Constraining Equitable Allocations of Tradable Greenhouse Gases Emission Quotas by Acceptability*

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Abstract

Allocations of tradable greenhouse gases (GHG) emission quotas among countries may take place according to several sharing rules corresponding to a certain perception of equity. For instance, allocating quotas in direct proportion to population, in inverse relation to GDP or according to past emissions has been advocated. Taking a long term perspective, we compute such allocations of tradable quotas with a dynamic model developped on the basis of the RICE model (Norhaus and Yang, 1996). The total amount of quotas to be distributed in each period corresponds to the total optimal amount of emissions to be realised at each period. We observe that the 'equitable' quotas allocation rules the most often referred to are not acceptable by every country at every period: some of them would be better off by not co-operating. We then propose a mechanism which determines allocations of GHG emission quotas that satisfy as much as possible each 'equitable' allocation rule while keeping acceptability for each country.

JEL classification : C73, F42, H23, Q25, Q28

Keywords : environmental economics, climate change, dynamic games, tradable permits, equitable allocations

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1 Introduction

Anthropogenic emissions of gases such as carbon dioxide, methane or nitrous oxide have an influence on the world climate. These emissions mix uniformly and concentrate in the atmosphere, which reinforces the greenhouse effect and leads to temperature increases. This concentration of greenhouse gases (GHG) may be seen as a public 'bad' that is overprovided. One may therefore define an optimal abatement policy that specifies, through time, an optimal level of emissions (or emission reductions) for each country. This policy must satisfy the usual Samuelson condition: the marginal costs of abatement of each country must equal the sum of all countries' marginal benefits of this abatement.

A whole stream of literature has focused on 'self-enforcing' agreements, that is on agreements specifying the optimal emissions abatement level (or quotas) and side payments for each country (see for instance Barrett (1992), Carraro and Siniscalco (1993) and Chander and Tulkens (1995, 1997)). Indeed, because countries are not altruistic and because there is no supranational authority able to impose cooperation, the optimal policy may be such that a country or a group of countries is worse off with this policy. Side payments are then necessary to compensate potential losers.

The implementation of the optimal policy may take place through various instruments, among which the imposition of tradable emission quotas. In this case, an agreement has to be reached on (i) the optimal amount of emissions to be realised in the world per period of time and (ii) the distribution –among the countries– of the quotas corresponding to this optimal amount of emissions. Another stream of literature has proposed so-called 'equitable' sharing rules for this distribution of the quotas (see especially Rose et al. (1998)). According to some of them, the *outcome-based rules*, the resulting welfare (or opposite of total costs) should satisfy some properties. According to others, the *allocation-based rules*, the quotas themselves should be distributed in a certain way. Some of these rules may however lead a country or a group of countries to a level of welfare which is below the one that it would enjoy if the optimal policy was not implemented.

The aim –and the main contribution– of this paper consists in gathering the two streams of literature mentionned above by adressing the following question: in the long run, how far can we go in applying equitable sharing rules for an agreement to be self-enforcing ? We propose a mechanism in order to compute allocations of tradable quotas which are based on 'equitable' sharing rules but which are constrained by acceptability. Indeed, we assume that countries do a 'cost-benefit analysis' of their participation in an international treaty –specifying allocations of tradable quotas– and do accept to participate only if their net gain is higher than if no commitment at all were to take place ; cooperation thus requires *individual rationality*.

A short but nice review of the literature on the effects of different 'equitable' sharing rules has been made in Rose et al. (1998). They conclude that the reviewed papers (mainly Larsen and Shah (1994), Bohm and Larsen (1994), Edmonds et al. (1995), Richels et al. (1996), Rose and Stevens (1993) and Barrett (1992)) have one or severall limitations, among which (i) the choice of a set of regions which does not fully covers the globe, (ii) a too short time horizon, (iii) identical cost functions for the regions and (iv) the impossibility to model or to compute all types of sharing rules. These limitations were overcome in Rose et al. (1998). However, as the authors suggest it, their own model is not fully dynamic and ‹‹*does not incorporate benefits associated with greenhouse gases mitigation*››.

A second contribution of this paper is to adress these two further limitations. To do so, we use a closed-loop simplified version of the RICE 96 model (Nordhaus and Yang (1996)) that has been developped by Germain and van Ypersele (1999). This dynamic model allows an agreement to be negotiated by the regions at each period, while a non fully dynamic (i.e. open loop) model assumes that an agreement is established once for all. Furthermore, it incorporates explicitly *damages* (or avoided damages) caused by the global warming. This is crucial because damages may differ to a large extend accross the regions of the world ; some of them might even benefit from the global warming, which would decrease their acceptability of an agreement on GHG emissions reductions.

When we take a long term perspective, sharing rules may also vary accross time. This has for instance been advocated by Grubb (1995) or Kverndokk (1995) in the view of making more acceptable an allocation of an equal amount of quotas per head. As a third contribution, we devote some attention to the implementation of such evolutive rules. The dynamic aspect of the model is particularly relevant for such an analysis.

The structure of the paper is the following. Section 2 introduces and discusses the main so-called 'equitable' sharing rules. The closed-loop model that we use is presented in section 3. We also explain the way by which tradable quotas are introduced in the model. The results of the different sharing rules are then analysed in section 4. We check whether the most common 'equitable sharing rules' induce the cooperation of every country or not. As suggested above, cooperation is assumed to take place if it is individually rational for every country to cooperate. We find that participation constraints are strong, as no pure allocation-based equitable rule does satisfy individual rationality. In section 5, we then compute allocations of quotas that are based on 'equitable sharing rules' but constrained by participation. These 'rationally equitable' allocations show how far we can go in the application of equitable sharing rules if countries are not altruistic. Section 6 aims at analysing a particular –evolutive– sharing rule: allocating the quotas according to past emissions in a first time and progressively tending to an equal allocation per head among the countries. Finally, section 7 concludes.

2 'Equitable' sharing rules

Sharing rules need to be based on some mesurable characteristics –or criteria– of every countries. The criteria the most often referred to are population (POP), gross domestic product (GDP) and historical emissions (Eo) ([1]) (see column 1 in the following table). These criteria then allow one to design sharing 'factors' (see column 2 in the following table). They specify how the pie has to be shared, like in direct proportion of population for instance, or in an inverse weighted proportion of GDP per capita ([2]).

But what is the pie to be shared ? It may be either the total amount of emission quotas

[1] Many other criteria have been proposed, like land for instance.

[2] Note that the use of any criteria is subject to a moral hazard problem when the sharing has to take place in the future according to a rule which is designed at the present time. Indeed, if a country knows that the amount of quotas that it receives at a certain time in the future will depend on a criterion that has to be measured at that time, it has an incentive to alter the level of the criterion in order to take this effect into account. For instance, Kverndock (1995) argues that some countries may pursue (more) 'natalist' policies if they receive tradable quotas in proportion to their population. While an evalutation of the extend of this problem would require more investigations, we avoid it by specifying a reference level (*baseline*) for each of these criteria from now to 'the end of the world'.

that have been defined or the total (ecological) surplus derived from cooperation. In the former case, the notion of equity bears directly on the distribution of the property rights on a resource that has been volontarily made scarce. Sharing the fixed number of emission quotas among the countries amounts to allocating an economic good that has never been allocated before. For any sharing factor λ, such a sharing rule that specifies directly the amount of tradable quotas received by each country i will be called *allocation-based* according to Rose et al. (1998) terminology (see column 3 in the following table) ([3]).

Table 1: Sharing rules

Criteria	**Sharing factors**	**Allocation-based rules**	**Outcome-based rules**
Population	$\lambda_i = \frac{POP_i}{\sum_i POP_i}$	*Egalitarian*	*Horizontal equity: pop.*
GDP	$\lambda_i = \frac{GDP_i}{\sum_i GDP_i}$	*GDP*	*Horizontal equity: GDP*
GDP and Pop.	$\lambda_i = \frac{POP_i\left(\frac{GDP_i}{POP_i}\right)^{-\gamma}}{\sum_i POP_i\left(\frac{GDP_i}{POP_i}\right)^{-\gamma}} \quad \gamma < 1$	*Ability to pay*	*Vertical equity*
Hist. emissions	$\lambda_i = \frac{Eo_i}{\sum_i Eo_i}$	*Grandfathering*	/

In the latter case, the notion of equity bears on the distribution of the net gains provided by the agreement, that is the difference between the total welfare of the countries under cooperation to limit the emissions of GHG ([4]) and their total welfare in a non cooperative scenario. Such sharing rules that specify the net gains enjoyed by each country i will be called *outcome-based* rules (see column 4 in the preceding table). From that outcome, it is then possible to infer the corresponding allocation of tradable quotas.

