Optimal Global Dynamic Carbon Abatement

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Abstract

I investigate the optimal distribution of greenhouse gas emission reductions over time and between regions. Sandmo (2006) has shown that optimal marginal abatement costs should differ between different countries if no lump-sum transfers between those countries are possible. I extend his static result to a dynamic stock externality, so that it can be applied to climate change. I then use the integrated assessment model FUND to compute optimal marginal carbon abatement costs schedules for sixteen world regions for the next century. I find that if lump-sum transfers are not possible, a utilitarian global planner would have rich countries mitigate more and poor countries less than in a policy that is based purely on efficiency considerations. Ruling out lump-sum transfers has an ambiguous effect on the optimal quantity of global emission reductions: under standard assumptions about inequality aversion, optimal emission reductions are lower if lump-sum transfers between countries are ruled out. In a sensitivity analysis, I assume a more inequality-averse decision maker. In this scenario, optimal emission reductions are larger when lump-sum transfers are ruled out.

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1. Introduction

It is almost a commonplace in the economics of climate change that a good response to the challenges posed by global warming would be a harmonized, global tax on greenhouse gas emissions that increases over time, roughly with the discount rate (e.g. Nordhaus, 2007). Many details of such a proposal are hotly discussed, but one aspect is rarely questioned in the economic literature: should a carbon tax really be harmonized across the world, i.e. should the same tax rate on carbon emissions be enforced in all countries?

There are at least three different approaches to answering this question. First, we can look for policies that make no one worse off and at least some better off, i.e. we can look for policies that are Pareto improving. Second, we can look for policies that are self-enforcing in the sense that all regions of the world have an incentive to stick to the policy because it is in their own best interest. Third, we can look for policies that follow from ethical considerations. I investigate a policy that falls squarely into the last category in this paper: how would a global utilitarian social planner set climate policy?

The contribution of this paper to this question is twofold: First, I extend previous theoretical results that addressed a static, one-time-period public good to a dynamic situation with a stock public good that accumulates over time. One of the most interesting current cases of a global public good (or rather bad) is climate change. Greenhouse gas emissions that accumulate in the atmosphere stay there for many centuries, and therefore a dynamic setting is the appropriate theoretical framework for analyzing climate change. Second, I numerically investigate a utilitarian climate change mitigation policy with the integrated assessment model FUND and compare that policy with a first-best Pareto-optimal mitigation policy.

Sandmo (2006) shows that the emission tax design of a global utilitarian planner depends on what other policy tools are at her disposal. In particular, if there are income inequalities between different world regions and the global planner cannot redistribute wealth between regions via some mechanism other than emission taxes, she would set emission taxes higher in high-income countries and lower in low-income countries. Effectively, the global planner would use climate policy as their only tool to achieve the distributional goals mandated by a utilitarian welfare function. If, on the other hand, the global planner can redistribute income in a lump-sum fashion between countries in addition to setting emission taxes, she would equalize emission tax rates between countries (thus reducing emissions at lowest cost) and implement the utilitarian distributional goals via lump-sum transfers of income.

I extend Sandmo's static analysis to a dynamic setting and derive how emission taxes should be differentiated between countries of different wealth levels when a global utilitarian planner cannot redistribute wealth between countries via lump-sum transfers.

One key limitation of the analysis in this paper and Sandmo's original paper is the assumption of zero lump-sum transfers. If the global planner has access to such lump-sum transfers, carbon taxes are the same in each region. When a carbon policy is implemented via a marketable permit system, there is a natural way to administer these lump-sum transfers, namely via the initial distribution of emission permits (Shiell, 2003). A rigorous analysis of the political economy of the initial distribution of emission permits is beyond the scope of this paper, but it appears unlikely that a global greenhouse emission permit system in which a large fraction or even all initial permits are allocated to poor countries would be implemented. If such a system were within the feasible set of policies, though, it is clear that it would Pareto dominate the kind of policy analyzed by Sandmo and in this paper.

A related literature investigates the efficient provision of privately produced public goods (Chichilnisky and Heal, 1994; Chichilnisky and Heal, 2000; Shiell, 2003). The results are similar to those of Sandmo (2006) and this paper: if the global planner has access to lump-sum transfers, an efficient policy will always equalize marginal abatement costs, whereas this is not necessarily true if no lump-sum transfers can be administered. Again, this transfer could be implemented via an initial emission permit allocation (Shiell, 2003).

