Sharing the Costs of Global Warming

Etienne Billette de Villemeur
Toulouse School of Economics (IDEI & GREMAQ)

Justin Leroux
HEC Montréal and CIRPÉE

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Abstract

We model global warming as a non-excludable public bad jointly produced by countries' emissions of greenhouse gases (GHG). The distribution of the environmental damage bears no relationship to the distribution of global emissions, due to meteorological factors. We argue that this discrepancy should be offset and propose that countries be fully compensated for the costs of damages they had to bear, while the financing of this "global insurance scheme" be shared according to countries' responsibility for climate change. GHG have a very slow decay (thousands of years) thus if climate is related emissions, it must be with cumulated emissions. We therefore consider that it make more sense to share the actual burden of global warming on the basis of cumulated emissions than sharing the expected costs of actual emissions as implicit in a taxation scheme. We propose different schemes to share the (flow of) costs of global warming that are associated with different views regarding the responsibility of the countries on their past emission levels and geographical characteristics. These cost-sharing schemes are first characterised along the (axiomatic) partial responsibility method. They are then brought to the data. It appears that, if countries are required to pay for the costs they are responsible for, some countries may go bankrupt unless protected by limited liability.

J.E.L. Classification: D62, D63, Q54.
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1 Introduction

The temperature rise around the globe over the last decade is well documented. Numerous studies are devoted to the phenomenon. In particular, progress has been made in the understanding of the drivers of the observed climate change. There is a growing consensus that *(i)* global warming is real and *(ii)* a great part of it is to be attributed to human activities. This is at least the view pushed by the **I**ntergovernmental **P**anel on **C**limate **C**hange (hereafter, IPCC).

The (apparently erratic) weather fluctuations makes it difficult to detect a trend in temperature changes. This is especially true if no special attention is devoted to the phenomenon. This may also explain why mankind became aware so late of the above mentioned temperature rise. However, the "temperature anomaly" of the last 10-15 years[1] is a statistical fact; not a conjecture or a theory. The doubts of the skeptics may only follow from the very fact that the "trend" of the last years may itself be "temporary". In other words, the temperature rise may be part of natural "long-term" fluctuations.

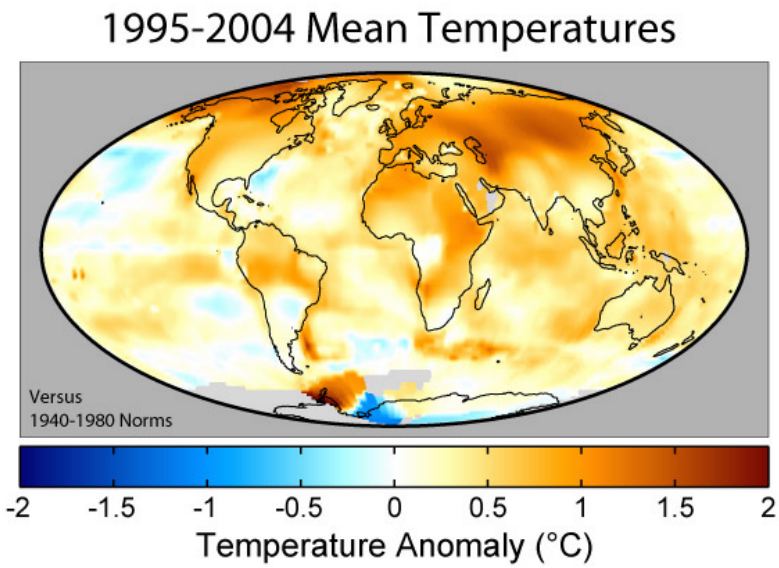


Figure 1:

Beyond the need to be more precise in the vocabulary, deciding upon the drivers of "global warming" and their relative importance requires a reliable climate model. Again, the stochastic nature of temperature series and the numerous unknowns that still pervade climatology may well induce the layman to believe that the cumulated knowledge is much too meager to allow anything that would approach it. This may explain in turn two widespread and opposite

[1] as compared to the average over the years 1940-1980, which are well documented.

views, that militants or opponents generally endorse almost as a creed. Some believe that human activities have no assessed impact on global warming and press for no intervention to curb their course. Others are frightening any human intervention on environment and calls for a comeback to an ideal "state of nature". However, there are some well established facts and there exists simple but solid lines of reasoning that should allow one to go beyond beliefs and take a rational position.

As nicely phrased by Arrow in a recent policy note on the subject (See [1]),

> The source of terrestrial temperature is of course solar radiation. (...) *[However],* since the Earth radiates into empty space, where the temperature approximates absolute zero, it would appear that in equilibrium the Earth should come to that temperature also, as is indeed the case with the Moon.
>
> What makes the difference is the Earth's atmosphere (...) which effect is to retain the outgoing radiation and so raise the temperature of the Earth to the point in which life can flourish.

Among the gases which confer this property to atmosphere, carbon dioxide which, as a by-product of combustion, accumulates at a sustained pace since the industrial revolution. Changes in CO_2 concentration can be traced back to thousands years ago thanks to ice cores. The fourth IPCC assessment report (2007) states that :

> The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm[2] in 2005. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years.

The associated change in Radiative Forcing, *i.e.* the additional amount of energy retained by the atmosphere appear to be quite significant. According to the just quoted report "The carbon dioxide radiative forcing increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years". For sure, changes in CO_2 concentration are only part of the story. Many other factors happen to have an influence on climate and their interactions are quite complex. In the end, it is extremely difficult if not impossible to ascertain the exact impact of anthropogenic emissions. However, it is also impossible to deny that human activities since 1750 have brought significant changes in the forces at work in determining global climate.

What is more debatable (and is indeed debated if not fight upon) are the costs of anthropogenic emissions. Their marginal and immediate impact on temperature or on the see level are already difficult to assess. But, since greenhouse gases emissions are almost *irreversible* (in that their decay takes centuries), long-term effects are to considered. This says that an appropriate cost-benefit

[2] ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air. For example: 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air.