Let's now turn to the set up of the dynamic model used to simulate the optimal abatement trajectories and the countries' behaviour under these various quotas sharing rules.

3 The model

3.1 Preliminaries

Consider the following model developped by Germain and van Ypersele (1999). n countries or regions indexed by $i \in N = \{1, 2, ..., n\}$ must decide on levels of CO_2 emissions abatement over some planning period $\Theta = \{1, 2, ..., T\}$ (T a positive and finite integer). At each period $t \in \Theta$, emissions of CO_2 are a proportion of country i's output Y_{it} ($i \in N$, $t \in \Theta$) which is exogenous. This proportion is determined by an exogenous emissions/output ratio ν_{it} ($i \in N$, $t \in \Theta$) and by the emissions control rate μ_{it} ($0 \leq \mu_{it} \leq 1$) chosen by country i at period t :

$$E_{it} = \nu_{it} [1 - \mu_{it}] Y_{it}. \tag{1}$$

The business as usual emissions of a country i at time t is thus given by $\nu_{it} Y_{it}$.

Wherever they are emitted, these pollutants accumulate in the atmosphere. The concentration of CO_2, M_{t+1}, with respect to its preindustrial level, M_0, writes as

$$M_{t+1} - M_0 = [1 - \delta] [M_t - M_0] + \beta \sum_{i=1}^{n} E_{it} \tag{2}$$

[3] Using Rose et al. (1998) and Rose (1992) terminology, we call 'equitable' sharing rules all the sharing rules presented below. Note furthermore that we only consider here the most common sharing rules among those envisaged by Rose et al. (1998).

[4] Given a certain allocation of the quotas.

where δ $(0 < \delta < 1)$ is the rate of decay of CO_2 in the atmosphere and β $(0 < \beta < 1)$ is the marginal atmospheric retention ratio of CO_2. This concentration modifies the radiative forcing which then influences the atmospheric temperature w.r.t. its preindustrial level, ΔT_t (the so-called 'greenhouse effect'). This effect is summarized by

$$\Delta T_t = \eta \ln \left(\frac{M_t}{M_0} \right) \tag{3}$$

where η $(0 < \eta)$ is exogenous.

Each country therefore bears two types of costs. On the one hand, the increase of the temperature causes damages to country i :

$$D_{it}(\Delta T_t) = b_{i1} \Delta T_t^{b_{i2}} Y_{it}$$

or

$$D_{it}(M_t) = b_{i1} \left(\eta \ln \left(\frac{M_t}{M_0} \right) \right)^{b_{i2}} Y_{it} \tag{4}$$

by (3), where b_{i1} and b_{i2} $(i \in N)$ are positive parameters (with $b_{i2} > 1$). On the other hand, the control of CO_2 emissions by a country $i \in N$ at a time $t \in \Theta$, through the choice of $\mu_{it} > 0$, requires the use of less polluting technologies which are more expensive. This cost is expressed by

$$C_{it}\left(E_{it}\right) = a_{i1} \left[1 - \frac{E_{it}}{\nu_{it} Y_{it}} \right]^{a_{i2}} Y_{it} \tag{5}$$

where $1 - \frac{E_{it}}{\nu_{it} Y_{it}} = \mu_{it}$ is the control rate, and where a_{i1} and a_{i2} $(i \in N)$ are positive parameters (with $a_{i2} > 1$).

Countries must therefore balance the abatement costs with the damage costs when deciding on a level of emissions. But as the emissions of a country contribute to the damages of all countries, the chosen abatement rate will be different according to whether the countries do take this externality into account or not.

3.2 The international optimum

If each country takes into account the impact of its emissions on the other countries, an international optimum is reached. Countries determine, at each period, an abatement policy that minimizes the sum of their respective discounted costs to be borne from that period until the last one, T. Formally, this optimal policy solves, *at each period of time* $t \in \Theta$:

$$\min_{\{E_s\}_{s \in \{t,\dots,T\}}} \left\{ \sum_{s=t}^{T} \sum_{i=1}^{n} \alpha^s \left[C_{is}\left(E_{is}\right) + \alpha D_{i,s+1}\left(M_{s+1}\right) \right] \right\} \tag{6}$$

subject to (1)-(5) and to $0 < E_{it} \leq \nu_{it} Y_{it}$ $\forall i \in N$, $\forall t \in \Theta$ and where α $(0 < \alpha \leq 1)$ is the discount factor. Call E_{it}^* the optimal level of emissions for country i at period t. The optimal rates of abatement at time t, μ_t^*, follows from (1) and the optimal stock of CO_2, M_t^*, at the same period is determined by (2). At each period t, the optimal policy satisfies the usual Samuelson condition for public goods :

$$C'_{i,t}\left(E_{i,t}^*\right) = -\alpha\beta \sum_{j=1}^{n} \sum_{s=t}^{T} \alpha^{s-t} \left[1 - \delta\right]^{s-t} D'_{j,s+1}\left(M_{s+1}^*\right) \tag{7}$$

that is the marginal abatement cost of every country is equal to the sum of the marginal damages across the countries and across time. Therefore, from a collective point of view, the optimum is better than any other (non-cooperative in particular) policy.

Nothing ensures however that this is also verified at the individual level. Indeed, countries being different, some of them may, at some periods, be better off at the non-cooperative equilibrium than at the optimum, so that cooperation is not profitable for those countries (at least at those periods)([5]).

3.3 Allocation of tradable quotas to sustain cooperation

Based on a theoretical work by Chander and Tulkens (1995-7) and Germain et al. (1999), Germain and van Ypersele (1999) propose for the climate change framework a system of financial compensation between countries that ensures that none of them (and even no subgroup of them) ever has an interest to deviate from the international optimum. Their mechanism of compensation is built by backward induction (starting at the last period) and is based on financial side payments. We adapt it to the context of tradable quotas.

As suggested in subsection 3.1, at every period of time t each country chooses between, on the one hand, cooperating and receiving $\widetilde{E}_{i,t}$ tradable quotas with $\sum_i \widetilde{E}_{i,t} = \sum_i E^*_{i,t}$ (signing the agreement)([6]) and, on the other hand, adopting a non-cooperative policy. We assume that the market for tradable quotas is perfectly competitive([7]) and that countries are neither allowed to borrow quotas, nor to bank some of them.

At the last decision period –period T– and in the absence of cooperation, the fall-back position of each country is supposed to be the non-cooperative Nash equilibrium. In that case, given an inherited stock M_T, it solves the following problem

$$\min_{E_{iT}} \left\{ C_{iT}\left(E_{iT}\right) + \alpha D_{i,T+1}\left(M_{T+1}\right) \right\} \tag{8}$$

subject to (1)-(5), $0 < E_{iT} \leq \nu_{iT} Y_{iT}$ and E_{jT} $(j \neq i)$ given. Call $V_{i,T}$ the resulting cost for country i of the simultaneous resolution of this problem by the n countries, $E^v_{i,T}$ the resulting emission level and $\mu^v_{i,T}$ the corresponding abatement rate.

Let $W_{i,T}$ be the cost beared by country i at time T if it was allocated an amount of quotas corresponding to its optimal level of emissions, that is

$$W_{i,T} = C_{i,T}\left(E^*_{i,T}\right) + \alpha D_{i,T+1}\left(M^*_{T+1}\right).$$

Given (7) with $t = T$, the price of the tradable quotas at period T, σ^*_T, is given by

$$\sigma^*_T = -C'_{i,T}\left(E^*_{i,T}\right) = \alpha\beta \sum_{j=1}^{n} D'_{j,T+1}\left(M^*_{T+1}\right) \;\; \forall i \in I$$

[5] The same phenomenon can occur for subsets of counties –i.e. coalitions– in the sense that, by limiting cooperation to such coalitions, the members of the latter could be better off than at the international optimum.

[6] We may then wonder whether it is realistic or not to impose negative quotas for any country. If a country was allocated negative quotas, it would have to buy quotas on the market even if s/he plans not to emit at all. We could therefore add the following condition for outcome-based rules :

$$\widetilde{E}_{i,t} \geq 0 \;\; \forall i, t.$$

We do not incorporate this constraint in the model; we will rather check it ex-post.

[7] It is a reasonable assumption as long as countries translate their quotas into domestic permits and allocate these to their private sector.

Indeed, because the market for quotas is perfectly competitive, every country chooses to abate (and to buy or to sell quotas according to their level of abatement) such that its marginal cost of abatement (the opportunity cost of buying or the opportunity gain of selling a quota) equals the price of the quotas.

