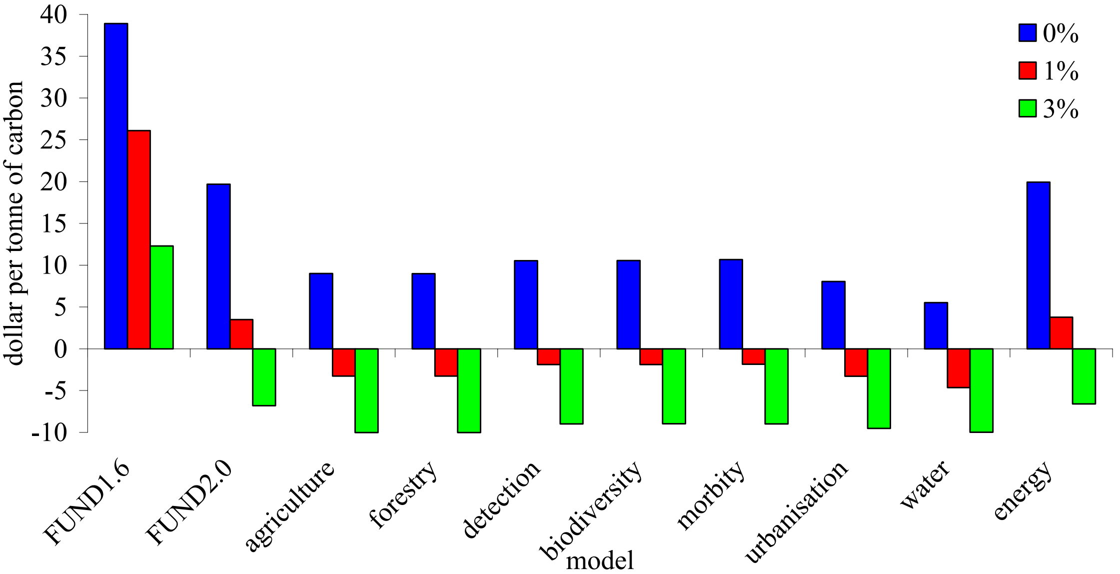

Figure 1. The marginal costs of carbon dioxide emissions according to different versions of the *FUND* model. Results for *FUND*1.6 (Tol, 1999a) are leftmost, next to *FUND*2.0 (Tol and Downing, 2000). Moving to the right, incremental changes are made to *FUND*2.0 as described in the text. The rightmost results are from the *FUND*2.4 model. Results are given for pure rates of time preference of 0, 1 and 3% per year.

4. Marginal damage costs

In the previous section, we already presented some marginal costs estimates, particularly focussing on the relationship between the different versions of the *FUND* model. In this section, we present the marginal costs estimates following the standard valuation assumptions in the GreenSense project, as well as a limited sensitivity analysis.

Figure 2 shows the marginal costs of carbon dioxide emissions. At the left, we repeat the estimate of Figure 1. This is based on a value of a statistical life that equals 200 times the regional per capita income. The GreenSense standard value is 270. Using this value, the marginal costs fall because the positive impacts of climate change on cold related mortality counts heavier. The same effect is observed if we use a value of 80, which corresponds to the official value of a statistical life used by the UK Government. However, GreenSense prefers to use the value of a life year lost. If we use the *FUND* estimate of 10 times per capita income, the marginal costs increase considerably. This is again because of the cold-related cardiovascular deaths; mostly elderly people die, and they count less with the life year lost methodology. If we use GreenSense standard value of a life year lost of 13 times per capita income instead, the marginal costs fall slightly. So far, we have used the *FUND* value of a year diseased, which is 0.8 times per capita income. The GreenSense value is 1.3, If we use this instead, the marginal costs hardly change. Even if we quintuple this number, the estimate hardly changes. As was already seen in Figure 1, the marginal costs of carbon dioxide emissions are not very sensitive to morbidity.

Figure 2 also shows the sensitivity of the marginal costs to the assumed income elasticity of the willingness to pay for avoiding health risks. The standard assumption in both *FUND* and GreenSense is unity. As a sensitivity test, we use income elasticities of .35 – due to REF – and 0 – essentially valuing everybody the same; the reference point is always a Western European life in 2000. If we lower the income elasticity, the marginal cost estimate always declines. A lower income elasticity implies a higher willingness to pay in countries currently poorer than the EU, and a lower willingness to pay in all countries in the future. The result is that near term positive health impacts of climate change are emphasized relative to long term negative impacts.

