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# Optimal Global Dynamic Carbon Taxation

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*Abstract*: A necessary condition of an efficient global climate change mitigation policy is to equate marginal abatement costs across world regions to ensure use of the cheapest abatement options available. The welfare economic justification for such an approach rests on lump sum transfers between regions to compensate for any unwanted distributional consequences of such a policy. I contrast this efficient solution with a second best situation in which lump sum transfers between regions are impossible. I derive that in a dynamic setting optimal taxes are different in such a case for regions with different per capita consumption. I estimate the optimal tax rates with the integrated assessment model FUND and find that optimal mitigation is less stringent when equity is explicitly considered for widely used parameter choices of a utilitarian social welfare function.

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# 1. Introduction

It is almost a common place 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 proposal are hotly discussed, but one aspect receives relatively little questioning 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?

The classical role of a Pigouvian tax on an economic activity that creates an externality is to correct the inefficiency associated with damages that are not reflected in market prices of goods. Traditionally distributional consequences are not dealt with at this stage, but rather it is assumed that other instruments can or will be used to “make up” for any unwanted distributional consequence caused by the correction of the externality. This is in the spirit of the Kaldor-Hicks criterion (Kaldor, 1939; Hicks, 1939), i.e. that distributional issues ought to be separated from questions of economic efficiency. While there is a convincing argument that within one jurisdiction a government that could impose a tax on an externality does also have the necessary means (e.g. the income tax) to correct any undesirable distributional consequence caused by such a Pigouvian tax, this argument does not apply equally to cross-national cases of externalities or public goods. Climate change as a truly global public good is a classical example of that.

An early discussion of this problem was provided in Chichilnisky and Heal (1994)[1]. They contrasted optimal marginal abatement costs of carbon emissions in a multi region setting when lump sum transfers are possible between different regions with a situation in which such transfers are ruled out. They found that in the latter optimal marginal abatement costs were different in each region, whereas with lump sum transfers the classical result of equated marginal abatement costs prevailed. They used a static model around a global public bad as an approximation to the climate change problem, but given the inherent dynamic nature of the climate problem, they mostly derived basic theoretical results that as such are hard to apply to concrete climate change policy questions.

[1] Sheeran (2006) provides an extended discussion of the same result.

Sandmo (2006) investigates the question of optimal Pigouvian taxes in relation to a global externality, again in a static utilitarian framework. He comes to a similar conclusion as Heal and Chichilnisky: Unless one assumes that lump sum transfers between regions are possible, optimal Pigouvian taxes on the externality producing activity should not be harmonized or equalized across countries, but rather poor countries should impose lower taxes than rich countries.

The basic result that under certain welfare functions and an absence of lump sum transfers marginal abatement costs ought not to be equated has been discussed in a number of other papers as well. Most of these treatments stick to a static description of the problem, which makes their results not immediately applicable to a simulation of a stock externality problem like climate change with an integrated assessment model. Eyckmans *et al.* (1993) show not only that marginal abatement costs might differ between world regions in an optimum for specific welfare functions, but also discuss how various choices of welfare weights correspond to different results from negotiation processes. Shiell (2003b) acknowledges the basic result in Chichilnisky and Heal but argues that with a permit market the necessary lump sum transfers can always be obtained via the initial allocation of permits and that therefore differentiated marginal abatement costs could be avoided[2]. In this paper I look at a situation where this option is for whatever reason not possible. I will not give a stringent argument for this, but it seems at least plausible that large wealth transfers from rich to poor countries via initial allocation rules in a permit market might be politically infeasible.

Other papers have dealt with equity in climate change abatement in broader terms. Tol (2001) and Tol (2002c) look at optimal emission abatement under a variety of different welfare functions. Böhringer and Helm (2008) look at equity with respect to abatement costs only.

In this paper I build upon those results and extend them such that they can readily be employed for the analysis of climate change. On a theoretical level, I extend the analysis into a dynamic setting with a global stock externality, thus allowing an application to climate change. In doing so I also clarify how the discount rate is modified in an optimal setting that does not allow for lump sum transfers between regions. In a second step I then apply the integrated assessment model FUND to the problem and derive numerical estimates of optimal tax rates on carbon emissions, the corresponding optimal emission trajectory and optimal temperature targets. In a final step I do

[2] Shiell (2003a) uses a similar set up of welfare functions, dynamic optimization and regional disaggregation as used in this paper, but by assumption rules out differences in marginal abatement costs between regions, thereby focusing on a different question than I try to answer in this paper.

a sensitivity analysis of the results with respect to the key preference parameters of the pure rate of time preference and the inequality aversion.

