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Does Distribution Matter? When Flexibility, Equity and Efficiency in Greenhouse Gas Abatement

Gunter Stephan
Georg Müller-Fürstenberger

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Universität Bern
Volkswirtschaftliches Institut
Gesellschaftstrasse 49
3012 Bern, Switzerland
Tel: 41 (0)31 631 45 06
Web: www.vwi.unibe.ch

DOES DISTRIBUTION MATTER?

When Flexibility, Equity and Efficiency in Greenhouse Gas Abatement

By

Gunter Stephan and Georg Müller-Fürstenberger ♣

Institute of Applied Micro-Economics
University of Bern

Gesellschaftsstrasse 49 CH 3012 Bern
Email: gunter.stephan@vwi.unibe.ch

Abstract:

This paper analyses banking and borrowing of carbon emission rights within the framework of a simple, integrated assessment model. Breaking the world economy in just two regions it will be shown: (1) Increasing when-flexibility in greenhouse gas abatement through banking and borrowing of carbon emission permits has a positive effect on welfare for regions with a poor endowment in carbon emission rights, but negatively affects rich-endowed regions. (2) Intergenerational fairness advocates intertemporal flexibility in greenhouse gas abatement, irrespectively of the initial allocation of carbon rights. (3) Optimal carbon accumulation is not independent of the initial allocation of carbon rights. Different initial sharing rules clearly influence the development of atmospheric carbon concentration.

Keywords: Carbon rights, climate policy, integrated assessment, banking and trade.

JEL-Classification: Q4, F2

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1 Introduction

There are different ways to look at the global climate problem. One is to identify efficient abatement strategies through cost-benefit considerations. Another is to relate the global climate problem to ideas of intergenerational fairness and equity. This paper links both aspects to the issue of flexibility in *when to abate* greenhouse gas emissions. *When flexibility* in greenhouse gas abatement is established through banking and borrowing of carbon emission rights. With banking, emission rights can be saved for future use; with borrowing present emissions might be extended against future abatement. This should reduce costs simply by transferring abatement activities over time. But does it enforce regional welfare?, and does it increase intergenerational equity? Addressing these questions is the issue of this paper.

When flexibility is not a novel institution. It is nothing else than a specific kind of permit trade in which individuals, firms or even nations sell to or buy from themselves. Nonetheless there are some important differences between international trade of carbon rights on the one hand and *when flexibility* in greenhouse gas abatement on the other. First, global climate change is a stock damage problem. If nations are allowed to shift emissions over time, this could affect the dynamics of climate change, the marginal costs of damages and – equally important - the marginal productivity of capital. Second, efficiency in greenhouse gas abatement requires equal marginal costs of abatement across nations, - a requirement that is not granted without international trade in emission permits. This motivates to have a closer look on the issues of equity and efficiency if *when to abate flexibility* prevails.

Unfortunately, the economic literature is not very helpful on this issue. On the one hand, theoretical analyses are rather ambiguous. For example, Biglaiser et al. (1995) conclude that intertemporal permit trade must not be efficient. Kling and Rubin (1997) argue that although banking and borrowing do not assure Pareto-efficiency, banning *when flexibility* is also not optimal. And recently, Leiby and Rubin (2001) have shown that in the case of starting from a non-optimal emission path intertemporal permit trade could improve welfare. On the other hand, although *where flexibility* is a feature of almost any integrated assessment model, banking and borrowing is typically not included. Exceptions are among others the papers by Manne and Richels (1995), Kosobud et al. (1994) and Westskog (2000). However, these studies do not focus on Pareto-efficient abatement strategies, nor do they analyze the interplay between equity, efficiency and *when flexibility* as is intended in this paper.

This analysis abstracts from the issue of uncertainty. And we are not interested in considering gaming or threat situations. Instead, we are interested in cooperative solutions, where one region cannot improve its welfare without a reduction in the welfare of another. Given that the percentage shares of global emissions are determined exogenously, a multi-region computable general equilibrium model is employed to answer the questions: Does *when flexibility* in greenhouse gas abatement affect the atmospheric accumulation of greenhouse gases? Will banking and borrowing of carbon emission rights improve regional welfare? Does the initial allocation of carbon emissions rights matter?

The rest is organized as follows: Section 2 carries out a simple analytical analysis. Section 3 presents our version of an integrated assessment model. Although highly stylized, essential features and numerical parameters are taken over from the MERGE (see Manne et al. 1995), the ROR (see Manne and Stephan 1999) and the MEDEA framework (see Stephan and Müller-Fürstenberger 1998). Scenarios are discussed in Section 4. Section 5 reports the major findings, while sensitivity analysis with respect to key parameters is given in Section 6. Finally, Section 7 covers concluding remarks.

2. Preliminary considerations

To fix ideas, consider a simple analytical example. Suppose R regions cooperate in the solution of the global climate problem over a time horizon of two periods. Global climate change is viewed as public bad and is driven by the accumulation of greenhouse gas emissions. Regional welfare W_r, $r = 1,...,R$, solely depends on the consumption $c_r(t)$ of the private good during periods $t = 1, 2$. That means, emissions do not enter directly into the utility function. Instead they directly affect regional production.

To sidestep a detailed energy-production model conventional output $y_r(t)$ of region r is viewed as a function of its greenhouse gas emissions $s_r(t)$

$$y_r(t) \quad = \quad F_r(s_r(t)),$$

where the *production* function F_r has the conventional properties. Now, let ω_r be the Negishi-weights associated to region r. Then a Pareto-efficient allocation must maximize the objective function (see Ginsburgh and Keyzer 1977)

$$\sum_r \omega_r W_r[c_r(1),c_r(2)]$$

subject to the constraints

(2.1) $$\sum_r F_r(s_r(1)) - \sum_r c_r(1) \quad = \quad 0,$$

(2.2) $$\sum_r \Phi_r(Q)F_r(s_r(t)) - \sum_r c_r(2) \quad = \quad 0,$$

(2.3) $$Q - \sum_r s_r(1) - \sum_r s_r(2) \quad = \quad 0.$$

Equation (2.1) requires that in period 1 the world's total output covers the sum of consumption across regions. (2.2) establishes a similar balance for produced goods in period 2, but takes into account that climate change negatively affects conventional production. Φ_r is the region-specific damage factor and measures the fraction of conventional gross output that is at a region's disposal. That means, the higher the stock of accumulated global emissions Q, the lower is $\Phi_r(Q)$ and the lower will be the fraction, $\sum_r \Phi_r(Q)F_r(s_r(t))$, of conventional wealth that is available for consumption in period 2.