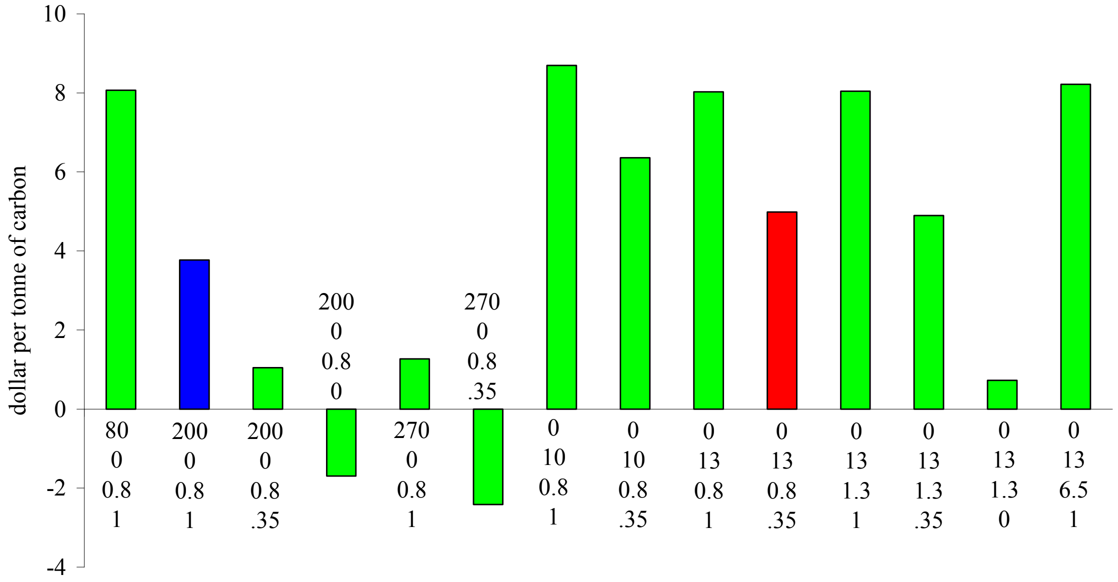

Figure 2. The marginal costs of carbon dioxide emissions, simple sum and with an annual pure rate of time preference of 1%. The numbers denote, respectively, the value of a statistical life, the value of a life year lost, the value of a year diseases, and the income elasticity of the willingness to pay for health impacts.

Figure 3 shows the sensitivity of the marginal cost estimate to the assumed discount rate. We show results for both conventional, exponential discounting and Weitzman discounting. The result is not surprising: The lower the discount rate, the higher the marginal costs. Figure 3 also shows that the equity-weighed marginal cost estimates are lower than the unweighed estimates; this holds for the GreenSense standard health values, but not for the FUND values (cf. Tol, 1999; Tol and Downing, 2002; results for FUND2.4 not shown). The reason is that, with the GreenSense values, health becomes less important; as a consequence, impacts on agriculture, and particularly the positive impacts on Chinese agriculture in the coming 15-20 years, become more important – and are further emphasized with equity weighing.