The rest of the paper is structured as following: In section 2, I present a theoretical model of optimal marginal abatement costs of a global public bad in a setting with and without lump sum transfers and derive key necessary conditions for an optimal emissions trajectory. In section 3 a brief description of the integrated assessment model FUND is given. Section 4 presents results and section 5 concludes.

# 2. Theory

Let $x_{t,r}$ be carbon emissions in year $t$ in region $r$. Total emissions in year $t$ are defined as $X_t \equiv \sum_r x_{t,r}$. 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 current emissions from all regions.

Per capita consumption $c_{t,r}$ in year $t$ in region $r$ is

$$c_{t,r}(S_t, x_t) = \frac{C_{t,r}(x_{t,r}) - D_{t,r}(S_t, X_t)}{P_{t,r}} \tag{2}$$

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

Consumption is assumed to depend on emissions, where we assume that $C_{t,r}(0) = 0$, that there is an emissions level $\overline{x}_{t,r}$ that maximizes consumption and that $C_{t,r}$ is strictly concave. It follows that for all emission levels between 0 and $\overline{x}_{t,r}$, increasing emissions will increase consumption, i.e. $C_{t,r}^{'}(x) > 0$ for all $x \in (0, \overline{x}_{t,r})$. $C$ 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 in period $t$ depends both on the stock of carbon in the atmosphere at that time. Due to the formulation of the transition function, $S_t$ only accounts for emissions in periods before $t$, but actual carbon concentrations at $t$ also depend on emissions in $t$. Therefore damage in period $t$ is a function of both $S_t$ as well as $X_t$ concentrations , as well as on total emissions of all regions in the current period.

## Optimal emissions path

The optimization problem of a global planner is given as

$$\max_{\{x_t\}_{t=0}^{T}} \sum_{t=0}^{T} \delta^t \sum_r P_{t,r} U\left(c_{t,r}(S_t, x_t)\right) \quad (3)$$
$$\text{s.t.} \quad S_0 = \bar{S}_0$$

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. We also assume that the utility function $U$ has the usual iso-elastic form:

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

The Bellman equations[3] for this problem are

$$V_t(S_t) = \max_{\{x_{t,r}\}_r} \sum_r P_{t,r} U\left(c_{t,r}(S_t, x_t)\right) + \delta V_{t+1}(S_{t+1}) \quad \forall t \quad (5)$$

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

$$\frac{\partial}{\partial x_{t,i}} \left( \sum_r P_{t,r} U\left(c_{t,r}(S_t, x_t)\right) + \delta V_{t+1}(S_{t+1}) \right) = 0 \; \forall i. \quad (6)$$

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.

[3] The problem could of course also be solved by simply using Lagrange multiplier, given the finite time horizon of the model. A dynamic programming approach seems nevertheless easier and less convoluted.

$$MD_{s,r}(t) \equiv \begin{cases} \dfrac{\partial D_{s,r}(S_s, X_s)}{\partial X_s} & \text{for } t = s \\ \dfrac{\partial D_{s,r}(S_s, X_s)}{\partial S_s} & \text{for } t < s \end{cases} \tag{7}$$

With some manipulation we can rewrite the first order conditions as

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

This is a variation of the familiar rule that marginal abatement costs should equal marginal damage costs, but with some important modifications. On the left hand side are marginal abatement costs for a specific region $i$ in year $t$. The right hand side of the equation is the weighted sum of marginal damages happening 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 $\rho$. The second weight after the summation sign over regions (part a) is a combination of distributional weights 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

$$\delta^{s-t} \underbrace{\left(\frac{c_{t,i}(S_t, x_t)}{c_{s,r}(S_s, x_s)}\right)^{\eta}}_{a} \approx \underbrace{\left(\frac{c_{t,i}(S_t, x_t)}{c_{t,r}(S_t, x_t)}\right)^{\eta}}_{b} \underbrace{\left(\frac{1}{1 + \rho + \eta g\big(c_{t,r}(S_t, x_t), c_{s,r}(S_s, x_s), s - t\big)}\right)^{s-t}}_{c} \tag{9}$$

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 we have marginal abatement costs in the equation will always be one, so that abatement and damages are valued equally and consistently (Anthoff *et al.*, 2009). Marginal damages in other regions receive a distributional weight that

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

will be >1 (<1) for regions with lower (higher) per capita consumption than the regions for which abatement costs are calculated.