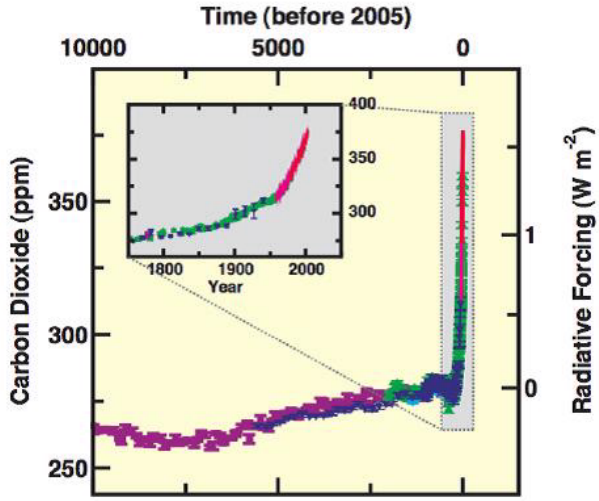


Figure 2: Changes in CO_2 concentration (associated effect on radiative forcing) over the last 10000 years.

analysis *must* bear upon hundreds years; with all the uncertainties that go along the analysis of a system with complex feedbacks; and all the questionable choices that are attached to discounting across periods.

This difficulty in assessing in real marginal costs of greenhouse gases yields us to consider that it would be more appropriate to adopt a scheme that splits the costs of climate change on a *yearly* basis. Rather than requiring countries to pay up-front for the *estimated* (future) costs of their *current* emissions, each country ought pay for the *observed* (current) costs, that follow from their *cumulated* emissions. From that point of view, emitting is like issuing debts.

Interestingly, the debate on "global warming" focus almost exclusively upon the *efficiency* problem. The question is essentially one of opportunity to limit emissions and, if so, of appropriate magnitude and timing of intervention. It is usually addressed by the means of a cost-benefits analysis. And, in most of the cases, the analysis is performed through the lens of a global warming model which, albeit its complexity, attaches uniform effects to "global warming".
Unless ignored, the question of *responsibility* is often inappropriately patched to the issue. In fact, it may be possible to firmly establish the responsibility for "global warming" of the richest nations; and yet to have the costs for curbing emissions so high that the later do not appear to be justified in regards of their potential benefits. By contrast, it may be appropriate to act as to limit the temperature rise, even if the later follows from natural fluctuations[3] only.
The issue of *solidarity* has also been almost completely dismissed. Greenhouse

[3] as opposed to human driven changes.

gases constitutes a "public bad" *par excellence*. They travel around the world in a few days; hence their emissions is a truly global externality. However, their accumulation and the resulting temperature changes may impact populations very differently. In fact, a temperature increase will result in a productivity improvement of agriculture in Canada and northern Russia. It should also reinforce chronic draughts in Sahel Africa. The sea level rise is expected to erase from the maps some islands like the Maldives or the Tonga. The problem can clearly be ignored by tens of countries. Thus heterogenous distribution of damages resulting from "global warming" clearly raises some questions in terms of global justice.

In this paper, we depart from the monolithic view of global warming associated to the actual debate. The *heterogeneity* of countries *contributions to emissions* as well as the different *energetic needs* and the different magnitudes of *incurred damages* are explicitly considered. In this framework, we attempt to carefully disentangle the issues of efficiency, responsibility and solidarity. This yields us to consider several schemes to share the costs of global warming. If the temperature rise is considered to follow from natural fluctuations only, the issue of global warming is purely one of solidarity in facing an global adverse event. If the temperature rise was triggered by human activities (at least partly), the issue is *also* one of responsibility. The question of efficiency should enter the picture whenever it is believed that some (costly) actions could mitigate the problem. This is to say that, in the realistic cases, there ought to be an inter-play of the three principles.

We model global warming as a non-exclusive public bad, jointly produced by countries emissions of **G**reen**H**ouse **G**ases (hereafter GHG). Every country benefits privately from emitting, while the resulting environmental damage is borne by all, though unequally distributed. Our approach is one of responsibility. We take the view that countries are *not* responsible for the distribution of environmental damage due to atmospheric movements. As a result, we ask that *yearly* environmental damage be jointly borne by all countries, and propose a specific side payments to do so while making each country responsible to its contribution to the flow of damages.

A common solution to the externality problem is to impose a tax equal to the marginal damage caused by each country. Such a procedure internalizes the externality or, in responsibility terms, makes countries exactly responsible for their own contribution to total damage. This approach can be maintained even if, as we propose, the scheme refers to cumulated emissions and tackle the flow damages. It presents a number of advantages, especially related to efficiency. However, it fails at balancing the budget because it charges collectively more (resp. less) than total damage in the presence of increasing (resp. decreasing) marginal damage. In other words, a tax at marginal damage is satisfactory in terms of efficiency, but is wasteful (or insufficient) in terms of redistribution.
As we will argue when looking at data, the unsatisfactory redistributive properties of taxation is not a purely normative problem. It may pose a real challenge to its implementation. This says the relevance of considering *both* efficiency and risdistribution, which is precisely our approach.

It is worth noting that the redistribution problem itself is not tension free. In particular, an important one exists between responsibility and compensation. A desirable mechanism should make countries pay for the damages their are responsible and compensate them for the consequences of characteristics they are not responsible for. As it turns out, strong interpretations of these two features are incompatible (Bossert, 1995 [3]). However, less demanding interpretations are compatible, and characterize two mechanisms (see, Bossert and Fleurbaey, 1996 [4]).

We believe that one contribution of this paper consists in clearly identifying the normative stands attached to various cost-sharing scheme. We also put a particular emphasis upon the issue of responsibility. In particular, we systematically identify the consequences of considering that past greenhouse gases emissions should (or should not) be taken into account in sharing the present costs of global warming. Finally, we point to a procedural property which we claim, given the context, might be of importance. Indeed, as the issue is inherently a global one, the problem at hand encompasses extended periods of time over which the structure of countries and political landscapes are subject to change (e.g. Europe, Yougoslavia, etc.). We argue that well-defined recommendation should be insensitive to the structure of countries and their coalitions. We call this property *Aggregation Independence* and show that it imposes severe restrictions on admissible transfers.

