The Polluter Pays Principle and Cost-Benefit Analysis of Climate Change: An Application of *Fund*

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Summary

I compare and contrast five climate scenarios: (1) no climate policy; (2) non-cooperative cost-benefit analysis (NC CBA); (3) NC CBA with international permit trade; (4) NC CBA with joint and several liability for climate change damages; and (5) NC CBA with liability proportional to a country's share in cumulative emissions. As estimates of the marginal damage costs are low, standard NC CBA implies only limited emission abatement. With international permit trade, emission abatement is even less, as the carbon tax is reduced in countries with fast-growing emissions, and because a permit market ignores the positive, dynamic externalities of abatement. Proportional liability shifts abatement effort towards the richer countries, but away from the fast-growing economies; again, long-term, global emission abatement is reduced. Joint and several liability would lead to more stringent climate policy. These findings are qualitatively robust to the size and accounting of climate change impacts, to the definition of liability, and to the baseline scenario

Keywords: Climate Change, Cost-benefit Analysis, Liability, Permit Trade

JEL Classification: Q540

This paper is based on an idea of David F. Bradford. We often talked about writing this paper together, but we never really started until it was too late. I have tried my best to reflect David's thoughts. This paper is dedicated to his memory.

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1. Introduction

Cost-benefit analysis of greenhouse gas emission control is one way of deciding on climate policy. Cost-benefit analysis has the advantage of being rigorously rooted in welfare theory. If benefits and costs are representative and correctly estimated, the course of action advised by a cost-benefit analysis would result in the greatest good for the greatest number (Nordhaus, 1991; Manne *et al.*, 1995; Tol, 1999).

Practicalities aside (Pearce, 1976; van den Bergh, 2004), there is a fundamental problem with cost-benefit analysis. Cost-benefit analysis is based on Pareto superiority. A situation is Pareto superior to another situation if no one is worse off and at least someone is better off. For practical purposes, Pareto superiority is replaced with potential Pareto superiority, in which the winners compensate the losers; and no one is worse off after compensation (cf. Farrow, 1998). This is fine if in a national context (if compensation indeed works). It is fine in the case of many sovereign actors, with compensation and *if the baseline/no policy case is agreeable*.

In climate change, neither of these conditions are met. Essentially, the Pareto superiority criterion states that the "policy case" must be better for all than the "no policy case". The no policy case is elevated to being the yardstick against which everything is measured. However, without policy, one country's emissions impose impacts on other countries. Using cost-benefit analysis to look at improvements over this baseline situation is tantamount to declaring that there is a right to emission greenhouse gases. Instead, one may argue that there is a right to a stable climate. In this paper, I follow Coase (1960) and investigate the implications for cost-benefit analysis of greenhouse gas emission abatement of assigning the property rights of the atmosphere to the victims of climate change.

There are a large number of papers on equity and climate change (Azar, 2000; Bosello and Roson, 2002; Byrne *et al.*, 1998; Ikeme, 2003; Jamieson, 1996; LeCocq *et al.*, 2000; Müller, 2001; Ridgley, 1996; Rose *et al.*, 1998; Sagar, 2000; Sugiyama and Deshun, 2004; Tonn, 2003; Yohe and van Engel, 2004; Yohe *et al.*, 2000; see Arrow *et al.*, 1996, and Banuri *et al.*, 1996, for reviews of the earlier literature). Many of these papers have difficulty separating the inequities of a world with climate change and the inequities of a world without climate change. There are many papers on cost-benefit analysis of climate change (Ambrosi et al., 2003; Azar and Lindgren, 2003; Azar and Sterner, 1996; Gaertner, 2001; Hasselmann *et al.*, 1997; Maddison, 1995; Nordhaus, 1991, 1992, 1993, 1994; Nordhaus and Boyer, 2000; Nordhaus and Yang, 1996; Peck and Teisberg, 1992, 1994, 1995; Tol, 1997, 1999a,b), but these papers duck the equity issue. There are many papers on alternatives to cost-benefit analysis (Alcamo and Kreileman, 1996; Lempert *et al.*, 1996; Petschel-Held *et al.*, 1999; Toth *et al.*, 2002), but these papers often ignore equity and typically use hand-waiving rather than rigorous arguments.

