Valuing equally the environmental goods in rich and poor countries in a Post-Kyoto world.

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Abstract

The optimal pollution abatement levels are found by maximizing global social welfare in a permit and no-permit trade systems under the constrain that environmental goods are evaluated equally in rich and poor countries. Evaluating equally environmental goods in poor and rich countries makes possible to build a relation between the income elasticity of marginal utility e and the inequality aversion parameter γ (Fankhauser et al., 1997; Stenman, 2000), which narrows the variation of e for a particular value of γ. As a result, smaller variation for optimal abatement levels is obtained, which allows to inspect what Post-Kyoto abatement levels for poor and rich countries respect the requirement of evaluating equally the environmental goods in rich and poor countries. One finding is that in a Post-Kyoto world, the optimal abatement levels of poor countries have to be significantly big, if we aim to evaluate equally the environmental goods in poor and rich countries. Furthermore, in a permit trade system, if we plan big amount emission reductions then, it can happen that poor countries have to carry out higher emission reductions than rich ones.

Keywords: cost-benefit analysis, distributional weights, global warming, welfare theory, integrated assessment modeling.

JEL: D61, D62, D63

1 Introduction

Environmental equity is a sensible concept in global warming debates. It addresses the distributional issue which is the cumbersome point of benefit-cost analysis. The capita income is lower in poor countries in comparison to rich ones. Consequently, the willingness-to-pay (WTP) in order to avoid climate damages in poor countries are lower than in the developed countries even though the impact is identical in human, physical or ecological terms. One way of managing this would be to use a normative approach by introducing weight factors based on the different marginal value of money in the different regions of the world. This would give higher weight to costs in the poor countries. Environmental equity can be understood as assuming a new decision criterion that requires that the value of lost lives (also any environmental goods) in rich and poor countries has to be weighted differently. I would like to test when Post-Kyoto emissions reduction targets respect that the value of life is identical in poor and rich countries when distributional weights (or equity weights) are used.

There are different views in favor and against of using weight factors. I do not plan to review this discussion. I simply assume that weight factors are considered appropriate from a normative point of view, and then examine when Post-Kyoto emission's reduction targets are consistent with the requirement of valuing the life in poor and developed countries by weighting them differently.

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Following Ray (1984) and Stenman (2000), I obtain the equity weights by totally differentiating the social welfare function. The social welfare function depends on three parameters, which are the income per capita, the elasticity of marginal utility e and the inequality aversion parameter γ. The income per capita depends on GDP, population and pollution abatement costs and benefits, which are obtained from integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) developed by Richard Tol (see Section 2).

The essential point of the paper is investigating the consequences of abatement policies when global welfare is maximized under the constrain that environmental goods are evaluated equally in rich and poor countries. Following Stenman (2000), using weights and equalizing the value of life in poor and rich regions, we develop a relation between e and γ. However, I consider a larger range of parameter values that relates e and γ compared to Stenman (2000). As e and γ take their values in intervals, there is a significant advantage to have a relation between them, as it is possible to restrict the intervals for e and γ when the world regions are approximated in only two types, namely poor and rich. That is, when the world social welfare for different e and γ is maximized (under the constrain that environmental goods are evaluated equally in rich and poor countries), and pollution abatements levels are found, one focuses on smaller intervals for e and γ which are going to give smaller variation for abatement levels. Finally, it is possible to inspect if the abatement targets of a Post-Kyoto protocol respect the condition that the value of life is identical in poor and rich countries when equity weights are used, which is the main contribution of this research. The costs and benefits from pollution abatements are calculated for the year 2015, which is considered as the representative year of a selected commitment period of Post-Kyoto protocol that includes the years 2013 through 2017.

The optimization global welfare models are similar to Eyckmans et al. (2002), Rose et al. (1998) and Rose and Stevens (1993). Eyckmans et al. (2002) maximize a social welfare function (only for EU) with only one parameter, namely e, which is less general that our social welfare function with two parameters (namely e and γ). Rose et al. (1998) minimize cost of pollution abatement (or maximize benefits in Rose and Stevens (1993)) and use different international equity criteria, while in this paper a social welfare function is maximized when the value of life is equal in rich and poor countries.

The paper is structured as follows. Section two introduce the FUND model. The third section reviews the utility and welfare functions and derives the distributional weights. Different types of welfare functions, are considered, including the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function ($\gamma = 2$)[1]. in this section, I assume that the value of life in poor and developed countries is the same by weighting them differently in order to derive a relation between the elasticity of marginal utility e and the inequality aversion parameter γ. Section four presents the optimization global welfare models without permit systems and with permit systems for the integrated assessment model FUND. The fifth section presents the results. The section six provides the conclusions. The appendix contains different tables, which present the results, and parameters intervals that produce the relation between e and γ, main parameters of the FUND model, and Figures that illustrate the optimal abatement levels of poor and rich regions.

2 FUND 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 (2006).

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 (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact of the previous year, in this way reflecting the process of adjustment to climate change. Because the initial

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[1] The reason why I do not use bigger values than 2 for γ is clarified in Footnote (6).

values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be poorly represented in the first few decades of the model runs. 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 of the World Resources Databases (W.R.I., 2001). 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 decarbonization 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 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 (W.R.I., 2001). 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 market 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, an option not considered in this paper.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean surface 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, 2006).

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 (2002b,c) 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) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol, 2002c). 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 monetized. 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 (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 (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 (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 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 (Tol, 2002b). 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 (Tol, 2002c). 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 (Tol, 2002c). 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) (Tol, 2002c).

3 Utility, Welfare Function and Equity Weights

It is common to use a conventional iso-elastic utility function that depends solely on consumption:

$$u = \begin{cases} \dfrac{Y^{(1-e)}}{1-e} + u_0 \ , & e \neq 1 \\ \\ ln(Y) + u_0 \ , & e = 1 \end{cases} \tag{1}$$

where $e = -[du'/dY]Y/u' = -Yu''/u'$ is the income elasticity of marginal utility, which shows that e is a measure of the curvature of u(Y).

The class of welfare functions for which inequality parameter γ is constant is given by the Bergson-Samuelson form:

$$W = \begin{cases} \sum_{i=1:n} \dfrac{u_i^{(1-\gamma)}}{1-\gamma} \ , & \gamma \neq 1 \\ \\ \sum_{i=1:n} ln(u_i) \ , & \gamma = 1 \end{cases} \tag{2}$$

where γ is the parameter of inequality aversion. The smaller is γ, the smaller is the worry about equality. For $\gamma = 0$, equation implies the classical utilitarian welfare function and $\gamma = 1$ is associated with the Bernoulli-Nash function, while $\gamma \to \infty$ represents the maximin case. However, what value[2] to choose for e ? Pearce (2003) suggests a simple way, in case of the classical utilitarian welfare function, for estimating the value of e. He judges the value of e by employing equity weights in order to evaluate the climate damages between poor and rich regions:

$$D_{WORLD} = D_p \left(\frac{\bar{Y}}{Y_p}\right)^e + D_r \left(\frac{\bar{Y}}{Y_r}\right)^e \tag{3}$$