Let p_1, p_2 and π be the Lagrange-multipliers that are associated to equations (2.1), (2.2) and (2.3), respectively. Then, first order conditions immediately imply almost conventional optimality conditions for any region r:

(2.4) $$p_1/p_2 \quad = \quad [\partial W_r/\partial c_r(1)]/[\partial W_r/\partial c_r(2)],$$

(2.5) $$p_1/p_2 \quad = \quad -[\sum_{j=1,...,R} \Phi'_j(Q)F_j(s_j(2))]/F'_r(s_r(1)),$$

(2.6) $$\Phi_r(Q)F'_r(s_r(2)) \quad = \quad -[\sum_{j=1,...,R} \Phi'_j(Q)F_j(s_j(2))].$$

Equation (2.4) is a well known Ramsey-condition. (2.5) establishes optimality in the presence of a public bad. To see this combine (2.4) and (2.5)

(2.5a) $$[\partial W_r/\partial c_r(1)]F'_r(s_r(1)) \quad = \quad -[\sum_{j=1,...,R} \Phi'_j(Q)F_j(s_j(2))]\ [\partial W_r/\partial c_r(2)]$$

and suppose that region r - ceteris paribus - reduces abatement by one unit in period 1. This increases consumption, hence regional welfare, as the left hand side of (2.5a) indicates. And it increases atmospheric carbon, hence imposes climate change induced costs on each region. For Pareto-efficiency it is necessary, however, to internalize these external effects as the right hand side of (2.5a) expresses.

What can be learned from the specific public bad model adopted here? First, for Pareto-efficiency marginal cost of abatement has to be identical across regions as (2.5) and (2.6) together indicate. Second, the right hand side of (2.5) corresponds to the slope of the intertemporal transformation frontier. The later is independent of the initial allocation of regional emission shares as well as the Negishi-weights. However, since Negishi-weights are proportional to the present value of the respective region's wealth (see Manne and Olsen 1996), this suggests separability between efficiency in greenhouse gas abatement and the initial distribution of convention wealth. [1]

This could have far reaching policy implications. If the Pareto-efficient stock of atmospheric carbon is independent of the initial allocation of conventional resources, a sharp distinction might be drawn between determining the global level of abatement and negotiating the cost sharing rules. Equity would be an issue of allocating shares of the global total to the individual nations through international negotiations. Efficiency could be achieved through trading these rights internationally without major changes in the historical ownership of labor, capital and other conventional resources (see Manne 1999). This is in sharp contrast to Chichilnisky and Heal (1994) who insist that the global climate problem cannot be solved without international wealth transfers. In particular they showed that international trade in carbon negatively affects the poorer countries. However, their argument hinges on the fact that global climate change directly affects utilities. This means that the public good enters into the objective function, - an issue that is neglected in the present paper.[2]

So far our considerations have been based upon the assumption that there is full flexibility in greenhouse gas abatement, both in terms *when* and *where* flexibility. But what, if emission rights are assigned to the individual regions, but not allowed to be traded internationally? There are two observations that will be important for the rest of this paper. First, regions domestically have to abate a certain fraction of their carbon emissions. Or, to put it differently, regions are allowed to produce a certain, exogenously determined fraction m_r of the atmospheric carbon stock Q. Therefore condition (2.3) has to be replaced by

(2.3a) $$m_rQ - s_r(1) - s_r(2) \;=\; 0$$

which has to be obeyed by each region r. Solving again for optimality gives

(2.5a) $$p_1/p_2 \;=\; -[\textstyle\sum_{r=1,\dots,R}\Phi_r(Q)F'_r(s_r(2))]/[\sum_{r=1,\dots,R} m_rF'_r(s_r(1))],$$

(2.6a) $$\textstyle\sum_{r=1,\dots,R} m_r\Phi_r(Q)F'_r(s_r(2)) \;=\; -[\sum_{r=1,\dots,R} \Phi'_r(Q)F_r(s_r(2))].$$

Now emission shares, m_r, are part of the optimality conditions and marginal cost of abatement is not equalized between regions. This implies that the optimal stock of atmospheric carbon

[1] For any pair of regions, r, k, first order conditions imply: $\omega_r > \omega_k$ if and only if $\partial U_k/\partial c_k > \partial U_r/\partial c_r$. Given strictly quasi-concave utility functions, region r is wealthier in terms of conventional consumption than region k.

[2] We are grateful to an anonymous referee who made us aware of this difference.

depends on the allocation of emission shares. In other words, the issues of equity cannot be separated from that of efficiency.

Second, banking only - and the same holds true in the case of borrowing only – turns out being a Pareto-inferior flexibility regime. To see that recall that for any pair of regions i, j, conditions (2.5) and (2.6) for optimality together imply

(2.7) $$\Phi_i(Q)F'_i(s_i(2)) / F'_i(s_i(1)) \quad = \quad \Phi_j(Q)F'_j(s_j(2)) / F'_j(s_j(1)).$$

Now, suppose region i reduces emissions by one unit in period 1 to extend emissions in period 2. Since the production functions F_r have the usual properties, transferring emissions into the future reduces the numerator and increases the denominator, hence the left hand side quotient of condition (2.7). To fulfill the necessary requirement (2.7) for Pareto-efficiency, all other regions have to act in the same way. That means, regions simultaneously either bank or borrow carbon emission rights.

The consequences of that observation are almost obvious. If regions exploit intertemporal flexibility through banking, given the naive one-to-one banking rule, this does not change the atmospheric stock of carbon (see (2.3)). But reduces first period consumption and increases consumption in the second period (recall (2.1) and (2.2)). Hence, if utilities are discounted at positive rates, banking can turn out to be Pareto-inefficient.

3. Regional MEDEA

Of course, numerical simulations are not a perfect substitute for analytical considerations. However, since the interplay between banking and borrowing, Pareto-efficiency in greenhouse gas abatement, burden sharing and equity are highly complex, numerical thought experiments will provide additional insight. Having this in mind, the general equilibrium framework with public good is deliberately simple. There are two regions of the world: North (N) and South (S). North consists of the OECD countries including the former Soviet Union. Roughly this corresponds to the so-called ANNEX I parties. South covers the rest of the world and should be viewed as an acronym for the developing part of the world.

Time is discrete and periods are one decade in length. Each region produces a homogenous output that may be used for consumption, investment, net exports and to cover energy costs. Carbon-free energy resources such as hydro or solar are viewed as backstop resources. They are provided at constant, but high marginal costs. Greenhouse resources such as oil, gas and coal are supplied at initially lower but increasing costs.

Among the various greenhouse gases, carbon dioxide is considered as the most relevant one. We neglect the cooling effects of aerosols and the heating effects of greenhouse gases other than carbon dioxide. We neglect the thermal inertia lag between global concentrations and climate change. And we neglect climate externalities that are not valued in a market. Instead, global warming is directly attributed to cumulative CO_2 emissions and affects production of different regions of the world in different ways (for a discussion, see Joos et al. 1999).

