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Correcting the climate externality:

Pareto improvements across generations and regions[1]

by

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Abstract

Many argue that the present generation must reduce consumption to mitigate future climate change. However, as significant climate change is due to market failure, the correction of market failures, by definition, gives rise to the possibility of Pareto improvements. In this paper, we examine the implications of Pareto improvements both within and across generations. We employ the representative consumer model RICE-10 (a global model including different regions) to see how we could potentially distribute any benefits across and within generations such that nobody loses. The model shows that different combinations of present and future consumption along the Pareto-improving frontier yield different combinations of capital investment and emissions. We also calculate a conventional social optimum. While the social optimum, by definition, is on the Pareto efficiency frontier, it is not necessarily on the Pareto-improving segment of this frontier. Total emissions, and hence temperature change, vary significantly across different Pareto-improving scenarios. It obviously matters which generations get the utility gain, and one of our results is that for Pareto improvements where none of the gain goes to the distant future, and allowing transfers, total emissions will be higher than in the social optimum. Even without any welfare gain to the distant future, total emissions may be lower in the Pareto-improving scenarios we have considered than under the social optimum if transfers are not permitted. Moreover, in this case, carbon taxes differ substantially across regions for all Pareto improvements.

Keywords: Pareto improvements; climate agreements; intergenerational distribution; intragenerational distribution

JEL classifications: C63, D63, D99, H23, Q54

1 Introduction

Recent climate negotiations have shown that it is difficult to establish an international agreement that yields significant reductions in greenhouse gas (GHG) emissions. Even under the agreed targets set in the Paris agreement, emissions in 2030 will be 37%–52% higher than their 1990 level (UNFCCC, 2015). There are several possible reasons for this apparent failure. These include the public good character of the atmosphere that provides an incentive for free-riding, the time profile of the climate problem whereby present generations may bear the burden of improving the climate of future generations (intergenerational equity), and the question of how to distribute the mitigation burden among countries today (intragenerational equity). While the problem of free riding has been approached using game theory to study stable coalitions of emissions-reducing countries (e.g., Barrett, 2005), discussion of the other reasons for failure are mainly based on ethical reasoning, and is the topic of this article.

Intragenerational equity is about burden sharing, i.e., how we should distribute burdens within a generation, either within the generation living today or in future generations, and will therefore depend on different ethical views on distribution (see Kverndokk and Rose, 2008). In contrast, discussion of intergenerational equity has focused mainly on the appropriate discount rate for climate change policy decisions, as the optimal level of abatement is very sensitive to the choice of discount rate. Discount rates are weights put on the future benefits of climate change policies in order to compare them to present and future costs. If we use a high discount rate (a low weight on future generations), the mitigation burden for the present generation will be low, but the burden of damage will be higher on future generations.[1] The choice of the appropriate discount rate is an ethical issue and has been controversial for many years. For a discussion, see the Stern Review (Stern, 2007) and the subsequent discussion in e.g., Nordhaus (2007), Weitzman (2007), and Dasgupta (2008).

While the literature on the optimal path of GHG emissions or optimal abatement is dominated by the assumption of a (Ramsey) representative agent maximizing a social welfare function,

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[1] Rezai (2011) and Rezai et al. (2012) have discussed the intergenerational aspect of climate policies. According to their argument, the main reason for the burden for present generations found in integrated assessment models (IAM) is that most studies use a hybrid constrained optimal path as the business-as-usual (BAU) path, which partially internalizes the emissions externality but, by assumption, no mitigation is undertaken. Thus, the path is inefficient and the consumption level and the capital accumulation are both too high. A potential loss for current generations could therefore substantially reduce and may even disappear if an efficient BAU path is used. We employ a BAU scenario similar to that in Rezai (2011) in our analysis.

where Negishi weights (Stanton, 2011) are used for the international distribution of policies, there are alternative models that consider other social objectives. One early contribution includes Chichilnisky and Heal (1994), while more recent contributions are Llavador et al. (2011) and Hänsel and Quaas (2015). Our paper contributes to this literature. In particular, we build on new research that suggests that the appropriate discount rate may not be so important in climate change policy, as it may be possible to reduce the burden for the present generation without increasing future climate damage. Pareto improvements are possible wherever market failure exists, and the Stern Review (2006, p. xviii) has designated climate change as "…the greatest market failure the world has ever seen." Thus, the possibility of climate policies that yield Pareto improvements must exist, by definition.

The design of an international treaty where no generation would lose is the focus of Foley (2009). Such a treaty would eliminate the conflict of interests across generations that follows from debate of the appropriate discount rate. If a social optimum exists that is beneficial to all generations, it should be possible to compensate the losers so that everybody would gain from the treaty.[2] For instance, it is often claimed that the present generation needs to bear the primary burden of mitigation, and that the benefits of reduced climate change will occur in the future, i.e., the people that pay for mitigation are not the same as those enjoying the benefits of a better climate. Foley (ibid) argues, however, that this does not have to be the case, and that the winners (future generations) can compensate the losers (the present generation) so that everybody gains from the treaty. What matters is the future generation's marginal value of a lower stock of atmospheric GHGs compared with an increase in conventional capital. If their valuation of the atmosphere were higher, it would be optimal for the present generation to substitute investments in conventional capital for mitigation capital without compromising their consumption.

The valuation of the atmospheric stock of GHGs versus the real capital stock thus determines the composition of the stocks available for future generations, and correcting the global warming externality is the way to induce the optimal composition between the two capital stocks. Thus, the resources needed for investments in mitigation could be from investments in conventional capital. In this way, we do not have to reduce consumption for the present

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[2] See also Broome (2012, pp. 43–48), Nordhaus (2008, pp. 179–181), and the latest IPCC assessments report (Kolstad et al., 2014, p. 227) for similar arguments, along with the discussion on international Paretianism in Posner and Weisbach (2010).

generation, and it may therefore not lose in utility terms if, as usually assumed, utility is a function of consumption. According to this argument, the discount rate is not directly important for the mitigation level of the present generation, but instead determines how we would distribute the additional consumption from correcting the inefficiency across generations.

Another way to protect the present generation from reducing its consumption would be to finance mitigation efforts today using governmental debt redeemed by future generations. Future generations would pay for the mitigation through, e.g., higher taxes, but would gain by having a better environment. These transfers from the present to the future generations would be a Pareto improvement, as every generation will be at least as well off as without a climate agreement. Such transfers have already been the subject of analyses using overlapping-generations (OLG) models.[3] For example, an early paper by Bovenberg and Heijdra (1998) looked at Pareto-improving mitigation when a government implements compensation by borrowing in foreign capital markets and repaying the debt by taxing future generations. A similar model in Heijdra et al. (2006) and Andersen et al. (2016) also designs debt policies that ensure that every generation gains, while Von Below et al. (2013) propose using the pension system as a transfer. This may work if young generations compensate old generations by paying for their retirement in the form of a pay-as-you-go pension. This reduces the incentive to save and accumulate capital, and therefore consumption will increase.

Other mechanisms are also proposed. For example, Gerlagh and Keyzer (2001) consider a "trust-fund" that entitles all members of present and future generations to an equal claim over natural resources. They show that this fund can ensure efficiency and protect the welfare of all generations. Finally, Karp and Rezai (2014) explain how asset pricing can yield Pareto improvements when introducing an environmental tax. Here the productivity of capital depends on the state of the environment. As capital is long lived, the present generation can benefit from the improved future productivity of capital through asset pricing. Using appropriate transfers across generations, all generations may again gain.

In this article, we examine the implications of Pareto improvements, focusing on the climate problem. While this principle is suggested as one way to reduce conflicts across generations,

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[3] A more general approach is by Arrow and Levin (2009), who focus on intergenerational transfers with an uncertain future population and when the size of the transferred resource can expand or contract.

we are also interested in ways to reduce conflicts within a generation, i.e., between countries or regions. Conflicts here may arise when one agent does not take into account the interests of the other agents when making its decisions. Across generations, the present generation may be unwilling to lower emissions to reduce the burden on future generations[4] while within a generation there has been an ongoing discussion on how to distribute the burden of mitigation. Pareto improvements ensure that no generation or region is worse off, and the possibilities to reach agreement may thereby increase.

This article therefore concerns inter- and intragenerational distributions. To examine these distributions, we use the representative consumer model to simulate Pareto improvements. We introduce different regions and periods to see how we could distribute the benefits across and within generations, thus representing diverse compromises including different preferences about the welfare of future generations. While most economic analyses on distributional issues in climate change analyze only the intergenerational or the intragenerational perspective, we add to the literature by incorporating both aspects (see also Kverndokk et al., 2014).

The remainder of the paper is organized as follows. Sections 2 and 3 introduce a simple theoretical model of two regions (rich and poor) and two periods (the present and the future). In this model, the present generation can affect the utility of the future generation with its emissions and investments, as they will benefit from reduced emissions as well as higher investments. Different combinations of consumption along the Pareto-improving frontier will also generally yield various combinations of capital investments and emissions. One region in a generation can grasp the whole benefit and leave the other regions just as well off as without any climate policy. However, if we allow transfers within a generation, it does not matter for emissions whether it is the poor or the rich region within the generation that gains the whole benefit, as we maximize total utility if any emission reductions are distributed cost-effectively (equal carbon prices). A conventionally defined social optimum is (obviously) on the Pareto efficiency frontier. However, it is not necessarily on the Pareto-improving segment of this frontier.