There are two key differences between that literature and the results in this paper. First, Chichilnisky and Heal (1994) and the subsequent literature derive their results not from assuming a global utilitarian welfare function but rather purely from efficiency considerations. In contrast, this paper's and Sandmo's (2006) results are driven by a strong utilitarian assumption on how wealth should be distributed across countries. The literature following Chichilnisky and Heal (1994), on the other hand, is looking for policies that are Pareto-optimal, i.e. policies in which no one can be made better off without simultaneously making someone else worse off. Second, while Chichilnisky and Heal (1994) find that an efficient policy does not need to equate marginal abatement costs if the global planner doesn't have access to lump-sum transfers, they also show that on the other hand efficiency in the absence of lump-sum transfers doesn't *require* different marginal abatement costs. They show that there is always at least one point on the efficiency frontier that equates marginal abatement costs, regardless of whether lump-sum transfers are available and that this point corresponds to the allocation that follows from optimizing a welfare function with Negishi weights (Chichilnisky and Heal, 1994; Shiell, 2003).[1] In contrast, if one derives optimal emission tax rates from a utilitarian welfare function (as done in this paper) and

[1] It is worth pointing out that the point on the efficiency frontier that corresponds to an optimum of a welfare function with Negishi weights is quite questionable from an ethical point of view (Eyckmans *et al.*, 1993). There is also no guarantee that this allocation is in the set of allocations that are a Pareto improvement over the status quo of an unregulated economy (Yang, 2008).

income is distributed unevenly, then emission tax rates will always be differentiated when the planner has no access to lump-sum transfers.

The second part of the paper compares a climate policy that a utilitarian global planner who does not have access to lump-sum transfers would implement with an efficient climate policy. Of all efficient (i.e. Pareto-optimal) climate policies I compute the one that corresponds to the solution of a welfare function with Negishi weights (Negishi, 1960), i.e. the one Pareto-optimal climate policy that is Pareto-optimal regardless of whether the global planner has access to lump-sum transfers and that has become the benchmark case for most explorations of efficient climate policies in the integrated assessment literature (Nordhaus and Yang, 1996).

In section 2, I present a theoretical model of optimal marginal abatement costs of a global public bad for a utilitarian planner and the Negishi solution, and derive key necessary conditions for an optimal emissions trajectory. In section 3 I briefly describe the integrated assessment model FUND. Section 4 presents results and section 5 concludes.

2. Theory

Let x_{tr} be carbon emissions in year t in region $r \in R$, with R being the set of all regions of the world. Total emissions in year t are $X_t \equiv \sum_r x_{tr}$. Greenhouse gas concentrations S in each year are characterised by a transition function g

$$S_{t+1} = g(S_t, X_t). \tag{1}$$

Concentrations depend on previous concentrations and emissions from all regions.

Per-capita consumption c_{tr} in year t in region r is

$$c_{tr}(S_t, x_{tr}) = \frac{C_{tr}(x_{tr}) - D_{tr}(S_t)}{P_{tr}} \tag{2}$$

where C_{tr} is total consumption, D_{tr} is climate change damage and P_{tr} is population.

Consumption $C_{tr}(\cdot)$ is assumed to depend on emissions, and is thus a combined term that picks up baseline scenario consumption paths and carbon emission mitigation costs that result from reducing emissions below the scenario baseline. I assume that $C_{tr}(0) = 0$ (i.e. that abating all carbon emissions would be so costly that consumption is reduced to 0), that there is an emissions level $\overline{x}_{tr}$ that maximizes consumption and that $C_{tr}(\cdot)$ is strictly concave. It follows that for all emission levels between 0 and $\overline{x}_{tr}$, increasing emissions will increase consumption, i.e. $C'_{tr}(x) > 0$ for all $x \in (0, \overline{x}_{tr})$. C is calibrated such that the optimal emissions level $\overline{x}$ and its corresponding income C follow the business-as-usual scenario of the FUND model. Damage $D_{tr}(\cdot)$ in period t and region r depends on the state of the atmosphere at that time.