3.1 Climate-economy interaction

There are two channels through which the environment and the economy interact. One is the consumption of greenhouse resources, which directly determines the flow of CO_2 emissions into the global atmosphere. The second link is provided through the concept of the *green output* by which global climate change is translated into economic costs.

A two-box model is used to cumulate carbon emissions over time, and to translate them into global concentrations. (For a detailed discussion of functional specifications and choice of parameters, see Joos et al. 1999.) At any point of time the stock of atmospheric carbon dioxide, Q(t), is a function of the former one, Q(t-1), and global past period emissions, s(t-1):

$$Q(t) = \Psi Q(t-1) + \Theta s(t-1). \quad (3.1)$$

Ψ is the factor by which natural abatement reduces the current stock of atmospheric carbon. Θ is the fraction of past global emissions that has accumulated in the atmosphere.

Climate impact analyses usually focus on doubling atmospheric carbon. This is scanty, but sufficient information to calibrate a damage function. However, it does not tell how to specify such a functional relationship appropriately. In our model economic losses are a function of the square of the stock of atmospheric carbon Q(t) and are inversely proportional to a region specific catastrophe level Ω_r. At this atmospheric CO_2 perturbation, production in region r = N(orth), S(outh) is reduced to zero:

$$\Phi_r(Q(t)) = 1 - [Q(t) / \Omega_r]^2. \quad (3.2)$$

Note that contrary to a linear one, this specification gives rise to high marginal damages in the future but low ones in the present (for a discussion, see Peck and Teisberg 1992). For calibrating economic losses it is assumed that with zero abatement concentrations will rise from 353 ppm (the 1990 level) to 560 ppm (twice the pre-industrial level) by about 2070. This leads to damages of 3.5% of gross output in the South and 1.5% of GDP in the North.

3.2 Production, emissions and abatement

Principally, there are two ways to reduce CO_2 emissions. One is to replace greenhouse fuels by carbon-free energy inputs. A second option is to uncouple economic growth from fossil fuel consumption by increasing the energy efficiency and by substituting capital for energy. To capture both possibilities, the regional production possibilities are represented through nested constant elasticity of substitution (CES) production functions[3]:

$$y_r(t) = [\beta_1(l_r(t)^{\alpha} k_r(t)^{1-\alpha})^{\varepsilon} + \beta_2(e_r(t))^{\varepsilon}]^{1/\varepsilon}. \quad (3.3)$$

Capital $k_r(t)$, labor $l_r(t)$ and energy inputs $e_r(t)$ together produce the conventional (i.e. without climate effects) output, $y_r(t)$. β_1 and β_2 are CES-coefficients derived from base year data, and ε is the CES elasticity of substitution between capital/labor and energy.

Substitution between capital and labor is described by a Cobb-Douglas formulation where α is the corresponding parameter. Total energy inputs into regional production,

$$e_r(t) = f_r(t) + n_r(t), \quad (3.4)$$

are the sum of flows of fossil fuels $f_r(t)$ and of backstop energy resources $n_r(t)$.

3.3 Material balance of produced goods

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[3] For better readability regional indices on parameters are omitted. For more details on the specification of functional forms, see Stephan and Müller-Fürstenberger (1998).

Climate change negatively affects the productivity of the regional economies. Only the fraction $\Phi_r(Q(t))$ of conventional gross output $y_r(t)$ is still at their disposal (see Section 2). Within each region r, *green output*, $\Phi_r(Q(t))y_r(t)$, can be consumed, invested into conventional capital formation, or used to supply either greenhouse resources or carbon-free energy.

Energy supply costs are measured in units of gross production. Marginal costs b_r of carbon-free energy are constant, but approximately four times as high as costs of greenhouse resources in the initial year. Marginal costs $a_r(t)$ of greenhouse resources increase over time, depending upon the cumulated extraction in prior periods.

To prevent an excessively rapid rate of market penetration once renewable resources become competitive, it is assumed that after an energy supply system is installed, it is quasi-irreversible and cannot be abandoned immediately. Accordingly, the replacement rate is limited to 20% annually[4]:

(3.5) $$f_r(t+1) \geq 0.8 f_r(t).$$

With this formulation there is the possibility that market prices of energy temporarily overshoot the marginal costs of the renewable resources.

Regional output is considered as numeraire that can be traded internationally. Therefore, if $x_r(t)$ denotes net-exports, $c_r(t)$ consumption, and $i_r(t)$ investment in conventional capital, then for each period t

(3.6) $$\Phi_r(Q(t))y_r(t) \geq c_r(t) + i_r(t) + x_r(t) + a_r(t)f_r(t) + b_r n_r(t)$$

is the material balance of commodities produced and traded in region r. Finally, since net-imports have to balance out in each period t, condition

(3.7) $$x_N(t) + x_S(t) = 0$$

has to be obeyed globally.

3.4 Intertemporal decisions

At any point of time t, the regional endowment $k_r(t)$ in physical capital depends upon investment activities, $i_r(t-1)$, and the former capital stock, $k_r(t-1)$

(3.8) $$k_r(t) = (1-\upsilon_r)k_r(t-1) + i_r(t-1),$$

where υ_r is the regional capital depreciation rate.

At first glance, the natural approach to the economics of global climate change would be to employ an overlapping generations model. It was shown, however, that under reasonable assumptions both an infinitely lived agent framework and an overlapping generations model would identify the same greenhouse policies as being efficient (see Stephan et al. 1997). Therefore, without loss of generality it is supposed that for striking an optimal balance between consumption, physical investment and greenhouse gas abatement regions follow a Ramsey path.

[4] A phase-out constraint as applied here mimics sunk-costs in the energy sector. Alternatively, inertia within the energy system can be reflected through adjustment costs or limits on the speed of adopting new technologies.

Let δ be the social discount rate, then consumption, production, investment into physical capital and greenhouse gas abatement are determined in each region r = N, S, as if a policy maker has maximized the discounted sum of the logarithm of consumption, $c_r(t)$

(3.9) $$W_r = \Sigma_t \, \delta^{-t} \ln(c_r(t)).$$

If there were no capital mobility and no investment into greenhouse gas abatement, both regions would develop independently. But if the regions agree to cooperate on greenhouse abatement, prices, supplies and demands are generated through a multi-region multi-period general equilibrium model. Solutions are obtained via Rutherford's sequential joint maximization method - a specialization of the Negishi approach (see Rutherford 1999).

4. Scenarios

Several scenarios can be created simply by combining different degrees of *when* and/or *where to abate* flexibility with different rules of how to allocate of carbon emission shares to the individual regions.