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

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

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

We can now ask ourselves how optimal marginal abatement costs for different regions will look like. Another rearrangement of equation (8) gets us

$$C'_{t,i}(x_{t,i}) = \underbrace{\left[c_{t,i}(S_t,x_t)\right]^{\eta}}_{d}\sum_{s=t}^{T}\delta^{s-t}\sum_{r}\left[c_{s,r}(S_s,x_s)\right]^{-\eta}MD_{s,r}(t) \tag{11}$$

for marginal abatement costs in region $i$. Notice 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 $\eta$, where higher inequality also increases the difference between the optimal marginal abatement costs of different regions.

## Efficient emissions path

We now derive efficient abatement costs. Unlike the previous section, we ignore distributional questions between regions this time. The welfare economic rationale for such an approach would be the assumption that lump sum transfers are feasible and that any desirable distributional outcome can be achieved in a second step via such lossless transfers, after the externality has been internalized via a Pigouvian price signal – that is, the Coase (1960) Theorem holds.

Following the standard approach in the literature we replace our objective function with a new version that includes so called Negishi-weights

$$\max_{\{x_t,\tau_t\}_{t=0}^{T}} \sum_{t=0}^{T} \delta^t \sum_r \lambda_{t,r} P_{t,r} U\left(c_{t,r}(S_t, x_t)\right) \quad (12)$$
$$\text{s.t.} \quad S_0 = \overline{S}_0$$

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

$$\lambda_{t,r} = \left(\frac{c_{t,r}}{\sum_i C_{i,r}(x_{i,r}) / \sum_i P_{t,i}}\right)^{\eta} = \left(\frac{c_{t,r}}{c_t}\right)^{\eta} \quad (13)$$

where we define $c_t$ to be world average per capita consumption at time $t$.

The new Bellman equations are

$$V_t(S_t) = \max_{\{x_{t,r}\}_r} \sum_r \lambda_{t,r} P_{t,r} U\left(c_{t,r}(S_t, x_t)\right) + \delta V_{t+1}(S_{t+1}) \quad (14)$$

The new first order conditions are, after some algebraic manipulation

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

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 is reduced to the standard Ramsey discount factor

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

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 modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol, 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

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. Version 3.4, used in this paper, runs from 1950 to 3000 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. 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 to be used for the year 1950 cannot be approximated very 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 22$^{nd}$ and 23$^{rd}$ 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, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 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 period 2100-3000 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.[5] Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible 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 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.

[5] 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.

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; b) 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 set to be 200 times the annual per capita income.[6] 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; 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 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). Modelled 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 behaviour of farmers. Impacts are positive or negative depending on whether

[6] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz, 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser *et al.*, 1997).

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 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) 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).

# 4. Results

In this section I will present results for an optimal tax scheme in which lump sum transfers between regions are assumed to be possible and one where there are no transfers. These 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 $\eta$ of 1). In the case without the possibility of transfer payments, optimal tax rates (or marginal abatement costs) are equal in all regions at $23/tC[7]. When transfer or compensation payments are ruled out, tax rates

[7] All results are in 1995 USD.

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 previous. For the scenario with lump sum transfers the optimal tax increases 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 makes for a dramatic adjustment of its optimal tax rate over time: In the year 2050 the tax without transfers payments is just 15% below the global tax rate in a scenario with lump sum transfers (compared to 50% in the year 2005), and in the year 2100 China would actually have a higher tax on carbon emissions in a scenario without transfers compared to one with.

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] In the scenario with lump sum transfers the question in which regions reductions occur is only determined by the cost of emission reductions, i.e. 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 assumption of no lump sum transfers leads to a situation where those low cost abatement opportunities are not picked up, given that they would be paid for by the relatively low income population of that region. On the other hand, rich regions will mitigate a lot more, although it is costly, given that in the utilitarian welfare calculus those high costs do get less weight when they occur to the relatively wealthy population of the United States.

While the differences between regions vary greatly between a scenario with lump sum transfers and one in which this is ruled out, the total emission reduction stays almost the same at around 19%. While the difference is small, the assumption that no compensation will take place actually leads to a lower total optimal worldwide reduction in emissions. This is a somewhat surprising result, previously there was a sense that taking equity between regions explicitly into account in

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

climate change policy would lead to more stringent mitigation policies. As the results in this paper show, at least under one widely used ethical framework, utilitarianism, this need not be the case. Inequality aversion and a concern for equity will in general 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 (c.f. Fankhauser *et al.*, 1997; Pearce, 2003; Tol *et al.*, 2003; Anthoff *et al.*, 2009), from which 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 a lot of 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. As the results in this paper show, the latter effect dominates and overall mitigation is lower with a concern for equity.