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[4] Note that there is no one from the future generations to defend their interests. However, there may be conflicts among agents of the current generation with different altruistic preferences about the future.

To consider these Pareto improvements in detail, Sections 4 and 5 uses a numerical model that is similar in structure to the two-region two-period model described, i.e., the RICE 2010 model (Nordhaus, 2010). In the model, we aggregate the world into two regions (rich and poor) and two periods (present and future), and derive Pareto-improving efficient solutions in which no generation or region should lose from climate action relative to its reference scenario. We then explore four cases that satisfy the condition that they are Pareto improving for all four groups—today's rich, the future rich, today's poor, and the future poor. Policies that are Pareto improving can distribute benefits in an infinite number of ways across these four groups.

Our four scenarios explore circumstances in which no group is worse off than it would have been in the reference scenario, and one group captures all of the net benefits of moving to the Pareto-efficient frontier. The results show that the possibilities of transfers, as well as who grasps the benefits, matters significantly for the outcome of a Pareto-improving allocation. In the two of our scenarios without the possibility of transfers, total emissions are lower in the near future than in the social optimum. All of the other Pareto-improving scenarios we examine have higher total emissions than the social optimum. Section 6 concludes with a discussion of the main results.

2 A two-period two-region model

To illustrate the main mechanism of the numerical model in Section 4, we begin with a very simple theoretical model of two periods and two regions, with each having a constant population and labor force. We ignore any distributional issues within regions, so that a representative agent illustrates each region in every period. The full model and all derivations are in the appendix, with only the main features and the most important results explained below.

Using subscript t=1,2 to denote the period and superscript k=a,b the region, the utility of region k in period t is

$$U_t^k = u(C_t^k)\,, \tag{1}$$

where C_t^k is consumption in region *k* in period *t*. Output in region *k* in period *t* is

(2)
$$Q_t^k = \Omega^k(S_t)F^k(K_t^k, E_t^k).$$

Ignoring time and region references, *F* is a standard production function with *K* as capital and *E* is fossil energy, equal to carbon emissions. In each region, K_1 is assumed exogenous, while K_2 is equal to K_1 plus investment made in the region in period 1 (capital depreciation is ignored). Net output also depends on the stock of carbon *S* in the atmosphere, with $\Omega(0) = 1$ and $\Omega'(S) < 0$. The stock S_1 is total emissions in period 1, while S_2 is the sum of S_1 and total emissions in period 2.

In each period, the sum of consumption across regions must equal the sum of production minus investments (zero in period 2) across regions. A stricter requirement would be to assume "no transfers", i.e., that in each period, the consumption in each region must equal production minus investments in the same region.

2.1 Pareto-efficient outcomes

To identify all Pareto-efficient outcomes, we maximize

(3)
$$W = \sum_{t,k} \phi_t^k U_t^k,$$

given the restrictions on consumption and capital, where ϕ_t^k are positive welfare weights. The set of outcomes defined by the complete set of welfare weights that add up to an arbitrary positive constant is the Pareto-efficient set of outcomes.

Regardless of the welfare weights (see the appendix for details), we find

(4)
$$\frac{\partial\left[\Omega(S_2)F(K_2^k, E_2^k)\right]}{\partial K_2^k} = \frac{\phi_1^k u'(C_1^k)}{\phi_2^k u'(C_2^k)} \equiv 1 + r^k.$$

This is simply the Ramsey rule for optimal investments: the return to capital should be equal to the marginal rate of substitution between consumption in the two periods. Moreover, this return r^k should be the same across regions if we allow transfers between the two regions.

The marginal productivity of emissions (i.e., of fossil fuel use), also called the shadow price of emissions, is

$$\frac{\partial\left[\Omega^k(S_t)F_t^k(K_t^k,E_t^k)\right]}{\partial E_t^k}=q_t^k\ . \tag{5}$$

When we permit transfers between regions, the shadow prices of emissions q_t^k should equalize across regions, and is equal to

$$q_1=\sum_i[-\Omega^i\,'(S_1)]F_1^i(K_1^i,E_1^i)+(1+r)^{-1}\sum_i[-\Omega^i\,'(S_2)]F_2^i(K_2^i,E_2^i) \tag{6}$$

$$q_2=\sum_i[-\Omega^i\,'(S_2)]F_2^i(K_2^i,E_2^i)\ . \tag{7}$$

The right-hand sides of both equations are the social costs of carbon in the two periods, i.e., the marginal climate damage now and in the future caused by the emissions. The equations show us that in each period the common shadow price of emissions should equal the social cost of carbon.

If the carbon externality is fully internalized, each Pareto-efficient outcome corresponds to a competitive equilibrium. In this case, r^k is the market real interest rate in the two regions (which is equal when allowing transfers). The shadow prices of carbon emissions (q_1^k and q_2^k) are now actual carbon prices, typically carbon taxes or quota prices (also equal across regions when transfers are allowed).

2.2 Welfare weights, transfers, and the social optimum

Once the three relative welfare weights ϕ_2^a / ϕ_1^a, ϕ_2^b / ϕ_1^b, and ϕ_1^b / ϕ_1^a are given, the above equations give a particular outcome.[5] The whole set of Pareto-efficient outcomes follows from varying these relative weights over all nonnegative numbers. Given the possibility of consumption transfers within each period, all Pareto-efficient outcomes have the property that total consumption in one period is maximized for a given total consumption level in the other period. The size of the welfare weights will then determine how large total consumption will be in the two periods, as well as the distribution of consumption between the two countries in each period (through the use of appropriate transfers).

The two relative welfare weights ϕ_2^a / ϕ_1^a and ϕ_2^b / ϕ_1^b are often known as utility discount factors. As discussed, there is a large literature considering the appropriate size of these discount factors, and the corresponding consumption discount factors $\phi_2^k u'(C_2^k) / \phi_1^k u'(C_1^k)$. Choosing appropriate values of the relative welfare weights is, of course, irrelevant for deriving the Pareto-efficient outcomes. Nevertheless, if we wish to take the optimization a step further and derive the “best” of these Pareto-efficient outcomes, often called the social optimum, we must explicitly make a choice of all relative welfare weights.

One interpretation of a social welfare function with given welfare weights is that it represents the preferences of some hypothetical social planner (or “ethical observer”) who places exogenous weights on the utilities of all subjects (four in the present case). An alternative interpretation is that the utility discount factors represent altruistic preferences of those alive today, i.e., those who actually make current decisions regarding investments and climate policy. The utility discount factors could also represent a combination of altruistic preferences of those living today and a hypothetical social planner with preferences over the welfare both of those currently living and of future generations; see, e.g., Farhi and Werning (2007) and Belfiori (2017).

The exact interpretation of what a social optimum represents is not important for our analysis. However, if the social welfare function were a correct representation of the true preferences of each of our four subjects, there would be no conflict of interest regarding optimal policies. A more realistic interpretation is that it represents a compromise between the preferences of the

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[5] As three relative welfare weights are given, the fourth weight, ϕ_2^b / ϕ_2^a, will follow.

different agents. In this case, it is of interest to consider more of the Pareto frontier than the single point selected by the maximization of the social welfare function. In particular, it is of interest to consider the movements from an inefficient outcome that are Pareto improving, i.e., movements that improve the utility of all four agents in our model. We discuss this in detail in Section 3.

For most sets of welfare weights, the Pareto-efficient outcomes will involve transfers between countries in one or both periods. However, there is a subset of relative welfare weights, called Negishi weights, that equalizes the equilibrium transfers at zero in both periods. Formally, we can let the welfare weight ϕ_2^a / ϕ_1^a be exogenously given, and then let the remaining two (ϕ_1^b / ϕ_1^a and ϕ_2^b / ϕ_2^a) be determined endogenously so that equilibrium transfers in the two periods are zero. Further discussion of the use of Negishi weights in integrated assessment models is available in Stanton (2011) and elsewhere, and we return to this in Section 5.3.3.

If there were no allowance for transfers, the rates of return to capital and the shadow prices of carbon emissions would generally differ between countries. Without any climate externality, overall (constrained) Pareto efficiency would then simply involve Pareto efficiency for each country. In each country, efficiency would require equality between the return to capital and the marginal rate of substitution between consumption in the two periods. However, the return to capital would generally differ between the two countries. However, even without transfers, it is possible to affect the consumption distribution between countries through the choices of emissions when climate externalities exist. The allocation of emissions between countries will generally depend on the welfare weights, implying that the shadow prices of carbon emissions will generally differ between countries. We discuss this in Section 3.2.

2.3 The inefficient reference scenario (BAU)

The *reference scenario*, or Business-As-Usual (BAU), is similar to the social optimum, but now each country does not take into account that its emissions have a negative effect on present and future output, on either themselves or the other country. Hence, in the optimization problem, both countries act as if S_t were exogenous. Equation (4) remains valid, but in equation (5), we now have zero instead of q_t^k on the right-hand side.

Just like the social optimum, the equilibrium of this reference scenario depends on the welfare weights ϕ_2^a / ϕ_1^a, ϕ_2^b / ϕ_1^b, and ϕ_1^b / ϕ_1^a. An obvious choice of weights is the one that makes the reference scenario similar (ideally identical) to the actual observed outcome of period 1. In particular, the choice should in this case reflect the fact that equilibrium transfers are (close to) zero. Moreover, the choice should in this case provide an outcome where the interest and saving rates align with their observed values. We employ this type of calibration in the numerical analysis in Section 4. The equilibrium of this reference scenario gives values for all four utility levels, denoted by $\bar{U}_t^k$.