We consider three initial assignments of carbon rights (see Figure 4.1). GRAND represents the so-called grand-fathering rule. That is, shares are attributed to regions according to their fraction of the world's total emissions in the benchmark year (1990). CAP nicknames the assumption that shares smoothly move from GRAND values to an equal-man-equal-rights distribution. More precisely, in CAP the endowment of the North declines from 45% of the world's total in 2000 to a 10% share in 2050. Finally, OPTIMA is a particular distribution rule. Emission shares are determined such that marginal abatement costs are equal across regions. That is, OPTIMA assures Pareto-efficiency in greenhouse gas abatement from the scratch without the necessity of trading, banking or borrowing carbon emission rights.

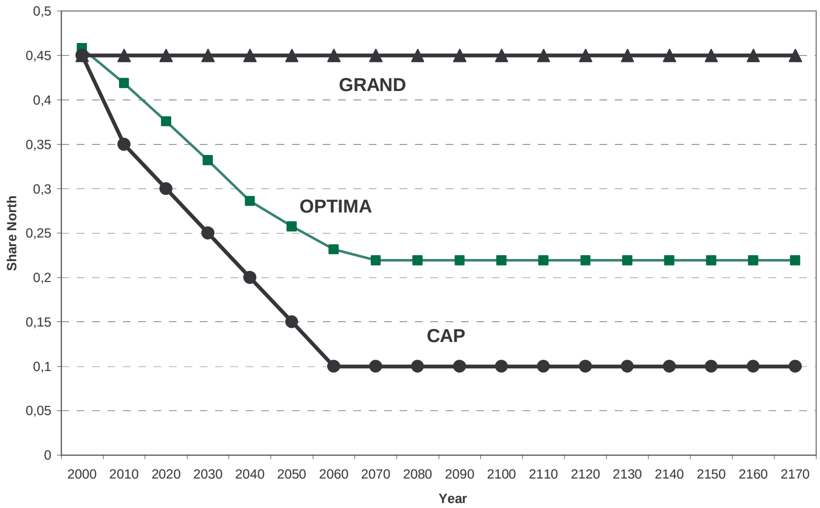


Figure 4.1: Exogenous allocation of carbon shares (North)

There are also three different flexibility regimes. FLEX allows for trading carbon rights on open international markets. BABO refers to banking and borrowing of carbon emissions, and the acronym NOF indicates that both options for creating flexibility are excluded.

Table 4.1 identifies six scenarios that differ with respect to how flexibility in greenhouse gas abatement and the initial endowment in emission shares are combined. The labeling of the different scenarios is self-explaining. For example, GRAND-BABO indicates that banking and borrowing of carbon emission rights is feasible, while emission shares initially were allocated according to the grand-fathering rule.

	WHEN FLEXIBILITY	**WHERE FLEXIBILITY**	**GRAND-FATHERING**	**PER-CAPITA**
GRAND-NOF	No	No	Yes	No
CAP-NOF	No	No	No	Yes
GRAND-FLEX	No	Yes	Yes	No
CAP-FLEX	No	Yes	No	Yes
GRAND-BABO	Yes	No	Yes	No
CAP-BABO	Yes	No	No	Yes

Table 4.1: Scenarios

The listing of scenarios in Table 4.1 needs two additional qualifications. First, the interested reader may recognize that a scenario seems missing that allows both for *when* and *where* flexibility in greenhouse gas abatement. Note, however, that – independent of the initial distribution of emission shares - trade in carbon permits will end up exactly at the regional distribution of emissions that emerges from OPTIMA. As such OPTIMA corresponds to a scenario with full flexibility, both in and over time. And it assures Pareto-efficiency by definition. This is a reason why we do not list the where-and-when flexibility scenario separately.

Second, scenarios where regions can save carbon permits but are not allowed to borrow permits are not considered here. As has been argued in Section 2 pure banking and pure borrowing policies will turn out being Pareto-inefficient. Since we focus the attention to Pareto-efficiency in greenhouse gas abatement, these scenarios are not considered in the following.

Before presenting results, let us consider how the different flexibility scenarios are implemented into our integrated assessment model. Suppose $m_r(t)$ denotes the share of carbon emission rights that is attributed exogenously to region r. Under NOF assumptions regions are authorized to consume only their own endowment. Hence, each region r has to obey

(4.1) $$m_r(t)s(t) - s_r(t) \geq 0,$$

where s(t) is the optimal global CO_2 emission target for period t. Since optimal emission targets are determined endogenously, they might vary from scenario to scenario.

International trade of carbon rights implies that the marginal cost of abatement is identical across regions (see Section 2). Consequently, compared to NOF regions should gain from implementing *where to abate* flexibility. Now, even if emission permits can freely be transferred between regions, both in GRAND-FLEX and CAP-FLEX the condition

(4.2) $[s(t) - s_N(t) - s_S(t)] \geq 0$

has to be fulfilled from period to period.[5] And since each region can generate additional income by selling carbon emission rights, it must be assured that it stays on its intertemporal budget constraint. This means, net-imports have to be financed through counter trade of carbon rights and vice versa.

With BABO regional economies may save and borrow carbon emission permits, but they are not allowed to trade them on open markets. Since we assume that carbon permits are specified non-discriminatory with respect to their date of execution, there is no re- or devaluation in terms of physical carbon units over time. Hence, each region r has to obey

(4.3) $\sum_t [m_r(t)s(t) - s_r(t)] = 0.$

At first glance it is expected that because of increased flexibility, banking and borrowing of carbon emission rights should reduce costs and positively affect welfare. However, there could be two countervailing effects. For an illustration, assume emission shares are allocated according to CAP. Abatement costs are borne early and benefits do not accrue until the distant future. Therefore, North has an incentive to borrow carbon emission rights. This might lead to what environmentalists fear - higher atmospheric carbon concentrations, hence higher ecological damages and - as a consequence - welfare losses.

Moreover, as the global climate is a public good, South is affected by the North's borrowing decision. For an optimal solution these effects have to be internalized. I.e., the South has to compensate the delay in greenhouse gas abatement by the North through increasing his abatement activities in the near-distant future. Again this can imply welfare losses, now for the southern economies.

Finally recognize that the rate of interest on carbon permits – which may be called the biological rate of interest – is endogenous in our modeling. By reason of intertemporal efficiency, it is equal to the rate of interest on physical capital.