Given the sharing rule that is being used for the quotas allocation $\left\{\widetilde{E}_{1,T},...,\widetilde{E}_{n,T}\right\}$ which is such that $\sum_i \widetilde{E}_{i,T}=\sum_i E^*_{i,T}$, the total cost of cooperating at period T for country i is thus:

$$\begin{aligned}\widetilde{W}_{i,T} &= C_{i,T}\left(E^*_{i,T}\right)+\alpha D_{i,T+1}\left(M^*_{T+1}\right)+\sigma^*_T\left[E^*_{i,T}-\widetilde{E}_{i,T}\right] \\ &= W_{i,T}+\sigma^*_T\left[E^*_{i,T}-\widetilde{E}_{i,T}\right].\end{aligned} \tag{9}$$

Following Germain and van Ypersele (1999), we choose the $\widetilde{E}_{i,T}$ in such a way that international cooperation –with tradable quotas– is individually rational for all countries, i.e. such that each country enjoys lower costs than at its fall-back position, the non-cooperative equilibrium. Formally, the $\widetilde{E}_{i,T}$ are such that ([8])

$$V_{i,T}\geq\widetilde{W}_{i,T}=W_{i,T}+\sigma^*_T\left[E^*_{i,T}-\widetilde{E}_{i,T}\right],\quad \forall i\in N. \tag{10}$$

We then make the following assumptions: (i) thanks to the allocation of quotas that guarantees that (10) is satisfied, countries will sign the agreement in period T; (ii) this cooperation in period T is perfectly anticipated in the preceding periods.

The same reasoning is then applied for the preceding periods : at each period, the countries face the same alternative of whether to cooperate or not, knowing that they will cooperate in the future thanks to allocations of quotas that make cooperation individually rational.

Formally, if each country cooperates at period t knowing that cooperation will also take place at the subsequent periods, country i bears the following total optimal cost with quotas :

$$\widetilde{W}_{i,t}=C_{i,t}\left(E^*_{i,t}\right)+\alpha D_{i,t+1}\left(M^*_{t+1}\right)+\sigma_t\left[E^*_{i,t}-\widetilde{E}_{i,t}\right]+\alpha\widetilde{W}_{i,t+1} \tag{11}$$

where $E^*_{i,t}$ is given by the resolution of the optimal problem (6) at period t, $\widetilde{E}_{i,t}$ is the amount of quotas distributed to country i at time t and the price of the tradable quotas at time t, σ^*_t, is given by:

$$\sigma^*_t=\alpha\beta\sum_{j=1}^{n}\sum_{s=t}^{T}\alpha^{s-t}\left[1-\delta\right]^{s-t}D'_{j,s+1}\left(M^*_{s+1}\right). \tag{12}$$

This optimal total cost is composed of the current costs, including the costs of the net purchase of quotas, and of the future costs, including the costs of the future net purchase of quotas.

If, on the other hand, they behave non-cooperatively at time t, each country calculates the following value function:

$$V_{it}(M_t)=\min_{\{E_{it}\}}\left\{\left[C_{it}\left(E_{it}\right)+\alpha D_{i,t+1}\left(M_{t+1}\right)\right]+\alpha\widetilde{W}_{i,t+1}(M_{t+1})\right\} \tag{13}$$

subject to (1)-(5), $0<E_{it}\leq\nu_{it}Y_{it}$, E_{jt} $(j\neq i)$ given and where $\widetilde{W}_{i,t+1}$ is defined following (11). The simultaneous resolution of the n problems (13) leads to what is called –by Germain and van Ypersele (1999)– the *fallback non-cooperative equilibrium* at period t.

[8] Allocating the quotas $\widetilde{E}_{i,T}$ such that (10) holds is indeed possible because the international optimum is collectively preferable to the Nash equilibrium –there is an ecological surplus–, so that $\sum_i V_{i,T}\geq\sum_i W_{i,T}$ with $\sum_i W_{i,T}=\sum_i \widetilde{W}_{i,T}$ by $\sum_i E^*_{i,T}=\sum_i \widetilde{E}_{i,T}$.

The quotas $\widetilde{E}_{i,t}$ are chosen such that cooperation is induced at period t, that is $\widetilde{E}_{i,t}$ satisfies $\widetilde{W}_{i,t} \leq V_{i,t}$ $\forall i \in N$, $\forall t \in \Theta$ with $\sum_{i=1}^{n} \widetilde{E}_{i,t} = \sum_{i=1}^{n} E_{i,t}^{*}$.

Because $\widetilde{W}_{i,t} \leq V_{i,t}$ $\forall i$, we again assume (as at period T) that countries will indeed cooperate in period t and that this is perfectly anticipated in the preceeding periods. Cooperation then extends to all periods by backward induction.

3.4 Evolutive sharing rules

Note that it is also possible to determine rules which are based on different sharing factors themselves based on different criteria. For instance, half of the ecological surplus could be allocated in direct proportion to the GDP (horizontal equity: GDP, see table 1), while the other half would be allocated according to the population (horizontal equity: pop., see table 1). Severall rules of this kind have been proposed during the negotiation of the Kyoto quotas allocation (see Ringus et al., 1998). Such mixed sharing rules will be called *evolutive* sharing rules whenever they are characterized by a progressive switch from one rule to another through time.

The dynamic aspect of our model makes the study of 'evolutive sharing rules' particularly relevant. Consider any two sharing rules A and B leading to allocations $\left\{\widetilde{E}_{1,t}^{A}, ..., \widetilde{E}_{n,t}^{A}\right\}$ and $\left\{\widetilde{E}_{1,t}^{B}, ..., \widetilde{E}_{n,t}^{B}\right\}$ with $\sum_{i=1}^{n} \widetilde{E}_{i,t}^{A} = \sum_{i=1}^{n} \widetilde{E}_{i,t}^{B} = \sum_{i=1}^{n} E_{i,t}^{*}$ at period t, as well as parameter π_t with $0 \leq \pi_t \leq 1$ $\forall t \in \Theta$. If we use a mixed or an evolutive criterion based on these sharing rules, (11) rewrites as:

$$\widetilde{W}_{i,t} = C_{i,t}\left(E_{i,t}^{*}\right) + \alpha D_{i,t+1}\left(M_{t+1}^{*}\right) + \pi_t \sigma_t^{*}\left[E_{i,t}^{*} - \widetilde{E}_{i,t}^{A}\right] + \left[1-\pi_t\right]\sigma_t^{*}\left[E_{i,t}^{*} - \widetilde{E}_{i,t}^{B}\right] + \alpha \widetilde{W}_{i,t+1}$$

for $t \neq T$ with $\pi_t = \pi$ for a mixed sharing rule and with $\pi_t = 1 - \left(\frac{t-1}{T-1}\right)^{\varphi}$, $\varphi > 0$ for an evolutive sharing rule.

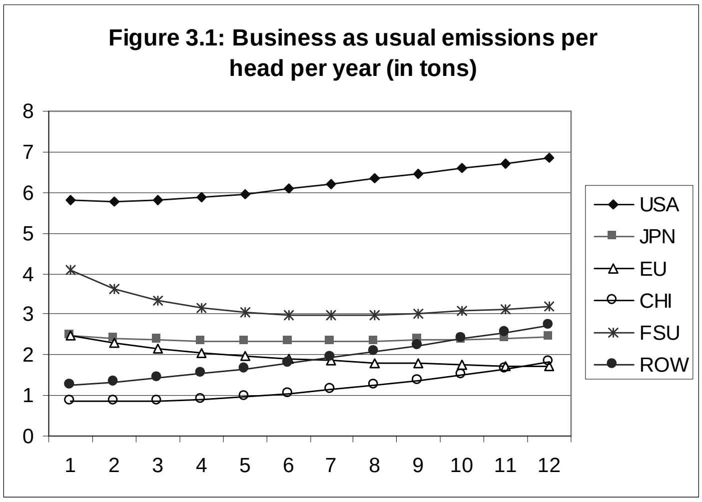
3.5 Data

Data are based on the RICE model (Nordhaus and Yang, 1996). The world is divided into six regions, namely (1) USA, (2) Japan, (3) European Union (EU), (4) China, (5) Former Soviet Union (FSU) and (6) Rest of the World (ROW). Time is divided in periods of ten years, the first one being decade 1991-2000. The annual discount rate is chosen to be .01 ([9]).