## 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 over both different preference parameters and scenarios with and without transfer payments, while even the difference between a business as usual scenario and optimal policy scenarios is small. Note also that some of the combinations should not be taken too serious, 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.[9] While this result would not be surprising if inequalities between regions were neglected (in which case higher inequality versions would simply increase

[9] With one minor exception, but that is so small that it seems not important.

the discount rate), it does not follow analytically for a setup as used in this paper, where higher inequality aversion between regions might have led to a different result. 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 a transfer with a no transfer scenario, the results for different utility function calibrations is more nuanced. While for an inequality aversion of 1, the optimal temperature target is always less stringent if one assumes that no transfers are possible, 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 actually wealth transfers between rich and poor regions and what the optimal wealth transfer according to the welfare function would be (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 recognised in the literature, but not yet been resolved (Saelen *et al.*, 2008).

# 5. Conclusion

In this paper I contrast a first-best world in which an optimal emissions path is calculated purely based on an efficiency criterion, i.e. under the assumption that any distributional consequences of a specific policy can be dealt with at a later stage with different (and costless) instruments, with a look at a specific ethical framework and a global decision maker that is constraint in its policy options. In particular, I assumed in a second step 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. In this second scenario I looked at a specific welfare function, namely a classical utilitarian one, and derived optimal emission reduction pathways for different regions.

The results show that the two cases have dramatically different emission reductions targets per region, but at the same time the overall global optimal emission path is affected a lot less by these considerations. In particular, taking account of equity between regions as I did in this paper 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 takes too extremes into account: Either all transfers between regions are ruled out or they are assumed to have no limits as pure lump sum transfers. 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 practise 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 of high importance. 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 any problems of incentives of different regions, i.e. the game theoretic problem of reaching an actual agreement to mitigate climate change emissions is ignored. At the same time I see a contribution of this paper to that literature: in any attempt to come up with some global agreement that circumvents the free-riding problem associated with a global public bad like climate change there is a need for a benchmark optimal solution. What is the optimum that *should* be achieved by a achieved by an international agreement? This is principally a normative question, and I hope this paper demonstrates that purely looking at an efficient outcome might not do the magnitude of the distributional problem justice.