1.1 Relation with the literature

Scientists have been aware that human activities might result in climate change since, at least, the early seventies (See Sawer, 1972 [30]). While the effect of carbon dioxide emissions was initially hidden by the cooling trend of last century, the exponential rise in the atmospheric carbon dioxide content appeared rapidly as having the potential to drive the mean planetary temperature beyond the limits experienced during the last 1000 years (See Damon and Kunen, 1976 [14] and Broecker, 1975 [5]). Looking at temperature changes in the past, it was soon obvious that such a temperature increase could result in dramatic changes (See McLean, 1978 [18]).

Economists entered the debate at the beginning of the nineties. At that time, there were still many scientific uncertainties about the greenhouse effect (See Cline, 1991 [8]). Part of the specific contribution of economists consisted precisely in introducing in the debate the major concepts of decision theory in uncertain environment (See e.g. Seater 1993 [32]) _ including the notion of optimal stopping rules and accounting for the possibility of learning (See Conrad, 1997 [12] and Ulph and Ulph, 1997 [36]). The other major contribution is of course cost-benefit analysis and the very idea that maintaining nature unchanged cannot *per se* constitute an absolute value (See, e.g. Mendelsohn, Nordhaus and Shaw, 1994 [20] and Feng, Zhao and Kling, 2002 [16]). Along this line, noteworthy, although not undisputed, is the contribution of W. D. Nordhaus and the influence of his "**D**ynamic **I**ntegrated **C**limate **E**conomy" model (See Nordhaus, 1991 [23], 1993a [24], 1993b [25] and Schneider *et al.*,

1993 [31]).

In recent years, especially after the failure of the Kyoto protocol, the debate focussed more on the political economy of the problem and in particular on the issue of coalition formation (See e.g. Nordhaus, 2006 [27]). Another major issue is discounting, especially after economists became aware of the typical time scale for climate issue _ that overcomes by far even the long-term problems they use to address (See Stern 2007 [34] and Nordhaus 2007 [28]). As already mentioned, with the exception of few recent exceptions (See Dasguspta *et al. 2007* [15], Bacon and Bhattacharya 2007 [2]), country heterogeneity is rarely accounted for. To the best of our knowledge, the ridistributive issues have never been tackled.

2 The model

Let $N = \{1, ..n\} \subset \mathbb{N}$ be the set of countries[4]. The vectors $\mathbf{x}^0 = \left(x_1^0, ..x_n^0\right)$ and $\mathbf{x}^1 = \left(x_1^1, ..x_n^1\right)$ denote countries' *past* and *present* (or envisioned) GHG emissions respectively. In addition to their emissions levels, countries are described by a *profile of characteristics* $(\theta_1, ..., \theta_n) \in \mathbb{R}^{nm}$. Such data can be considered to be essentially geographic in nature (latitude, altitude, average temperature, soil fertility, etc) and will typically also include population. The set of all possible characteristic vectors is $\Theta \in \mathbb{R}^m$.

Each country's private *current* benefits is associated to its own characteristics and emissions levels via a mapping $b : \Theta \times \mathbb{R}_+^2 \to \mathbb{R}$, $(\theta_i, x_i^0, x_i^i) \mapsto b\left(\theta_i, x_i^0, x_i^1\right)$, which is continuous and non-decreasing in the last two arguments. We assume benefits to be fully transferable.

Total emissions are a public bad. More precisely, let $X = \sum_{i \in N} x_i$ be the total level of emissions, where $x_i = x_i^0 + x_i^1$ designates the emissions cumulated by country i. We denote by X^0 and X^1 past and current total emissions. The impact of global warming on country i is assumed to depend solely on $X = X^0 + X^1$. Formally, we denote by $d_i(X)$ the damage incurred by country i. We do not make any assumption on the functions $d_i(X)$ other than continuity. In particular, it may be the case that some countries actually benefit from global warming for some values of X. That is to say we do not exclude the possibility that $d_i(X) < 0$ for some countries $j \in N$. Yet, we assume total damage,

$$D(X) = \sum_{i \in N} d_i(X) . \mathbf{1}_{d_i(X) \geq 0},$$

where $\mathbf{1}_{d_i(X) \geq 0}$ is an indicator function associated to the positivity of the damage, to be positive and non-decreasing in X. We denote by $\mathcal{D}(N)$ the class of damage functions for countries in N and by $\mathbf{d} = (d_1, ...d_n)$ the profile of damage functions. We call (θ, x^0, x^1) a *global warming problem* and denote by $\mathcal{P}$ the class of such problems.

[4] We use the word "countries" for simplicity, but our analysis readily applies to regions, which is especially relevant for large countries.

Our goal is to design a transfer schedule to correct the arguably uneven distribution of damage due to global warming. In doing so, we shall consider that countries are *not* responsible for the individual damage they incur, nor are they responsible for their vector of characteristics. In other words, countries are only held (potentially) responsible for their past and present emissions levels. On the other hand, we wish to fully compensate countries for damage suffered due to aspects for which they are not responsible. This amounts to designing a cost allocation structure to share $D(X)$ between countries. Formally, this amounts to compensating every country for the damage it incurs, $d_i(X)$, while setting up vectors of transfer payments, $t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)$, to finance the total amount compensated: $\sum_i t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = D(X)$. The payoff of country i is then $b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)$.

We shall contrast several views of responsibility with regards to past emissions. First, since the cost of global warming depends upon total emissions, one may argue that transfer payments should only depend on the profile of all countries' cumulated emissions, $\mathbf{x} = (x_1, ..., x_n)$. We shall call this view **H**istorical **R**esponsibility (hereafter *HR*). Second, one may also argue that countries should not be held responsible for emissions that go back to a time when the impact of GHG emissions on climate change had not been suspected. According to this view, past emissions are irrelevant and countries should be held responsible for current emissions levels $\mathbf{x}^1 = (x_1^1, ..., x_n^1)$ only. We refer to it as **n**o **H**istorical **R**esponsibility (hereafter *nHR*). Third, past emissions may be considered as a natural benchmark to measure countries' "needs". According to this so-called **G**rand-**F**athering view (hereafter *GF*), countries are held responsible for variations between current and past emissions levels $\mathbf{x}^{GF} = (x_1^{GF}, ..., x_n^{GF})$, where $x_i^{GF} = x_i^1 - \gamma x_i^0$, for some γ. Finally, some still argue that no causal link between human emissions and climate change can be ascertained. According to this fourth viewpoint, which we shall call the **E**xternal **S**hock view *(*henceforth, *ES*), countries' emissions levels are irrelevant in redistributing the costs associated with climate change. Note that the **ES** view is not at odds with the desire to redistribute the impacts of climate change; it simply assumes that damages are not caused by emissions.