The 'business as usual' annual emissions per head ($\nu_{it} Y_{it}/POP_{it}$) are plotted in figure 3.1 ([10]). One must note that USA emits and is expected to keep emitting an amount of GHG which is, per head, more than two times higher than the one in all other regions (except FSU during the first decades). In these other regions, the CO_2 emissions per head converge more or less to a level which ranges from 1.5 to 3 tons in 2100.

[9] Nordhaus and Yang (1996) however choose a higher discount rate (.03). For a discussion on discouting, see Arrow et al. (1996).

[10] The initial output and emissions data are respectively
$\mathbf{Y}_{1990}$ = [5464.796, 2932.055, 6828.042, 370.024, 855.207, 4628.621] and
$\mathbf{E}_{1990}$ = [1.37, .292, .872, .805, 1.066, 3.43].
The output and emissions growth rates are taken from a model under development at CORE and which is based on the RICE'98 model (Nordhaus and Boyer, 1998).



The preindustrial level of the CO_2 atmospheric stock M_0 is equal to 590 billion tons of carbon equivalent. The rate of decay of CO_2 in the atmosphere, δ, is equal to 0.0833 per decade, while the marginal atmospheric retention ratio of CO_2, β, is equal to 0.64. Parameter η is equal to $2.5/\ln(2)$; it is calibrated in such a way that a doubling of the CO_2 atmospheric concentration results in an increase of global temperature of 2.5 degrees Celsius with respect to its preindustrial level.

Parameters characterizing damage and abatement cost functions (4) and (5) are given in the following table ([11]) :

i	USA	JAP	EU	CHI	FSU	ROW
a_{i1}	.07	.05	.05	.15	.15	.1
a_{i2}	2.887	2.887	2.887	2.887	2.887	2.887
b_{i1}	.01102	.01174	.01174	.015523	.00857	.02093
b_{i2}	1.5	1.5	1.5	1.5	1.5	1.5

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4 Results

For each of the sharing rules decribed in section 2, the model is run assuming a time horizon of 310 years. Results are however shown only for the first twelve to fourteen decades in order to avoid boundary problems ([12]).

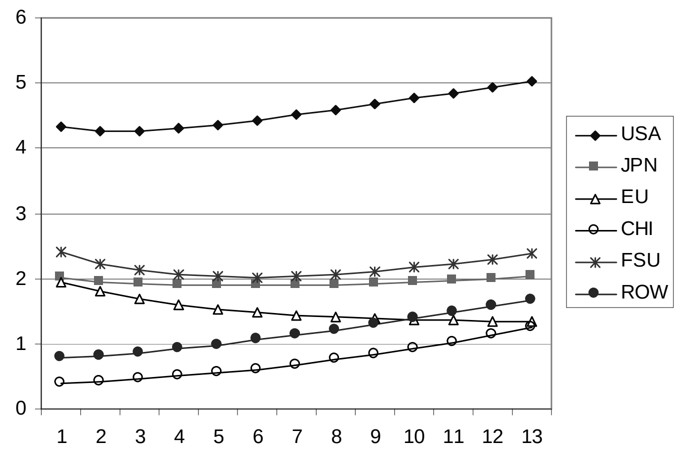
4.1 The optimal path

The optimal average annual emissions per head (E^*_{it}/POP_{it}) are shown in figure 4.1. The trends closely follow the business as usual emissions trends. We note that US has an optimal level of emissions per head that is twice higher than those of JPN, EU and FSU. On the contrary, ROW and CHI have a very low optimal level of emissions per head, which however doubles after 100 years.

[11] For more details, see Nordhaus and Yang (1996), pp. 744-745.

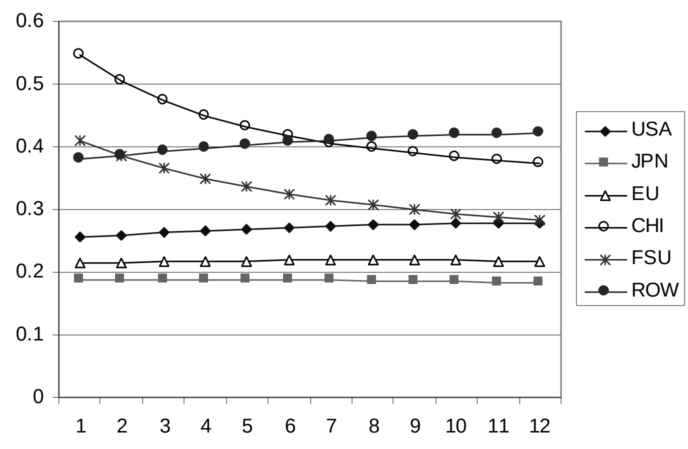
[12] We refer the interested reader to Germain et al. (1999) for a description of the algorithm used. All computations were made with the MATLAB software.

Figure 4.1: Optimal emissions per head per year (in tons)



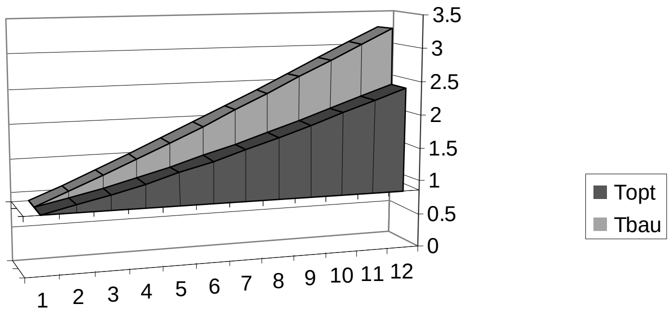
Through equation (1), the corresponding optimal abatement rates (μ_{it}^*) are presented in figure 4.2. These are such that the marginal abatement costs are equalized accross regions. They are lowest for the most industrialised regions and stay at a relatively high level for CHI and ROW, who pollute less but are characterized by a much higher emissions/output ratio (ν_{it}).

Figure 4.2: Optimal emissions abatement rates (%)



In figure 4.3, the optimal temperature increase, caused by the accumulation of the emissions, is then compared to the 'business as usual' (BAU) temperature increase. The latter lies in the average of IPCC's BAU temperature increase projections. The optimal temperature decrease –with respect to the BAU temperature– is of around $0.75°C$ at the beginning of the next century. This is larger than the $0.25°C$ and $0.20°C$ decreases in, respectively, Nordhaus and Yang (1996) and Nordhaus and Boyer (1999), but close to the $0.80°C$ decrease found by Eyckmans and Tulkens (1999).

Figure 4.3: Optimal and BAU temperature increase (in °C)



	1	2	3	4	5	6	7	8	9	10	11	12
Topt	0.865	0.973	1.088	1.211	1.342	1.48	1.625	1.776	1.931	2.09	2.251	2.413
Tbau	0.865	1.066	1.269	1.476	1.689	1.907	2.129	2.355	2.582	2.81	3.036	3.26

4.2 Are equitable sharing rules acceptable ?

In this section, we provisionally assume ex-ante that the allocation of quotas according to the different sharing rules induce cooperation and we check ex-post whether individual rationality is satisfied or not.

Note that once the optimal abatement policy (optimal amount of emissions per period) has been computed, each of the four *allocation-based* sharing rules directly determines the quotas to be received by each region. Indeed, neither the optimal policy, nor these sharing rules, do depend on the non-cooperative fallback equilibrium. On the contrary, the allocation of quotas according to each of the three *outcome-based* sharing rules does, by definition, depends on the fallback equilibrium, which is itself influenced by the subsequent allocations of quotas.

Because the sharing factors are all positive, every outcome-based equitable sharing rule leads to an increase of every country's welfare above the one it would enjoy if no agreement was reached. Thus, by definition,

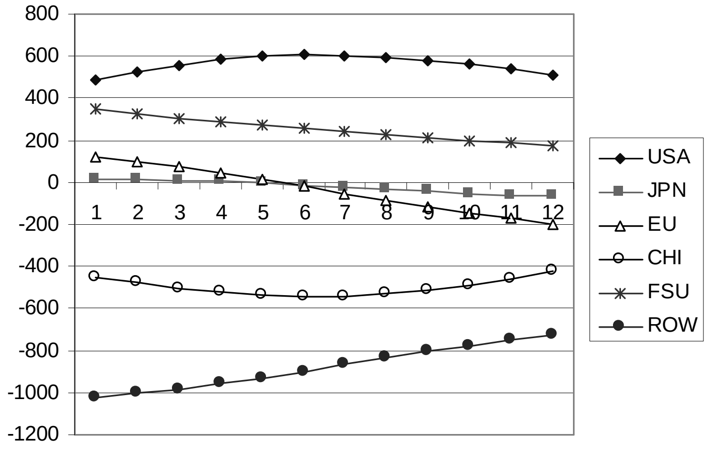
Claim 1 *Every* ***outcome-based*** *sharing rule is individually rational.*

However, simulations show that

Claim 2 *None of the* ***allocation-based*** *sharing rules satisfies individual rationality.*

Look for instance at the egalitarian sharing rule, assuming that all the regions cooperate even if it is not rational for some of them to do so. In figure 4.4, the variation of total costs due to cooperation –assuming cooperation of all the regions at every period, that is $\left[\widetilde{W}_{i,t} - V_{i,t}\right]$– are plotted for every region. Some of them are made worse off with respect to the reference equilibium, at least for some periods. Indeed, US and FSU would clearly lose very much by cooperating, while ROW and China would gain much in terms of saved damages and by selling quotas (their optimal level of emissions being below the amount of quotas that they have been allocated, as opposed to USA and FSU). EU and Japan would lose during the first five decades and start to gain afterwards. Thus an agreement based on an egalitarian sharing rule will not be accepted by every region at every period.