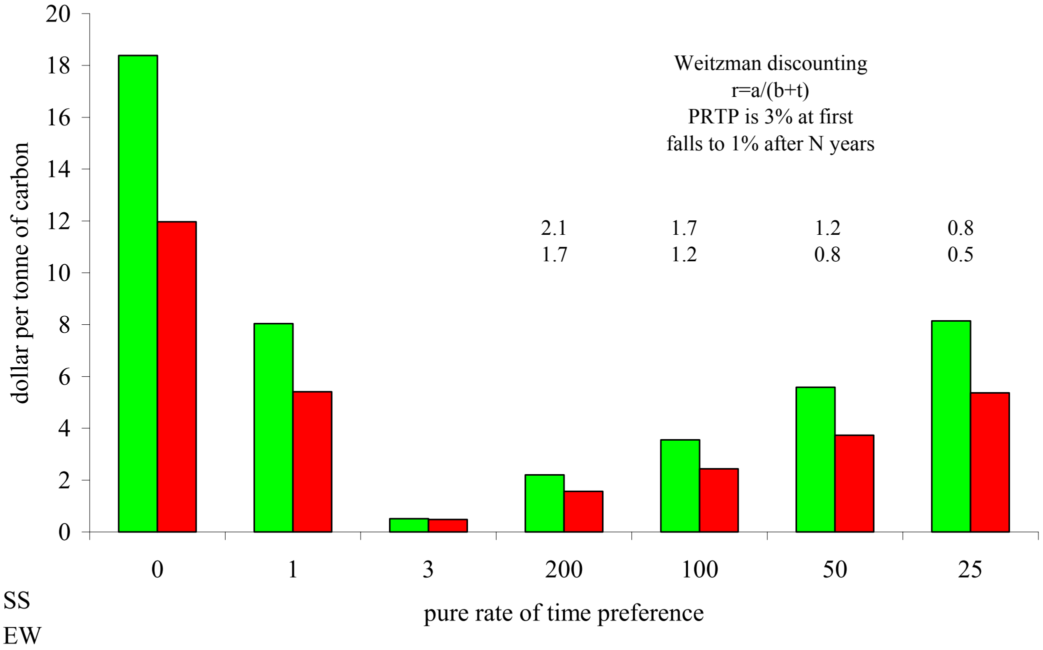

Figure 3. The marginal costs of carbon dioxide emissions under various discount rates, with (EW; right bars) and without (SS; left bars) equity weighing. The pure rate of time preference is either constant and varied between 0%, 1% and 3% per annum, or falls over time according the given equation. In the latter case, the numbers of the x-axis specify the time at which the pure rate of time preference falls to 1%; the numbers above the bars indicate the equivalent constant pure rate of time preference over a 100 and a 200 year period, respectively.

Figure 4 shows the sensitivity of the marginal cost estimate to the emissions scenarios. The SRES scenarios consistently lead to lower marginal costs than the older IS92 scenario (on which the default FUND scenario is based); the relative size of equity weighed and simply summed marginal costs is scenario dependent. Figure 4 also shows the results of changing the climate sensitivity, that is, the equilibrium global warming as a result of a doubling of the atmospheric concentration of carbon dioxide. Higher warming leads to higher costs, not least because the positive effects of CO_2 fertilisation on agriculture are relatively less important. A low warming would lead to benefits. Finally, Figure 4 shows the sensitivity of the marginal cost estimates to the time horizon. The shorter the time horizon, the lower the marginal costs; or, climate change is beneficial in the short run, but detrimental in the long run.

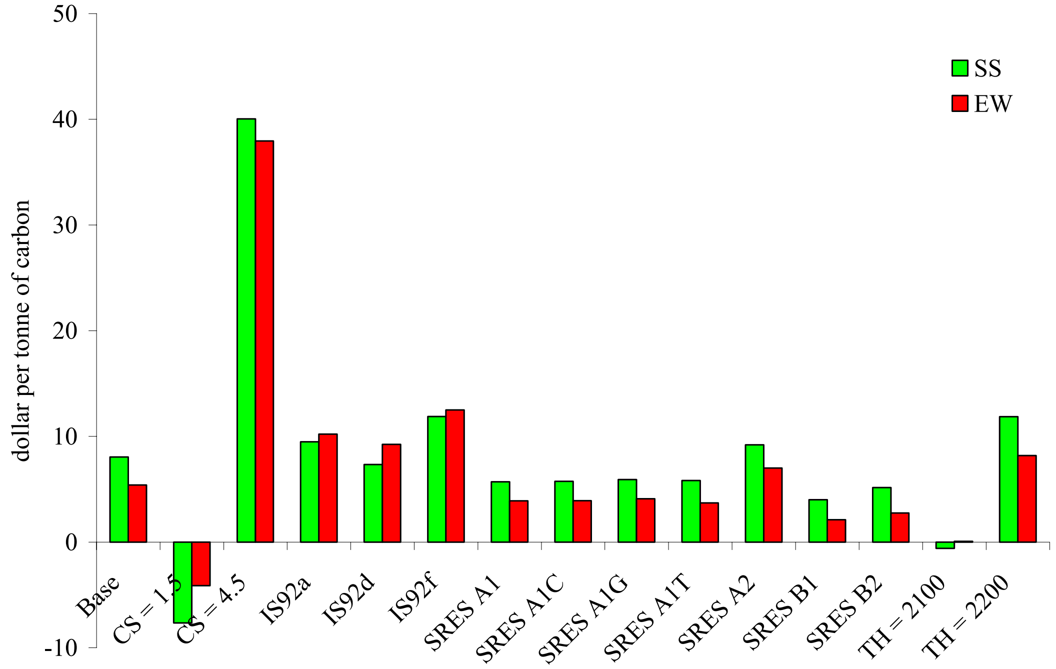

Figure 4. The marginal costs of carbon dioxide emissions under various climate sensitivities (CS; default is 2.5), time horizons (TH; default is 2150) and scenarios (default is the FUND scenario), with (EW; right bars) and without (SS; left bars) equity weighing.

Figure 5 shows the regional breakdown of the marginal cost estimates. Europe and the former Soviet Union together make up the bulk of the costs.