A minimal fairness requirement consists in imposing anonymity: countries with identical characteristics should be treated equally.

Axiom 1 (A) ***A****nonymity. For any* $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) \in \mathcal{P}$*, and any* $i, j \in N$*,*

$$(\theta_i, x_i^0, x_i^1) = (\theta_j, x_j^0, x_j^1) \implies t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)$$

We take the view that individuals inherit the responsibility attached to the characteristics of the country they are in. This makes it natural for the cost-sharing mechanism to directly refer to countries for what regards the responsibility aspect. For what regards fairness, hence compensation, we argue that one should return to the individual level, *i.e.* consider *per capita* concepts. Toward this aim, let n_i denote the population of country i.

3 Tension between responsibility and compensation

3.1 Penalizing (or rewarding) for differences in characteristics countries are responsible for

If a country is considered to be responsible for a set of characteristics, differences in those characteristics have to affect somehow their final payoffs. A first approach to responsibility consists in arguing that whatever the distribution of irrelevant characteristics (*i.e.* characteristics a country is *not* responsible for), changes in one country relevant characteristics (*i.e.* characteristics a country is responsible for), should affect only this country. This yields:

Axiom 2 (FMR) ***F****ull* ***M****arginal* ***R****esponsibility:*
For any $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right), \left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) \in \mathcal{P}$*, any* $k \in N$*,*

HR-FMR $[\theta_k = \hat{\theta}_k$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) = D\left(X\right) - D\left(\widehat{X}\right),$$

and $t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)$ *for all* $i \neq k$*.*

nHR-FMR $[(\theta_k, x_k^0) = (\hat{\theta}_k, \hat{x}_k^0)$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) = D\left(X\right) - D\left(\widehat{X}\right),$$

and $t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)$ *for all* $i \neq k$*.*

GF-FMR $[(\theta_k, x_k^0) = (\hat{\theta}_k, \hat{x}_k^0)$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) = D\left(X\right) - D\left(\widehat{X}\right),$$

and $t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)$ *for all* $i \neq k$*.*

Remark 1 *The* ***ES*** *version of* ***FMR*** *is not well defined because no country bears any responsibility in the matter.*

Full **M**arginal **R**esponsibility is very demanding. Actually, unless $D\left(X\right)$ is linear, it is actually impossible to find transfer functions such that would satisfy it. Formally:

Proposition 1 *If a cost-sharing mechanism* $\mathbf{t} = \left(t_1\left(.\right), t_2\left(.\right), ..., t_n\left(.\right)\right)$ *satisfies* ***FMR****, then damages* $D\left(X\right)$ *must be linear in total emissions* X*.*

Proof. The proof is done along the **nHR** viewpoint, but the proof technique is similar for the other "views".
Given any $\widehat{P} = \left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) \in \mathcal{P}$ let $P(a,b) = \left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) \in \mathcal{P}$ be defined as follows: $\boldsymbol{\theta} = \hat{\boldsymbol{\theta}}$, $\mathbf{x}^0 = \hat{\mathbf{x}}^0$ and $\mathbf{x}^1 = \hat{\mathbf{x}}^1 + \mathbf{y}$ where $\mathbf{y} = (a, b, 0, .., 0)$ and $(a,b) \in \mathbb{R}^2_+$. Denote $\mathbf{y}_0 = (0, 0, .., 0)$, $\mathbf{y}_a = (a, 0, .., 0)$, $\mathbf{y}_b = (0, b, 0, .., 0)$ and $\mathbf{y}_2 = (a, b, 0, .., 0)$. Let $P_k = \left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1_k\right)$ where $\mathbf{x}^1_k = \hat{\mathbf{x}}^1 + \mathbf{y}_k$ with $k = 0, a, b, 2$ be the associated profiles. We denote by $X_0 = \widehat{X}$, X_a, X_b and $X_1 = X(a,b)$ the total emissions associated respectively with $P_0 = \widehat{P}$, P_a, P_b and $P_1 = P(a,b)$.
From **nHR-FMR** applied to P_0 and P_a, we know that

$$t_1(P_a) - t_1(P_0) = D(X_a) - D(X_0),$$

and $t_i(P_a) = t_i(P_0)$ for all $i \neq 1$. From **nHR-FMR** applied to P_a and P_1, it follows

$$\begin{aligned} t_1(P_1) - t_1(P_0) &= D(a + X_0) - D(X_0), \\ t_2(P_1) - t_2(P_0) &= D(a + b + X_0) - D(a + X_0), \end{aligned}$$

and $t_i(P_1) = t_i(P_0)$ all $i \neq 1, 2$. However, from **nHR-FMR** applied to P_0 and P_b, we also have

$$t_2(P_b) - t_2(P_0) = D(X_b) - D(X_0),$$

and $t_i(P_b) = t_i(P_0)$ for all $i \neq 2$. From **nHR-FMR** applied to P_b and P_1, it follows

$$\begin{aligned} t_1(P_1) - t_1(P_0) &= D(a + b + X_0) - D(b + X_0), \\ t_2(P_1) - t_2(P_0) &= D(b + X_0) - D(X_0), \end{aligned}$$

and $t_i(P_1) = t_i(P_0)$ all $i \neq 1, 2$. Thus

$$D(a + X_0) - D(X_0) = D(a + b + X_0) - D(b + X_0),$$

all $a, b \geq 0$. Linearity follows. ■

This yields us to consider less demanding axiom, although in the same spirit. This is done by introducing a reference vector for the characteristics countries are responsible for and by considering "average costs differences":