Figure 4.4: Egalitarian : variation of total costs due to cooperation (in billion 1990 US$)



The same kind of analysis can be done for the three other allocation-based sharing rules. As expected, the *GDP* sharing rule would clearly provide a decrease of total costs due to cooperation for US, JPN and EU and an increase of those costs for CHI, FSU and ROW. The ability to pay (*ATP*) sharing rule (with $\gamma = .5$) gives results that are more similar to those obtained with the Egalitarian sharing rule (US and FSU losing; ROW and CHI gaining) but where EU and JPN would gain from cooperation only after the twelfth period. Finally, if the *Grandfathering* rule is used (with 1990 as the reference year), it would not be rational for US and FSU to cooperate during the first period, while it would be rational for them to do so afterwards. ROW would gain by cooperating during the three first periods but would lose very much from the fourth period onwards. Although CHI would also lose from cooperation after 80 years, JPN and EU would always enjoy a decrease of their total costs due to cooperation.

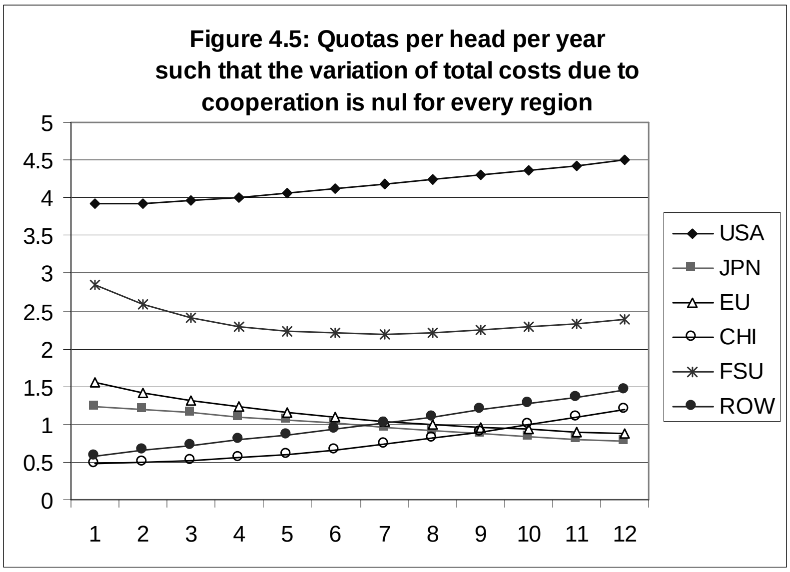
4.3 Cooperation surplus: what is the degree of freedom for allocating the quotas ?

What is the minimal amount of tradable quotas that each region requires for the agreement to be acceptable ? One may design an allocation of quotas such that, at every period, each region is exactly as well off as under no cooperation, that is such that the variation of their total costs due to cooperation is nul ([13]). The resulting quotas distributed per head and per year are shown in figure 4.5.

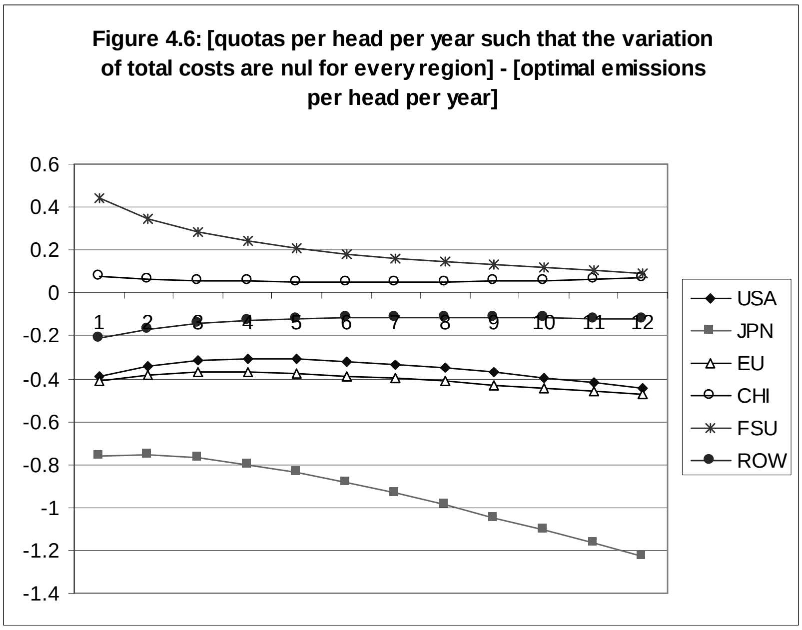
[13] In doing this, we consider that the price of the quotas is not determined by the amount of quotas distributed to the regions, but well by the total amount of quotas that have been defined at each period and which corresponds to the sum of each country's optimal emissions at each period. That is, the quotas not distributed to the regions are not wasted but given to a non-participating agent –an international environmental agency for instance– who supplies them inelastically on the international market. It is done by choosing $\widetilde{\widetilde{E}}_{i,t}$ such that $\widetilde{\widetilde{\widetilde{W}}}_{it} = W_{it} + \sigma_t \left[E^*_{i,t} - \widetilde{\widetilde{E}}_{i,t}\right] = V_{it}\ \forall i \in N,\ \forall t \in \Theta$, that is:

$$\widetilde{\widetilde{E}}_{i,t} = E^*_{i,t} + \frac{W_{it} - V_{it}}{\sigma_t}$$

where σ_t is defined by (12) if and only if the total amount of non distributed quotas $\sum_{i=1}^n E^*_{i,t} - \sum_{i=1}^n \widetilde{\widetilde{E}}_{i,t} = -\sum_{i=1}^n \frac{W_{it} - V_{it}}{\sigma_t}$ has been inelastically supplied on the market.



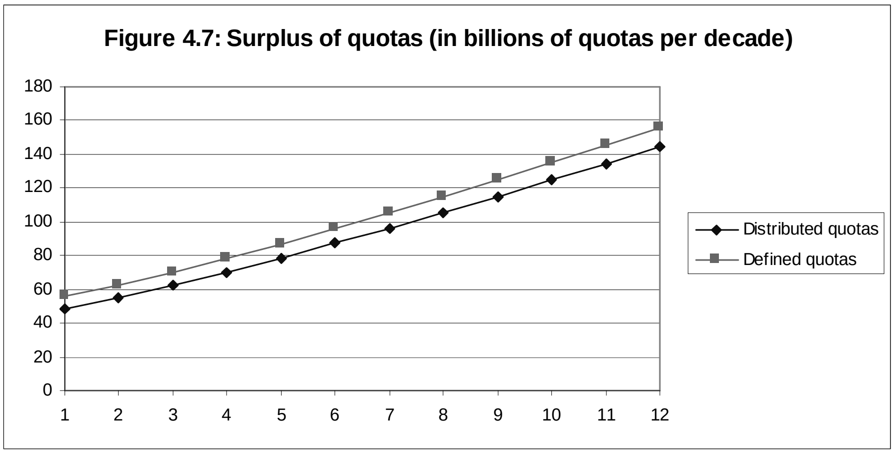
They can be compared to the optimal annual emissions per head. This comparison (see figure 4.6) reveals that CHI and especially FSU need to receive more quotas than those required to cover their optimal level of emissions. They need to be compensated for adopting the optimal cooperative policy. But this compensation does not involve any so-called 'hot air' as no region needs to receive more quotas than its business-as-usual amount of emissions ([14]).