Y is income, $\bar{Y}$ is the average world per-capita income, P and R refers to poor and rich regions, D is damage, and e is the elasticity of the marginal utility of income, $\left(\frac{\bar{Y}}{Y_p}\right)^e$, $\left(\frac{\bar{Y}}{Y_r}\right)^e$ are the equity weights for evaluating the damage in poor and rich regions. In equation (3) all damages are considered but the damage happened to developing countries (with incomes lower than world average) attracts higher weights than the damages in developed countries (with incomes higher than world average). One can judge the value of e by estimating the ratio of weights between poor and rich in equation (3) (that equals the ratio of the marginal utilities between poor and rich if the utility function of rich and poor are expressed by equation (1)) which is given by:

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[2] Evans (2005) calculates the values of elasticity of marginal utility e for 20 OECD countries based on a tax-model. However, I am going to focus on a relation between e and γ in stead of merely the value of e.

$$\left(\frac{\bar{Y}}{Y_p}\right)^e / \left(\frac{\bar{Y}}{Y_r}\right)^e = \left(\frac{Y_r}{Y_p}\right)^e$$

Assume $Y_R = 10Y_P$ is the case for international real-income comparisons between high income countries and low income countries. At $e = 1$, unit damage to the poor (or a marginal unit of income) is valued ten times the unit damage of the rich; if $e = 2$, the relative valuation is 100 times. On this simple calculation basis, values even of $e = 2$ are not justified. Clarkson and Deyes (2002), Pearce and Ulph (1999), Cowell and Gardiner (1999) and Cline (1992) consider the the value of e is $1 < e < 1.5$, although Pearce and Ulph (1994) suggest $e = 0.8$, while Dasgupta (2008) proposes the value of e between 2 and 3.

However, what values can γ take? Firstly, note that γ must be an integer in order to make possible for welfare function to take real values and not complex ones[3]. The values for γ will be found by developing in the next subsection a relation between e and γ (Fankhauser et al., 1997; Stenman, 2000).

Equity weights can also be derived by totally differentiating the social welfare function(Ray, 1984; Stenman, 2000):

$$dW = \sum_{i=1:n} \frac{\partial W}{\partial u_i} \frac{du_i}{dy_i} dY_i = \sum_{i=1:n} q_i \, dY_i \tag{4}$$

where equity weights q_i are:

$$q_i = \frac{\partial W}{\partial u_i} \frac{du_i}{dY_i} = \begin{cases} u_i^{-\gamma} Y_i^{-e} \ , & e \neq 1 \quad \forall i \\ \\ u_i^{-\gamma} Y_i^{-1} \ , & e = 1 \quad \forall i \end{cases} \tag{5}$$

Equity weights must be used as the utility function can be concave in income, so that for the same income variation, utility changes more for a poor than for a rich person; alternatively, the social welfare function may be concave in utilities, so that the same utility variation from a low level, changes the social welfare more than the same utility variation from a high level.

3.1 Monetary Evaluation for Environmental Quality

One of the most debated issues related to the cost-benefit analysis (CBA) is the fact that the economic value of the environmental quality can be lower in poorer countries in comparison to richer ones due to positive income elasticity for risk reductions, if one does not apply any distributional weights. The condition for an equal monetary value of environment between poor and rich regions (or any other good like value of statistical life (VOSL)) to be used in a CBA can be written as follows (Fankhauser et al., 1997; Stenman, 2000):

$$\frac{\partial W}{\partial u_r} \frac{du_r}{dY_r} V_r = \frac{\partial W}{\partial u_p} \frac{du_p}{dY_p} V_p \Longleftrightarrow q_r V_r = q_p V_p \tag{6}$$

where V_r, V_p are values of environmental quality in rich and poor regions, and q_r, q_p are equity weights for rich and poor regions. After replacing in the equation (6), the derivative from equation (1) and equation (2), and noting that $V_r/V_p = (Y_r/Y_p)^\varepsilon$ where ε is the income elasticity of demand for environmental equality, it results:

$$\gamma = \frac{(e - \varepsilon) \, ln(Y_p/Y_r)}{ln(u_r/u_p)} \tag{7}$$

γ has to be an integer in order to ensure that welfare function take real values (and not complex ones). It implies that it makes sense to have e as a function of γ:

$$e = \gamma \, \frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} + \varepsilon \tag{8}$$

I am going to perform a simple sensible analysis of equation (8). The income elasticity of demand ε in equation (8) is upper bound for e; when $\gamma = 0 \Longrightarrow e = \varepsilon$; when γ increases (keeping other parameters unchanged) e decreases as[4] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$. Therefore, it makes sense to support values of $\varepsilon = 1.2$, which gives γ a chance of being bigger than 1 in spite of, there is evidence that the ε can take also values of 0.33. The numerical computations, by letting values of $\gamma = \{0, 1, 2\}$[5], $Y_r/Y_p = \{3, 4, 5\}$ and $u_r/u_p = \{1.2, 1.3, 1.4\}$, show that the value of $e \in [0.8, 1.2]$, see Tables 1, 2, 3 and 4 in Appendix[6] one.

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[3] Azar (1999) already noted that when $e > 1$ utility function takes negative values, which imply that γ will be the equality aversion parameter in stead of the inequality aversion one.

[4] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$ as $ln(Y_p/Y_r) < 0, \;\; ln(u_p/u_r) > 0$ for $Y_p < Y_r, \;\; u_p < u_r$

[5] $\gamma = \{0, 1, 2\}$ means $\gamma = 0$, $\gamma = 1$, $\gamma = 2$.

[6] When $\gamma = \{3, 4\}$ the value of e goes down to 0.58. Therefore, those values of γ are considered as too high.

The advantages of the numerical experiment above arise when there are only two types of countries, rich and poor. As the same social welfare function is used for both types of countries, then it is possible to find which values (or intervals) to use for e and γ in order to obtain a smaller variation for optimal abatement levels.

4 Allocation Model of Burden Sharing Emissions

The cost-benefit functions for every world region (or region) i are taken from integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) model. Two optimization problems are constructed for cost-benefit functions specified by FUND model: one without emissions trading and one with emission trading. The optimization problems are solved by using the MATLAB Optimization Toolbox[7]. The variables of the optimization problem without permit trade system are: R_i's which are *relative abatements levels* for every world region i.
R_k is the total relative abatement level; we simulate results for R_k equal to 1.6, 3.2, 4.8 and 6. The optimization problem without emission trading is stated below:

$$\max \sum_{i=1:n} SWF_i \tag{9}$$

$$\sum_{i=1:n} R_i \geq R_k \tag{10}$$

$$-1 \leq R_i \leq 1 \tag{11}$$

where SWF_i is the social welfare function for each region i.