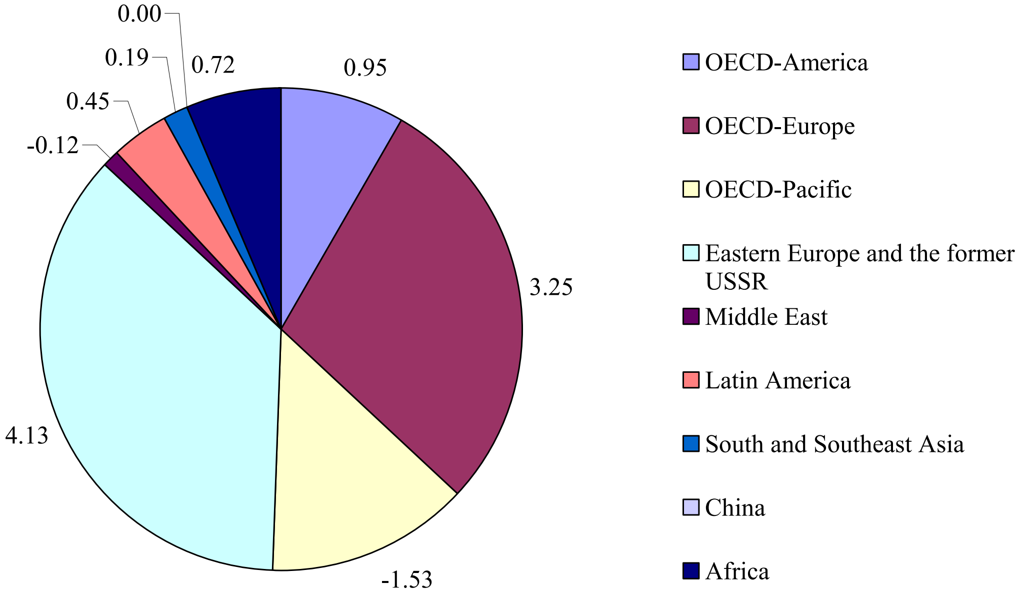

Figure 5. The marginal costs of carbon dioxide emissions for the nine regions of FUND2.4; the pure rate of time preference is 1%; the estimates are not weighed.

5. Avoidance costs

The costs of avoiding climate change depend on many factors. Chief among these are the target of emission reduction, the allocation of emission reduction targets over sectors and countries, and the allocation of targets over time. For intermediate sustainability, we selected 550 ppm as the maximum allowable ambient concentration of carbon dioxide; for strong sustainability, we picked 450 ppm as a target, strengthened with the demand that carbon dioxide emissions should be zero at the time horizon of the model (2200).

The disaggregated targets are based on the following considerations. Avoidance costs, as a measure of the distance to sustainability, are an idealised concept. Even though the ultimate target of intermediate sustainability is based on a political compromise, there is little reason to muddle the cost measurement with politics. Therefore, we measure the avoidance costs as the minimum cost necessary to meet the ultimate target. This implies that emission reduction efforts should be distributed such that the marginal costs are equalised everywhere. This corresponds to a uniform tax or a perfectly competitive global market in emission permits. Over time, the marginal costs should grow with the discount rate. This corresponds to a perfect capital market and perfect banking and borrowing of emission permits. The two combined form the cost-effective solution to emission reduction.

We measure avoidance costs as average costs, which is more appropriate as a measure of distance than are marginal costs. Costs are presented as the average costs per decade. In the first decade (2001-2010), we assume that the OECD bears all emission abatement costs. Thus, the average costs to the OECD equal the average global costs.

Figure 6 displays the avoidance costs for the intermediate sustainability scenario for entire century for the world as a whole as well as for the OECD and the less developed countries. By assumption, the average costs grow. As expected, emission reduction costs are lower in less developed countries.