Axiom 3 (FARR) ***F****ull* ***A****verage* ***R****eference* ***R****esponsibility:*
Let $\left(\tilde{x}^0, \tilde{x}^1\right)$ *be a reference vector for* per capita *emissions and let total emissions* $\widetilde{X} = \left(\sum_{j \in N} n_j\right) \tilde{x}$, *where* $\tilde{x} = \tilde{x}^0 + \tilde{x}^1$, *be defined accordingly.*
For any $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right), \left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) \in \mathcal{P}$, *any* $k \in N$,

HR-FARR $[\theta_k = \hat{\theta}_k$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - (x_j - n_j\tilde{x})\left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}}\right)$$
$$= t_j\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) - (\hat{x}_j - n_j\tilde{x})\left[\frac{D\left(\widehat{X}\right) - D\left(\tilde{X}\right)}{\widehat{X} - \tilde{X}}\right],$$

for all $j \in N$.

nHR-FARR $[(\theta_k, x_k^0) = (\hat{\theta}_k, \hat{x}_k^0)$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left(x_j^1 - n_j\tilde{x}^1\right)\left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}}\right)$$
$$= t_j\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) - \left(\hat{x}_j^1 - n_j\tilde{x}^1\right)\left[\frac{D\left(\widehat{X}\right) - D\left(\tilde{X}\right)}{\widehat{X} - \tilde{X}}\right],$$

for all $j \in N$.

GF-FARR $[(\theta_k, x_k^0) = (\hat{\theta}_k, \hat{x}_k^0)$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[\left(x_j^1 - \gamma x_j^0\right) - n_j\left(\tilde{x}^1 - \gamma\tilde{x}^0\right)\right]\left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}}\right)$$
$$= t_j\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right) - \left[\left(\hat{x}_j^1 - \gamma\hat{x}_j^0\right) - n_j\left(\tilde{x}^1 - \gamma\tilde{x}^0\right)\right]\left[\frac{D\left(\widehat{X}\right) - D\left(\tilde{X}\right)}{\widehat{X} - \tilde{X}}\right],$$

for all $j \in N$.

Remark 2 *Again, the* ***ES*** *version of* ***FARR*** *is not well defined because no country bears any responsibility in the matter.*

Remark 3 *If* $D(X)$ *is linear,* ***FMR*** *and* ***FARR*** *do not differ.*

Some interpretations of responsibility are based upon countries' "contributions" to the burden of climate change. Define countries' "contributions" as their financial transfers *net* of the costs of the marginal damage they are responsible for. A possible interpretation of responsibility consists in requiring that individuals in two countries for which the characteristics they are *not* responsible for are identical should provide equal "contributions".

Axiom 4 (EpcCEIC) ***E****qual* ***p****er* ***c****apita* ***C****ontribution for* ***E****qual* ***I****rrelevant* ***C****haracteristics.*
For any $(\theta, x^0, x^1) \in \mathcal{P}$,

HR-EpcCEIC $\theta_i = \theta_j \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_i\right)\right]\right)/n_i \\ = \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_j\right)\right]\right)/n_j,$$

for all $i, j \in N$.

nHR-EpcCEIC $(\theta_i, x_i^0/n_i) = (\theta_j, x_j^0/n_j) \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_i^1\right)\right]\right)/n_i \\ = \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_j^1\right)\right]\right)/n_j,$$

for all $i, j \in N$.

GF-EpcCEIC $(\theta_i, x_i^0/n_i) = (\theta_j, x_j^0/n_j) \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_i^1 + \gamma x_i^0\right)\right]\right)/n_i \\ = \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_j^1 + \gamma x_j^0\right)\right]\right)/n_j,$$

for all $i, j \in N$.

ES-EpcCEIC $(\theta_i, x_i^0/n_i, x_i^1/n_i) = (\theta_j, x_j^0/n_j, x_j^1/n_j) \implies$

$$t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)/n_i = t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)/n_j,$$

for all $i, j \in N$.

The above requirement can be weakened to require an equal *per capita* "contribution" only in the case where countries share a given reference level in characteristics they are not responsible for.

Axiom 5 (EpcCRIC) ***E****qual* ***p****er* ***c****apita* ***C****ontribution for* ***R****eference* ***I****rrelevant* ***C****haracteristics.*
Let $(\tilde{\theta}, \tilde{x}^0, \tilde{x}^1) \in \Theta \times \mathbb{R}_+^2$.
For any $(\theta, x^0, x^1) \in \mathcal{P}$,

HR-EpcCRIC $\theta_i = \tilde{\theta}$ *for all* $i \in N \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_i\right)\right]\right)/n_i \\ = \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_j\right)\right]\right)/n_j,$$

for all $i, j \in N$.

nHR-EpcCRIC $(\theta_i, x_i^0/n_i) = (\tilde{\theta}, \tilde{x}^0)$ *for all* $i \in N \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(\widetilde{X}^0 + X^1\right) - D\left(\widetilde{X}^0 + X^1 - x_i^1\right)\right]\right)/n_i$$
$$= \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(\widetilde{X}^0 + X^1\right) - D\left(\widetilde{X}^0 + X^1 - x_j^1\right)\right]\right)/n_j,$$

for all $i, j \in N$.

GF-EpcCRIC $(\theta_i, x_i^0/n_i) = (\tilde{\theta}, \tilde{x}^0)$ *for all* $i \in N \implies$

$$\left(t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_i^1 + \gamma x_i^0\right)\right]\right)/n_i$$
$$= \left(t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - \left[D\left(X\right) - D\left(X - x_j^1 + \gamma x_j^0\right)\right]\right)/n_j,$$

for all $i, j \in N$.

ES-EpcCRIC $(\theta_i, x_i^0/n_i, x_i^1/n_i) = (\tilde{\theta}, \tilde{x}^0, \tilde{x}^1)$ *for all* $i \in N \implies$

$$t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)/n_i = t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)/n_j,$$

for all $i, j \in N$.

Remark 4 *For each interpretation of the above four axioms, the most demanding is* ***FMR*** *while the least demanding is* ***EpcCRIC****.*[5]

3.2 Compensating for differences in characteristics countries are *not* responsible for.

A first approach to dealing with the issue of compensation consists in arguing that differences in characteristics countries are *not* responsible for should *not* drive the outcome. In other words, only differences in characteristics countries are responsible for —$\left(x_i^0, x_i^1\right)$ under the **HR** view, x_i^1 under the **nHR** view, $x_i^{GF} = x_i^1 - \gamma x_i^0$ under the **GF** view and none under the **ES** view—should matter.