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# Figures

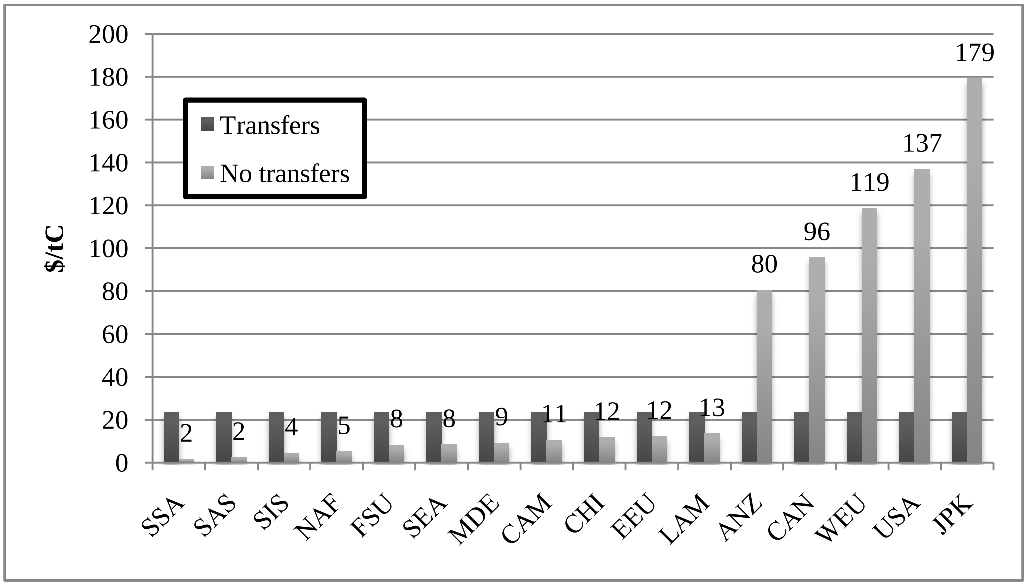


**Figure 1: Optimal tax per tC in the year 2005 for prtp=1% and η=1**

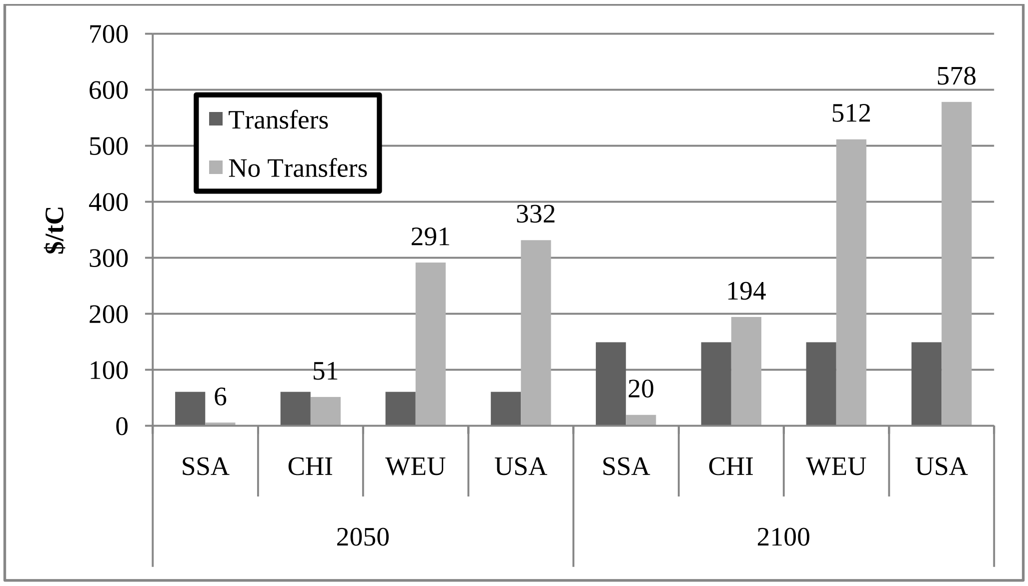


**Figure 2: Optimal tax per tC for selected regions in the year 2050 and 2100 for prtp=1% and η=1**

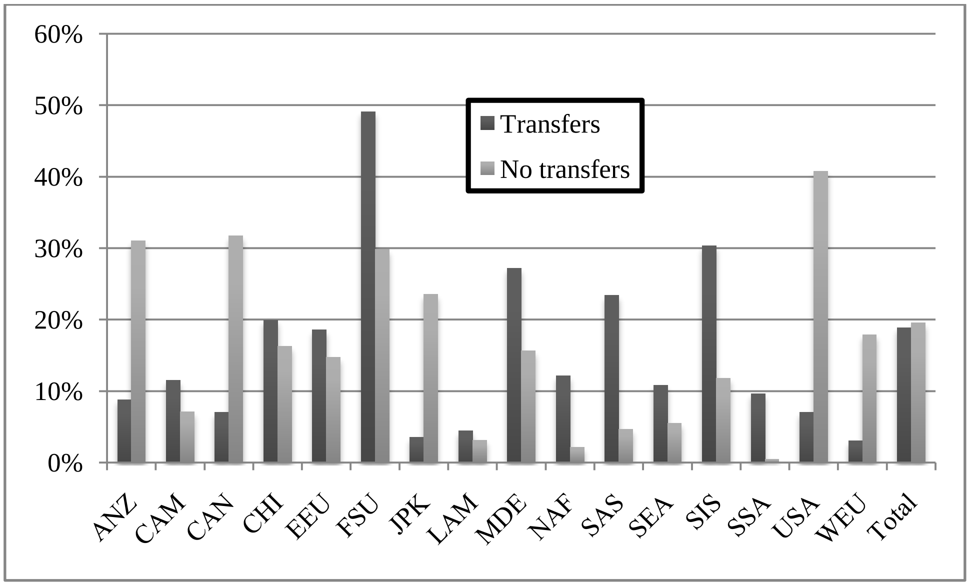


**Figure 3: Reduction in emissions compared to business as usual scenario in the year 2050 for prtp=1% and η=1**

# Tables

| Business as usual warming: 3.17 | | |
|---|---|---|
| | | |
| **Utility calibration** | No transfers | Transfers |
| 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 no policy intervention (business as usual) and optimal policies for different calibrations of the utility function**

| Year | Number | Title/Author(s)<br>**ESRI Authors/Co-authors *Italicised*** |
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