Optimal emissions path

The optimization problem of a global planner is given as

$$\begin{aligned} &\max_{\{x_{tr}\}_{t,r}} \sum_{t=0}^{T} \delta^t \sum_{r \in R} P_{tr} U\big(c_{tr}(S_t, x_{tr})\big) \\ &\text{s.t.} \quad S_0 = \overline{S}_0 \end{aligned} \tag{3}$$

for a standard utilitarian welfare function, with $\bar{S}_0$ being the carbon concentration at the start of the optimization period. $0 < \delta < 1$ is the per period discount factor. I also assume that the utility function U has the usual iso-elastic form:[2]

$$U(c) = \begin{cases} \ln c & \text{for } \eta = 1 \\ c^{1-\eta}(1-\eta)^{-1} & \text{for } \eta \neq 1 \end{cases}. \tag{4}$$

[2] I call the parameter η inequality aversion. This should be interpreted as inequality aversion to differences in consumption across time and between regions. The utility function U therefore plays a similar role as the imposed utility-of-income function of the social planner in Lambert *et al.* (2003). Note that η can also be interpreted as the inverse of the inter-temporal elasticity of substitution of the social planner.

The Bellman equations for this problem are

$$V_t(S_t) = \max_{\{x_{tr}\}_r} \sum_{r \in R} P_{tr} U\big(c_{tr}(S_t, x_{tr})\big) + \delta V_{t+1}(S_{t+1}) \quad \forall t \tag{5}$$

for each time t, with $V_t(S_t)$ as the value function for time t. The first order conditions for the maximization problem of the value function for year t are

$$\frac{\partial}{\partial x_{ti}} \left(\sum_r P_{tr} U\big(c_{tr}(S_t, x_{tr})\big) + \delta V_{t+1}(S_{t+1}) \right) = 0 \quad \forall i \in R. \tag{6}$$

Using standard finite time horizon dynamic programming practice, we start deriving first order conditions at the end of the time horizon T, and then derive first order conditions for earlier time steps t going back in time until we reach $t = 0$. Given the complexities of the integrated assessment model used for this exercise, I do not derive an analytical solution for the value function, but rather find first order conditions that I can then use in a numerical search algorithm for the optimal emissions path.

Let a marginal emission of carbon in year t cause marginal damage MD in year s and region r, i.e.

$$MD_{sr}(t) \equiv \frac{\partial D_{sr}(S_s)}{\partial X_t} \tag{7}$$

With some manipulation we can rewrite the first order conditions for year t as

$$C'_{ti}(x_{ti}) = \sum_{s=t}^{T} \delta^{s-t} \sum_{r \in R} \underbrace{\left(\frac{c_{ti}(S_t, x_{ti})}{c_{sr}(S_s, x_{sr})} \right)^{\eta}}_{a} MD_{sr}(t) \qquad \forall i \in R \tag{8}$$

This is a variation of the familiar rule that marginal abatement costs in each region i should equal the net present value of marginal damage costs, but with some important modifications. On the left hand side are marginal abatement costs for a specific region i in year t[3]. The right hand side of the equation is the weighted sum of marginal damages felt in every year after t in all regions. There are two weights applied: first the pure time preference factor $\delta^{s-t} = 1/(1+\rho)^{s-t}$ with the pure rate of time preference ρ. The second weight after the summation sign over regions (part a) is a combination of distributional weights

[3] Note that $C'(x)$ is the marginal benefit of emissions, which is conceptually identical to marginal abatement costs.

and the growth part in the standard Ramsey discount rate. Two different interpretations can help understand this second weight.

To see the first we rewrite both weights for a specific region r and time s as

$$\underbrace{\delta^{s-t}\left(\frac{c_{ti}(S_t,x_{ti})}{c_{sr}(S_s,x_{sr})}\right)^{\eta}}_{a} \approx \underbrace{\left(\frac{c_{ti}(S_t,x_{ti})}{c_{tr}(S_t,x_{tr})}\right)^{\eta}}_{b} \underbrace{\left(\frac{1}{1+\rho+\eta g(c_{tr}(S_t,x_{tr}),c_{sr}(S_s,x_{sr}),s-t)}\right)^{s-t}}_{c} \tag{9}$$

Here $g(c_1,c_2,t)$ is defined as the average constant growth rate at which per-capita consumption would grow from c_1 to c_2 over a time span of t years.[4] Part *c* is the standard Ramsey type discount factor for region r, based on per-capita growth of the region where the damages occur.