$$(Z_i = GDP_i + B_i - C_i)/POP_i \tag{12}$$

where GDP_i is Gross Domestic Production for every region i, $B_i = f(R_i), C_i = f(R_i)$ is the benefit[8] and cost functions for every region i, and they are functions of the relative abatement level of region i, R_i. The costs and benefits from pollution abatements are calculated for the year 2015 which is considered as the representative year of the commitment period of the Post-Kyoto protocol that includes the years 2013 through 2017. The Social Welfare Function (SWF) for each world region i is defined as:

$$SWF_i = POP_i \, \frac{\left(\frac{Z_i}{(1-e)}^{(1-e)} \right)^{(1-\gamma)}}{(1-\gamma)} \qquad \forall\, e \neq 1, \forall\, \gamma \neq 1 \tag{13}$$

$$SWF_i = POP_i \, \frac{\left(logZ_i \right)^{(1-\gamma)}}{(1-\gamma)} \qquad e = 1, \forall\, \gamma \neq 1 \tag{14}$$

$$SWF_i = POP_i \; log \left(\frac{Z_i}{(1-e)}^{(1-e)} \right) \qquad \forall\, e \neq 1, \gamma = 1 \tag{15}$$

$$SWF_i = POP_i \; log\left(logZ_i\right) \qquad e = 1, \gamma = 1 \tag{16}$$

Without constraints on the trading volumes, individually rational countries (which maximize their utility of per capita income) will reduce their carbon emissions up to the point where their marginal abatement costs are exactly equal to the market price $C_i^{'}(R_i) = Pr$. This condition defines the emission reduction supply curve $RSi(Pr) = C_i^{'-1}(Pr)$ (Eyckmans et al., 2002). The emission reduction supply curve (or equivalently the inverse cost curve) is a linear function of the market price, see equation 24 for the shape of abatement cost function. The market clearing price is defined as the price for which total supply is sufficient to achieve the emissions reduction constrain:

$$\sum_{i=1:n} RS_i(Pr) = \sum_{i=1:n} C_i^{'-1}(Pr) = \sum_{i=1:n} \left(1\,/(\,2\,\alpha_i\,Y_i)\;E_i^2\right)\,Pr = R_k \tag{17}$$

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[7] The computation programs can be provided on request.

[8] The benefit and cost functions from pollution abatement are provided from the FUND model.

where α is the abatement cost parameter, which is unitless; E is the carbon dioxide emissions in billion metric tonnes of carbon; Y is gross domestic product, in billions US dollars, see Table 5. $n = 16$ as there are 16 world regions in FUND.

The variables of the optimization problem with permit trading system are: R_i's (similar to first optimization problem) which are *relative abatements levels* for every world region i, and Pr which is price of carbon emissions in dollars per metric ton of carbon, while the relative permissions levels for every world region i are equal to $(R_i - R_0)$ where $R_0 = 0.2$.

For both optimization problems, R_k is the total relative abatement level; we simulate results for R_k equal to 1.6, 3.2, 4.8 and 6. The optimization problem with emission trading system is stated below:

$$\max \sum_{i=1:n} SWF_i \tag{18}$$

$$\sum_{i=1:n} R_i = R_k \tag{19}$$

$$\sum_{i=1:n} RS_i(Pr) = \sum_{i=1:n} (1/(2\,\alpha_i\,Y_i)\ E_i^2)\ Pr = R_k \tag{20}$$

$$lb \leq R_i \leq ub \tag{21}$$

$$0 \leq Pr \leq 1000 \tag{22}$$

The optimization problem 18 has the same welfare function SWF, which is defined in equations (13), (14), (15) and (16), but Z_i is defined differently:

$$Z_i = (GDP_i + B_i - C_i + Pr(R_i - R_0)E_i)/POP_i \tag{23}$$

The price of selling (when selling $R_i < R_0$, when buying $R_i > R_0$) of 1 ton emissions equals Pr Dollars, which changes income by $Pr(Ri - R0)Ei$ (when emission permits are bought or sold), and changes also emissions cost, which is reflected at the cost function C_i.

The FUND 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 benefit B and the cost C of a country (region) i in the FUND model are given as:

$$B_i - C_i = \beta_i \sum_{j}^{n} R_j E_j - \alpha_i R_i^2 Y_i \tag{24}$$

where R denotes relative emission reduction, β marginal damage costs of carbon dioxide emissions, E unabated emissions, Y gross domestic product, indexes i denote regions and α is the cost parameter, see Table 5.

The world regions for model FUND can be fairly approximated by two types, OECD countries (or rich ones) and non-OECD countries (or poor ones)[9]. The social welfare function of the same shape is used for both types of countries. The values (or intervals) of the elasticity of marginal utility e and the inequality aversion parameter γ are taken from Tables 1, 2, 3 and 4 in Appendix, which makes use of the equation 8. The relation between e and γ allows to narrow the variation of e for a specific value of γ. As a consequence it is possible to attain smaller variation for the optimal emission reduction levels too.

5 Results

The results of the FUND model without a permit system (FUND-nopermit) and with a permits system (FUND-permit) are discussed. The emission's reductions (or abatement levels) are estimated as *fractions of the total world emissions.* Let me explain:

$$R_i = \frac{Er_i}{Eb_i} \tag{25}$$

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[9] Concerning FUND model, the world regions of United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones).

where Eb_i is the total emission budget *for the country (or world region)* **i** in absolute terms, before the abatement takes place; Er_i is the amount of emissions reduction *for the country* **i** in absolute terms; and R_i is the emission's reduction *for the country* **i** in relative terms (or relative emission's reduction).

$$Rf_i = \frac{R_i Eb_i}{\sum_{j=1}^{16} R_j Eb_j} \tag{26}$$

where $R_i Eb_i = Er_i$ is the amount of emission reductions in absolute terms *for the country* **i**; $\sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j$ is the total emission's reduction *for all the world*, and there are 16 world regions; and Rf_i is the emission's reduction *for the country* **i** as *fraction of the total world emission's reduction.*
We calculate Rf_i's for each world region. For FUND-nopermit model see Tables 6, 7, 8 and 9 while for FUND-permit model see Tables 10, 11, 12 and 13. Clearly $\sum_{i=1}^{16} Rf_i = 1$, and $Rf_i < 0$ indicates that the country **i** can increase its emissions. This occurs as it is expensive to reduce emissions in country **i**. In stead emissions are decreased in other regions of the world where it is cheaper.
Furthermore, emission's reductions for rich (A_r) and poor regions (A_p) are estimated as *fractions of the total world emissions* (see Figure 1 for FUND-nopermit, while see Figures 2, 3 and 4 for FUND-permit).

$$A_r = \frac{\sum_{l=1}^{5} R_l Eb_l}{\sum_{j=1}^{16} R_j Eb_j} \tag{27}$$

where $\sum_{l=1}^{5} R_l Eb_l = \sum_{l=1}^{5} Er_l$ is the amount of emission's reduction in absolute terms *for rich countries.* The FUND model has 5 rich world regions (or countries), which are United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand. The $Ewr = \sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j$ is the total emission's reduction *for all the world* (we have 16 world regions), and A_r is the abatement level (or emissions reduction) *for rich countries* as *fraction of the total world emissions Ewr.*