3 Pareto-improving deviations from the reference scenario

Starting with the reference utilities, we consider four Pareto improvements: maximize the utility of region *a* today (period 1) and tomorrow (period 2) and region *b* today and tomorrow. For all of these scenarios, three of the utility levels are kept constant at their reference level $\bar{U}_t^k$, while the utility for the fourth combination sh (country h in period s) is maximized.[6]

The solution to this problem is the same as before, except that the exogenous terms ϕ_1^k and ϕ_2^k are replaced by λ_1^k and λ_2^k, where $\lambda_s^h \equiv 1$ and λ_t^k are endogenous shadow prices for the three constraints $u(C_t^k) \geq \bar{U}_t^k$ ($tk \neq sh$). The appendix includes the details.

For a given reference scenario, emissions and other economic variables will typically depend on the choice of s and h. A simple graphical illustration of this is in the next subsection. As an alternative to allowing transfers, we could start with the same reference scenario but now assume no transfers when considering Pareto-improving changes in the other variables. This will typically yield a different outcome and a lower utility level U_s^h than with transfers.

3.1 Pareto improvements with transfers

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[6] This definition of Pareto improvements is based on the utilities U_t^k. If the true preferences of the two agents in period 1 include some altruism about the future (see Section 2.2), it would be reasonable to modify the definition of Pareto improvements.

When consumption transfers are permitted, all Pareto-efficient outcomes have the property that $C_2^a + C_2^b$ is maximized for any given value of $C_1^a + C_1^b$. This gives a Pareto-efficient frontier in the consumption space, as illustrated in Figure 1. The given utility levels in the reference scenario correspond to the given consumption levels, and hence given total consumption in each period. These consumption levels correspond to point N in Figure 1. Nevertheless, this reference scenario is inefficient as it is not on the Pareto-efficient frontier.

The social optimum M is a particular point on the Pareto-efficient frontier, determined by the welfare weights.[7] The welfare weights determine total consumption in the two periods, and the distribution of these consumption levels via appropriate transfers. However, even if M is on the Pareto frontier and N is inside the frontier, it is not obvious that M is a Pareto improvement from N. The Pareto-improving points on the Pareto efficiency frontier are on the segment PQ, and Figure 1 illustrates the case where M is not a Pareto improvement.

Maximizing period 2 consumption in one country holding other consumption levels equal to their reference values gives us point P in Figure 1, while there are appropriate transfers so that the gain goes to the chosen country. Similarly, maximizing period 1 consumption in one country holding other consumption levels equal to their reference values gives us point Q in Figure 1.

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[7] The same weights determine point N, which is a particular point on the inefficient consumption possibility curve (not depicted in Figure 1).

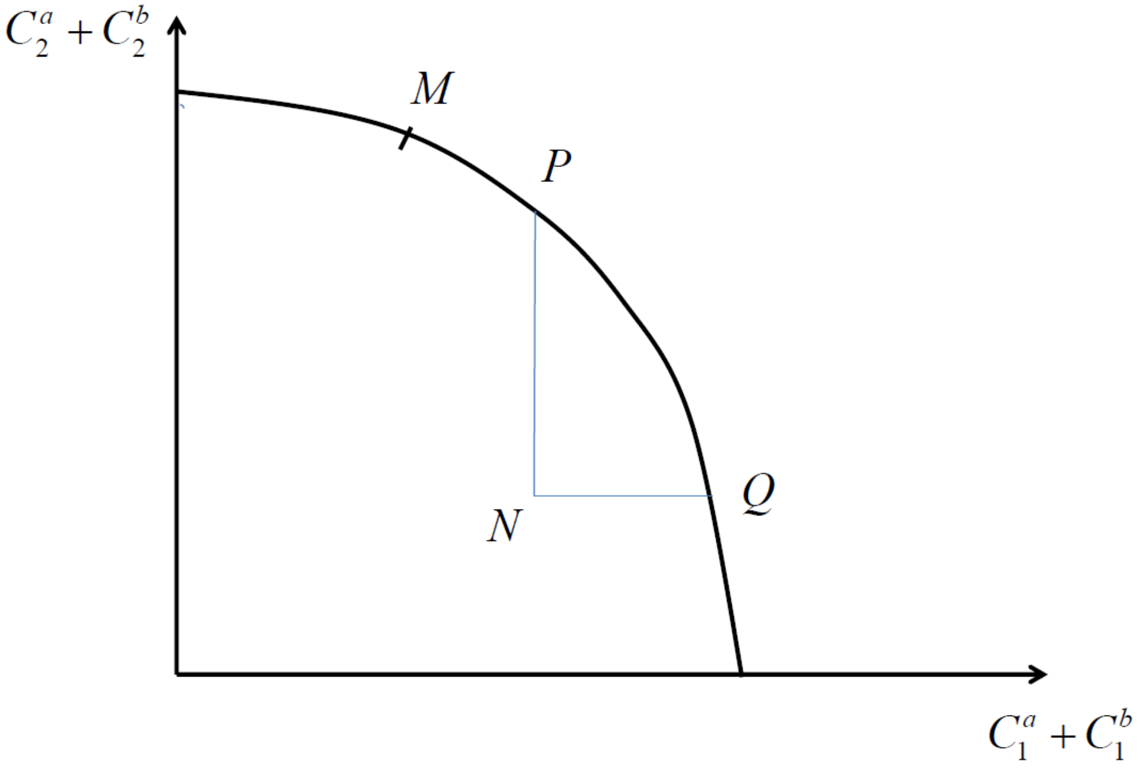

Figure 1: An illustration of Pareto-optimal deviations from the reference scenario.

How do important variables (such as emissions in the two periods and investment) change as we move up and to the left along the Pareto-efficient frontier? The answer is not obvious. However, there may be some intuition in that moving up and to the left on the utility frontier means that we sacrifice total consumption in period 1 in order to increase total consumption in period 2. In this simple model, this must imply higher investment I in physical capital and/or reduced emissions E_1. Moreover, due to declining returns to both types of investments, we might expect *both* effects to occur for most functional forms. However, even if the functions in the model are such that E_1 goes down as we move up and to the left along the utility frontier, we cannot conclude anything about how *total* emissions over the two periods will change.

3.2 Pareto improvements without transfers

Without the possibility of consumption transfers, it is no longer the case that all efficient outcomes maximize total consumption in one period given total consumption in the other period. The reason is that decisions on investment and emission choices cannot only be to maximize the *sum* of consumption in any period but must also consider the *distribution* of consumption when we cannot use transfers as a distributional instrument.

To illustrate some of the consequences of not having transfers, it is useful to consider a one-period version of our model. Ignoring the capital stock (and investments) and omitting the time subscripts, we have

$$C^k = \Omega(E^a + E^b)F^k(E^k)\,, \tag{11}$$

where the choices of E^a and E^b will determine C^a and C^b. An efficient outcome will maximize a weighted sum of utility, i.e., $\max\left[u(C^a) + \phi u(C^b)\right]$ where ϕ is now the welfare weight of country *b* relative to country *a*. It is straightforward to verify that this gives

$$q^a = \Omega(S)F^a{}'(E^a) = -\Omega'(\mathrm{S})\left(F^a + \omega F^b\right) \tag{12}$$

$$q^b = \Omega(S)F^b{}'(E^b) = -\Omega'(\mathrm{S})\left(\omega^{-1}F^a + F^b\right), \tag{13}$$

where

$$\omega = \phi\frac{u'(C^b)}{u'(C^a)}. \tag{14}$$

We immediately see that $q^a = q^b$, i.e., the shadow prices of carbon emissions are equal, if $\omega = 1$. If consumption transfers were allowed, it would be optimal to use these so that $u'(C^a) = \phi u'(C^b)$ no matter the value of ϕ, implying $\omega = 1$ for this case. Without transfers, however, the endogenous value of ω will depend on the exogenous value of the welfare weight ϕ.

To understand how the equilibrium in this case depends on the welfare weight ϕ, it is useful to start with the value of this welfare weight being such that $\omega = 1$, i.e., zero transfers would be optimal even if permitted. From this starting point, consider an increase in ϕ, i.e., an increased welfare weight to country *b*. This would yield an increase in C^b and a reduction in C^a, and is achieved by E^a declining and E^b increasing. The increase in ϕ will also increase the value of ω, implying from (12) and (13) that $q^a > q^b$ in the new equilibrium.

To get a better understanding of the Pareto-improving allocations, we perform simulations using the RICE model (Nordhaus, 2010). Since this model has a similar structure as our two-region, two-period model, the theoretical model above can help explain the mechanisms in place. It also integrates the intergenerational and intragenerational perspectives discussed to see how they interact.

4 Pareto improvements in the RICE model

4.1 The RICE-2010 model

The RICE model is a regionalized version of the Dynamic Integrated model of Climate and the Economy (DICE) developed by Nordhaus (2008)[8]. While sharing many similarities with the simple theoretical model in Section 2, it differs in several respects, notably in the dimensionality of time and countries. In brief, RICE-2010 is calibrated for 12 countries/regions and the 60 decades from 2000 to 2600. Each decade is represented by a year, e.g. the year 2005 denotes the decade 2001–2010. Only results for the first ten or twenty decades have a substantive interpretation, with the remainder included to avoid ad hoc terminal conditions, with a constant savings rate from 2125 onwards. RICE also includes a backstop technology with an initially high but decreasing price, calibrated so that emissions decline rapidly after 2250.