Part *b* is a distributional weight that is applied to the net present value of damage in a particular region. The distributional weight given to marginal damages occurring in the region for which marginal abatement costs appear on the left hand side of equation (8) will always be 1, so that abatement and damages in that region are valued consistently (Anthoff *et al.*, 2009). Marginal damages in other regions receive a distributional weight that will be >1 (<1) for regions with lower (higher) per-capita consumption than the region for which marginal abatement costs appear on the left hand side of equation (8).

To see the second interpretation we rewrite part *a* and the time discount factor as

$$\underbrace{\delta^{s-t}\left(\frac{c_{ti}(S_t,x_{ti})}{c_{sr}(S_s,x_{sr})}\right)^{\eta}}_{a} \approx \left(\frac{1}{1+\rho+\eta g[c_{ti}(S_t,x_{ti}),c_{sr}(S_s,x_{sr}),s-t]}\right)^{s-t} \tag{10}$$

The expression on the right hand side of equation (10) is just the standard Ramsey type discount factor with a per-capita consumption growth rate that goes from the current level of per-capita consumption of the abating region to the per-capita consumption of the region and the time where the marginal damage is occurring. Note that in principle this rate can be negative, when abatement costs are calculated for a region with a high current per-capita income and the damages occur in a lower per-capita region.[5]

We can now examine optimal marginal abatement costs for different regions. Another rearrangement of equation (8) gets us

[4] g is defined by the equation $c_1[1+g(c_1,c_2,t)]^t=c_2$.

[5] This result formalizes an insight that Schelling (1995) mentioned already.

$$C'_{ti}(x_{ti}) = \underbrace{[c_{ti}(S_t, x_{ti})]^\eta}_{d} \sum_{s=t}^{T} \delta^{s-t} \sum_{r\in R} [c_{sr}(S_s, x_{sr})]^{-\eta} MD_{sr}(t) \tag{11}$$

for marginal abatement costs in region i in year t. Note that except for part d all terms on the right hand side of the equation are the same for all regions. This allows for an easy interpretation: Optimal marginal abatement costs are higher for higher per-capita consumption regions, and that effect is stronger for higher inequality parameters η, where higher inequality also increases the difference between the optimal marginal abatement costs of different regions.

Efficient emissions path

I now derive efficient abatement costs, in particular the one Pareto-optimal allocation that corresponds to an optimum of a welfare function with Negishi weights (Negishi, 1960).

Following this approach I replace the objective function with a new version that includes time variant Negishi weights λ

$$\begin{aligned} &\max_{\{x_{tr}\}_{t,r}} \sum_{t=0}^{T} \delta^t \sum_{r\in R} \lambda_{tr} P_{tr} U\big(c_{tr}(S_t, x_{tr})\big) \\ &\text{s.t. } \; S_0 = \overline{S}_0 \end{aligned} \tag{12}$$

I calibrate the Negishi weights λ such that in the base case run marginal welfare is equalized across all regions at each time step. In order to achieve this I follow the standard procedure (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) and set

$$\lambda_{tr} = \left(\frac{c_{tr}}{\sum_{i\in R} C_{ir}(x_{ir}) / \sum_{i\in R} P_{ti}}\right)^\eta = \left(\frac{c_{tr}}{c_t}\right)^\eta \tag{13}$$

where I define c_t to be world average per-capita consumption at time t.