$$A_p = \frac{\sum_{t=1}^{11} R_t Er_t}{\sum_{j=1}^{16} R_j Eb_j} \tag{28}$$

where $\sum_{t=1}^{11} R_t Eb_t = \sum_{t=1}^{11} Er_t$ is the amount of emission reductions in absolute terms *for poor countries.* The FUND model has 11 poor world regions, which are 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; $\sum_{j=1}^{16} R_j Eb_j = \sum_{j=1}^{16} Er_j = Ewr$ is the total emission's reduction *for all the world* (we have 16 world regions); and A_p is the abatement level (or emissions reduction) *for poor countries* as *fraction of the total world emissions Ewr.*
It is trivial to see that $A_r + A_p = 1$.
Tables 6 to 9 represent all regions and their optimal abatement levels for FUND-nopermit (and similarly Tables 10 to 13 for FUND-permit); different values of the elasticity of marginal utility e, different values of the inequality aversion parameter γ and different values of total relative abatement levels R_k are taken into account (the values of e and γ respect the relation of e and γ originating from equation (8)). The Figures[10] 2 to 4 (for FUND-permit), and Figure 1 (for FUND-nopermit) introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in [0, 1.5]$. *Optimal abatement levels mean that the world global welfare is maximized, and environmental goods are equally evaluated in poor and rich countries.* The intervals of e for every specific γ, which respect the requirement that environmental goods are equally evaluated in rich and poor countries, are shown in every figure. Different values of total relative abatement levels R_k are taken into account.
In all simulations for FUND-permit and FUND-nopermit (for different value of γ, e and R_k), the abatement levels of poor countries are different from zero. It implies that in a Post-Kyoto world, the abatement levels of poor countries have to be different from zero, if we aim to evaluate equally the environmental goods in poor and rich countries. See Figure 1 for FUND-nopermit[11], while see Figures 2, 3 and 4 for

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[10] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$, (for FUND-nopermit and FUND-permit) therefore, in Figure 4 (and in Figure 1 when $\gamma = 2$), a circle is placed in this particular point. However, the optimal abatement levels for the cumbersome point are presented in Tables 6-9 and 10-13, and they are consistent with conclusions. I think that the numerical instability is inherited from the shape of the social welfare function because the numerical experiments with the SWF for $e \neq 1$ (when $\gamma = 2$, see equation (18)) and, $e = 1$ (when $\gamma = 2$, see equation (19)) show that there is a discontinuity for both types of functions for the neighborhood of particular point $e = 1$ (which must not be).

[11] In Figure 1, when $\gamma = 0$ and R_k equals 1.6, 3.2, 4.8 or 6, the values of A_r and A_p differ by less than 10^{-2} for all R_k, so the graph looks identical for different R_k. Therefore one graph is presented for $\gamma = 0$ and all R_k. The same is true for $\gamma = 1$ and $\gamma = 2$, so one graph is presented for $\gamma = 1$ (and $\gamma = 2$) and all R_k.

FUND-permit.

FUND-nopermit predicts that the optimal abatement levels of poor countries A_p are always higher than abatement levels of rich countries A_r. The abatement levels of poor countries A_p increase from 25 % (for $\gamma = 0,\ e = 1.2$) to more than 45 % (for $\gamma = 2,\ e = 1.1$); see Figure 1. As a consequence in a Post-Kyoto world without permit systems, if we plan huge amount emission reductions then, poor countries have to carry out a significant part of it.

FUND-permit offers a different picture in comparison to FUND-nopermit. If the global abatement level R_k increases, then the relative abatement levels of poor countries A_p increase (or the relative abatement levels of rich countries A_r decrease, as $A_p + A_r = 1$) for all value of *gamma* and e, which respect the requirement that environmental goods are valued equally in poor and rich countries. Figures 2 to 4 show that $A_p < A_r$ when $R_k = 1.6$ for all value of gamma. However, as R_k increases to 6, then $A_p > A_r$ for all value of gamma. In the beginning, the abatement is cheaper in developed countries than the developing ones. Nevertheless, as the abatement levels are increased, then it reaches a point when the opposite is true, namely the abatement is cheaper in developing countries than the developed ones. The intuition behind is that if the global abatement targets are sufficiently high, it is more profitable for developing countries to sell their emissions permits (and to abate themselves) to developed countries than to use them by themselves. It is sufficient to mention that Japan and South Korea have abatement levels 57% higher than China, when $R_k = 1.6$ ($\gamma = 0,\ e = 1.2$); but when $R_k = 6$ ($\gamma = 0,\ e = 1.2$) Japan and South Korea have abatement levels 68% lower than China; see Tables 10 and 13. Similarly, to FUND-nopermit, it follows that, in a Post-Kyoto world in a permit system, if we plan big amount emission reductions then, it can happen that poor countries have to carry out higher emission reductions than rich ones.

No wonder that regions like USA, Western European Union and Japan have the biggest optimal abatement levels. It is necessary to mention that Former Soviet Union has to abate pollution in large amounts. All simulations for every combination of parameters e, γ and R_k suggests that Former Soviet Union has to play a central role in abatement policies among non-OECD countries (see Tables from 10 to 13). Canada and Australia have negative or low optimal abatement levels, while China, India and East European Countries are changing their optimal abatement levels from low to significant as the global abatement level is increased.

6 Conclusions

The paper examines if the abatement targets that a Post-Kyoto protocol assigns to different countries, are consistent with the normative requirement that environmental goods are valued equally in non-OECD (or poor) and OECD (or rich) countries. Two global welfare maximization problems with a permit system and without a permits system are established, which are constrained to different global abatement level. Global welfare optimization problems are able to find optimal abatement targets, which maximize the world global welfare, and respect the requirement that environmental goods are equally evaluated in poor and rich countries. A wide range of social welfare functions is used such as the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function ($\gamma = 2$). In global welfare maximization problems, I make use of benefits and costs of pollution abatement of integrated assessment model FUND (Climate Framework for Uncertainty, Negotiation and Distribution) model developed by Richard Tol.

One finding is that in a Post-Kyoto world, the optimal abatement levels of poor countries have to be significantly big, if we aim to evaluate equally the environmental goods in poor and rich countries. Furthermore, if the global abatement targets are sufficiently high, it is more profitable for developing countries to sell their emissions permits to developed countries than to use them by themselves. It follows that, in a Post-Kyoto world in a permit trade system, if we plan big amount emission reductions then, it can happen that poor countries have to carry out higher emission reductions than rich ones.

No surprise that USA, Western European Union and Japan have the biggest optimal abatement levels. It is necessary to mention that Former Soviet Union has to abate pollution in large amounts. Canada and Australia have negative or low optimal abatement levels, while China, India and East European Countries are changing their optimal abatement levels from low to significant as the global abatement level is increased.

As always, further extensions are possible such as the implementation of a dynamic framework for a longer time interval, or finding a way of including of political factors in modeling approach.

Acknowledgment

I am grateful to Richard Tol for his comments and suggestions.