The specification of the per capita utility function in RICE-2010 is with a constant flexibility of marginal utility of 1.5. The utility discount rate is 1.5% per annum, set to ensure that the real interest rate in the model is close to the return on capital in real-world markets. The welfare function uses a modification of the Negishi calibrated weights that “equalize the

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[8] The RICE-2010 model is in the form of a Microsoft Excel optimization model and is available for download along with the supporting documentation from http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm. To facilitate transparency and changing model formulations, we have transferred the RICE-2010 model to GAMS and solved with the CONOPT solver. The GAMS model is available from the authors upon request.

period-by-period marginal utilities using the weighted average marginal utility, where each region's weights are the region's shares of the global capital stock in a given period" (Nordhaus, 2010, p. 2). The population is growing at an exogenous rate for each country.

Since the rich and poor regions are located at different latitudes and have different production structures, any climate change damage will not be symmetric. The damage is a function of temperature change in the atmosphere, which again depends on carbon concentrations in three reservoirs (atmosphere, biosphere and upper oceans, and lower oceans). To reach steady-state equilibrium takes several centuries or more because of oceanic thermal lag. In the model, the calibrated parameters correspond to a coefficient of equilibrium temperature sensitivity of 3.2°C for each doubling of CO_2.

We model production using a Cobb–Douglas production function with a capital output elasticity of 0.3 and labor output elasticity of 0.7, and the fuel input modeled somewhat differently from our model in Section 2. In Section 2, output was given by (ignoring region and period references) $\Omega F(K,E)$, where E is the fuel input. In RICE, the output available for consumption and investments is given by (ignoring the labor input) $\Omega F(K)-g(A)$, where A and $g(A)$ denote the abatement and the abatement costs, respectively. The fuel input is proportional to output, but at country-specific rates that decline over time. Moreover, the proportionality factor for each country is lower the higher the country's abatement effort A.

Our use of the RICE-2010 model follows the assumptions of Nordhaus (2010) with one major exception, namely that the BAU scenario follows Rezai (2011). Rezai argues that the Nordhaus scenario in a typical integrated assessment model as RICE is a hybrid in that it takes into account the effect the GHG concentration in the atmosphere has on future production possibilities, but still sets mitigation to zero. Thus, it is a constrained optimum. This lowers the return on conventional capital in the future and therefore reduces investment and increases current consumption. Using a BAU where the agent does not consider their effect on GHG accumulation at all would increase capital accumulation and reduce current consumption[9]. In the following simulations, we use this definition of a BAU, numerically found in an iteration process as in Rezai (2011).

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[9] Rezai (2011) internalizes a fraction (1/N) of the total emissions in the optimization for each of a large number (N) of dynasties. In our model, we follow the standard atomistic assumption where each agent treats all emissions as exogenous. Numerically, the results are almost identical.

4.2 Aggregating into two regions and four periods

To be able to illustrate the results from the two-country two-period model discussed in Sections 2 and 3, we aggregate the regions in the RICE model into two regions, *rich* and *poor*, and four periods (*t0*-*t3*), but focus on just two of these, *present (t0)* and *future (t2)*. Note that this aggregation is only in terms of the objective function and the presentation of results as we run the model using the original RICE-2010 countries and decades (Nordhaus 2010). The *rich region* consists of the USA, the EU, Japan, Russia and "other high-income countries (OHI)" as defined in the RICE model and we aggregate the remaining RICE countries into the *poor region*, comprising Eurasia, China, India, the Middle East, Africa, Latin America and "other non-OECD Asia".[10]

To perform the optimization over present and future welfare, we aggregate time into the following periods:

- *t0*: 2001–2050
- *t1*: 2051–2100
- *t2*: 2101–2150
- *t3*: 2151–2600

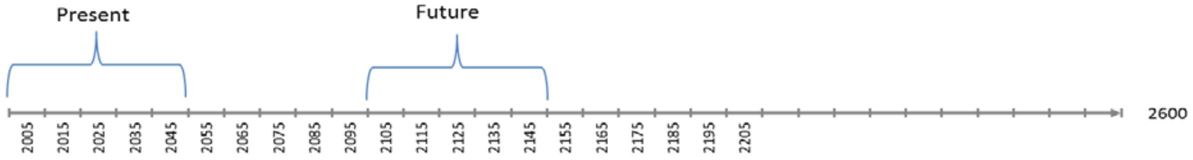

Figure 2: Illustration of the present and future within the RICE time horizon.

As discussed, we title period *t0* (the first half of the 21st century) as *the present (or today)* and period *t2* (the first half of the 22nd century) as *the future*.[11]

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[10] We aggregate the utility of the regions based on the weights of each RICE country in the social welfare function.

[11] To aggregate utility within a period from the five or more decades it comprises, we use the present value based on the social discount rate. Most graphs are based on the actual decades in the RICE model, but where we report other variables for the periods *t0*–*t3* we use the same discounting.

4.3 The different scenarios

In the model simulations, we work with the following scenarios. The first two are standard scenarios used in the integrated assessment literature:[12]

1. *BAU*: Business-As-Usual
2. *OPT*: Social optimum.

The welfare weights are from RICE, where they are set so that no direct consumption transfers are optimal within each generation in the BAU scenario. In BAU, there is no abatement, while in OPT abatement is undertaken to maximize total welfare, i.e., the sum of discounted weighted utility. As noted above, OPT follows from the choice of welfare weights made in RICE.

In addition to the above scenarios, we derive constrained optima across four dimensions where nobody loses in welfare terms compared with BAU:

3. *RICH20*: Maximize the utility of the rich region today
4. *RICH21*: Maximize the utility of the rich region in the future
5. *POOR20*: Maximize the utility of the poor region today
6. *POOR21*: Maximize the utility of the poor region in the future.

In the following, we also refer to the different scenarios as agreements. In these scenarios, the optimizing region receives all of the benefits from the agreement, while the other regions and generations are just as well off as before. While we only report results for *t0* and *t2,* we constrain *t1* and *t3* as well, so that no generation will lose compared with BAU. In each scenario, we introduce consumption transfers within a generation, but we also report the cases where transfers are not possible.

5 Simulation results

As in the theoretical model, a region has two possibilities to affect the output of future generations: with *GHG emissions* that have an impact on future damage (and therefore output

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[12] With the modification of the BAU scenario detailed above.

and welfare), and through *real investments* that increase future capital stocks (and therefore, production possibilities). In the model, real investment decisions are made via the savings rate, i.e., the share of net output (net of climate damage) not consumed but used for real investments.[13]

In the RICE model, the only possibility to affect other regions in the same decade is via transfers, as there is no trade or other interactions between regions in the model. However, as we aggregate the periods in our model over five decades, GHG emissions also have an impact on other regions within the same generation.

5.1 Consumption transfers

We first consider the case with consumption transfers. The optimizing region, i.e., the rich or poor region today or in the future, maximizes its utility level, given that the other regions (today and in the future) should not be worse off than in BAU. We find that as long as we consider only our four aggregated periods, the social optimum is a Pareto improvement over the BAU scenario. Hence, we have a situation that differs from Figure 1, where point M is now on the equivalent to line PQ. However, the social optimum is not a Pareto improvement for the underlying RICE decades in the middle of this century (2030–2060). This is similar to the results in Rezai (2011), where the social optimum is not a Pareto improvement for all DICE decades, but when aggregated to lifetime welfare, no generations lose.

Figure 3 displays the development in temperatures for the BAU, for our two Pareto improving scenarios, and for the social optimum. As explained in Section 3.1, abatement and temperature depend only on whether we are maximizing with respect to present or future generations. When we allow transfers, it makes no difference to abatement and temperature whether we are maximizing with respect to the rich or poor region, as transfers make it optimal to maximize the total consumption in any period for a given total consumption in the other period. See Figure 1.[14] This is because appropriate transfers take care of the allocation of these total consumption levels between countries.

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[13] Thus, the savings rate is endogenous. However, for technical reasons, the savings rate is exogenous from 2170 in the simulations.

[14] In the figure, «poor/rich20» are the simulations maximizing the utility of poor and rich today. In the same way, «poor/rich21» are the common results for the future generation.

Not surprisingly, the temperature is highest in the BAU scenario as there is no abatement. Less obvious is the result that the temperature is lowest in the social optimum, while the Pareto-improving scenarios are toward the middle. Our conjecture is that this is because more weight is given to the distant future (period *t3* in Section 4.1) in the social optimum than in our four Pareto-improving scenarios, as the utility of the distant future remains at its BAU level in the Pareto improving scenarios.

Although temperature is higher in the Pareto-improving scenarios we have considered than in the social optimum, this is not a general result even in the specific numerical model considered. Since the social optimum has strictly higher utility levels for all aggregated time periods than the BAU scenario, the Pareto-improving outcome that gives all the improvement to the distant future (period *t3*) implies more weight to the future than the social optimum. Our conjecture is that temperature is lower in this Pareto-improving outcome than in the social optimum.

In line with this, Figure 3 reveals that optimizing the outcomes for the present generation (*POOR/RICH20*) gives slightly higher temperatures than optimizing for the future generation (*POOR/RICH21*). Future generations have larger impacts from climate change than the present generation. They will therefore prefer to reduce emissions more when they receive the extra benefit from an agreement. When present generations optimize, they grasp the extra benefit themselves, and only perform the necessary abatement to ensure that future generations are no worse off.