This may yield one to consider that all individuals should equally suffer—or benefit—from the effect of a change in one country's characteristic, if that country does not bear any responsibility for it. Formally, this writes:

Axiom 6 (GSIC) ***G****roup* ***S****olidarity towards* ***I****rrelevant* ***C****haracteristics.*
For any $(\theta, x^0, x^1), (\hat{\theta}, \hat{x}^0, \hat{x}^1) \in \mathcal{P}$, *any* $k \in N$,

HR-GSIC $[\left(x_k^0, x_k^1\right) = \left(\hat{x}_k^0, \hat{x}_k^1\right)$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$\left[b(\hat{\theta}_k, \hat{x}_k^0, \hat{x}_k^1) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_k - \left[b(\theta_k, x_k^0, x_k^1) - t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_k$$
$$= \left[t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_i,$$

for all $i \neq k$.

[5] See Fleurbaey and Bossert (1996).

nHR-GSIC $[x_k^1 = \hat{x}_k^1$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$\left[b(\hat{\theta}_k, \hat{x}_k^0, \hat{x}_k^1) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_k - \left[b(\theta_k, x_k^0, x_k^1) - t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_k$$
$$= \left[t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_i,$$

for all $i \neq k$.

GF-GSIC $[x_k^1 - \gamma x_k^0 = \hat{x}_k^1 - \gamma \hat{x}_k^0$ *and* $(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$\left[b(\hat{\theta}_k, \hat{x}_k^0, \hat{x}_k^1) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_k - \left[b(\theta_k, x_k^0, x_k^1) - t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_k$$
$$= \left[t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_i,$$

for all $i \neq k$.

ES-GSIC $[(\theta_i, x_i^0, x_i^1) = (\hat{\theta}_i, \hat{x}_i^0, \hat{x}_i^1)$ *for all* $i \neq k] \implies$

$$\left[b(\hat{\theta}_k, \hat{x}_k^0, \hat{x}_k^1) - t_k\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_k - \left[b(\theta_k, x_k^0, x_k^1) - t_k\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_k$$
$$= \left[t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) - t_i\left(\hat{\boldsymbol{\theta}}, \hat{\mathbf{x}}^0, \hat{\mathbf{x}}^1\right)\right]/n_i,$$

for all $i \neq k$.

Another possible interpretation of compensation consists in requiring that two countries for which the characteristics they are responsible for are identical should end up with the same *per capita* payoff:

Axiom 7 (EpcPER) ***E**qual **p**er **c**apita **P**ayoff for **E**qual **R**esponsibility*[6]. *For any* $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) \in \mathcal{P}$,

HR-EpcPER $\left(x_i^0, x_i^1\right) = \left(x_j^0, x_j^1\right) \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

nHR-EpcPER $x_i^1 = x_j^1 \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

GF-EpcPER $x_i^1 - \gamma x_i^0 = x_j^1 - \gamma x_j^0 \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

[6] This axiom, and others considered here, results from the reinterpretation of an axiom found in Bossert and Fleurbaey (1996).

ES-EpcPER *In all cases:*

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

A considerably weaker version of the above axiom requires final payoff equality only in the case where characteristics countries are responsible for are equal to a given reference level. By construction, this weakening has no effect under the **ES** view.

Axiom 8 (EpcPRR) ***E****qual* ***p****er* ***c****apita* ***P****ayoff for* ***R****eference* ***R****esponsibility. Let* $\tilde{x}^0, \tilde{x}^1 \geq 0$. *For any* $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) \in \mathcal{P}$,

HR-EpcPRR $\left(x_i^0/n_i, x_i^1/n_i\right) = \left(\tilde{x}^0, \tilde{x}^1\right)$ *for all* $i \in N \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

nHR-EpcPRR $x_i^1/n_i = \tilde{x}^1$ *for all* $i \in N \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

GF-EpcPRR $\left(x_i^1 - \gamma x_i^0\right)/n_i = \tilde{x}^1 - \gamma\tilde{x}^0$ *for all* $i \in N \implies$

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

ES-EpcPRR *In all cases:*

$$\left[b(\theta_i, x_i^0, x_i^1) - t_i\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_i = \left[b(\theta_j, x_j^0, x_j^1) - t_j\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)\right]/n_j,$$

for all $i, j \in N$.

Remark 5 *For each interpretation of the above three axioms, the most demanding is* ***GSIC*** *while the least demanding is* ***EpcPRR****.*[7]

4 Redistribution mechanisms and characterizations

When considering cost-sharing mechanisms in a framework with responsibility, there two "separability" issues. A first issue consists in disentangling the specific impact of each country on the total damage, a central question in cost-sharing

[7] See Fleurbaey and Bossert (1996).

theory. A second issue that add itself to the first consists in disentangling the impact of characteristics countries are responsible for from that of characteristics they are not responible for.

As it turns out, it is generally impossible to compensate countries for differences in characteristics they are not responsible for while penalizing or rewarding them for differences in characteristics for which they are responsible, at least in the strong interpretation of these concepts. In fact, even in the case where $D(X)$ is linear (which makes the impact of each country easily distinguishable), **FMR** (or **FARR)** and **GSIC** are incompatible unless the benefit function is additively separable in the characteristics countries are responsible and not responsible for.

Theorem 2 *Assume $D(X)$ is linear.*

HR-GSIC *and* ***HR-FMR*** *are incompatible unless there exists functions $g : \Theta \to \mathbb{R}$ and $h : \mathbb{R}^2_+ \to \mathbb{R}$ such that*

$$b(\theta_i, x_i^0, x_i^1) = g(\theta_i) + h(x_i^0, x_i^1)$$

for all $(\theta_i, x_i^0, x_i^1) \in \Theta \times \mathbb{R}^2_+$.

nHR-GSIC *and* ***nHR-FMR*** *are incompatible unless there exists functions $g : \Theta \times \mathbb{R}_+ \to \mathbb{R}$, $h : \mathbb{R}_+ \to \mathbb{R}$ such that*

$$b(\theta_i, x_i^0, x_i^1) = g(\theta_i, x_i^0) + h(x_i^1),$$

for all $(\theta_i, x_i^0, x_i^1) \in \Theta \times \mathbb{R}^2_+$.