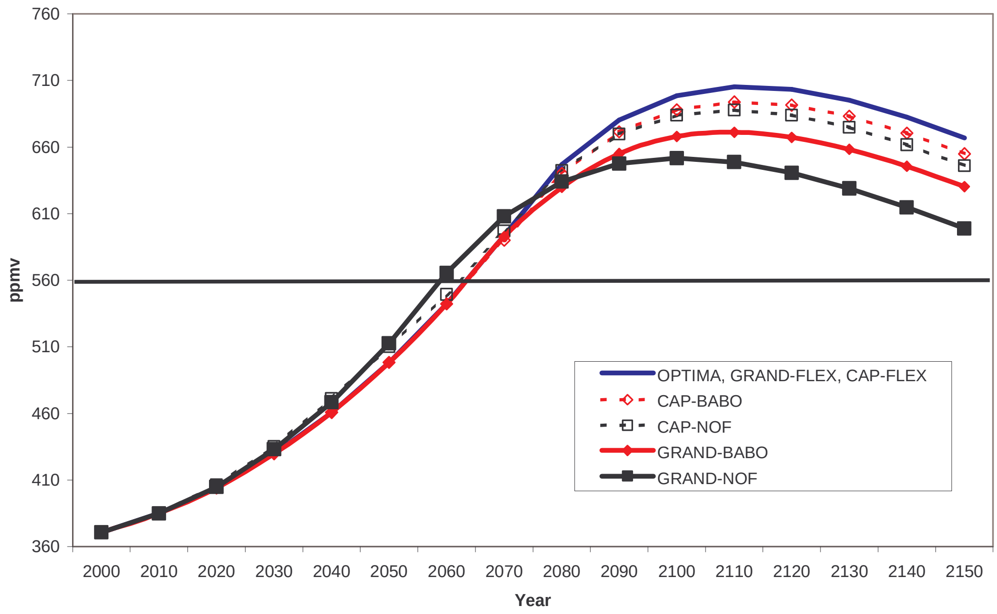
5. Numerical results

5.1 Atmospheric carbon

Does *when to abate* flexibility lead to what environmentalists fear - excessive borrowing of carbon emission permits at early periods?

[5] $s^r(t)$, r =N,S, denote the CO_2 emissions of region r in period t.

Figure 5.1: Atmospheric Carbon



The answer is neither no nor really yes (see Figure 5.1). Increasing *when* flexibility forces higher atmospheric carbon concentration. Depending upon the scenario, peak-levels vary from 660 ppm to 710 ppm. This implies market damages between 3.9% and 4.9 % GDP in the North, while the South experiences GDP-losses in the order of 7.8% to 9.8%. Of course, these are not dramatic differences, but nevertheless significant - in particular, since effects depend upon the initial distribution of carbon rights. If emission shares are distributed according to GRAND, then the differences in peak-levels between *no* flexibility (GRAND-NOF) and *when* flexibility (GRAND-BABO) are higher than under CAP distribution (compare CAP-NOF and CAP BABO). In any case however, peak-levels under GRAND are smaller than those with the CAP initial allocation of carbon emission rights (see Figure 5.1).

Our simulations reveal that *where* flexibility yields exactly the same trajectory in atmospheric carbon as OPTIMA, irrespectively to the initial allocation of carbon rights. This supports the hypothesis we have formulated in Section 2: The optimal carbon stock is independent of the initial allocation emission shares if it were feasible to trade carbon rights on open international markets. But, if *where* flexibility is absent and *when* flexibility prevails only, separability in that sense is not observed – again as expected in Section 2.

Moreover, consistent with Copeland and Taylor (2001) who employ a trade-theory approach instead of a CGE-model, *where* flexibility in greenhouse gas abatement is associated with the highest carbon levels. There are two explanations. First, we do not include non-market damages. External effects of climate change can be fully internalized by assigning carbon emissions rights, and Pareto-efficiency is assured through trade. Second, trade-induced economic growth outweighs the negative impact of higher climate damages. That is, an efficient economy may provide higher green GDP by producing more conventional output as well as higher emissions.

5.2 Regional emissions

When flexibility does not significantly affect the atmospheric accumulation of carbon, but the development of regional emissions changes notably as Figures 5.2 and 5.3 illustrate.

Figure 5.2: Carbon emissions North

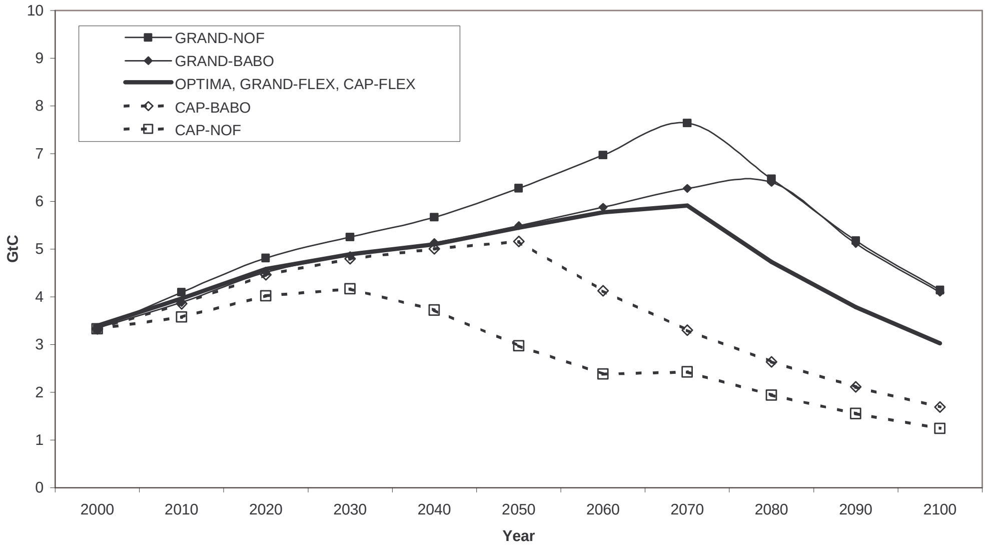
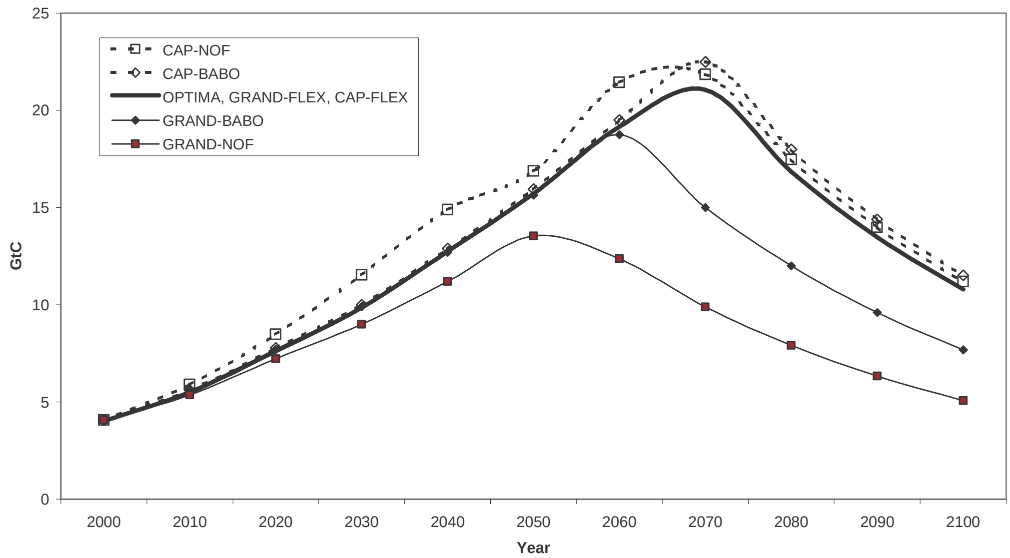