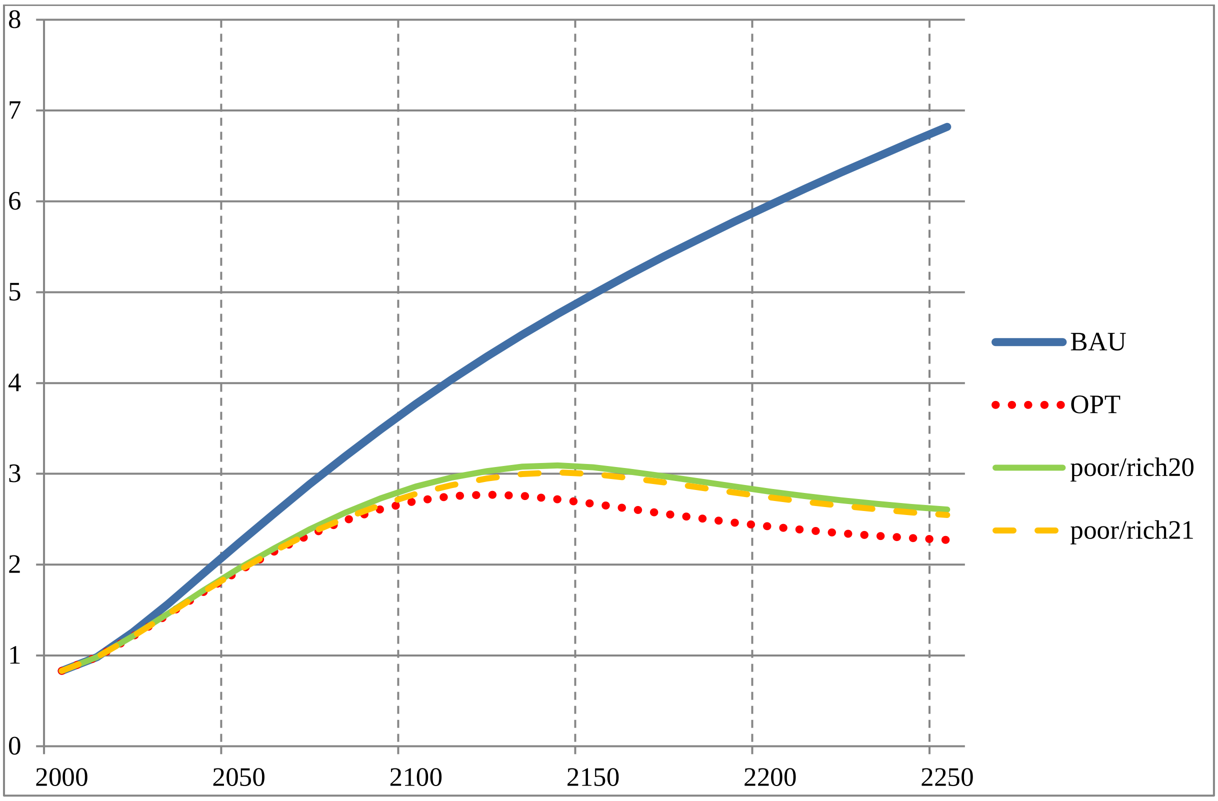

Figure 3: Development of global mean temperature compared with the preindustrial temperature under the different scenarios. Consumption transfers allowed.

In our scenarios, transfers today are generally from rich to poor countries, while transfers in the future depend on the region whose utility is maximized. The transfers in the present period are in the order of half a percent of GDP from the rich region, which amounts to the same percentage received in the poor region as their GDP is of similar size in *t0*. In the future period, where the poor region GDP has grown much more, the poor will transfer up to 3.7% of their GDP to the rich region when maximizing the utility of the latter (RICH21), and still not lose compared with BAU.

Figure 4 illustrates the time paths for the carbon tax under the Pareto-improving scenarios. We know from Section 3.2 that with transfers carbon taxes will equalize across regions.[15] However, the carbon tax will depend on whether we are optimizing with respect to the present

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[15] In our actual calculations, the carbon taxes do not fully equalize. The reason is that we do not optimize for each RICE country, but for the aggregated region, and within each region, the distribution of the consumption transfers follows the weights used in the aggregation. In a simulation where we have utility transfers at the regional level instead, we obtain equalized carbon taxes. The taxes shown in Figure 4 are averages of the tax rates in each of the two regions.

generation or the future generation. Not surprisingly, carbon taxes for most of this century are higher when we maximize welfare for the future generation rather than for the present generation.

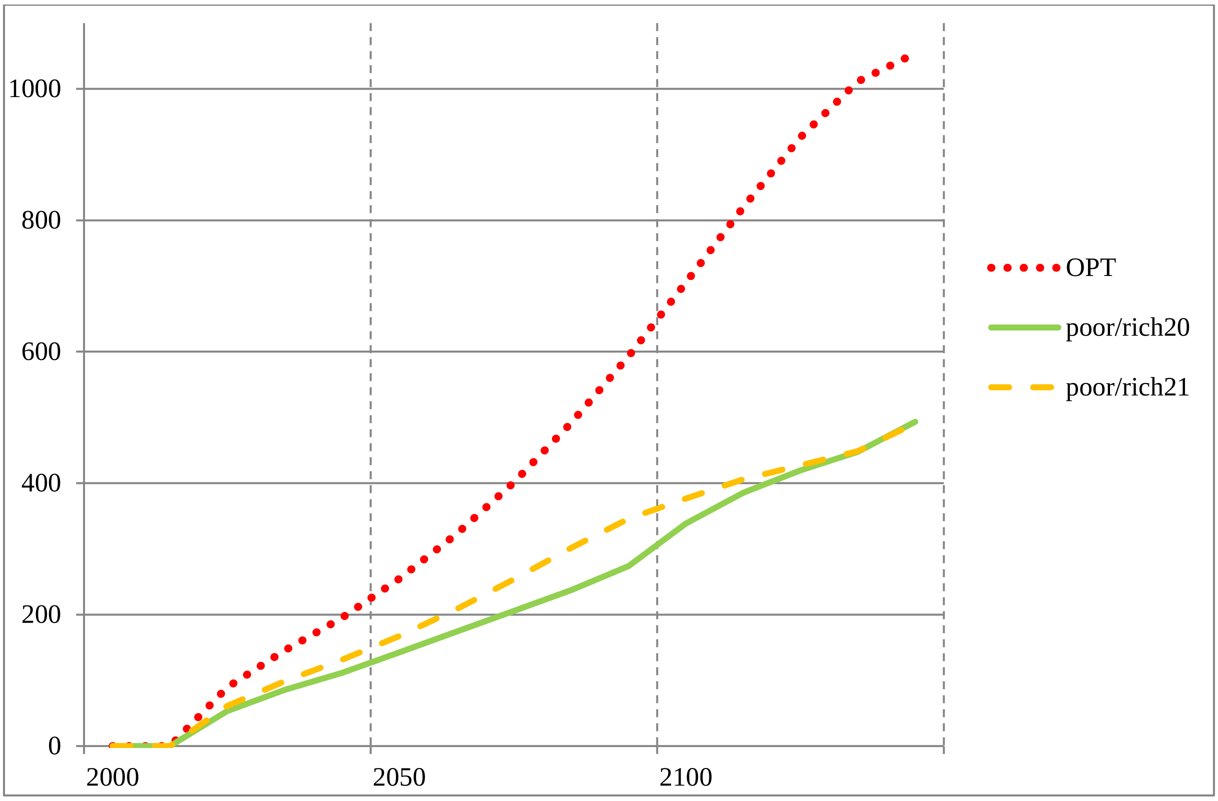

Figure 4: Carbon taxes (2005 USD per ton of carbon) under the different scenarios. Consumption transfers allowed.

5.2 No transfers

We next turn to the case without transfers. Figure 5 shows the development in temperatures in this situation. As before, the temperature is highest in the BAU scenario as there is no abatement. The temperature is lowest in the social optimum from the end of the next century, while it is actually higher than when optimizing for rich countries (*RICH20* and *RICH21*) up to that point in time.

As for the case with transfers, it does not matter much if it is the present or the future generation that maximizes. However, it matters whether it is the poor region or the rich region that takes the whole benefit. There is more abatement in the Pareto-improving scenarios in this century if the rich countries optimize. The poor region values consumption relatively more than environmental impacts compared with the rich region. Thus, they are more willing to increase their consumption at the expense of a worse climate than is the rich region.