Appendix 1

Table 1: The values of elasticity of marginal utility **e** for different values of γ, when $u_r/u_p = 1.2$, $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
1.2	1.1408	1.0816

Table 2: The values of elasticity of marginal utility **e** for different values of γ and u_r/u_p, when $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
$u_r/u_p = 1.2$	1.2	1.0867	0.9734
$u_r/u_p = 1.3$	1.2	1.037	0.874
$u_r/u_p = 1.4$	1.2	0.9909	0.7819

Table 3: The values of elasticity of marginal utility **e** for different values of γ and Y_r/Y_p, when $u_r/u_p = 1.2$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739
$Z_r/Z_p = 4$	1.2	1.0982	0.9965	0.8947	0.793
$Z_r/Z_p = 5$	1.2	1.117	1.034	0.9511	0.8681

Table 4: The values of elasticity of marginal utility **e** for different values of γ, Z_r/Z_p and u_r/u_p, when $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$	
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739	$u_r/u_p = 1.2$
$Z_r/Z_p = 4$	1.2	1.0536	0.9071	0.7607	0.6143	$u_r/u_p = 1.3$
$Z_r/Z_p = 5$	1.2	1.0469	0.8937	0.7406	0.5875	$u_r/u_p = 1.4$

Table 5: The FUND data from the year 2015, where α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E the carbon dioxide emissions (in billion metric tonnes of carbon), Y gross domestic product, in billions US dollars and population in millions people. Source: FUND

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	α	β	E	Y	*Population*
USA	0.015194	1.98	1.816	13372	296.5
CAN	0.015205	0.1	0.139	1054	33.3
WEU	0.01568	3.05	0.81	15569	394.4
JPK	0.015591	-0.86	0.61	11130	193.5
ANZ	0.015149	0	0.092	606	26.2
EEU	0.014733	0.11	0.201	544	122.4
FSU	0.013839	1.1	1.093	872	293
MDE	0.0144	0.17	0.551	871	320.7
CAM	0.014911	0.1	0.137	524	162.9
LAM	0.015161	0.24	0.266	1804	409.7
SAS	0.014455	0.38	0.756	1296	1681.3
SEA	0.014881	0.69	0.492	1770	637.4
CHI	0.014589	5.21	1.798	3795	1475.6
NAF	0.014706	0.83	0.12	309	195.9
SSA	0.014718	0.82	0.169	445	899.4
SIS	0.014387	0.07	0.049	76	51.9

Table 6: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model without permits system, $R_k = 1.6$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	1.1785	0.1868	0.2245	0.2082	1.875	0.1641
Canada	-0.4544	0.1284	0.1492	0.1437	-1.875	0.1161
Western Europe	0.3322	0.0617	0.0762	0.069	1.875	0.0544
Japan and South Korea	0.4858	0.095	0.1249	0.1096	1.875	0.0808
Australia and New Zealand	-0.8838	0.1086	0.1197	0.1076	-1.875	0.1014
Central and Eastern Europe	-0.0107	0.0524	0.0417	0.0493	-1.0463	0.0576
Former Soviet Union	0.4463	0.127	0.0945	0.1106	0.9968	0.1449
Middle East	0.1488	0.0563	0.041	0.0483	0.1843	0.0648
Central America	-0.0623	0.0267	0.02	0.0233	-0.677	0.0301
South America	0.0201	0.0203	0.0164	0.0187	-0.2123	0.0222
South Asia	0.0352	0.0147	0.0083	0.0111	0.0052	0.0192
South East Asia	0.0603	0.0246	0.018	0.0209	0.0613	0.0282
China	0.148	0.0396	0.0287	0.0341	0.3095	0.0458
North Africa	-0.0572	0.0199	0.0132	0.0165	-0.1131	0.0241
Sub-Saharan Africa	-0.0045	0.006	0.0032	0.0044	-0.0394	0.0083
Small Island States	-0.3823	0.0319	0.0205	0.0246	-0.3439	0.038

Table 7: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model without permits system, $R_k = 3.2$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.603	0.1868	0.2245	0.2082	0.9375	0.1641
Canada	-0.0871	0.1284	0.1492	0.1437	-0.9375	0.1161
Western Europe	0.178	0.0617	0.0762	0.069	0.9375	0.0544
Japan and South Korea	0.2685	0.095	0.1249	0.1096	0.9375	0.0808
Australia and New Zealand	-0.2833	0.1086	0.1197	0.1076	-0.9375	0.1015
Central and Eastern Europe	0.0216	0.0524	0.0417	0.0493	-0.3408	0.0576
Former Soviet Union	0.234	0.127	0.0945	0.1106	0.5392	0.1449
Middle East	0.0838	0.0563	0.041	0.0483	0.1305	0.0648
Central America	-0.0124	0.0267	0.02	0.0233	-0.2474	0.0301
South America	0.0179	0.0203	0.0164	0.0187	-0.0429	0.0222
South Asia	0.019	0.0147	0.0083	0.0111	0.0031	0.0192
South East Asia	0.0348	0.0246	0.018	0.0209	0.0506	0.0282
China	0.076	0.0396	0.0287	0.0341	0.1626	0.0458
North Africa	-0.0146	0.0199	0.0132	0.0165	-0.0418	0.0241
Sub-Saharan Africa	0.0002	0.006	0.0032	0.0044	-0.0132	0.0083
Small Island States	-0.1394	0.0319	0.0205	0.0246	-0.1374	0.038

Table 8: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model without permits system, $R_k = 4.8$

	$\gamma = 0$	$\gamma = 1$		$\gamma = 2$		
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.4109	0.1867	0.2245	0.2093	0.625	0.1641
Canada	0.0347	0.1292	0.1505	0.1401	-0.625	0.1161
Western Europe	0.1264	0.0617	0.0765	0.0698	0.625	0.0545
Japan and South Korea	0.1957	0.0949	0.1249	0.1097	0.625	0.0808
Australia and New Zealand	-0.08	0.1088	0.1174	0.112	-0.625	0.1014
Central and Eastern Europe	0.032	0.0526	0.0425	0.0485	-0.0963	0.0576
Former Soviet Union	0.1631	0.1269	0.0944	0.1103	0.384	0.1449
Middle East	0.0621	0.0563	0.0409	0.0489	0.1108	0.0648
Central America	0.004	0.0265	0.02	0.024	-0.1045	0.0301
South America	0.017	0.0202	0.0164	0.0183	0.0114	0.0222
South Asia	0.0136	0.0147	0.0083	0.0113	0.0023	0.0192
South East Asia	0.0262	0.0245	0.018	0.0212	0.0462	0.0282
China	0.052	0.0396	0.0288	0.0341	0.1133	0.0458
North Africa	-0.0006	0.0199	0.0133	0.0156	-0.0184	0.0241
Sub-Saharan Africa	0.0017	0.0061	0.0032	0.0045	-0.0047	0.0083
Small Island States	-0.0589	0.0315	0.0204	0.0224	-0.0693	0.038

Table 9: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model without permits system, $R_k = 6$

	$\gamma = 0$	$\gamma = 1$		$\gamma = 2$		
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.334	0.1856	0.2245	0.2095	0.5	0.1376
Canada	0.0828	0.1296	0.1503	0.1398	-0.5	0.1312
Western Europe	0.1057	0.0615	0.0765	0.0698	0.5	0.0473
Japan and South Korea	0.1664	0.0945	0.1249	0.1099	0.5	0.0716
Australia and New Zealand	0.0024	0.1101	0.1179	0.1118	-0.5	0.131
Central and Eastern Europe	0.0361	0.0526	0.0425	0.0484	0.004	0.0597
Former Soviet Union	0.1347	0.1262	0.0944	0.1104	0.3211	0.1238
Middle East	0.0533	0.0561	0.0409	0.0489	0.1024	0.058
Central America	0.0105	0.0269	0.0199	0.024	-0.0471	0.0343
South America	0.0166	0.0202	0.0164	0.0183	0.0324	0.0218
South Asia	0.0114	0.0146	0.0083	0.0113	0.0021	0.0168
South East Asia	0.0228	0.0244	0.018	0.0212	0.0443	0.0255
China	0.0424	0.0394	0.0288	0.0341	0.0936	0.0385
North Africa	0.005	0.0201	0.0133	0.0157	-0.0092	0.0286
Sub-Saharan Africa	0.0023	0.0061	0.0032	0.0044	-0.0014	0.0089
Small Island States	-0.0267	0.032	0.0202	0.0224	-0.0421	0.0654