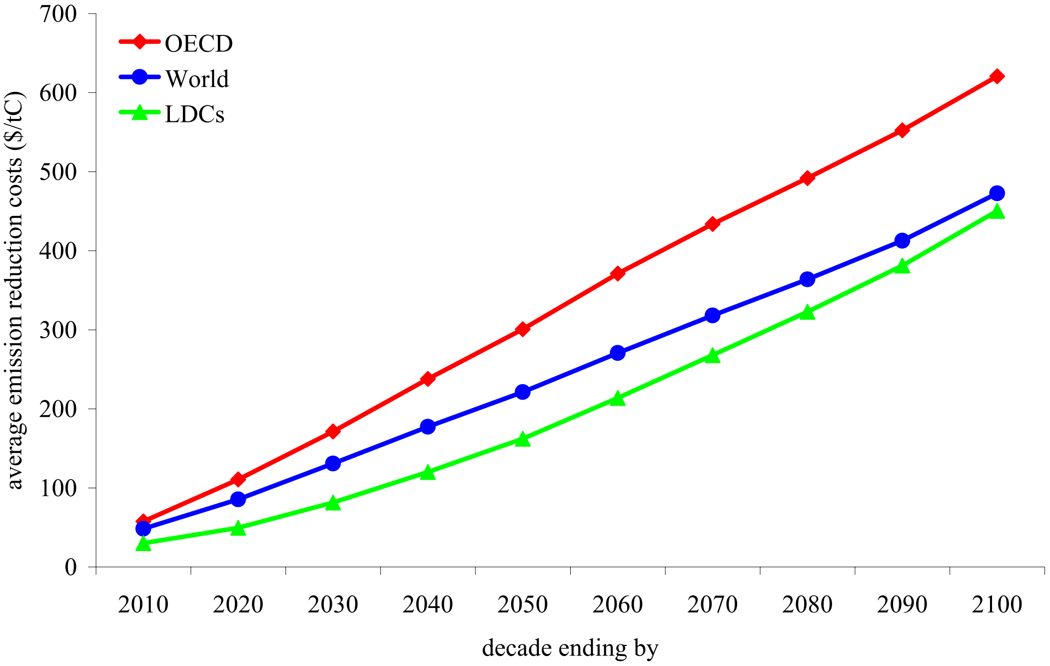

Figure 6. The development of the average costs of emission reduction for the OECD, less developed countries and the world over the century.

Table 6 shows the results of a limited sensitivity analysis. We vary two things, viz, the cost structure and the scenarios. In the short run, knowledge spillovers have little effect on the cost. Faster diffusion of knowledge leads to lower costs. If emission reduction is less permanent or unit costs are higher, total costs are higher. If the baseline emissions are lower, the costs of meeting a 550 ppm concentrations target are lower. All this is as expected.

Table 6. Sensitivity analysis of the avoidance costs in the case of intermediate sustainability.

Description	Technical description	Costs
Base case	FUND scenario; parameters as in Section 2	48.5 \$/tC
No knowledge spillovers	γ_R=0 (8); γ_G=0 (9)	48.6 \$/tC
Long life time abatement	α=0.75 (2-5)	37.0 \$/tC
Short life time abatement	α=0.25 (2-5)	65.8 \$/tC
High maximum abatement costs	β_{Max}=4.48 (7)	77.8 \$/tC
Low maximum abatement costs	β_{Max}=1.12 (7)	28.4 \$/tC
High diffusion of abatement costs	β_{Diff}=0.48 (7)	45.6 \$/tC
Low diffusion of abatement costs	β_{Diff}=0.12 (7)	49.9 \$/tC
Alternative base	IS92a	52.5 \$/tC
High base	IS92f	69.2 \$/tC
Low base	IS92d	23.8 \$/tC

6. Conclusions

Table 7 shows the estimated marginal damage costs of climate change. Marginal damage costs represent weak sustainability. Climate change impacts are discounted with a pure rate of time preference of 1%, or a discount rate of about 3%. Dollar impacts are summed without weighting.

Table 7 also shows the estimated avoidance costs of climate change. Avoidance costs represent intermediate and strong sustainability. Under intermediate sustainability, carbon dioxide concentrations are limited to 550 ppm, roughly a doubling of pre-industrial concentrations. Under strong sustainability, carbon dioxide concentrations are limited to 450 ppm, and emissions are forced to zero by 2200. Costs are average costs, calculated as the ratio of the net present consumption losses and the net present emission reductions. The pure rate of time preference is 1%. Emissions and emission reduction costs are summed without weighting. Under intermediate sustainability, all regions with an income above \$2500/person/year reduce their emission; under strong sustainability, this is lowered to \$2000. Emission allocations are such that each region faces the same initial relative emission reduction – emission reduction increases such that the present marginal emission reduction costs is constant, corrected for the differential carbon cycle effects. The emission allocations are the basis for international trade in emission permits in which all regions participate, regardless of their income.

Table 7 shows that the marginal damage costs are about \$8/tC. The avoidance costs under intermediate sustainability are about an order of magnitude larger, around \$49/tC. Under strong sustainability, the costs are again an order of magnitude larger, at around \$495/tC.

Table 7. Estimated damage and sustainability costs of carbon dioxide emissions.

Name	Description	Monetary value

Weak sustainability	Marginal damages of climate change	$8/tC
Intermediate sustainability	Limit CO2 concentrations to 550 ppm	$49/tC
Strong sustainability	Limit CO2 concentrations to 450 ppm; zero emissions by 2200	$495/tC

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