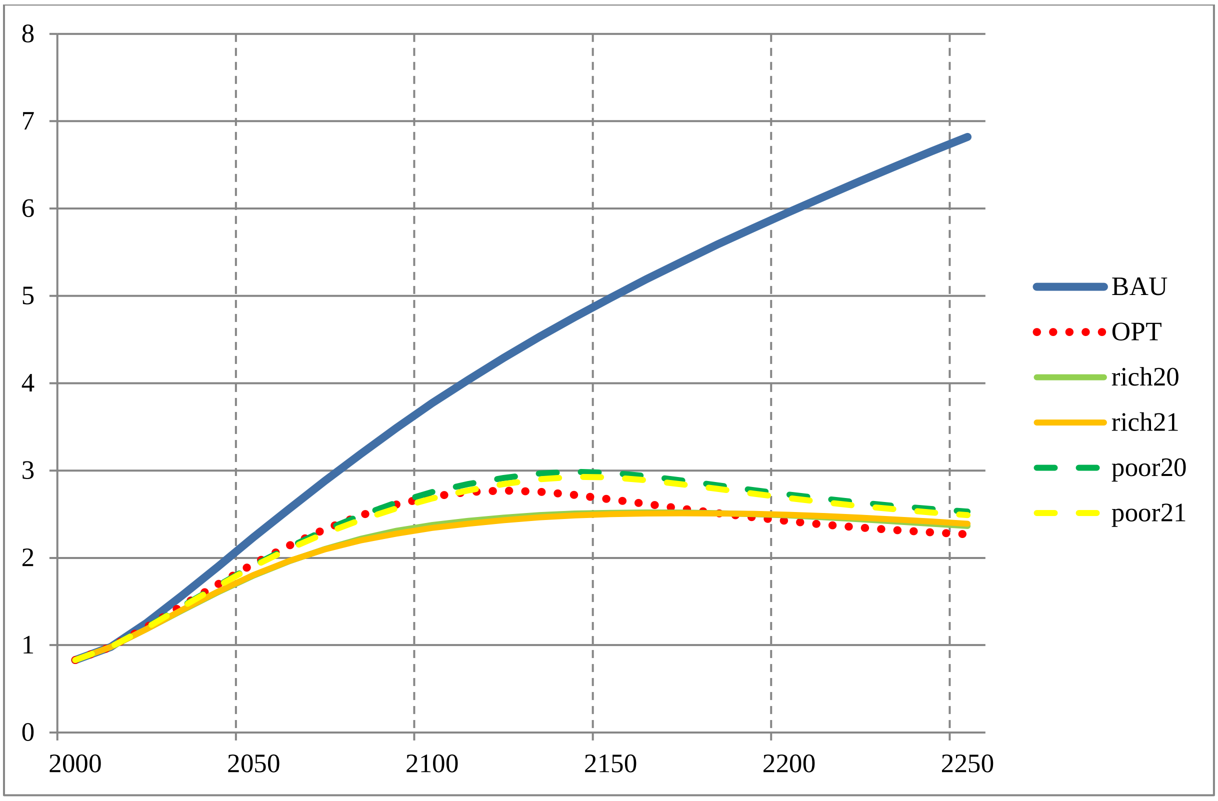

Figure 5: Development of global mean temperature compared with the preindustrial temperature under the different scenarios. No consumption transfers.

Comparing Figures 5 and 3, we can see that there is less warming without transfers than with transfers for the Pareto-improving scenarios. As mentioned in Section 2.2, climate policy can serve as a redistribution instrument when there is no allowance for transfers. Introducing transfers implies that there is less abatement needed to satisfy the distributional requirements. See also Eyckmans et al. (1993).

Figure 6 depicts the time paths of the carbon tax for the two scenarios where we maximize the welfare of future generations (we obtain similar results when maximizing the welfare of present generations). To start, we can see that the carbon price is much higher in the poor region than the rich under *RICH21*. We can also see that if the poor region optimizes, the result reverses, with a much higher tax in the rich region. The optimizing region thus places a higher burden on the other region and takes the net benefit itself. This is in line with the discussion in Section 3.2 whereby the increased welfare weight for one region increases the abatement (and therefore the tax) for the other region. Further, as the rich region is already more carbon efficient than the poor region, carbon taxes in the poor region yield more abatement than in the rich region. This is why emissions and temperatures are lower in the scenarios when the rich region optimizes.

Note also that as the carbon tax differs across regions, neither of these scenarios yield cost-effective solutions, as is the case with the social optimum (*OPT*). The carbon taxes can be very high, up to almost $900 per ton carbon in the nonoptimizing region by the beginning of the next century, but the development is hump shaped for the highest tax levels, even if the optimal temperature levels start falling during the 22nd century. The reason is that the backstop technology involves an exogenous technological development that makes abatement cheap when this technology becomes cheaper.

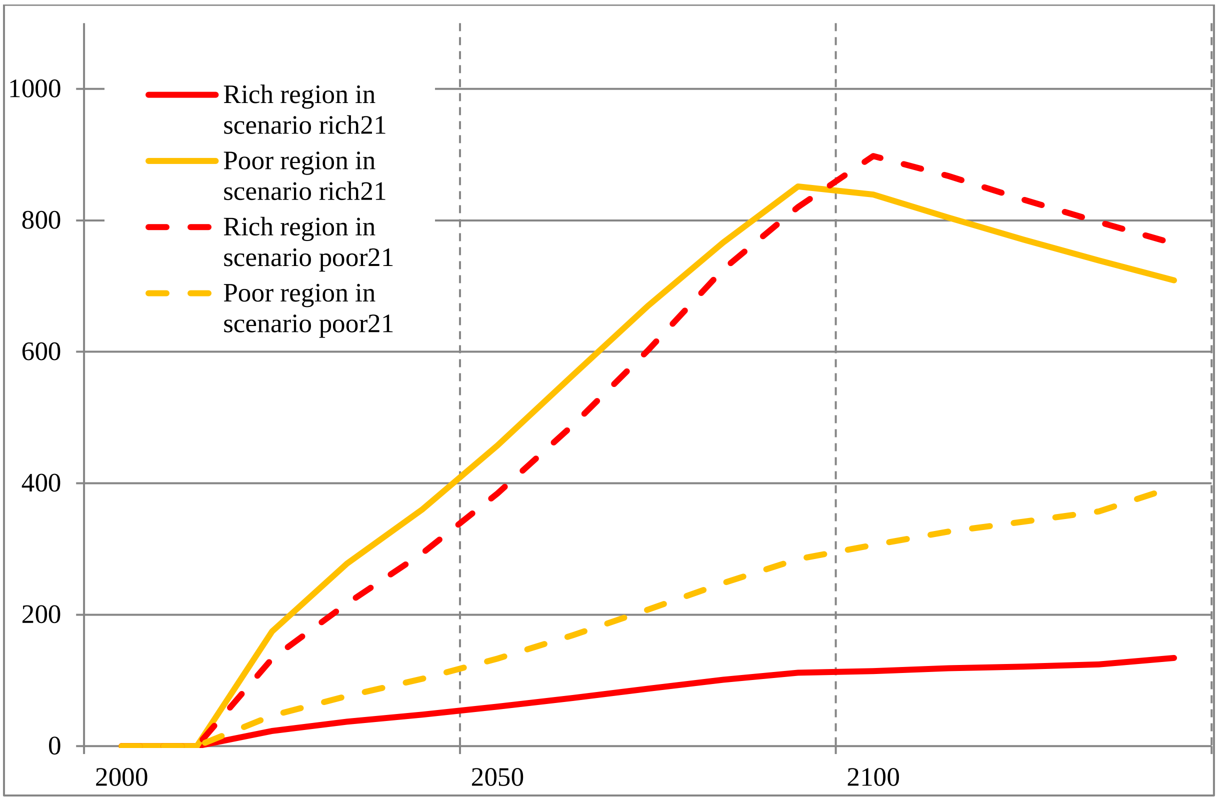

Figure 6: Carbon taxes (2005 USD per ton of carbon) under two Pareto improvement scenarios. No consumption transfers.

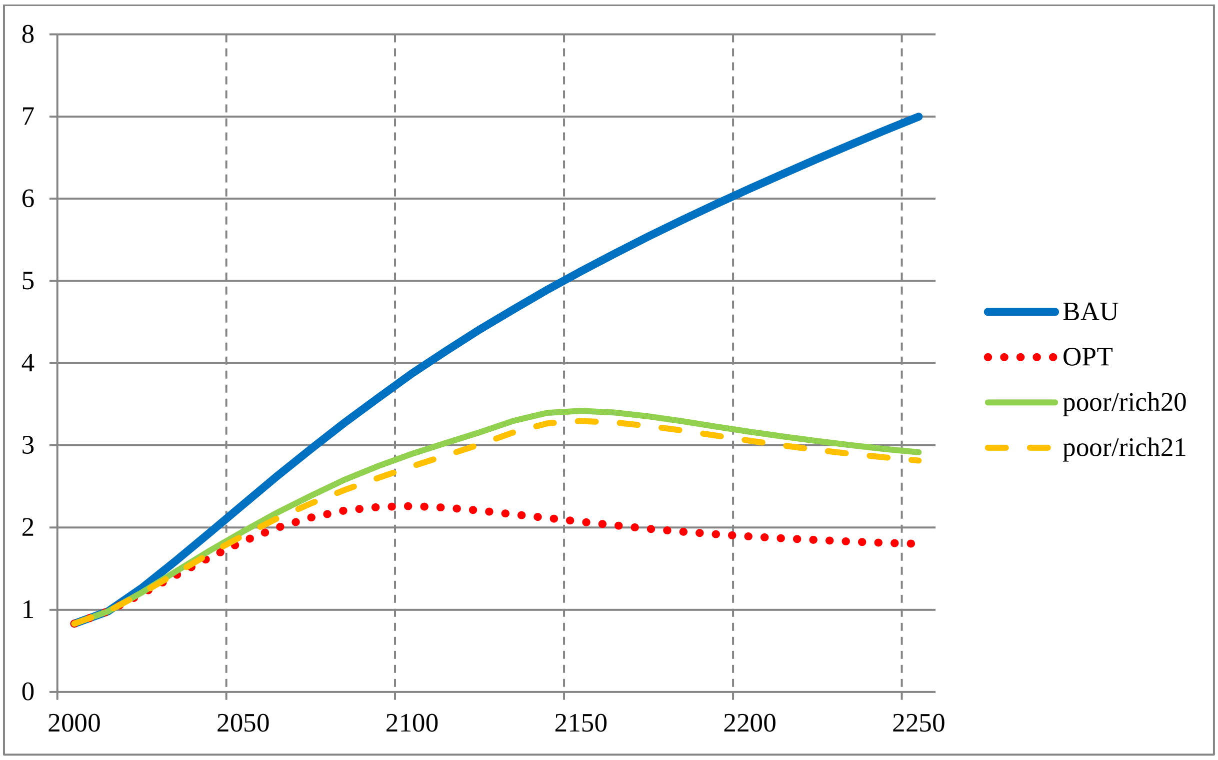

Figure 7: Development of global mean temperature compared with the preindustrial temperature under the different scenarios. Consumption transfers allowed. ρ=0.5 p.a.