Because, at each period, the non cooperative equilibrium is dominated by the international optimum, we know that not all the defined quotas need to be distributed to the regions in order to make all of them indifferent between cooperating and not cooperating. There is then a certain amount of quotas left. This surplus of quotas is illustrated in figure 4.7 by the difference between the total amount of defined quotas –which corresponds to the total

[14] By comparison of figures 3.1 and 4.5.

optimal amount of emissions at each period– and the total amount of quotas that must be distributed to the regions in order to make each of them indifferent between cooperating and not cooperating([15]).



The value of these quotas –i.e. their amount multiplied by their price– may be interpreted as the total gains (the ecological surplus) derived from cooperation. The *discounted* value of this surplus, which also corresponds to $\sum_i V_{it} - \sum_i W_{it}$, is given in the following table (in billions 1990 US$) :

Period	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Discounted surplus	508	516	534	557	582	609	635	659	680	697	709	716

It may seem surprising to note that the discounted value increases although the total surplus of quotas is relatively constant across time. It is due to a significant increase of the price of the quotas through time, which reflects the increase of the marginal abatement costs and of the marginal damages following the temperature variations.

5 Building equitable sharing rules constrained by acceptability

We now turn to our main concern : how to make equitable allocations of quotas acceptable? We propose a method which allows to compute allocations of quotas that are acceptable while taking as much as possible into account any equitable sharing rule. This method is applied to allocation-based sharing rules –the outcome-based rules being individually rational by definition.

5.1 The intuition

If an allocation-based sharing rule leads to an outcome such that it is not rational for some regions to cooperate, let's give to those regions the amount of quotas that will leave them

[15] The surplus of quotas approximates the degree of freedom for allocating quotas to the regions above the levels (per head) shown in figure 4.5. Except for the very last period, it is only an approximation because the costs at the non cooperative fallback equilibrium V_{it} differ slightly according to which rule is being used for sharing the quotas at the subsequent periods (where cooperation is assumed to take place).

indifferent between cooperating and not cooperating, and let's redistribute the rest of the quotas to the other regions *according to the initial sharing rule*. Some of the regions that were firstly induced to cooperate may not be willing to do so anymore because, by necessarily receiving fewer quotas than previously, they may now lose from cooperation. Those are then also just compensated in order to be induced to cooperate, and so on until every region enjoys non negative net gains.

5.2 The method : looking for 'close' allocations of quotas

Let's distribute the quotas according to a certain allocation-based sharing rule. If, given the computed outcome, it is not rational for some countries to cooperate, the method consists in finding another allocation of the quotas which (i) is feasible, (ii) satisfies individual rationality for every region and (iii) is as close as possible to the initial one in the sense of the sharing rule that has been used. That is, the notion of distance between the initial allocation and the new one –i.e. between the initial outcome and the new one– takes the sharing rule into account.

Recall that $\widetilde{E}_{it}$ is the amount of quotas received by country i at time t according to the chosen sharing rule and that $\widetilde{W}_{it}$ is the cost beared by the same country at the same time when every country cooperates at this period as at every subsequent period. Consider $\widehat{E}_{it}$ as an alternative allocation of quotas to country i at time t. Formally, the method consists in solving, at each period t:

$$\min_{\{\widehat{E}_{it}\}} \sum_i \frac{\left[\widehat{E}_{it} - \widetilde{E}_{it}\right]^2}{\lambda_{it}} \tag{14}$$

where λ_{it} ($\sum_i \lambda_{it} = 1 \ \forall t$) is the sharing factor used in the sharing rule, subject to the feasibility constraint ([16])

$$\sum_i \widehat{E}_{it} = \sum_i \widetilde{E}_{it} \tag{15}$$

and the individual rationality constraints

$$\widehat{W}_{it} \leq V_{it}, \quad \forall i. \tag{16}$$

where $\widehat{W}_{it}$ is given by

$$\widehat{W}_{it} = \widetilde{W}_{it} + \sigma_t^* \left[\widetilde{E}_{it} - \widehat{E}_{it}\right] \tag{17}$$

and where σ_t^* is the price of the quotas at time t. The aim of the method is thus to minimize the deviation from the sharing rule in order to satisfy the participation constraint. The dynamic (backwards) resolution of the optimal and fallback equilibrium scenarios must then consider $\widehat{W}_{it}$ –and not $\widetilde{W}_{it}$– as the future costs of cooperation at each period.

The langrangian of problem (14) writes

$$L_t = \sum_i \frac{\left[\widehat{E}_{it} - \widetilde{E}_{it}\right]^2}{\lambda_{it}} + \mu_t \sum_i \left[\widehat{E}_{it} - \widetilde{E}_{it}\right] + \sum_i \pi_{it} \left[\widetilde{W}_{it} + \sigma_t^* \left[\widetilde{E}_{it} - \widehat{E}_{it}\right] - V_{it}\right]$$

where μ_t is the multiplier associated to constraint (15) and π_{it} are the multipliers associated

[16] With $\sum_i \widetilde{E}_{i,t} = \sum_i E^*_{i,t}$.

to constraints (16). The Kuhn-Tucker conditions of this problem are

$$\frac{\partial L_t}{\partial \widehat{E}_{it}} = \frac{2\left[\widehat{E}_{it}-\widetilde{E}_{it}\right]}{\lambda_{it}} - \mu_t - \sigma_t^* \pi_{it} = 0, \quad \forall i, \tag{18}$$

$$\frac{\partial L_t}{\partial \mu_t} = \sum_i \widehat{E}_{it} - \sum_i \widetilde{E}_{it} = 0, \tag{19}$$

$$\frac{\partial L_t}{\partial \pi_{it}} = \widetilde{W}_{it} + \sigma_t^* \left[\widetilde{E}_{it}-\widehat{E}_{it}\right] - V_{it} \leq 0, \quad \pi_{it} \geq 0 \text{ and } \pi_{it}\left[\widetilde{W}_{it} + \sigma_t^* \left[\widetilde{E}_{it}-\widehat{E}_{it}\right] - V_{it}\right] = 0, \quad \forall i. \tag{20}$$

Let I ($I \subset N$ and $N \backslash I \neq \emptyset$) be the set of regions whose participation constraint is not binding. Thus $\pi_{it} = 0 \ \forall i \in I$ and these regions contribute to the compensation of the other regions according to the (initial) sharing rule. Indeed, (18) then leads to

$$\frac{\left[\widehat{E}_{it}-\widetilde{E}_{it}\right]}{\lambda_{it}} = -\frac{\mu_t}{2}, \quad \forall i \in I, \tag{21}$$

with $\widehat{E}_{it} < \widetilde{E}_{it}$ as $\lambda_{it} > 0 \ \forall i$ and as $\mu_t > 0$ by combining (18) and (19). Note that this also gives $\widehat{W}_{it} \leq V_{it} \ \forall i \in I$ form (17) and (20).

The initial equitable sharing rule is then preserved *among the compensating regions*. Indeed, for *allocation-based sharing rules*, allocations of quotas are (initially) such that $\frac{\widetilde{E}_{it}}{\lambda_{it}} = \frac{\widetilde{E}_{jt}}{\lambda_{jt}}$, $\forall i \neq j$ ([17]). By (21), that is $\frac{\widehat{E}_{it}}{\lambda_{it}} = \frac{\widetilde{E}_{it}}{\lambda_{it}} - \frac{\mu_t}{2}$, $\forall i \in I$, the new allocation of quotas is thus also such that $\frac{\widehat{E}_{it}}{\lambda_{it}} = \frac{\widehat{E}_{jt}}{\lambda_{jt}}$, $\forall i, j \in I$, $i \neq j$ (that is only among the compensating regions).

On the other hand, $\widetilde{W}_{it} > V_{it}$ and $\widetilde{W}_{it} + \sigma_t^* \left[\widetilde{E}_{it}-\widehat{E}_{it}\right] - V_{it} = 0 \ \forall i \notin I$, which leads to $\widehat{E}_{it} > \widetilde{E}_{it} \ \forall i \notin I$. Thus

$$\frac{\left[\widehat{E}_{it}-\widetilde{E}_{it}\right]}{\lambda_{it}} = \frac{[\pi_{it}\sigma_t^* - \mu_t]}{2}, \quad \forall i \notin I, \tag{22}$$

with $\pi_{it}\sigma_t^* > \mu_t$. The initial equitable sharing rule is therefore not necessarily preserved among the compensated regions ([18]).