The papers that come closest to my analysis are Tol (2001, 2002c), Kemfert and Tol (2002), Tol and Verheyen (2004), and Gerlagh and Keyzer (2001). Gerlagh and Keyzer (2001) study the implications if the ownership of the atmosphere is with future generations rather than with the present; they do not look at regional differences, and pay scant attention to the damage costs of climate change. Tol and Verheyen (2004) discuss liability for climate impacts in some detail, but do not study the effects on climate policy. Tol (2001, 2002c) looks at a range of generalisations of and alternatives to utilitarian cost-benefit analysis, but not at a Coasian swap of property rights. Kemfert and Tol (2002) do include the polluter-pays-principle, but among a range of alternatives, and really focus on the effects of spillovers of emission reduction.

This paper is on the effect on climate policy of assigning property rights to a stable climate. One may interpret this as a Coasian analysis (Coase, 1960). One may interpret this as the polluter-pays-principle (e.g., O'Connor, 1997). One may also interpret this as liability for climate change impacts (Whitmore, 2000).

The paper proceeds as follows. Section 2 presents the model used. Section 3 discusses the basic results in detail for four climate policy scenarios, all based on non-cooperative decision making. The first scenario is standard; the second adds international trade in emission permits, the third scenario includes joint and several liability, and the fourth partial liability. Section 4 shows sensitivity analysis on key assumptions and parameters. Section 5 discusses and concludes.

2. The model

This paper uses version 2.8 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.8 of *FUND* corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (forthcoming).[1]

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialise the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetised impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to account for the fact that key impacts of a weakening or a shutdown of the thermohaline circulation would be disregarded if the time horizon of the simulations were shorter. Previous versions of the model stopped at 2200.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonisation of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are

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[1] A full list of papers and the source code of the model can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process is accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al.* (1992). The model also contains sulphur emissions (Tol, forthcoming)

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al.* (1990). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by the radiative forcing *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module, based on Tol (2002a,b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetised. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

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

Vulnerability to climate change 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 urbanization), and ecosystems and health (with 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- and water-borne diseases (with improved health care) (cf. Tol, 2002b).

Carbon dioxide emissions are calculated on the basis of the Kaya identity. Abatement policy reduces emissions *permanently* (by changing the trajectories of carbon and energy intensities) as well as *transiently* (reducing current energy consumptions and carbon emissions). One may interpret the difference between permanent and transient emission reduction as affecting commercial technologies and capital stocks, respectively. The behaviour of the emission reduction module is similar to that of the models of Grubb *et al.* (1995), Ha-Duong *et al.* (1997) and Hasselmann *et al.* (1997). It is a reduced form way of modelling that part of the emission reduction fades away after the policy intervention is reversed, but that another part remains through technological lock-in.

The costs of emission reduction fall, through learning by doing, with cumulative emission reduction (Goulder and Mathai, 2000). Emission reduction is assumed to be relatively expensive for the region that has the lowest emission intensity. The calibration is such that a 10% emission reduction cut in 2003 would cost 1.57% (1.38%) of GDP of the least (most) carbon-intensive region, and an 80% (85%) emission reduction would completely ruin its economy. Emission reduction is relatively cheap for regions with high emission intensities. 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 and are therefore closer to the technological frontier of emission abatement. The model has been calibrated to the results reported in Hourcade *et al.* (1996); for relatively small emission reduction, the costs in *FUND* correspond closely to those reported by other top-down models, but for higher emission reduction, *FUND* finds higher costs, because *FUND* does not include backstop technologies, that is, a carbon-free energy supply that is available in unlimited quantities at fixed average costs. Tol (2005b) describes the details of the model.

The costs of methane and nitrous oxide emission reduction are based on the analysis of the USEPA (2003). They report supply curves of emission reduction, stating how much can be abated at a certain price. First, these supply curves were shifted to exclude negative costs. Note that this increases costs. Second, emission reductions were expressed as fractions of baseline emissions. Third, total emission reduction costs (the area under the supply curve) was calculated, and expressed as a fraction of GDP. Fourth, the regional results of the EPA analysis were attributed to the *FUND* regions. Fifth, the bottom-up curve was approximated with a quadratic curve.

Marginal damage costs are computed by running two scenarios, one with slightly higher emissions in the decade of interest; the net present value of the difference in impacts, normalised by the additional emissions is used to approximate the marginal damage costs.