5.3 Sensitivity analyses

As there are different views on many of the assumptions in the RICE model, we perform several sensitivity analyses. We first consider the impact of reducing the utility discount rate. Other sensitivity variations include setting all welfare weights to one and increasing climate damage.

5.3.1 The utility discount rate

As a number of studies have criticized the size of the utility discount rate (e.g., Stern, 2007), we undertake a sensitivity analysis with a lower utility discount rate by setting the utility discount rate lower to 0.5% p.a. With the lower discount rate, the social optimum is no longer a Pareto improvement for our 50-year aggregated periods, as in the *t1* period (2050–2099) both the rich and the poor regions are worse off than in BAU.

In what follows, we plot the case with consumption transfers, but the alternative with no transfers illustrates similar developments. Not surprisingly, Figure 7 depicts that a lower discount rate gives less global warming under the social optimum as we care more about future warming. Overall, the effect of decreasing the utility discount rate from 1.5% to 0.5% is to lower the temperature increase by about 0.5°C by 2100.

For the Pareto-improvement scenarios, we obtain the opposite result such that the optimal temperature will be higher with a utility discount rate of 0.5% than with 1.5%. To understand this, we know that these scenarios depend on the BAU scenario, as the BAU constrains the solutions. With a lower utility discount rate, the social discount rate is lower, which makes investments more profitable, i.e., future outcomes count more. Larger investment also involves higher production, and therefore, more emissions in the BAU scenario. This mechanism then provides higher production in the Pareto-improvement scenarios.

While not illustrated, the carbon tax for the Pareto-improving scenarios reaches a maximum in around 2100. The reason is that we need less abatement with lower utility discounting; thus, a higher carbon tax is no longer necessary at the end of the 22nd century. The turning point for the carbon tax also comes earlier than is the case with a high utility discount rate.

5.3.2 Double damage

Integrated assessment models use a highly aggregated representation of damage. The Intergovernmental Panel on Climate Change (IPCC) has criticized this representation, as it claims that it may understate the aggregate damage arising from climate change (Kolstad et al., 2014). In particular, Hoel and Sterner (2007) and Sterner and Persson (2008) have argued that climate-related damage to nonmarket goods may be higher than what is typically assumed in most integrated assessment models. To respond to this criticism, we increased the damage from global warming in our model, so that it is twice the earlier level for all temperature levels, i.e., we have multiplied the damage function by a factor of two.

As any climate-related damage is much higher than before, the differences between the BAU and the Pareto-efficient cases increase. Thus, as depicted in Figure 8, the optimal temperature is lower in all scenarios compared with our previous cases. However, we will still not reach the two-degree target by 2100, as outlined by the Copenhagen Accord,[16] in any of the scenarios. Another interesting result is that the differences in the Pareto-improving scenarios where the present generation and the future generation optimize have increased (as compared

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[16] From the 15th Session of the Conference of Parties (COP 15) to the United Nations Framework Convention on Climate Change that took place in Copenhagen in 2009.

with Figure 3). The reason for this is that the benefits from mitigation increase with greater damage, and this benefit mainly accrues to future generations. Thus, they would prefer an agreement with higher mitigation for the present generation. Carbon taxes will also need to be higher as there is more mitigation in this scenario. These taxes will reach their maximum (more than $800 per ton of carbon in some scenarios) by the middle/end of this century, as mitigation needs to increase rapidly.

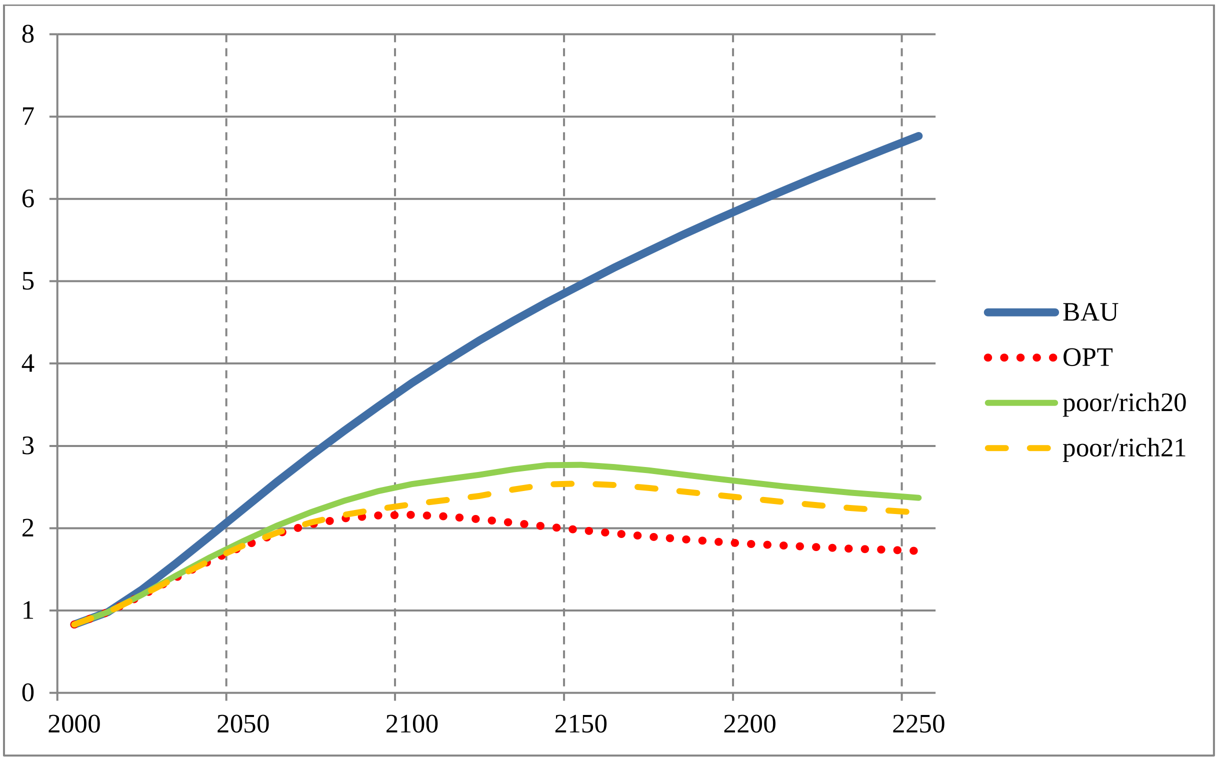

Figure 8: Development of global mean temperature compared with the preindustrial temperature under the different scenarios. Double damage. Consumption transfers allowed.

5.3.3 Negishi weights

The RICE model uses Negishi weights to compare the different utilities of the regions in the social welfare function. These weights do not explicitly consider equity and are set to make the current distribution optimal in the model, so that the optimization without climate change (BAU) would not divert much from the present real-world situation initially (see also Section 2.2). Thus, richer regions have higher welfare weights than poorer regions to remove the impact of the higher marginal welfare of consumption in poor countries. This implies that the present income (consumption) distribution is optimal, i.e., the weighted marginal utility of income is the same in all countries. Thus, by using Negishi weights, we accept the diminishing marginal utility of income for intergenerational choices, but not for intragenerational choices. Without such weights, it would be optimal to redistribute income so that the marginal utility of consumption equalizes across regions as part of climate policy (see, e.g., Stanton, 2011).

As the use of Negishi weights is controversial from an equity perspective, we run a set of simulations setting the welfare weights equal to one for both regions. As illustrated in Figure 9, this would reduce emissions compared with when we use Negishi weights. These emissions hurt the poor region more, and as we give the poor region greater weight in our decisions, emissions in the Pareto-improving scenarios will fall. We can also see that the difference between the scenarios where present and future generations optimize increases. This is because of the larger impact of future damage on poor countries. As our weights reflect this, future impacts will count more in the social welfare function.