GF-GSIC *and* ***GF-FMR*** *are incompatible unless there exists functions $g : \Theta \to \mathbb{R}$ and $h : \mathbb{R}_+ \to \mathbb{R}$ such that*

$$b(\theta_i, x_i^0, x_i^1) = g(\theta_i) + h(x_i^1 - x_i^0),$$

for all $(\theta_i, x_i^0, x_i^1) \in \Theta \times \mathbb{R}^2_+$.

Proof. Adapted from Bossert (1995). ■

Consequently, the only way to reconcile the concepts of compensation and responsibility is to weaken at least one of the two axioms. We discuss these weakening in turn and characterize the corresponding mechanisms: the **E**galitarian **E**quivalent mechanism and the **C**onditionally **E**quivalent mechanism.

4.1 Egalitarian Equivalent mechanism

The *Egalitarian Equivalent mechanism* splits the consequences of deviations from a reference vector of *irrelevant* characteristics while sharing equally the residual impact of global warming, once each country has paid for its marginal contribution. The four approaches to responsibility we discussed above each lead to their own version of the **E**galitarian **E**quivalent mechanism:

Definition 3 ***E****galitarian* ***E****quivalent transfer:*
For any $(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1) \in \mathcal{P}$ and any reference vector of irrelevant *characteristics* $\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, \tilde{n}\ \tilde{x}^1\right)$

HR-EE *For any $i \in N$,*

$$\begin{aligned} t_i^{HR-EE} &= b\left(\theta_i, x_i^0, x_i^1\right) - b\left(\tilde{\theta}, x_i^0, x_i^1\right) + \left[D\left(X\right) - D\left(X - x_i\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \sum_{j\in N} \left[b\left(\theta_j, x_j^0, x_j^1\right) - b\left(\tilde{\theta}, x_j^0, x_j^1\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} \left[D\left(X\right) - D\left(X - x_j\right)\right] - D(X)\right). \end{aligned}$$

nHR-EE *For any $i \in N$,*

$$\begin{aligned} t_i^{nHR-EE} &= b\left(\theta_i, x_i^0, x_i^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, x_i^1\right) \\ &\quad + \left[D\left(\tilde{X}^0 + X^1\right) - D\left(\tilde{X}^0 + X^1 - x_i^1\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \sum_{j\in N} \left[b\left(\theta_j, x_j^0, x_j^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, x_j^1\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} \left[D\left(\tilde{X}^0 + X^1\right) - D\left(\tilde{X}^0 + X^1 - x_j^1\right)\right] - D(X)\right). \end{aligned}$$

GF-EE *For any $i \in N$,*

$$\begin{aligned} t_i^{GF-EE} &= b\left(\theta_i, x_i^0, x_i^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, x_i^{GF} + \gamma\tilde{n}\ \tilde{x}^0\right) + \left[D\left(X\right) - D\left(X - x_i^1 + \gamma x_i^0\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \sum_{j\in N} \left[b\left(\theta_j, x_j^0, x_j^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, x_j^{GF} + \gamma\tilde{n}\ \tilde{x}^0\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} \left[D\left(X\right) - D\left(X - x_j^1 + \gamma x_j^0\right)\right] - D(X)\right). \end{aligned}$$

ES-EE *For any $i \in N$,*

$$\begin{aligned} t_i^{ES-EE} &= \left[b\left(\theta_i, x_i^0, x_i^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, \tilde{n}\ \tilde{x}^1\right)\right] \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} \left[b\left(\theta_j, x_j^0, x_j^1\right) - b\left(\tilde{\theta}, \tilde{n}\ \tilde{x}^0, \tilde{n}\ \tilde{x}^1\right)\right] - D(X)\right). \end{aligned}$$

For each of the four views, the **E**galitarian **E**quivalent mechanism is characterized by the appropriate combination of **GSIC** and **EpcCRIC**.

Theorem 4

*A mechanism satisfies **HR-GSIC** and **HR-EpcCRIC** if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = \mathbf{t}^{HR-EE}.$$

A mechanism satisfies ***nHR-GSIC*** *and* ***nHR-EpcCRIC*** *if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta},\mathbf{x}^0,\mathbf{x}^1\right)=\mathbf{t}^{nHR-EE}.$$

A mechanism satisfies ***GF-GSIC*** *and* ***GF-EpcCRIC*** *if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta},\mathbf{x}^0,\mathbf{x}^1\right)=\mathbf{t}^{GF-EE}.$$

A mechanism satisfies ***ES-GSIC*** *and* ***ES-EpcCRIC*** *if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta},\mathbf{x}^0,\mathbf{x}^1\right)=\mathbf{t}^{ES-EE}.$$

Proof. We shall prove the result using the **nHR** viewpoint, but the proof technique is similar for the other "views".
It is easily checked that t^{nHR-EE} satisfies the required axioms.
Conversely, let $\left(\boldsymbol{\theta},\mathbf{x}^0,\mathbf{x}^1\right)\in\mathcal{P}$ and $(\tilde{\theta},\tilde{n}\ \tilde{x}^0)\in\Theta\times\mathbb{R}_+$. Denote $\tilde{P}=\left(\tilde{\boldsymbol{\theta}},\tilde{n}\ \tilde{\mathbf{x}}^0,\mathbf{x}^1\right)$ that is

$$\tilde{P}=((\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_1^1),(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_2^1),...,(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_n^1)).$$