Figure 5.3: Carbon emissions South

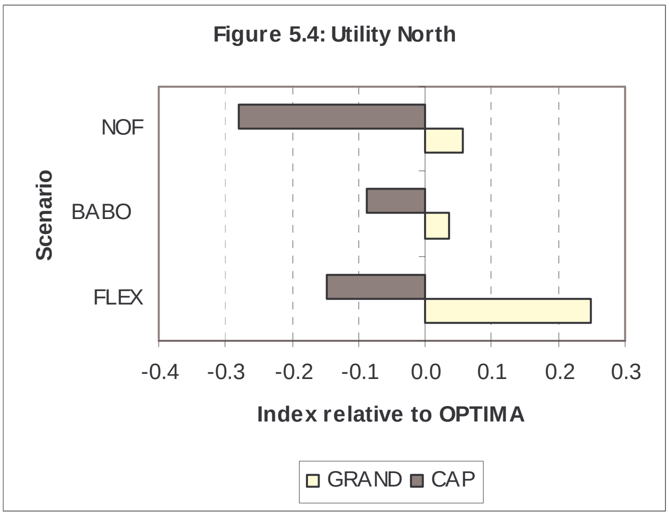


It is immediate from Figures 5.2 and 5.3 that a region's decision either to bank or to borrow carbon permits depends upon its initial endowment of carbon rights. If carbon shares are assigned according to GRAND, North uses the banking option to postpone emissions almost till the end of the century. The South, in turn, heavily borrows carbon permits, in particular during the decades after 2030. This indicates that under GRAND burning fossil fuels has a relatively high marginal value to the South, whereas the North reacts by cutting back emissions. But if carbon shares are attributed according to the CAP-rule, borrowing is favorable to North and banking to the South (see Figures 5.2 and 5.3). The argument behind this observation is the same as in GRAND with reversed roles.

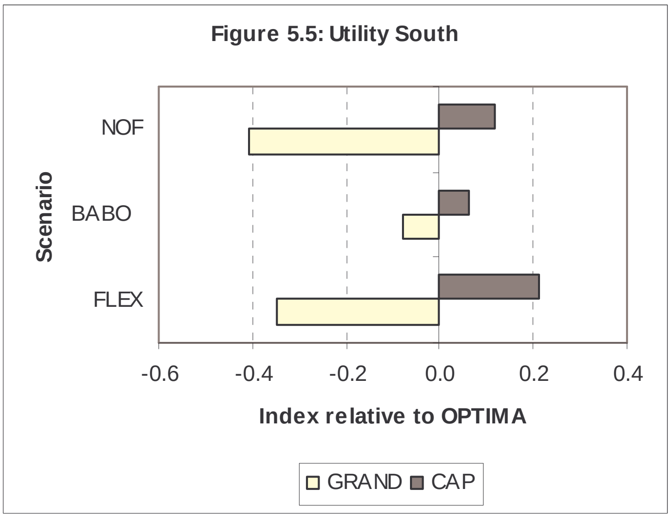
Note that independent of how emission shares are attributed, international trade of carbon emission rights leads to the same regional emission as observed in OPTIMA. And note that both under CAP and GRAND allocation rules *when* flexibility stipulates emissions to approach the OPTIMA path. Indeed, till the middle of our century OPTIMA, CAP-BABO and GRAND-BABO coincide. Moreover, the other region's banking exactly offsets one region's borrowing. This explains why differences in atmospheric carbon are so small.

5.3 Aggregated welfare

How do the different flexibility regimes and initial distribution rules affect present values of regional welfare? If expressed in percent deviations from OPTIMA values, welfare effects are extremely small (see Figures 5.4 and 5.5). Typically, they stay below the half-percent margin.



That the initial allocation of emission shares matters is unambiguous. Independent of the degree of flexibility in greenhouse gas abatement, North is best with GRAND (see Figure 5.4). Relative to OPTIMA the North gains both in the GRAND-FLEX and the GRAND-BABO scenario. If emission shares are distributed according to the CAP rule, North looses welfare relative to OPTIMA in any of the flexibility scenarios. As such, North's best choice would be the GRAND distribution - independent of the degree of intertemporal flexibility.



For the South the situation is just reversed (see Figure 5.5). If the South had a choice, in any case he would vote for CAP. Compared to OPTIMA the South suffers welfare losses both in the GRAND-BABO and the GRAND-NOF scenario, whereas it can gain in overall welfare, if emission rights are distributed according to the CAP principle.

Our analysis supports the hypothesis that introducing *where to abate* flexibility increases welfare compared to a situation where carbon emission rights cannot be traded on international competitive markets. It also indicates - just as McKibbin et al. (1999) predict – that permit trade on international markets will cause large distributional effects. And it shows that allowing for international trade in carbon emission rights is a win-win situation: As Figures 5.4 and 5.5 indicate, compared to NOF scenarios, FLEX scenarios either reduce welfare losses or increase welfare relative to OPTIMA.

Contrary to that banking and borrowing is a win-loose option. Regions with a high initial endowment of carbon emission rights are suffering from introducing *when* flexibility, whereas regions which are poorly equipped only can gain from intertemporal flexibility in greenhouse gas abatement. This is not too big a surprise. Economists' conventional wisdom tells that welfare can decrease with *when to abate* flexibility. First, an international agency that seeks to promote Pareto-efficiency by issuing permits based on flows of emissions looses control over the dating of emissions, if banking and borrowing is allowed. Second, Leiby and Rubin (2001) have shown that banking can lead to welfare losses unless carbon emission rights are traded at the correct intertemporal exchange rate. The latter is determined by the ratio of current marginal stock damages to discounted future value of marginal stock damages less the decay rate of emissions.

5.4 Per-capita consumption

Present values bear no information about the intertemporal distribution of welfare. However, since regional welfare is directly related to the logarithm of consumption (see (3.9)), per-capita consumption might be used as rough indicator for the distribution of welfare over time.