Thus, to summarize :

$$\forall i \in I: \quad \widehat{E}_{it} < \widetilde{E}_{it} \quad \text{and} \quad \widehat{W}_{it} \leq V_{it} \quad \text{with} \quad \frac{\widehat{E}_{it}}{\lambda_{it}} = \frac{\widehat{E}_{jt}}{\lambda_{jt}}, \forall i, j \in I, i \neq j$$

$$\forall i \notin I: \quad \widehat{E}_{it} > \widetilde{E}_{it} \quad \text{and} \quad \widehat{W}_{it} = V_{it} \quad \text{with} \quad \frac{\widehat{E}_{it}}{\lambda_{it}} \gtreqless \frac{\widehat{E}_{jt}}{\lambda_{jt}}, \forall i, j \notin I, i \neq j.$$

Applying this method to a simple sharing rule like the egalitarian rule gives more insights on its purpose. This is done in the next subsection.

[17] According to any allocation-based sharing rule, each country i receives $\widetilde{E}_{it} = \lambda_{it} \sum_{j=1}^{n} E_{jt}^*$ quotas at period t.

[18] Note that by conditions (21) and (22), the feasibility constraint (15) may be rewritten as

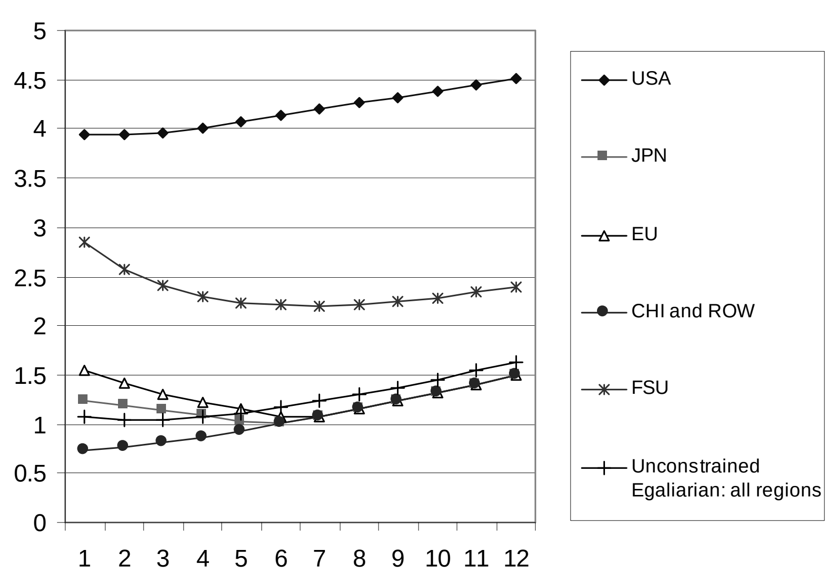
$$\sum_{\forall i \in I} \lambda_{it}\mu_t = \sum_{i \notin I} \lambda_{it}\left[\pi_{it}\sigma_t^* - \mu_t\right]$$

that is the amount of quotas given to the compensated regions equals the amount of quotas taken from the compensating ones.

5.3 Results : illustration for the egalitarian rule

Recall that the egalitarian sharing rule amounts to allocate $\widetilde{E}_{it} = \lambda_{it} \sum_i E^*_{it}$ quotas $\forall i, t$ with $\lambda_{it} = POP_{it} / \sum_i POP_{it}$. Constraining this sharing rule by individual rationality leads to an allocation of quotas per head which is very different from the unconstrained egalitarian one (see figure 5.1). Indeed, the latter leads by definition to the same amount of quotas per head in each region (in figure 5.1, see Unconstrained Egalitarian: all regions) while especially FSU and US receive much more quotas per head than the other regions under the constrained egalitarian rule.

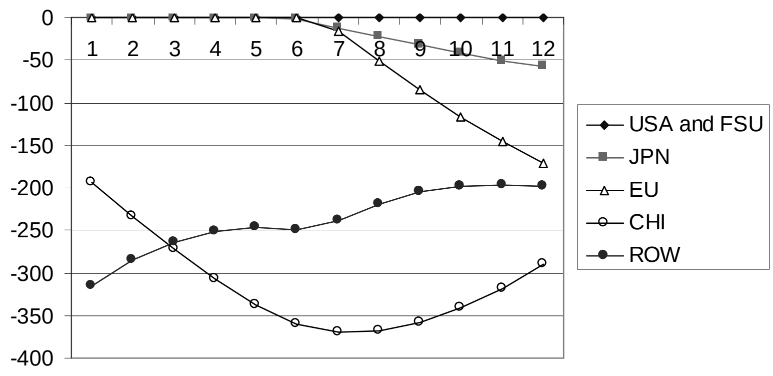
Figure 5.1: Egalitarian allocation constrained by individual rationality: quotas per head per year



In terms of welfare, it has been shown in section 4.2 (figure 4.4) that the egalitarian rule would lead to an increase of total costs due to cooperation at every period for US and FSU and during the first five decades for JPN and EU. These regions therefore need to be compensated. Indeed, during the first five decades, each of them receives an amount of quotas that makes them indifferent between cooperating and not cooperating. The variation of their total costs due to cooperation ($\widehat{W}_{it} - V_{it}$), illustrated in figure 5.2, is thus nul. The two unconstrained regions, namely CHI and ROW, receive the remaining quotas according to the egalitarian sharing rule. They therefore receive the same amount of quotas per head. At the sixth decade, both JPN and EU were enjoying a decrease of their total costs with the egalitarian rule. They are therefore asked to contribute –with CHI and ROW– to the compensation of US and FSU. But the gains of EU were not sufficient for it to participate to the compensation of US and FSU in the same proportion (egalitarian) as CHI, ROW and JPN. Its variation of total costs is thus nul and it receives more quotas per head than CHI, ROW and JPN. From the seventh decade onwards, these four regions receive the same amount of quotas per head and all enjoy gains from the cooperation. Note also that the unconstrained regions receive less quotas than the amount they would get with the unconstrained egalitarian rule (see figure

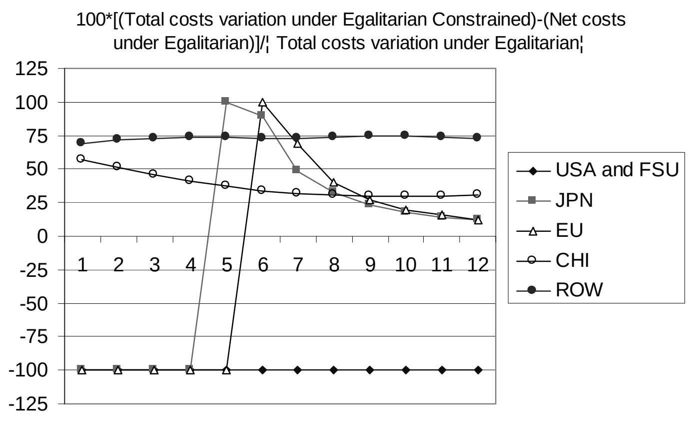
5.1).

Figure 5.2: Egalitarian constrained by individual rationality : decrease of total costs due to cooperation (in billions 1990 US $)



The relative difference between the variation of total costs beared under the constrained egalitarian rule and the one beared under the unconstrained egalitarian rule is plotted in figure 5.3. At each period, the compensated regions (i.e. US, FSU, JPN during the first four periods and EU during the first five periods) enjoy a decrease of 100% of their total costs variation, which is necessary for the agreement to be acceptable by those countries at those periods. In order to compensate them, the other regions have to bear a significant increase of their total costs variation (i.e. a decrease of their gains). The proportion amounts to around 75% for ROW, varies between 60% and 30% for CHI and goes from 100% to 12% for JPN and EU.

Figure 5.3: Egalitarian and Constrained Egal.: relative difference of total costs variation due to cooperation (in %):



Note however that this difference between the total costs variation under the constrained egalitarian rule and the one under the unconstrained egalitarian rule is, *per head*, the same for those compensating regions. Indeed, because the egalitarian rule applies to those regions, the same amount of quotas per head is withdrawn from their allocation in order to compensate the others.

6 An evolutive sharing rule : from grandfathering to egalitarianism

According to Grubb (1995, p. 488), several authors have suggested an allocation ‹‹*which combines egalitarian and status quo/comparable burden sharing principles in the form of a combination of population and current emissions measures, but do not specify an equal weighting of these componants. Rather, they argue that the weighting accorded to population should increase over time towards a more pure per capita allocation.*›› Of a same nature, Kverndokk (1995, p. 145) states : ‹‹*Even if the population allocation rule appears to be politically unacceptable today, the strong arguments for this rule could become more persuasive in the future.*›› These authors seem to favour the egalitarian rule, but are willing to take acceptability into account, notably by incorporating status quo principle in the short run.