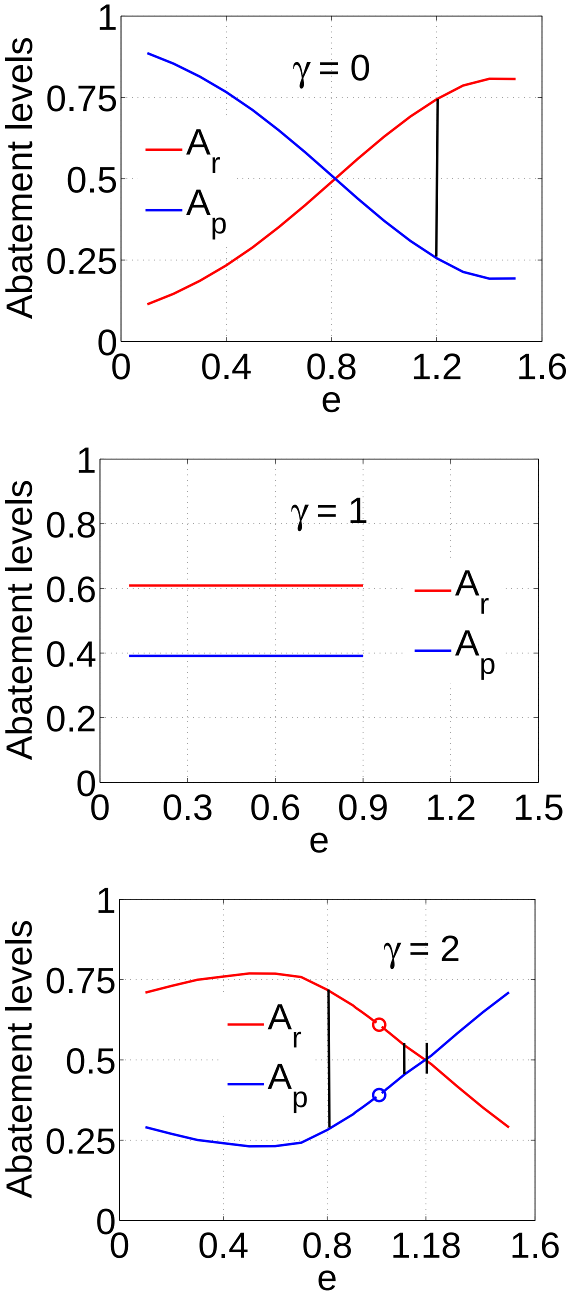

Figure 1: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0, \gamma = 1$ and $\gamma = 2$ in the FUND model without permit trading system. When $\gamma = 0$ and R_k equals 1.6, 3.2, 4.8 or 6, the values of A_r and A_p differ by less than 10^{-2} for all R_k, so the graph looks identical for different R_k. Therefore one graph is presented for $\gamma = 0$ and all R_k. The same is true for $\gamma = 1$ and $\gamma = 2$, so one graph is presented for $\gamma = 1$ (and $\gamma = 2$) and all R_k. $\gamma = 0$, e $= 1.2$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 1.2$ that connect A_r and A_p. As social welfare take complex values for $e > 0.9$. $\gamma = 1, e = 0.9$ satisfy the most appropriately the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore the graph of A_r and A_p are presented for value of $e \in [0, 0.9]$. $\gamma = 2$, $e \in [0.78, 1.08]$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 0.8$ and $e = 1.1$ that connect A_r and A_p.

Table 10: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model in a permits system, $R_k = 1.6$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	1.1647	0.6249	1.1646	0.8561	1.875	0.4582
Canada	-0.853	-0.4529	-0.853	-0.6197	-1.875	-0.3329
Western Europe	0.3054	0.1629	0.3052	0.2218	1.875	0.121
Japan and South Korea	0.4136	0.2049	0.4139	0.2904	1.875	0.1462
Australia and New Zealand	-1.3084	-0.7755	-1.3082	-1.0099	-1.875	-0.5955
Central and Eastern Europe	-0.0033	0.0174	-0.0034	0.0082	-1.4045	0.0241
Former Soviet Union	0.7543	0.6957	0.7543	0.7225	1.2085	0.6723
Middle East	0.2838	0.2693	0.2837	0.2765	0.2282	0.2628
Central America	-0.0567	-0.0374	-0.057	-0.0449	-0.8692	-0.0314
South America	0.0315	0.0327	0.0316	0.0324	-0.3696	0.0328
South Asia	0.1833	0.1871	0.1833	0.185	0.1563	0.1895
South East Asia	0.1157	0.1099	0.1156	0.1127	0.0691	0.1076
China	0.2642	0.2473	0.2642	0.255	0.4084	0.2409
North Africa	-0.0027	0.001	-0.0024	-0.0002	-0.0611	0.0007
Sub-Saharan Africa	0.0854	0.0827	0.0854	0.0843	0.0381	0.0807
Small Island States	-0.3778	-0.3702	-0.3777	-0.3702	-0.2792	-0.3769

Table 11: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model in a permits system, $R_k = 3.2$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.5887	0.3216	0.5887	0.4359	0.9375	0.2395
Canada	-0.485	-0.2725	-0.4851	-0.363	-0.9375	-0.2061
Western Europe	0.1511	0.0823	0.1511	0.1105	0.9375	0.0622
Japan and South Korea	0.1967	0.098	0.1969	0.1383	0.9231	0.0705
Australia and New Zealand	-0.7116	-0.4434	-0.7115	-0.5626	-0.9375	-0.3483
Central and Eastern Europe	0.0295	0.0382	0.0293	0.0346	-0.7131	0.0402
Former Soviet Union	0.5437	0.5126	0.5437	0.5268	0.7664	0.4998
Middle East	0.2191	0.2105	0.2191	0.215	0.1787	0.2065
Central America	-0.0064	0.0014	-0.0065	-0.0015	-0.4385	0.0027
South America	0.0294	0.0295	0.0294	0.0297	-0.1957	0.0292
South Asia	0.1671	0.1686	0.1671	0.1678	0.1543	0.1694
South East Asia	0.0903	0.0869	0.0903	0.0885	0.0603	0.0853
China	0.1923	0.1836	0.1923	0.1876	0.2632	0.1802
North Africa	0.04	0.0387	0.0401	0.0397	0.0106	0.0368
Sub-Saharan Africa	0.0901	0.0877	0.0901	0.0891	0.0649	0.0859
Small Island States	-0.1349	-0.1435	-0.1349	-0.1363	-0.0743	-0.1537