In the policy scenarios below, the marginal costs of carbon dioxide emission reduction are set equal to the marginal damage costs. The marginal costs of methane and nitrous oxide emission reduction are equal to the marginal costs of carbon dioxide emission reduction times the global warming potential.

3. Results

I compare and contrast five scenarios. The first scenario is the business as usual, or no emission control scenario. In the second scenario, the regional marginal costs of emission reduction are equal to the regional marginal damage costs of climate change. This corresponds to the non-cooperative, Nash-Cournot equilibrium. In this scenario, regions are indifferent to their impact on other regions. This may be politically realistic. However, marginal abatement costs differ across regions, so there is no permit trade either.

In the third scenario, I implement Bradford’s (2004) proposal for the design of the international climate policy regime. There are no negotiations on emission control, let alone obligations. Instead, countries contribute voluntarily to an international climate fund, which uses the collected money to buy emission reduction where that is cheapest. This design respects sovereignty, and it guarantees cost-effective emission reduction.[2] The fund is the intermediary necessary in non-cooperative games with permit trade (cf. Rehdanz and Tol, 2005); in a non-cooperative game, each country has a different marginal damage costs; with emission trade, marginal abatement costs are equal; with the fund in between, countries may care differently at the margin about climate change, but have equal marginal abatement costs nonetheless. I assume that each country contributes to the fund an amount of money that is equal to its marginal damage cost times its annual emissions. If emission reduction costs are approximately linear,[3] then, the global marginal abatement costs equal the weighted average of the regional marginal damage costs of the regions, where the weights are the regional shares in global emissions.

In the fourth scenario (joint and several liability), I introduce liability for climate change impacts. Countries are held liable for all damages they do to other countries. This implies that the regional marginal damage costs – or rather damage plus liability – equals the global marginal damage costs. This solution equals the cooperative equilibrium, in which countries collaborate to maximise the sum of their welfare. This implies, however, that all countries are

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[2] Provided that the fund operates without excessive transaction costs; note that cost-effectiveness only holds at each point in time, but not intertemporally.

[3] In a sufficiently small neighbourhood of the solution, cost curves are linear.

liable for all damages. Therefore, in the fifth scenario (proportional liability), countries are liable only to the extent that they contributed to climate change. Contributions are measured as the share in cumulative emissions since 1990. The regional marginal abatement costs equal this share times the global marginal damage costs.

Obviously, greenhouse gas emissions and marginal damage costs depend on climate policy. The model is iterated until the marginal damage costs equal marginal abatement costs. Convergence is rapid. Note that, through learning by doing and international technology spillover, emission reduction costs also depend on climate policy; as this happens with a delay only, the model solves this without additional iterations.

Table 1 shows the results for the atmospheric concentration of carbon dioxide. In the standard non-cooperative scenario, emission reduction is small: The 2100 concentration of carbon dioxide is only 13 ppm lower than in the business as usual scenario. Table 2 shows why: The regional marginal damage costs are small. The global marginal damages are only $13/tC in 2005; regional marginal damages are only a fraction of that. In 2055, marginal damages are a bit lower; this is because the rate of climate change is slower, and because societies are overall less vulnerable to climate change because of economic growth.

With emission trade, emission reduction is even smaller. This may be surprising: Willingness to pay for greenhouse gas emission reduction has not changed, but emission reduction is cheaper; the same sum of money should go a longer way. This reasoning is not correct. Emission trade *redistributes* emission reduction effort – see Table 3. Marginal abatement costs increase in some regions, but decrease in others – see Table 2; the latter regions buy emission permits from the former. In 2005, the three importers of permits are the EU, the USA and China. Although climate change impacts are large in developing countries relative to their GDP, in absolute dollar terms, impacts are larger in the EU and the USA. China’s economy is projected to continue to grow rapidly; and its large share in emissions and population imply that there is a substantial internal share of the climate change damages it causes.

Another reason is that the contributions to the international fund are determined by emissions and marginal damage costs – and not by the costs of emission reduction.

Finally, emission trade as implemented here ignores the dynamic externalities of emission reduction. There is cost-reducing learning-by-doing in the model, but long-term structural changes in the energy sector are more important. In the short-term, permit trade implies higher emissions in China and lower emissions in, say, South America. The two cancel. This implies a higher emission intensity in China and a lower one in South America, not only in the short-term, but also in the long-term. As China’s economy grows faster, global long-term emissions are higher if abatement is shifted to South America.