In our context, we interpret these statements as a choice in favour of an evolutive sharing rule which is based on the grandfathering rule at the first period and which progressively tends to the egalitarian rule. We arbitrarily assume that the transition is linear and ends up at the tenth period. This gives the annual quotas per head shown in figure 6.1.

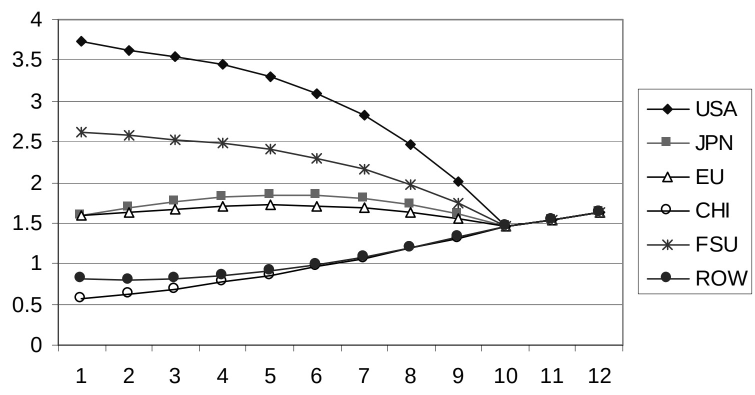
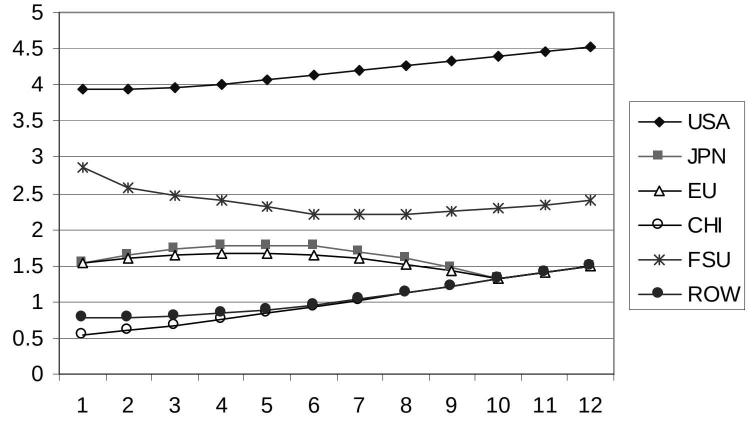


Figure 6.1: Grandfathering to Egalitarian: quotas per head per year

We know that this evolutive sharing rule will not be acceptable by every country at every period because both the 'pure' grandfathering rule and the 'pure' egalitarian rule, which are used respectively at the first and from the tenth period onwards– are not acceptable (see section 4.2). More precisely, simulations show an increase of total costs due to cooperation for US and FSU –except during periods 3 to 7 for FSU–, but a decrease of these costs for all other regions at every period.

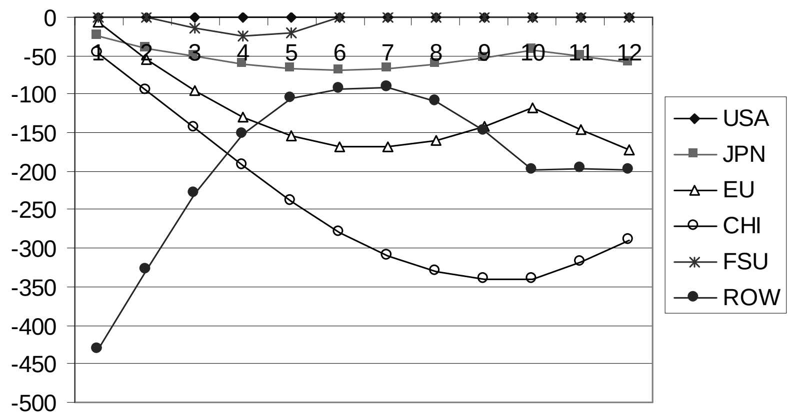
Although this sharing rule was supposed to entail some degree of acceptability, US and FSU will thus never be willing to cooperate. Let's therefore turn to this sharing rule constrained by individual rationality. This leads to the quotas per head per year and the decrease of total costs due to cooperation illustrated in figures 6.2 and 6.3.

Figure 6.2: Grandfathering to Egalitarian constrained by IR: quotas per head per year



In terms of quotas per head, these are relatively close to those allocated under the constrained egalitarian rule (see figure 5.1). However, the 'grandfathering' component of the evolutive rule plays –with respect to the constrained egalitarian rule– in favour of JPN and ROW and against EU and especially CHI.

Figure 6.3: Grandfathering to Egalitarian constrained by IR: decrease of total costs due to cooperation (in billion 1990 US$)



As shown in figure 6.3, this is reflected in the variation of total costs due to cooperation $(\widehat{W}_{it} - V_{it})$. JPN and EU benefit the most from the introduction of the grandfathering component in the sharing rule : they now gain from cooperation at every period (by comparison of figures 5.2 and 6.3). FSU is not constrained anymore at periods 3 to 5 and thus also gains from cooperation at those periods.

More strikingly, the US does not enjoy any decrease of its total costs due to cooperation at any period. For that country, the (negative) effect of the egalitarian component of the evolutive sharing rule dominates the (positive) effect of the grandfathering one.

The main losers –with respect to the constrained egalitarian rule– are CHI and ROW, but their loss does not follow the same path. Although ROW even benefits from the grandfathering component during the first two decades, its decrease of total costs due to cooperation becomes much lower than under the constrained egalitarian rule after thirty years. On the contrary, CHI loses the most at the begining.

For all countries, total costs variations due to cooperation are however the same as those under the constrained egalitarian sharing rule after 10 periods as the grandfathering componant is then no longer present in the sharing rule.

7 Conclusions

With a fully dynamic (closed loop) model developped by Germain and van Ypersele (1999), this paper has analyzed different rules to share tradable GHG emission quotas among the regions of the world. The total amount of quotas to be distributed at a each period of time corresponds to the optimal amount of emissions to be realized during that period.

The computations have been done for the most often referred sharing rules which rely on some perception of equity. Following Rose et al. (1998), we distinguish the rules which apply directly to the quotas –*allocation-based* sharing rules– from those which apply to the surplus derived from the implementation of the optimal policy –*outcome-based* sharing rules. Assuming that countries are individually rational and are not willing to cooperate if the agreement on the quotas allocation does not make them better off, every *outcome-based* sharing rule leads to an allocation of quotas that is by definition acceptable by every country at every period ; by sharing a necessarilly positive surplus, each country is better off than under no cooperation, i.e. than if the optimal policy was not implemented. However, computations show that none of the envisaged *allocation-based* 'equitable' sharing rules is acceptable by every country at every period.

Consequently, we have developped a method in order to find the allocation of quotas which respects as much as possible an 'equitable' sharing rule but which is acceptable by every country at every period. 'Equitable' allocations are thus constrained by acceptability: the countries for which an allocation-based sharing rule is not acceptable are just compensated in order to be indifferent between cooperating and not cooperating by receiving, relative to the sharing rule, more quotas than the others. The 'equitable' sharing rule is however applied among the unconstrained countries. For instance, constraining an egalitarian allocation (same amount of quotas per head) by acceptability leads to gains –with respect to the non-cooperative equilibrium– for China, the Rest of the World and, after 2050, for Japan and Europe. The United States, the Former Soviet Union and, before 2050, Japan and Europe are compensated in order to be just induced to cooperate; their gains from cooperation are thus nul.

The computations have also been done for an evolutive sharing rule that has been proposed by several authors and that was supposed to entail some degree of acceptability: allocating the quotas according to past emissions (*grandfathering*) and progressively tending to an equal allocation per head. Assuming a linear transition from the first sharing rule to the second one over 100 years, this evolutive sharing rule is not acceptable. Some countries, and more particulartly the United States and the Former Soviet Union, still need to be compensated in order to be induced to cooperate. Having constrained this allocation by acceptability, we observe that the grandfathering component of the sharing rule plays very much in favour of Japan and Europe and against China and the Rest of the World.

The results were obtained with a model that covers the entire globe, takes damages into account and is dynamic. This latter feature is crucial for dealing with cooperation in a long term because it allows to define allocations of tradable quotas that are acceptable at *each* period of time.

However, these features were only tracktable in a model excluding economic interactions between the countries, with the level of emissions abatement as the only control variable of the countries and with a decomposition of the world in only six regions. These limitations could be adressed in a first extension of the paper. A second extension could be to widen the concept of acceptability of the allocations in order to include coalitional rationality rather than limiting ourselves to individual rationality as it is done in the present paper.

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