The new Bellman equation is

$$V_t(S_t) = \max_{\{x_{tr}\}_r} \sum_{r\in R} \lambda_{tr} P_{tr} U\big(c_{tr}(S_t, x_{tr})\big) + \delta V_{t+1}(S_{t+1}) \quad \forall t \tag{14}$$

The new first order conditions are, after some algebraic manipulation

$$C_{\mathrm{ti}}'(x_{\mathrm{ti}}) = \sum_{\mathrm{s=t}}^{\mathrm{T}} \delta^{s-t} \sum_{r} \left(\frac{c_t(S_t, X_t)}{c_s(S_s, X_s)}\right)^\eta MD_{sr}(t) \quad \forall i \in R \tag{15}$$

for all time periods. Note that in this case in each time step marginal abatement costs are equal for all regions, given that the right-hand side of equation (15) is the same for all regions. The weight given to the marginal damage term now equals the standard Ramsey discount factor

$$\delta^{s-t}\left(\frac{c_t(S_t,X_t)}{c_s(S_s,X_s)}\right)^{\eta}=\left(\frac{1}{1+\rho}\right)^{s-t}\left(\frac{1}{1+\eta g_s}\right)^{s-t}\approx\left(\frac{1}{1+\rho+\eta g_s}\right)^{s-t} \tag{16}$$

with g_s being the annual growth rate of world average per-capita consumption from time t to s.

3. The Model

FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetarized in 1995 dollars and are modeled over 16 regions. The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

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. Version 3.4, used in this paper, runs from 1950 to 3000 in time steps of one year. In *FUND*, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, reflecting the process of adjustment to climate change. Because the initial values used for the year 1950 cannot be approximated well, both physical impacts and monetized welfare 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 provide a proper long-term perspective. The remaining centuries are included to avoid endpoint problems for low discount rates; they have only a very minor impact on overall results.

The period of 1950-1990 is used for the calibration of the model based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The 1990-2000 period is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. 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 2100-3000 period is extrapolated.

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

Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol, 2005).

The scenarios of economic growth are perturbed by the effects of climatic change.[6] Climate-induced migration between world regions causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The welfare 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

[6] Note that in the standard version of FUND population growth is also perturbed by climate change impacts. That particular feature was switched off in the runs for this paper because endogenous population changes cannot be evaluated with the kind of welfare function investigated.

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 can be 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 effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy 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 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 is derived by 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 welfare impact module, based on Tol (2002a; 2002b) includes the following categories: agriculture, forestry, hurricanes, 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 are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is region and time specific and 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 three times the per-capita income (Tol, 1995; Tol, 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 modeled explicitly. The monetary value of a loss of one square kilometer 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 kilometer. Wetland losses are valued at $2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have a 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 welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Modeled effects 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 behavior 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 welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modeled 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) and heat-related disorders (with urbanization), or more valuable, such as 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).

The FUND model does not account for international trade in goods and services or for inter-regional investment flows. It models sixteen closed economies that are linked via a common atmosphere. As such it also does not account for carbon leakage between regions. At the time being, this is a shortcoming of most major established integrated assessment models of climate change that can be used for cost-benefit analysis of climate change policy.

4. Results

In this section I will present results for an optimal tax scheme from a utilitarian point of view in which lump sum transfers between regions are ruled out and contrast it with an efficient climate policy. These two cases correspond to the two welfare functions presented in section 2. After presenting some results for key indicators like tax rates, emission rates and temperature development, I will present sensitivity analysis for a number of key parameters.

Central results

Figure 1 contrasts tax rates for the different regions of FUND in the year 2005 for a specific calibration of the utility function (pure rate of time preference of 1% and η of 1). In the efficient case, tax rates (or marginal abatement costs) are equal in all regions at $23/tC[7]. For the utilitarian welfare function, tax rates differ greatly between regions, with optimal tax rates for rich regions (ANZ, CAN, WEU, USA and JPK) increasing up to $179 for Japan, while the tax rate decreases in all other regions, to below $2 for very poor regions like sub-Saharan Africa. China's optimal tax is almost reduced by 50% to $12.

As income differences between regions change over time, so does the spread of tax rates between different regions. Figure 2 shows optimal tax rates for a few selected regions in the year 2050 and 2100 for the same utility function calibration as above. For the efficient policy, taxes increase to $60 in the year 2050 and $148 in the year 2100 for all regions. The assumed rapid economic growth of China in the scenario causes a dramatic increase of its optimal tax rate over time: In the year 2050, the tax in the utilitarian case is just 15% below the global efficient tax rate (compared to 50% in the year 2005), and in the year 2100 China would actually have a higher tax on carbon emissions under the utilitarian regime.