In the joint and several liability scenario, the 2100 concentration of CO_2 is some 70 ppm below the baseline – see Table 1. This emission reduction is not substantial – not surprising given the low carbon tax – but much higher than in the standard non-cooperative case. Table 2 shows the marginal damages.

In the proportional liability scenario, the 2100 concentration of CO_2 is again a little higher than in the standard non-cooperative scenario. Again, this may surprise. Liability would fully internalise the damage done. However, this scenario has *proportional* liability only, according to the shares given in Table 3. That means that a country is liable for only a share of the damage done. Furthermore, there is mutual liability, so that a large share of one’s own damages can be claimed from other countries. So, proportional liability redistributes the emission abatement effort, just like permit trade does. Again, the regions with the highest marginal damage costs – China, the EU and the USA – do less while others regions do more – see Table 2. The result is reduced global effort in the long-term – see Table 1.[4]

4. Sensitivity analysis

The limited emission abatement above is driven by the low marginal damage cost estimates. In a first sensitivity analysis, I increase the climate sensitivity – the equilibrium warming due to a doubling of atmospheric CO_2 – from 2.5°C to 4.5°C. Table 1 shows the results; Table 4 has the marginal damage costs. Non-cooperative emission reduction is more stringent; the 2100 CO_2 concentration is 100 ppm below the previous baseline, but some 30 ppm of this is due to the fact that the increased damages reduce baseline emissions. With joint and several liability, the concentration is 315 ppm lower; concentrations never exceed 730 ppm. With permit trade and with proportional liability, CO_2 concentrations are close to, but slightly higher than those in the standard non-cooperative case. A higher climate sensitivity makes the pattern I found above more pronounced, but does not qualitatively change it.

In matters of liability, attention is often focused on the negative impacts. The positive impacts of the culpable act are ignored. Similarly, the negatively affected are more inclined to lobby politicians than those who are positively affected. In a second sensitivity analysis, I ignore all positive impacts of climate change and restrict the attention to the negative impacts. Table 1 shows the results; Table 4 has the marginal damage costs. Marginal damage costs obviously increase, and CO_2 concentrations fall. Ignoring positive impacts does not increase the marginal damage costs by as much as does increasing the climate sensitivity. The relative position of the four abatement scenarios does not change.

Above, proportional liability is determined by a region's share in cumulative emissions since 1990, roughly the year that climate policy started. There are, however, many possible starting points (see Tol and Verheyen, 2004, for an extensive discussion). As a sensitivity analysis, I take an extreme case, the "Brazilian proposal", which counts all fossil-fuel emissions since the start of the industrial revolution. Table 1 shows the results; Table 3 has the regional shares in cumulative emissions. Liability is redistributed towards the OECD; emission abatement is more stringent there – compare Tables 2 and 4. However, emission abatement falls in the rest of the world, including in China and India, and global emission abatement is reduced as a result.

Energy use is essential for life. One may argue that one cannot be liable for emissions that result from covering basic needs. Therefore, as a fourth sensitivity analysis, regions are proportionally liable for their share in *excess* emissions only. Arbitrarily, I define excess emissions as emissions above one metric tonne per person per year; this is roughly the global average per capita emission today. Table 1 shows the results; Table 2 has the regional share in cumulative emissions. Again, liability and abatement are redistributed towards the OECD – compare Tables 2 and 4 – and global abatement falls – see Table 1.

All the liability scenarios above are based on the compensation principle. That is, damages are valued as the victim would value them. See Schelling (1984) for a brilliant defence. However, one may also value impacts as the polluter would value them. That is, rather than using the monetary equivalent of the utility loss of the victim, I impose this utility loss on the polluter and use the monetary equivalent of that. If the utility function is logarithmic, this can be

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[4] In the short-term, abatement also falls. This is because some regions have negative marginal damage costs; in the non-cooperative scenario, these countries do not subsidise greenhouse gas emissions, but in the proportional liability scenario, their welfare gains are subtracted from the global welfare loss. In the long-term, this effect is negligible.

approximated by multiplying the regional marginal damage cost with the ratio of the per capita income of in the liable region and the victimised region (Fankhauser *et al.*, 1997).