Table 12: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model in a permits system, $R_k = 4.8$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.396	0.22	0.396	0.295	0.625	0.1662
Canada	-0.3614	-0.2114	-0.3612	-0.2762	-0.625	-0.1633
Western Europe	0.0994	0.0552	0.0994	0.0735	0.625	0.0424
Japan and South Korea	0.1237	0.062	0.1238	0.087	0.5394	0.0452
Australia and New Zealand	-0.5107	-0.3319	-0.5106	-0.4122	-0.625	-0.2648
Central and Eastern Europe	0.04	0.0449	0.0399	0.0431	-0.4628	0.0454
Former Soviet Union	0.4743	0.4519	0.4743	0.4624	0.625	0.4426
Middle East	0.1974	0.1909	0.1974	0.1941	0.169	0.1877
Central America	0.0101	0.0141	0.0101	0.0126	-0.2828	0.0141
South America	0.0286	0.0283	0.0286	0.0286	-0.1277	0.0279
South Asia	0.1617	0.1623	0.1617	0.162	0.1537	0.1626
South East Asia	0.0817	0.079	0.0817	0.0804	0.0608	0.0777
China	0.1682	0.1623	0.1682	0.165	0.2169	0.1599
North Africa	0.054	0.0513	0.054	0.053	0.0366	0.0486
Sub-Saharan Africa	0.0916	0.0893	0.0916	0.0906	0.0749	0.0876
Small Island States	-0.0548	-0.0682	-0.0549	-0.059	-0.003	-0.0798

Table 13: Relative abatement levels (as fraction of global abatement levels) for different world regions, FUND model in a permits system, $R_k = 6$

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$			
	$e = 1.2$	$e = 0.9$	$e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
United States of America	0.3186	0.1793	0.3186	0.2386	0.5	0.137
Canada	-0.3114	-0.1866	-0.3113	-0.2414	-0.5	-0.1458
Western Europe	0.0785	0.0443	0.0785	0.0584	0.5	0.0344
Japan and South Korea	0.0943	0.0477	0.0943	0.0666	0.4302	0.0351
Australia and New Zealand	-0.4292	-0.2862	-0.4291	-0.3512	-0.5	-0.2316
Central and Eastern Europe	0.0441	0.0473	0.0439	0.0463	-0.3554	0.0474
Former Soviet Union	0.4469	0.4278	0.4469	0.4368	0.5	0.4199
Middle East	0.1887	0.1829	0.1887	0.1859	0.1681	0.1801
Central America	0.0166	0.0188	0.0166	0.0184	-0.2157	0.0187
South America	0.0282	0.0278	0.0282	0.0282	-0.0963	0.0275
South Asia	0.1595	0.1598	0.1595	0.1597	0.1535	0.1599
South East Asia	0.0783	0.0759	0.0782	0.0771	0.0625	0.0746
China	0.1586	0.1537	0.1586	0.156	0.1992	0.1517
North Africa	0.0595	0.0562	0.0594	0.0581	0.048	0.0533
Sub-Saharan Africa	0.0922	0.0899	0.0922	0.0912	0.0793	0.0882
Small Island States	-0.0233	-0.0386	-0.0232	-0.0287	0.0266	-0.0505

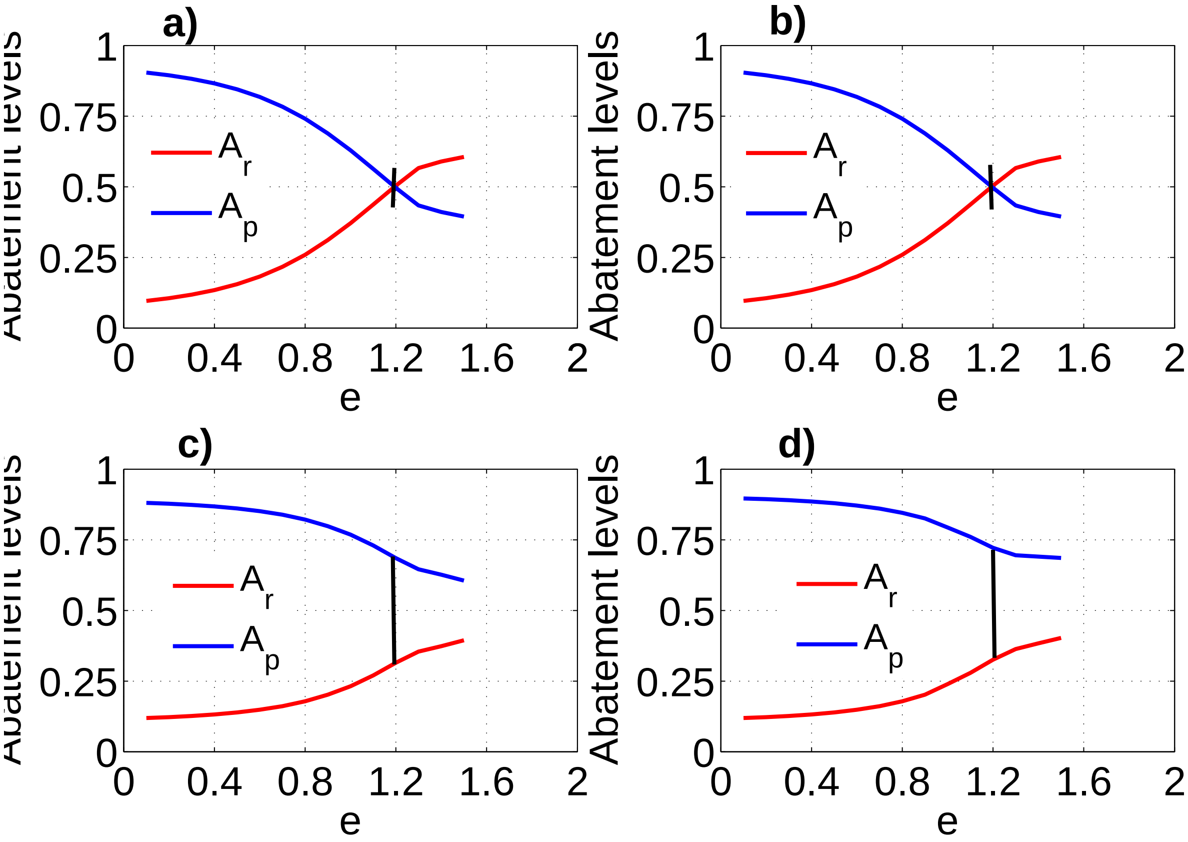

Figure 2: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ in a permit trading system, FUND model. $\gamma = 0$, e $= 1.2$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 1.2$ that connect A_r and A_p. In part **a)** $R_k = 1.6$; in part **b)** $R_k = 3.2$; in part **c)** $R_k = 4.8$; in part **d)** $R_k = 6$.