[7] All results are in 1995 USD.

Figure 3 demonstrates what these tax rates imply in terms of emissions reductions per region. The graph shows the reduction of emissions in percent in the year 2050 for each region compared to its emissions in a business-as-usual scenario.[8] For the efficient policy, only the cost of emission reductions determine in which regions reductions happen. Regions with a lot of low-cost mitigation opportunities will show large reductions in emissions while regions with only costly mitigation options will reduce less. In regions such as the former Soviet Union, where mitigation can be achieved at low cost, the utilitarian approach does not take advantage of those low cost abatement opportunities, because they would be paid for by the relatively low-income population of that region. Rich regions mitigate much more, despite higher costs there, because the utilitarian welfare calculus gives less weight to those high.

While the emission reductions per individual region vary greatly between the utilitarian and efficient policy, the total world emission reduction stays almost the same at around 19% for both cases. Although the difference is small, the utilitarian assumption actually leads to a lower total optimal worldwide reduction in emissions. Inequality aversion and a concern for equity give more weight to both impacts and mitigation costs in poor regions than in high-income regions. The poor are especially vulnerable to climate change impacts and it has been shown repeatedly that when one only looks into impacts of climate change, a concern for equity increases damage estimates (Fankhauser *et al.*, 1997; Pearce, 2003; Tol *et al.*, 2003; Anthoff *et al.*, 2009). From this, one might conclude that more mitigation would be justified under such an approach. The analysis in this paper, on the other hand, also gives higher weight to mitigation costs in poor regions. If most cheap mitigation options are located in poor regions, such a treatment will have the effect that lower mitigation is appropriate when a concern for equity is present. This paper shows that the latter effect dominates and overall mitigation is lower with a concern for equity.

[8] In particular these are not reductions compared to a historic base line point (like 1990 or today).

Sensitivity analysis

Do these findings vary for different calibrations of the welfare function, in particular for different choices for the pure rate of time preference and inequality aversion? Table 1 shows the resulting temperature increase above pre-industrial temperatures in °C in the year 2100 for the business-as-usual scenario and contrasts it with the temperature increase that would result if one would choose the optimal mitigation path for various calibrations of the utility function.

The first general result is that for a high pure rate of time preference of 3% there is hardly any difference in the optimal temperature target in the year 2100 between the utilitarian and efficient policy. Note also that some of the combinations of preference parameters should not be taken too seriously, in particular, one would not want to combine a high pure rate of time preference with a high inequality aversion, given that this would lead to real interest rates that are above the observed market rate, unless total factor productivity growth has been overestimated (cf. Nordhaus, 2008 for a careful discussion).

A second general conclusion is that for higher choices of inequality aversion, in general less stringent temperature targets are optimal. As such, the findings in this paper support the conclusion that while higher inequality aversion might alter the distribution of mitigation efforts between regions, overall it will not lead to more stringent optimal global mitigation targets.

When comparing the utilitarian with the efficient policies, the results for different values of inequality aversion are more nuanced. While for an inequality aversion of 1, the optimal temperature target is always less stringent if ones chooses the utilitarian policy, this result reverses for higher inequality aversion choices. While higher inequality values have been suggested as reasonable for purely intertemporal decisions (Dasgupta, 2008), they would further widen the gap between observed wealth transfers from rich to poor regions and the transfers that would be optimal from a normative point of view (Okun, 1975). The difficulty of using one parameter to both specify inter- as well as intra-temporal inequality aversion (and in non-deterministic models risk aversion as well) has been recognized in the literature, but not yet been resolved (Sælen *et al.*, 2009).

5. Conclusion

In this paper I contrast an efficient climate policy with a utilitarian policy that assumes that the global planner does not have lump-sum transfers at her disposal. In particular, I assume that a global decision maker has the ability to set mitigation paths for all regions, but does not have any instruments at hand to compensate for unwanted distributional disturbances caused by the emission control policy.

The results show that the two cases have dramatically different emission reduction targets per region, but at the same time the overall global optimal emission path is affected much less by these considerations. In particular, taking into account equity between regions does not change the optimal global emission path in a dramatic way from the emission path that is calculated when only taking efficiency into consideration.