I show two variants of this. In the first, regions are proportionally liable based on their share in cumulative emissions. Table 1 has the results; Table 5 has the marginal damage costs. Emission abatement goes up and CO_2 concentrations fall, but only to a limited extent, as abatement only increases in the OECD – see Tables 1 and 5. In the second variant, regions are jointly and severally liable. Concentrations fall considerably, as emission abatement is more stringent in most regions, and in all regions with substantial greenhouse gas emissions in the business as usual scenario – see Tables 1 and 5.

As a final set of sensitivity analyses, I vary the baseline emissions. Above, the business as usual scenario is the FUND scenario, which is somewhere in between the IS92a and IS92f scenarios (Leggett *et al.*, 1992). Table 1 has the results for four SRES scenarios, Table 5 the marginal damage costs for A2 and B1, the two extremes. The FUND scenario has higher emissions than any of the SRES scenarios. Yet, the A2 scenario has higher marginal damages – compare Tables 2 and 5. This is because the economies of developing countries are assumed to grow slower in this scenario; these countries are therefore more vulnerable to climate change. In the A2 scenario, emission abatement is relatively more stringent than in the FUND scenario. Table 1 shows this for the Nash equilibrium, but this would carry over to the other policy scenarios.

In the B1 scenario, global marginal damages are negative in 2005; the positive impacts dominate when discounted. However, marginal damages are positive in 2055, but small – see Table 5. In the B1 scenario, emission abatement is minimal. This is shown for the Nash equilibrium in Table 1, but the result would carry over to the other policy scenarios.

5. Discussion and conclusion

I present a no policy scenario and four alternative climate policy scenarios. In the second scenario, countries equate their marginal damage costs and marginal abatement costs. Emission reduction is limited. This is in line with the literature (Nordhaus, 1991). The main reason is that the estimates of the marginal damage costs are so low (Tol, 2005a).

In the third scenario, I allow for international trade in emission permits. Contrary to expectations, emission abatement falls because the market ignores the dynamic impacts of emission reduction and shifts abatement to where it is cheapest. This conclusion is not model-specific. However, permit trade *averages* marginal costs. This result holds as long as countries with fast-growing emissions have above-average marginal damage costs.

In the fifth scenario, countries are liable for the share of the marginal damages that they caused. This increases abatement effort in the OECD, but reduces effort in the rest of the world, with their fast-growing emissions. As a result, long-term emission control is weakened. Again, this result is not limited to the model used here. If, however, emission abatement would be limited to the OECD, then proportional liability would increase emission control.

In the fourth scenario, countries are jointly and severally liable. Emission abatement increases everywhere, in the short-term as well as in the long-term. As this coincides with full cooperation, this result is anticipated (e.g., Nordhaus and Yang, 1996).

I present five sensitivity analyses, some with variants. Although the numbers are different, the insights of the four policy scenarios are not affected. Qualitatively, my results are robust – at least as far as I saw.

This paper confirms Coase (1960), but not literally. In Coase (1960), there is a polluter and a victim. A bargain between the two would result in the same total welfare and pollution regardless of whether there is a right to pollute or a right not to be polluted; the distribution of welfare would be different. That is, equity is separated from efficiency and efficacy. In this paper, all players are polluters and victims at the same time, but to a different degree. This makes the analysis more fuzzy, but it does not change the fundamental insight of Coase (1960). The initial allocation of property rights matters for issues of equity; proportional liability leads to a different distribution of emission abatement efforts and costs. Because I ignore dynamic externalities, a redistribution of property rights affects efficiency and efficacy as well – but to a limited extent only. Again following Coase (1960), trade in emission permits would not increase emission abatement.

In political terms, attempts to establish liability for greenhouse gas emissions would have reduce emissions in rich countries, but, if drawn to its logical conclusion, would increase emissions in poor countries and way well increase global emissions. Only if joint and several liability is established would global emissions go down. Joint and several liability, however, would imply that the victims of climate change are compensated many times over; this is unlikely. It appears that establishing liability for greenhouse gas emissions is not *the* solution to the climate problem.

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Table 1. The atmospheric concentration of carbon dioxide (in ppm) and the global mean temperature (in °C above pre-industrial) in 2100 according to business as usual scenario and four policy scenarios; sensitivity analyses are also shown.