Figure 5.6: Per-capita consumption North

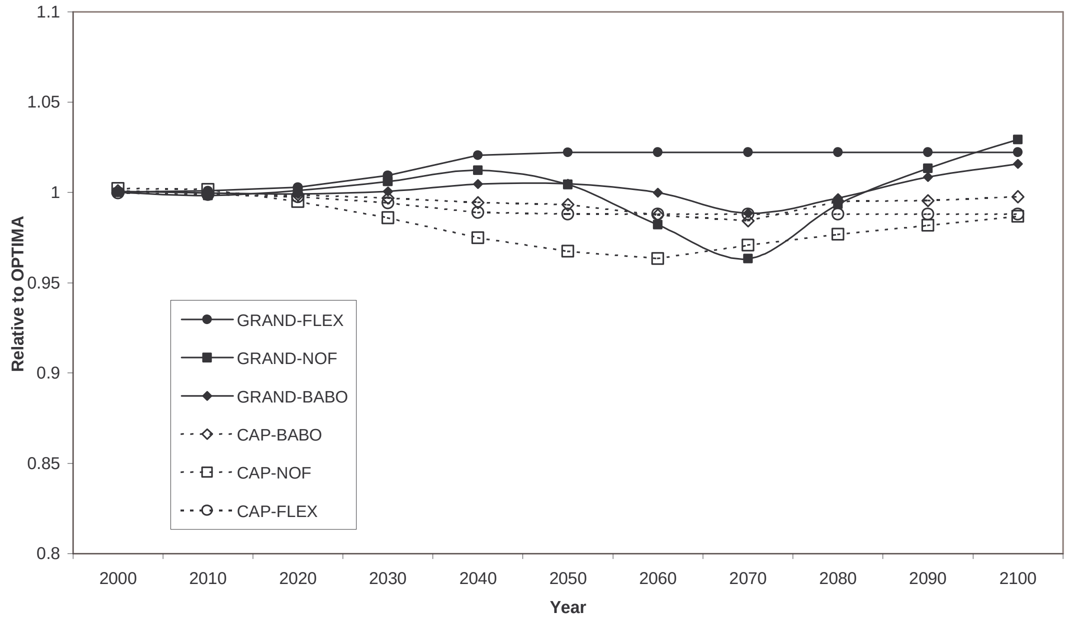
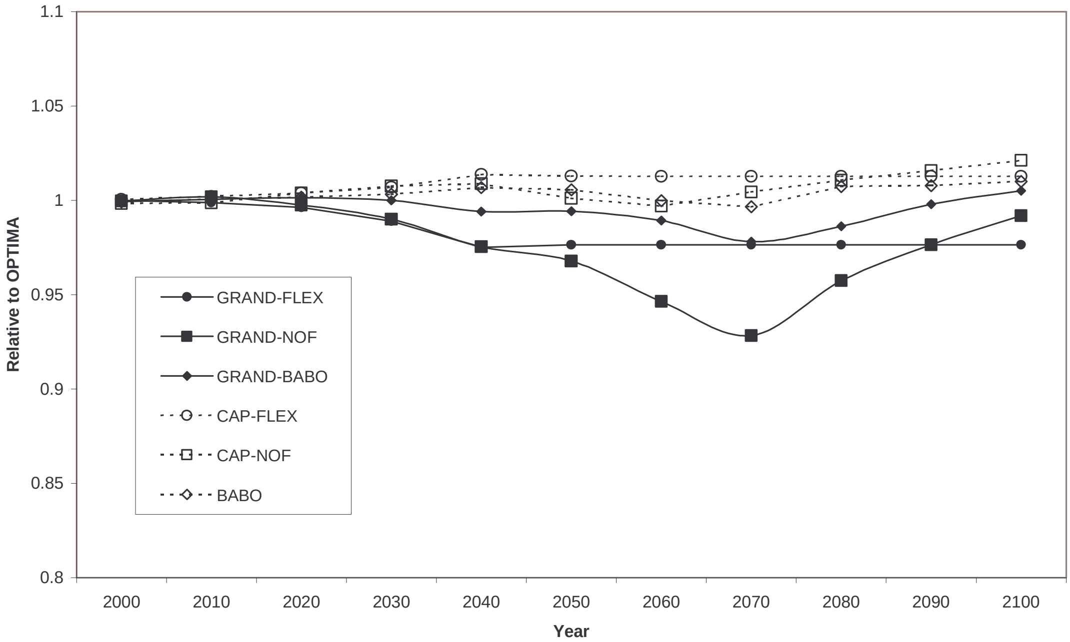


Figure 5.7: Per-capita consumption South



In Figures 5.6 and 5.7 OPTIMA is taken as reference. Per-capita consumption of all other scenarios is represented as deviation from OPTIMA values. The reasoning is that compared to other scenarios, OPTIMA exhibits the lowest intertemporal variation in per-capita consumption. From a Rawlsian perspective, OPTIMA might be regarded as inter-generational *fair*, since it is closest to constant per capita consumption.

Dashed lines represent how per-capita consumption would evolve over time, if emission shares attributed according to the CAP rule. Solid lines represent deviations in per-capita consumption from OPTIMA if the grand-fathering (GRAND) rule applies. This leads to suggestive results as Figures 5.6 and 5.7 show. Whether or not per-capita consumption streams are above OPTIMA values solely depends upon the initial allocation of carbon emission shares – with quite opposite effects in both regions.

But the degree of flexibility in greenhouse gas abatement also matters. To identify how different flexibility requiems affect welfare, let us first consider the GRAND distribution of carbon rights. In the North GRAND-FLEX clearly is the winning scenario (see Figure 5.6). The other scenarios exhibit both winner and looser generations. In the middle of the 21th century GRAND-BABO as well as GRAND-NOF make people worse compared to OPTIMA. Now, since intertemporal distribution effects are more pronounced in GRAND-NOF than in GRAND-BABO, GRAND-BABO seems favorable from the perspective of intergenerational fairness, although GRAND-NOF is superior from an overall utility.

In South (see Figure 5.7), GRAND-NOF is the loosing scenario. Compared to OPTIMA it imposes lower consumption levels for a whole century - and a trough on consumption in the middle of our century. Increasing flexibility improves per-capita consumption, although OPTIMA values are never reached.

Now let us assume that emission shares are allocated according to CAP rule. As can be seen from Figures 5.6 and 5.7, the impact of different flexibility regimes is less pronounced than it was in the GRAND distribution of shares, and the direction of the effects are just reversed. If emission shares are allocated according to CAP, then in North OPTIMA is characterized by the highest per-capita consumption. No other scenario can create higher per-capita consumption streams. The lowest deviations from OPTIMA are obtained for CAP-BABO, which comes close to OPTIMA. In the South introducing flexibility stipulates per-capita consumption. Now CAP-FLEX allows the highest consumption, whereas CAP-BABO lies between OPTIMA and CAP-FLEX values.