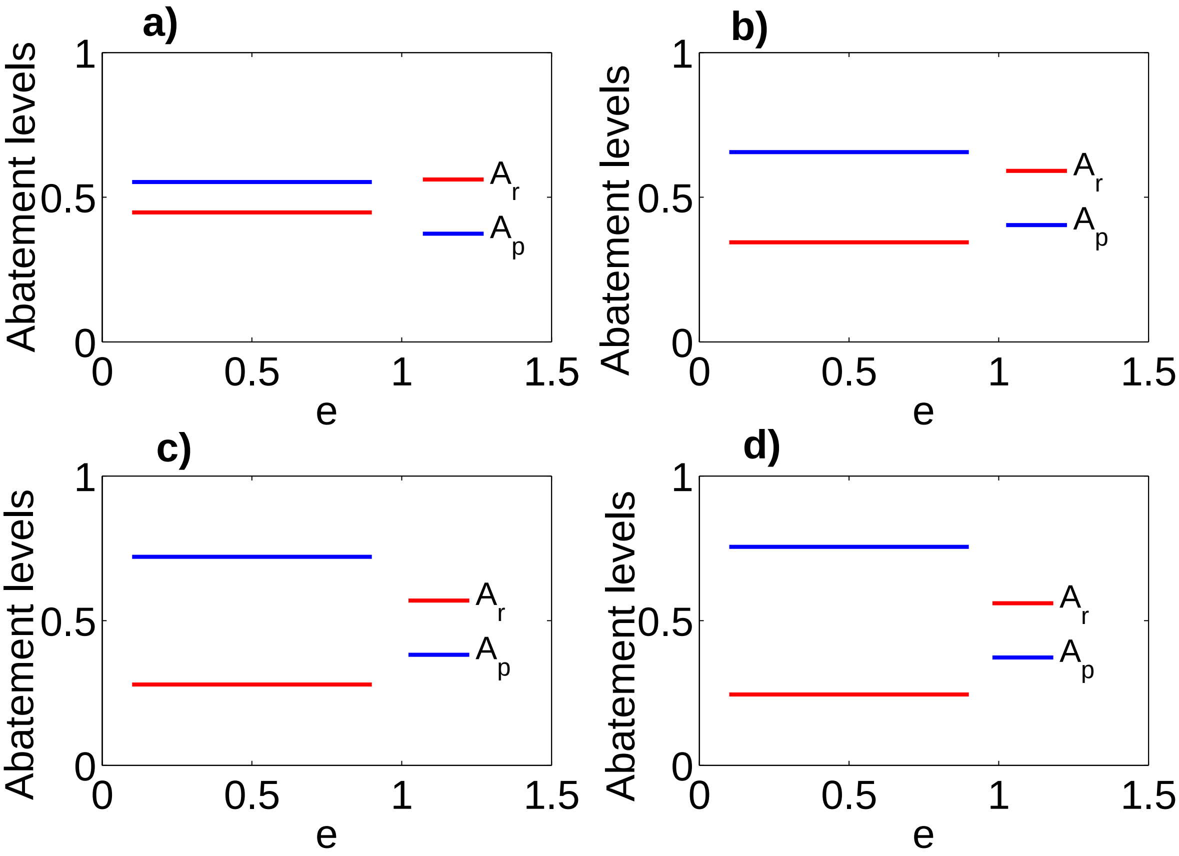

Figure 3: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ in a permit trading system, FUND model. $\gamma = 1$, $e \in [0.99, 1.1]$ are values that respect the requirement that environmental goods are equally evaluated in poor and rich countries. As social welfare take complex values for $e > 0.9$. $\gamma = 1, e = 0.9$ satisfy the most appropriately the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore the graph of A_r and A_p are presented for value of $e \in [0, 0.9]$. In part **a)** $R_k = 1.6$; in part **b)** $R_k = 3.2$; in part **c)** $R_k = 4.8$; in part **d)** $R_k = 6$.

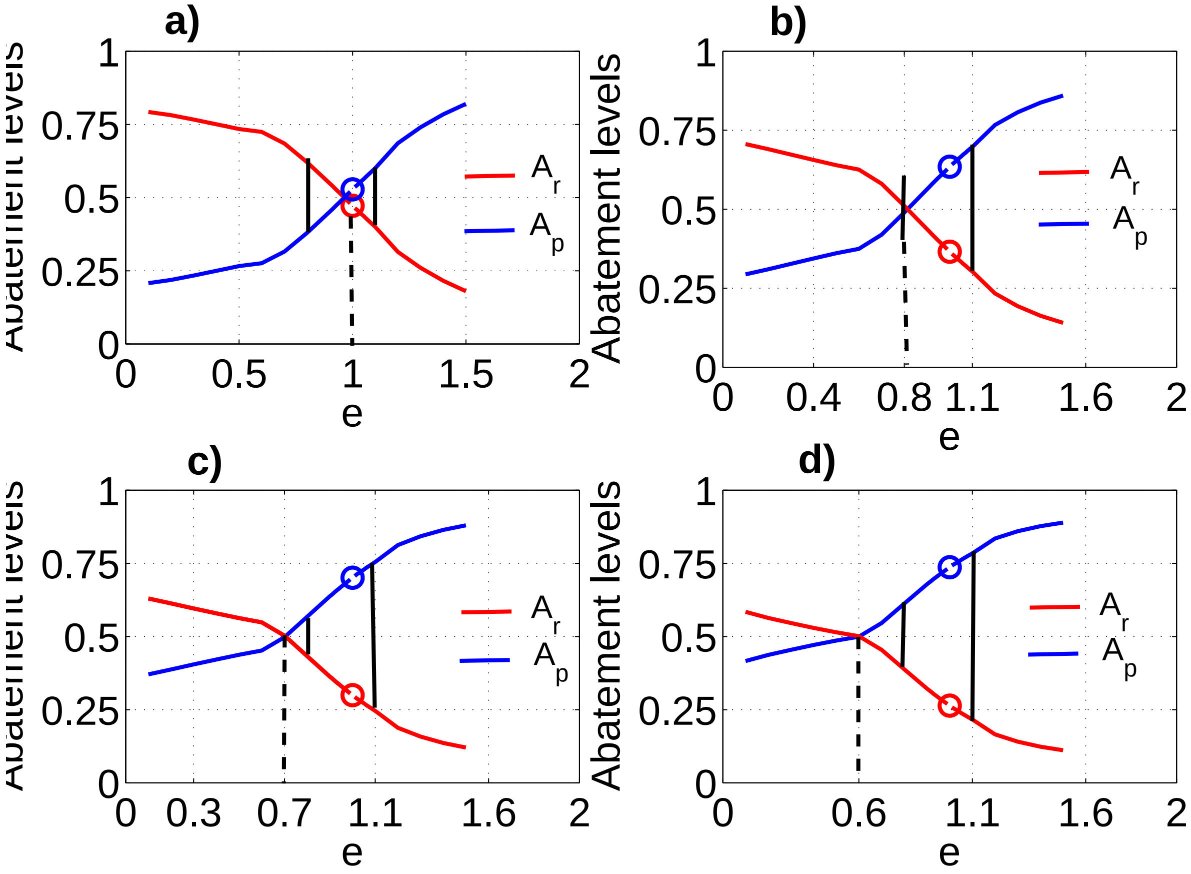

Figure 4: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 2$ in a permit trading system, FUND model. $\gamma = 2$, $e \in [0.78, 1.08]$ respect the requirement that environmental goods are equally evaluated in poor and rich countries. Therefore a straight line is placed on $e = 0.8$ and $e = 1.1$ that connect A_r and A_p. In part **a)** $R_k = 1.6$; in part **b)** $R_k = 3.2$; in part **c)** $R_k = 4.8$; in part **d)** $R_k = 6$.

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