	Base case		High climate sensitivity		Negative impacts only	
	CO_2	Temp	CO_2	Temp	CO_2	Temp
Business as usual (BaU)	942.8	3.70	913.4	6.58	942.8	3.70
Nash equilibrium (NE)	929.3	3.67	842.2	6.29	887.9	3.59
NE, permit trade (PT)	929.4	3.67	845.1	6.30	888.2	3.59
Joint and several liability (JSL)	872.9	3.55	628.0	5.31	810.5	3.41
Proportional liability (PL)	930.6	3.67	851.9	6.33	888.0	3.59
PL, Brazilian proposal	932.4	3.67				
PL, excess emissions	929.9	3.67				
PL, polluter’s values	922.6	3.65				
JSL, polluter’s values	830.6	3.44				
BaU, SRES A1B	809.2	3.73				
NE, A1B	807.8	3.71				
BaU, A2	811.9	3.49				
NE, A2	798.2	3.45				
BaU, B1	576.7	3.10				
NE, B1	576.3	3.10				
BaU, B2	749.4	3.41				
NE, B2	741.6	3.38				

Table 2. Regional marginal damage costs (in $/tC) in 2005 and 2055 in four alternative policy scenarios.

	2005				2055			
	NE	PT	JSL	PL	NE	PT	JSL	PL
USA	2.20	2.08	13.27	2.61	1.15	2.10	11.40	1.80
CAN	0.09	2.08	13.27	0.20	0.08	2.10	11.40	0.14
WEU	3.16	2.08	13.27	1.29	2.08	2.10	11.40	0.84
JPK	-1.42	2.08	13.27	0.86	0.21	2.10	11.40	0.63
ANZ	-0.05	2.08	13.27	0.13	0.08	2.10	11.40	0.09
EEU	0.10	2.08	13.27	0.31	0.09	2.10	11.40	0.27
FSU	1.27	2.08	13.27	1.45	0.61	2.10	11.40	1.36
MDE	0.05	2.08	13.27	0.66	0.33	2.10	11.40	0.65
CAM	0.07	2.08	13.27	0.18	0.12	2.10	11.40	0.15
SAM	0.27	2.08	13.27	0.36	0.15	2.10	11.40	0.30
SAS	0.36	2.08	13.27	0.86	0.34	2.10	11.40	0.84
SEA	0.73	2.08	13.27	0.52	0.45	2.10	11.40	0.54
CHI	4.36	2.08	13.27	3.39	4.88	2.10	11.40	3.40
NAF	0.97	2.08	13.27	0.16	0.42	2.10	11.40	0.13
SSA	1.07	2.08	13.27	0.24	0.33	2.10	11.40	0.19
SIS	0.06	2.08	13.27	0.06	0.07	2.10	11.40	0.06
World	13.27	2.08	13.27	13.27	11.40	2.10	11.40	11.40

Table 3. Regional shares in 2005 and 2055 in current carbon dioxide emissions for the permit trade (PT) scenario and in cumulative emissions for three alternative proportional liability scenarios (PL: cumulative emissions since 1990; BP: cumulative emissions since 1850; EE: cumulative emissions in excess of 1 tC/p/yr since 1990).

	2005				2055			
	PT	PL	BP	EE	PT	PL	BP	EE
USA	0.192	0.197	0.266	0.350	0.130	0.158	0.188	0.241
CAN	0.015	0.015	0.021	0.024	0.010	0.012	0.015	0.017
WEU	0.085	0.097	0.201	0.104	0.060	0.074	0.111	0.077
JPK	0.062	0.065	0.050	0.093	0.046	0.055	0.052	0.070
ANZ	0.009	0.009	0.009	0.015	0.007	0.008	0.008	0.011
EEU	0.020	0.023	0.039	0.016	0.025	0.024	0.029	0.025
FSU	0.107	0.109	0.123	0.156	0.124	0.119	0.121	0.172
MDE	0.053	0.050	0.029	0.045	0.060	0.057	0.050	0.054
CAM	0.014	0.013	0.010	0.000	0.014	0.014	0.013	0.003
SAM	0.027	0.027	0.023	0.000	0.026	0.026	0.025	0.000
SAS	0.073	0.065	0.035	0.000	0.076	0.074	0.063	0.000
SEA	0.046	0.039	0.021	0.000	0.049	0.047	0.040	0.003
CHI	0.263	0.256	0.148	0.198	0.340	0.298	0.253	0.325
NAF	0.012	0.012	0.008	0.000	0.012	0.012	0.010	0.000
SSA	0.017	0.018	0.016	0.000	0.017	0.017	0.016	0.000
SIS	0.005	0.004	0.004	0.000	0.005	0.005	0.005	0.001

Table 4. Regional marginal damage costs (in $/tC) in 2005 and 2055 in four alternative policy scenarios and two sensitivity analyses: high climate sensitivity (CS) and negative impacts only (NO).