6. Sensitivity Analysis

So far numerical parameters have been benchmarked against data that were taken over from Nordhaus and Yang (1996), Manne et al. (1995) as well as Stephan and Müller-Fürstenberger (1998) (for details, see Appendix). This allows relating our results of Section 5 to the literature. It should be kept in mind, however, that numerical inputs into long-term models are more or less educated guesses. This motivates for sensitivity analyses with respect to the most important parameters.

	Highest Carbon Levels		Lowest Carbon Level		
Parameter	Peak Level	Scenario	Peak Level	Scenario	Spread (%)
Base Ω_r	705	OPTIMA	651	GRAND-NOF	4
Ω_r + 25	650	CAP-BABO	612	GRAND-NOF	3
Ω_r – 25	784	CAP-BABO	715	GRAND-NOF	4.6
$\Omega_r = \Omega_S$	665	OPTIMA	641	GRAND-NOF	1.8
$\Omega_r = \Omega_N$	796	OPTIMA	786	GRAND-NOF	0.6

Table 6.1: Sensitivity of atmospheric carbon with respect to Ω_r.

Welfare effects are almost invariant when key parameters such as regional climate damages, discount factors or potential GDP growth rates are altered. But projections of climate change impacts respond to parameter changes. Now, any integrated assessment model relates changes in atmospheric carbon stocks to economic losses. Obviously, Ω_r is the key parameter in such a relationship (see (3.2)). It expresses a region's perception at which CO_2 concentration its entire conventional wealth would be worthless (see Section 3.1). In Section 5 for numerical calculations Ω_N and Ω_r have been set equal to 1624 ppm and 1254 ppm, respectively. That means, South fears catastrophic climate damages, if the 1990 atmospheric CO_2 concentration is raised by factor 3.5. In the North the catastrophic level is expected to be 4.5 times higher than the actual one.

Table 6.1 reports how different numerical assumptions about the regional catastrophe levels affect the peak of atmospheric carbon concentration. To get an impression about the order of magnitude, the column *Spread* represents the percentage deviation of peak-levels from the mean taken over all scenarios. Four alternative specifications are contrasted with the numerical assumption used in Section 5: Two of them assume that North and South still have different perceptions, but at different levels: Ω_r + 25 means Ω_r is uniformly increased by 25 %, Ω_r - 25 represents a 25 % decrease of perceptions in each region. Identical catastrophe levels are supposed in the last two cases. Regional perceptions of a climate catastrophe are either that of the South (Ω_S) or the North (Ω_N), respectively.

OPTIMA is worst in terms of atmospheric carbon. However, this result is sensitive with respect to $\Omega_{r.}$ A uniform increase or decrease of Ω_r changes the ranking of scenarios with respect to peak atmospheric carbon. In case of a decrease in Ω_r, CAP-BABO induces highest climate damages. GRAND-NOF exhibits lowest atmospheric concentrations independent of the choices of the parameter. This actually supports environmentalists' hypothesis that adding flexibility increases climate damages. Note however that the spread between highest and lowest peak levels do not vary much (see Table 6.1).

Potential GDP growth is a further critical numerical input. If labor inputs are measured in efficiency units, then potential GDP growth is closely related to population growth: It represents the potential growth of a regional economy as function of population growth only. Now Section 5 employs different potential GDP growth rates for North and South (see Appendix). In the North potential GDP growth is assumed being 1.5 % uniformly, while potential growth in the South starts at a rate of 3.5 % in 2000 and drops down to 1.5 % by 2200. Alternatively one might set potential GDP growth to 3% in the South over the whole time horizon. That is – due to the long time horizon – a quite significant deviation from the original numerical assumption. It leads to a slight reduction of Pareto-efficient carbon concentration, but only by meager 0.7 per cent. And – more important - the ranking of scenarios with respect to peak carbon levels changes. *When* flexibility now exhibits slightly higher peak levels than OPTIMA, whereas lowest levels are again observed for GRAND-NOF.

Finally, let us focus on a key technology parameter - inertia within the energy supply system to phase out fossil fuels. To provide greater flexibility in adopting non-fossil fuels, maximal feasible rate of annual phase out is increased by 25 per cent. Increasing the speed of potential de-carbonization reduces the Pareto-efficient peak-level of carbon concentration by 4 %. A slightly lower reduction is observed in CAP-NOF. No effects are obtained for CAP-BABO, while peak levels are increased for the remaining scenarios.

7. Conclusions

Among economists there is almost general agreement that *where* flexibility in greenhouse gas abatement should be an integral part of an international treaty on climate policy. Our analysis supports such a viewpoint. International trade of carbon emission rights ensures efficiency in greenhouse gas abatement irrespectively to the initial allocation of carbon rights. And since the Pareto-efficient stock of atmospheric carbon is independent of the initial distribution of carbon emission shares, it is feasible to separate the issues of efficiency from that of equity.

However, *where* flexibility is not the main focus of this paper. Instead, banking and borrowing of carbon emission rights is considered as an alternative for creating flexibility in greenhouse gas abatement. Now, does w*hen* flexibility work in a similar direction as international trade of carbon rights on competitive markets does? In principle the answer is *yes*, but needs some qualifications.

In contrast to *where* flexibility w*hen to abate* flexibility does not guarantee that the optimal carbon accumulation is independent of the initial allocation of carbon rights. Different initial sharing rules clearly influence the development of atmospheric carbon concentration. Coasian separability between the initial allocation of emission shares and the optimal concentration of atmospheric carbon as mentioned does not apply, although *when* flexibility moves the development of atmospheric carbon towards the Pareto-efficient concentration - however, without full convergence.

W*here* flexibility represents a win-win situation. All regions can improve welfare through trading carbon emission rights. *When* flexibility creates a win-loose option. Regions that have a high initial endowment in carbon rights suffer from intertemporal flexibility, while regions with a small carbon budget can gain from it. Therefore, *when* flexibility is likely to counteract unequal initial distributions of carbon shares. This is consistent with our observation that *when* flexibility seems to support fairness between generations and across regions.

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Appendix

Table 1
Basic Economic Data

Data	North	South
GDP 1990 (US$ trillions)	16.3	4.5
Capital-GDP ratio	2.5	3.0
Energy consumption (Exajoules)	176	168
Elasticity of substitution energy-value added	0.2	0.35
Carbon emissions (GtC)	2.9	3.0
Economic damage due to double pre-industrial CO_2 (%)	1.5	3.5
Utility discount rate	0.03	0.03

Table 2
Potential GDP growth rates

	North	South
1990 - 2120	1.5	3.5
2130	1.5	3.25
2140	1.5	3
2150	1.5	2.75
2160	1.5	2.5
2170	1.5	2.25
2180	1.5	2
2190	1.5	1.75
2200	1.5	1.5