At the same time the approach in this paper has severe limitations. First, it only looks at two extremes: Either all transfers between regions are ruled out, or only one efficient policy is considered. These two choices clearly constitute the boundaries of the problem. In reality one can imagine much more nuanced frameworks, with partial compensation payments between regions, payments that are not lossless and transfers only between specific regions.

Secondly, I base the analysis of the situation without transfers on a utilitarian welfare function, without any philosophical justification for it. There is no good reason for this other than this is common practice in most of the literature on the economics of climate change. Once one leaves the world of pure efficiency, the question of *which* ethical framework to pick becomes highly relevant. In this paper I do not argue that the specific utilitarian welfare function I used is the appropriate one, I only show that under that specific choice, distributional questions are of significant importance to the optimal marginal abatement costs.

Finally, this paper ignores the problem of reaching an actual agreement to mitigate climate change emissions.[9] Nevertheless, it does show that any attempt to reach a global agreement to overcome the free-rider problem associated with a global public bad like climate change requires a benchmark optimal solution. The optimum that *should* be achieved by an international agreement is a normative question. This paper demonstrates that purely looking at an efficient outcome might not do justice to the magnitude of the distributional problem.

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[9] A different question (but closely related to the topic of this paper) is what emission abatement allocations would make every region better off than the status quo, when there are no transfers between regions. See Yang (2008) for a thorough investigation of that question.

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Figures

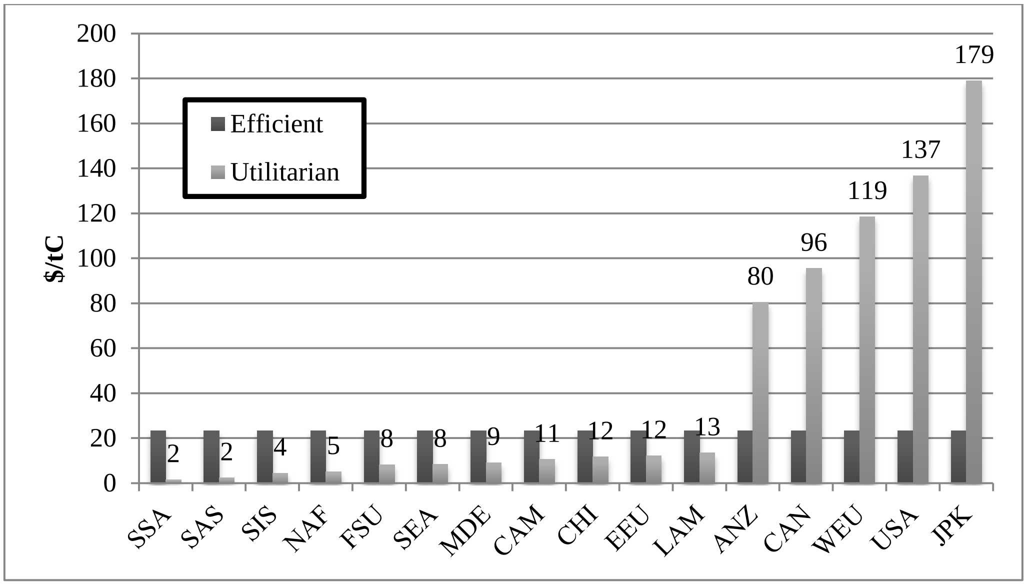

Figure 1: Tax per tC emission in the year 2005 by region for utilitarian policy without lump-sum transfers and for Pareto-efficient policy (prtp=1% and η=1)