	2005				2055			
	CS, NE	CS, PL	NO, NE	NO, PL	CS, NE	CS, PL	NO, NE	NO, PL
USA	7.01	19.86	3.43	5.45	3.55	10.09	1.38	2.05
CAN	0.47	1.52	0.22	0.42	0.31	0.77	0.08	0.16
WEU	14.99	9.81	5.94	3.07	8.28	4.69	2.54	0.95
JPK	4.14	6.56	0.89	1.85	3.86	3.51	0.54	0.71
ANZ	0.57	0.96	0.07	0.26	0.54	0.53	0.06	0.11
EEU	0.72	2.34	0.24	0.77	0.44	1.50	0.10	0.31
FSU	4.78	11.02	1.71	3.46	2.50	7.48	0.63	1.55
MDE	2.69	5.04	0.61	1.23	2.03	3.67	0.39	0.74
CAM	1.16	1.34	0.24	0.35	0.75	0.86	0.14	0.18
SAM	1.48	2.71	0.65	0.71	0.67	1.68	0.22	0.34
SAS	2.95	6.53	0.67	1.55	1.85	4.68	0.36	0.95
SEA	4.04	3.98	1.34	0.89	2.13	3.00	0.56	0.61
CHI	49.35	25.84	9.31	6.60	33.42	18.85	5.11	3.87
NAF	3.11	1.19	1.03	0.31	1.51	0.73	0.43	0.15
SSA	2.90	1.82	1.14	0.53	1.11	1.06	0.33	0.22
SIS	0.61	0.45	0.08	0.11	0.46	0.31	0.06	0.06
World	17.12[a]	100.96[b]	4.05[a]	27.56[b]	13.13[a]	63.41[b]	2.27[a]	12.97[b]

[a] Weighted average marginal damage costs, where the weights are the regional shares in current emissions. This value is used in the permit trade (PT) scenario.

[b] Sum of the regional marginal damage costs. This value is used in the joint and several liability (JSL) scenario.

Table 5. Regional marginal damage costs (in $/tC) in 2005 and 2055 for four sensitivity analyses: polluter's values (PV) with joint and several liability (JSL) and proportional liability (PL), and alternative baseline scenarios (A2 and B1).

	2005				2055			
	JSL, PV	PL, PV	A2	B1	JSL, PV	PL, PV	A2	B1
USA	232.95	45.83	2.57	1.37	86.76	13.71	1.46	0.74
CAN	164.01	2.47	0.10	0.01	60.07	0.72	0.10	0.03
WEU	201.64	19.60	3.77	0.65	75.73	5.57	2.57	0.50
JPK	304.43	19.79	-1.29	-1.96	114.73	6.30	0.26	-0.32
ANZ	132.76	1.25	-0.03	-0.10	50.96	0.42	0.10	0.03
EEU	20.60	0.48	0.17	0.01	15.08	0.36	0.15	0.04
FSU	14.30	1.56	1.87	0.79	10.33	1.23	0.98	0.31
MDE	15.28	0.76	0.09	-0.26	8.86	0.51	0.35	0.03
CAM	17.82	0.24	0.30	-0.08	10.34	0.14	0.30	0.03
SAM	22.91	0.62	0.49	0.01	13.09	0.35	0.26	0.02
SAS	3.99	0.26	0.34	-0.18	2.38	0.18	0.36	0.01
SEA	14.16	0.56	0.58	-0.14	8.57	0.41	0.40	0.00
CHI	19.10	4.88	8.03	-1.98	14.99	4.47	8.25	0.57
NAF	8.92	0.11	0.94	0.30	4.98	0.06	0.45	0.07
SSA	2.81	0.05	1.17	0.38	1.60	0.03	0.40	0.06
SIS	7.42	0.03	0.17	0.01	4.44	0.02	0.17	0.03
World[a]	1183.11	98.49	19.26	-1.18	482.93	34.48	16.56	2.14

[a] Sum of the regional marginal damage costs. This value is used in the joint and several liability (JSL) scenario.

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