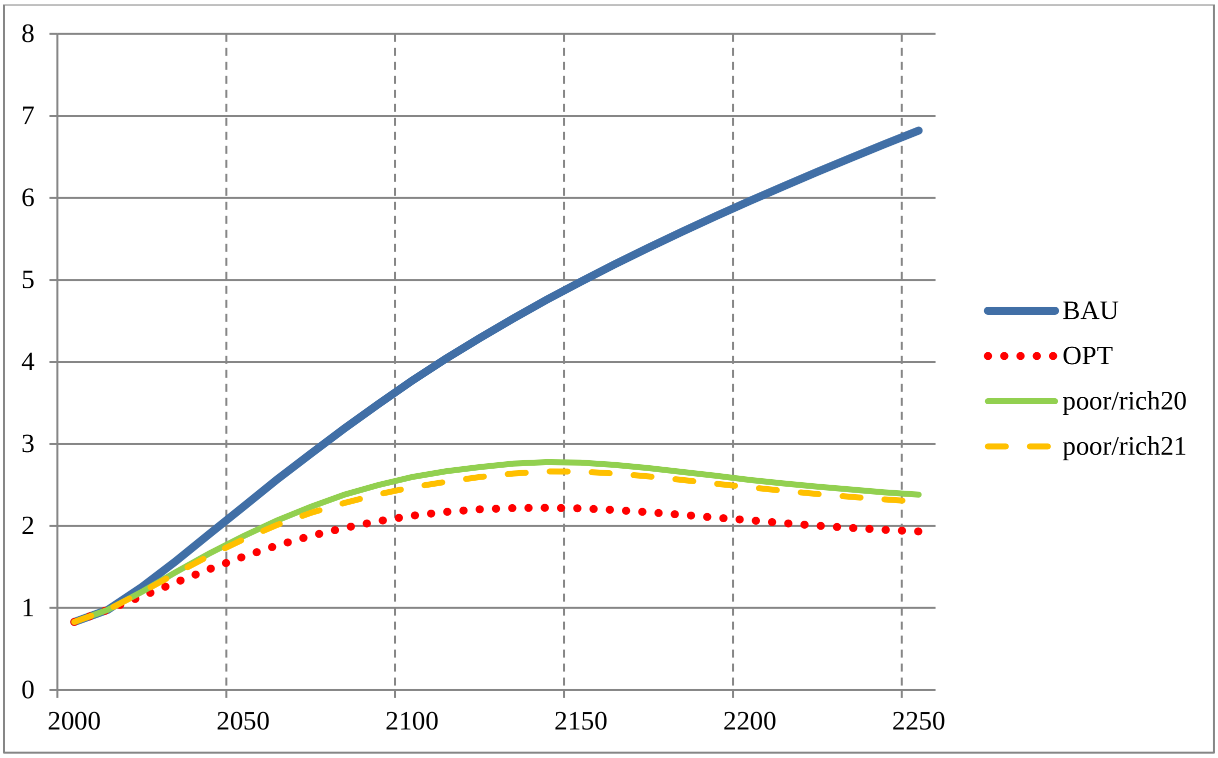

Figure 9: Development of global mean temperature compared with the preindustrial temperature under the different scenarios. Equal welfare weights. Consumption transfers allowed.

6 Conclusion and discussion

The focus of this paper is the implications of international climate agreements where no generation or region would lose compared with doing nothing. Many studies only compare a somewhat arbitrary social optimum with the inefficient BAU outcome. A conclusion from many of these studies is that the present generation must reduce consumption to mitigate future climate change. However, this means that the comparison of the social optimum with the BAU outcome is not only a comparison between an efficient and an inefficient outcome but also a comparison of different consumption distributions. Because significant climate change is due to market failure, it is possible to find Pareto improvements from the BAU outcome. Our study derives the properties of some of the possible Pareto-improving outcomes in the context of a two-period, two-region model. The distribution of welfare between the present and future generation is determined by real capital investments and GHG emissions. As we expect, different combinations of present and future consumption along the Pareto-improving frontier provide different combinations of capital investments and emissions.

In most of our model simulations, the Pareto-improving allocations invoke higher total emissions than does the social optimum. These Pareto-improving outcomes also depend significantly on when and who receives the efficiency gain, and on what we assume about consumption transfers across regions. If the present generation gets the efficiency gain, climate change will be higher than if the gain is to future generations. The larger the damage from climate change, and the more the future generations count in the social welfare function, the greater this difference.

The question is whether Pareto-improving climate allocations are relevant. The history of climate negotiations since the 1992 United Nations Conference on Environment and Development (UNCED) in Rio has shown that it is extremely difficult to implement policies that involve significant emissions reductions. One reason for this is the problem of burden sharing. As our model simulations with RICE show that most of the Pareto-improving outcomes we have considered yield less abatement than our social optimum, the transition to a green society will be less rapid, and probably easier to accept for the present generation. In addition, the policies reduce investments to be able to keep consumption intact compared with BAU, which also reduces total costs.

When it comes to transfers between regions, these are part of the Paris agreement as developed countries have already promised to provide climate finance of up to $100 billion a year to help developing countries reduce their emissions and adapt to climate change (UNFCCC, 2010). This shows that Pareto-improving agreements can be more successful than an international treaty where some generation must sacrifice its own welfare for another generation. However, we can design Pareto-improving agreements in a variety of ways, as shown by our simulations, and if most of the gain goes to one region (either today or in the future), any inequality between regions may increase, even if all regions are at least as well off as without an agreement. Accordingly, if countries care about relative inequality, such as through inequality aversion (Fehr and Schmidt, 1999; Kverndokk et al., 2014), all Pareto-improving agreements may be unacceptable. Thus, the careful design of such an agreement is important.

Appendix: Details of the model in Sections 2 and 3

In addition to (2), the model consists of the following equations.

The first two equations explain how the harmful stock of carbon in the atmosphere depends on emissions:

(A.1) $$S_1 = \sum_k E_1^k \quad \text{harmful stock of carbon in period 1}$$

(A.2) $$S_2 = S_1 + \sum_k E_2^k \quad \text{harmful stock of carbon in period 2.}$$

We ignore the depreciation of carbon, but including it (as in the numerical model) does not change our conclusions.

The capital stocks in period 1 are exogenous (historically determined), while the capital stocks in period 2 depend on net investments I^k:

(A.3) $$K_2^k = K_1^k + I^k .$$

In each period and for each region, a region can use output for consumption, investment (zero in period 2) and transfers Z_t^k to the other region:

(A.4) $$Q_1^k = C_1^k + I^k + Z_1^k$$

(A.5) $$Q_2^k = C_2^k + Z_2^k \quad .$$

Obviously, net transfers between regions must sum to zero in each period:

(A.6) $$\sum_k Z_t^k = 0 \quad \text{t=1,2}$$

A stricter requirement would be to dismiss any transfers between regions. This would imply that (A.6) is replaced by the stricter condition

(A.6’) $$Z_t^k = 0 \quad \text{k=a,b; t=1,2.}$$

To find all Pareto-efficient outcomes, we maximize (3) subject to the other equations in the model.

The Lagrangian for the optimization problem assuming (A.6) is ($j,k = a,b$)

(A.7) $$\begin{aligned} L &= \sum_k \phi_1^k u(C_1^k) + \sum_k \phi_2^k u(C_2^k) \\ &+\sum_k \mu_1^k \left[\Omega^k(\Sigma_j E_1^j) F_1^k(K_1^k, E_1^k) + Z_1^k - C_1^k - I^k\right] \\ &+\sum_k \mu_2^k \left[\Omega^k(\Sigma_t \Sigma_j E_t^j) F_2^k(K_1^k + I^k, E_2^k) + Z_2^k - C_2^k\right] \\ &-\gamma_1 \Sigma_j Z_1^k - \gamma_2 \Sigma_j Z_2^k, \end{aligned}$$

and the first-order conditions for the social optimum are ($i,k = a,b$)

(A.8) $$\phi_1^k u'(C_1^k) - \mu_1^k = 0$$

(A.9) $$\phi_2^k u'(C_2^k) - \mu_2^k = 0$$

(A.10) $$\mu_1^k \Omega^k(S_1) \frac{\partial F_1^k(K_1^k, E_1^k)}{\partial E_1^k} + \sum_t \sum_i \left[\mu_t^i \Omega^i{}'(S_t) F_t^i(K_t^i, E_t^i)\right] = 0$$

(A.11) $$\mu_2^k \Omega^k(S_2) \frac{\partial F_2^k(K_2^k, E_2^k)}{\partial E_2^k} + \sum_i \left[\mu_2^i \Omega^i{}'(S_2) F_2^i(K_2^i, E_2^i)\right] = 0$$

(A.12) $$-\mu_1^k + \mu_2^k \Omega^k(S_2) \frac{\partial F_2^k(K_2^k, E_2^k)}{\partial K_2^k} = 0$$

(A.13) $$\mu_1^k - \gamma_1 = 0$$

(A.14) $$\mu_2^k - \gamma_2 = 0\,.$$

Notice that the last two equations apply to the case with transfers, but not when transfers are ruled out.

Using (A.13) and (A.14), it is straightforward to derive (4) from (A.8), (A.9), and (A.12), where $1 + r^k = \frac{\gamma_1}{\gamma_2}$.

Together with (A.10) and (A.11), the above equations also imply that the marginal productivity of emissions, or the shadow price of emissions, is the same in each country. Denoting this shadow price q_t, we immediately obtain (5).

To solve the problem described in Section 3, we introduce a new Lagrangian. This is almost as it was for the social optimum, the only difference being that we replace the first line in (A.7) by

(A.15) $$\sum_{t,k} \lambda_t^k \left[u(C_t^k) - \bar{U}_1^k \right],$$

where $\lambda_s^h \equiv 1$ and the Lagrange multipliers λ_t^k are endogenous shadow prices for the three constraints $u(C_t^k) \geq \bar{U}_t^k$ ($tk \neq sh$).

The solution to this problem is as before given by (A.8)–(A.14), except that in (A.8) and (A.9) the exogenous terms ϕ_1^k and ϕ_2^k are replaced by λ_1^k and λ_2^k, which are endogenous for the three combinations of $tk \neq sh$.

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