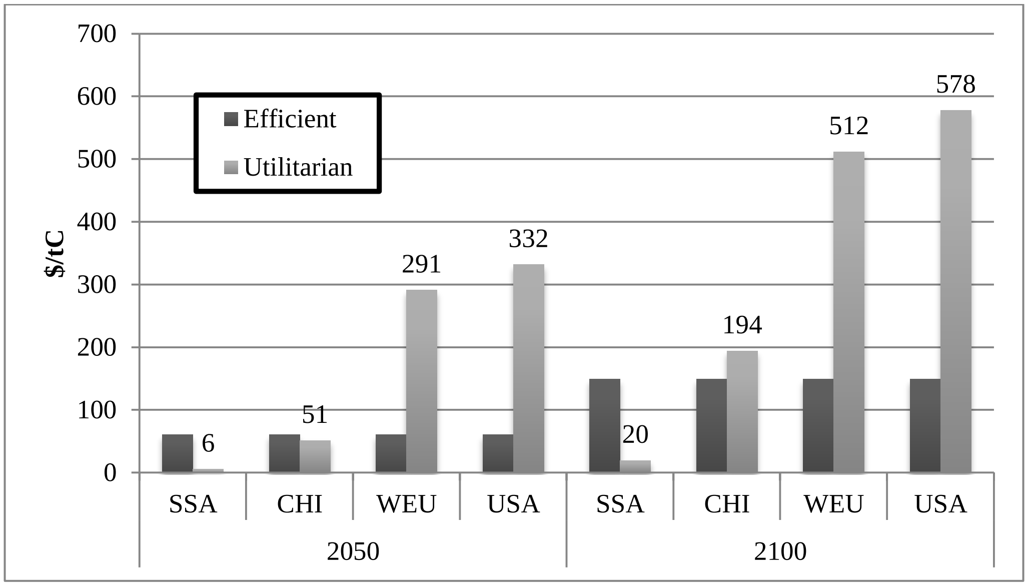

Figure 2: Tax per tC emission for selected regions in the year 2050 and 2100 for utilitarian policy without lump-sum transfers and for Pareto-efficient policy (prtp=1% and η=1)

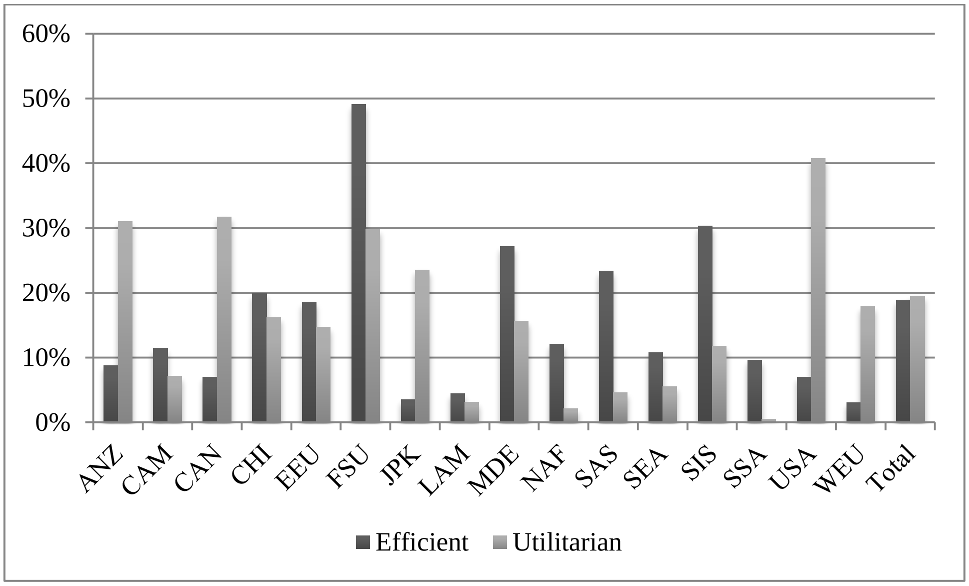

Figure 3: Reduction in emissions from a business-as-usual scenario in the year 2050 (prtp=1% and η=1)

Tables

Business-as-usual warming[a]: 3.17		
Utility calibration	Utilitarian[b]	Efficient[c]
η=1		
prtp=0.1%	2.41	2.34
prtp=1.0%	2.92	2.91
prtp=3.0%	3.12	3.12
η=1.5		
prtp=0.1%	2.65	2.75
prtp=1.0%	2.96	3.03
prtp=3.0%	3.13	3.13
η=2		
prtp=0.1%	2.69	2.98
prtp=1.0%	2.95	3.09
prtp=3.0%	3.13	3.14

Table 1: Temperature increase above pre-industrial in °C in the year 2100 for a) no policy intervention (business-as-usual), b) utilitarian policy without lump-sum transfers and for c) Pareto-efficient policy for different calibrations of the utility function