For all $k=1,...,n-1$, define

$$P^k=((\theta_1,x_1^0,x_1^1),...,(\theta_k,x_k^0,x_k^1),(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_{k+1}^1),...,(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_n^1)),$$

and let $P^n=P=\left(\boldsymbol{\theta},\mathbf{x}^0,\mathbf{x}^1\right)$.
Let $\tilde{X}$, X^k and X be the emissions levels associated with $\tilde{P}$, the P^k's and P^n respectively.
By Anonymity and **nHR-EpcCRIC**, we know that

$$\left(t_i\left(\tilde{\boldsymbol{\theta}},\tilde{n}\ \tilde{\mathbf{x}}^0,\mathbf{x}^1\right)-\left[D\left(\tilde{X}\right)-D\left(\tilde{X}-x_i^1\right)\right]\right)/n_i$$

should not depend upon country i. It follows

$$\begin{aligned}t_i^{nHR}(\tilde{P}) &= \left[D\left(\tilde{X}\right)-D\left(\tilde{X}-x_i^1\right)\right]\\ &\quad+\frac{n_i}{\sum_{j\in N}n_j}\left(D(\tilde{X})-\sum_{j\in N}\left[D\left(\tilde{X}\right)-D\left(\tilde{X}-x_j^1\right)\right]\right),\end{aligned}$$

for all $i\in N$.
Next, switching from global warming problems $\tilde{P}$ to P^1, **nHR-GSIC** writes

$$\begin{aligned}&\left[b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_1^1\right)-t_1^{nHR}\left(\tilde{P}\right)\right]/n_1-\left[b\left(\theta_1,x_1^0,x_1^1\right)-t_1^{nHR}\left(P^1\right)\right]/n_1\\ &\qquad=\left[t_i^{nHR}\left(P^1\right)-t_i^{nHR}\left(\tilde{P}\right)\right]/n_i,\end{aligned}$$

all $i\neq 1$. This yields:

$$\begin{aligned}t_1^{nHR}\left(P^1\right)-t_1^{nHR}\left(\tilde{P}\right) &= \frac{n_1}{\sum_{j\in N}n_j}\left[D\left(X^1\right)-D\left(\tilde{X}\right)\right]\\ &\quad-\left(1-\frac{n_1}{\sum_{j\in N}n_j}\right)\left[b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_1^1\right)-b\left(\theta_1,x_1^0,x_1^1\right)\right]\end{aligned}$$

and

$$t_i^{nHR}\left(P^1\right)-t_i^{nHR}\left(\tilde{P}\right) = \frac{n_i}{\sum_{j\in N} n_j}\left[D\left(X^1\right)-D\left(\tilde{X}\right)\right] + \frac{n_i}{\sum_{j\in N} n_j}\left[b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_1^1\right)-b\left(\theta_1,x_1^0,x_1^1\right)\right],$$

for all $i \neq 1$.Moving up from P^1 to P^2 and applying again **nHR-GSIC** gives

$$t_2^{nHR}\left(P^2\right)-t_2^{nHR}\left(P^1\right) = \frac{n_2}{\sum_{j\in N} n_j}\left[D\left(X^2\right)-D\left(X^1\right)\right] - \left(1-\frac{n_2}{\sum_{j\in N} n_j}\right)\left[b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_2^1\right)-b\left(\theta_2,x_2^0,x_2^1\right)\right],$$

so that

$$\begin{aligned} t_2^{nHR}\left(P^2\right)-t_2^{nHR}\left(\tilde{P}\right) &= b\left(\theta_2,x_2^0,x_2^1\right)+\frac{n_2}{\sum_{j\in N} n_j}D\left(X^2\right) \\ &\quad -b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_2^1\right)-\frac{n_2}{\sum_{j\in N} n_j}D\left(\tilde{X}\right) \\ &\quad +\frac{n_2}{\sum_{j\in N} n_j}\sum_{k=1}^{2}\left[b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_k^1\right)-b\left(\theta_k,x_k^0,x_k^1\right)\right]. \end{aligned}$$

Successively applying **nHR-GSIC** while moving up to P^n yields the result:

$$\begin{aligned} t_i^{nHR}\left(P\right)-t_i^{nHR}\left(\tilde{P}\right) &= b\left(\theta_i,x_i^0,x_i^1\right)+\frac{n_i}{\sum_{j\in N} n_j}D\left(X\right) \\ &\quad -b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_i^1\right)-\frac{n_i}{\sum_{j\in N} n_j}D\left(\tilde{X}\right) \\ &\quad -\frac{n_i}{\sum_{j\in N} n_j}\sum_{j\in N}\left[b\left(\theta_j,x_j^0,x_j^1\right)-b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_j^1\right)\right], \end{aligned}$$

that is

$$\begin{aligned} t_i^{nHR}\left(P\right) &= b\left(\theta_i,x_i^0,x_i^1\right)-b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_i^1\right)+\left[D\left(\tilde{X}\right)-D\left(\tilde{X}-x_i^1\right)\right] \\ &\quad -\frac{n_i}{\sum_{j\in N} n_j}\sum_{j\in N}\left[b\left(\theta_j,x_j^0,x_j^1\right)-b\left(\tilde{\theta},\tilde{n}\ \tilde{x}^0,x_j^1\right)\right] \\ &\quad -\frac{n_i}{\sum_{j\in N} n_j}\left(\sum_{j\in N}\left[D\left(\tilde{X}\right)-D\left(\tilde{X}-x_j^1\right)\right]-D\left(X\right)\right), \end{aligned}$$

where $\tilde{X}=\tilde{X}^0+X^1$. ■

4.2 Conditionally Equivalent mechanism

The *Conditionally Equivalent mechanism* guarantees each agent the average payoff of a hypothetical situation in which all countries have the characteristics

they are responsible for equal to a reference level. Each country bears the consequences of any deviation from this reference level. Formally,

Definition 5 ***C****onditionally* ***E****quivalent transfer:*
For any $(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1) \in \mathcal{P}$ *and any reference vector of* relevant *characteristics* $(\tilde{x}^0, \tilde{x}^1) \in \mathbb{R}_+$,

HR-CE *For any* $i \in N$,

$$\begin{aligned} t^{HR-CE} &= b(\theta_i, n_i\tilde{x}^0, n_i\tilde{x}^1) + (x_i - n_i\tilde{x}) \left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}} \right) \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} b(\theta_j, n_j\tilde{x}^0, n_j\tilde{x}^1) - D\left(\tilde{X}\right) \right), \end{aligned}$$

where $\tilde{X} = \left(\sum_{j\in N} n_j\right) \tilde{x}$.

nHR-CE *For any* $i \in N$,

$$\begin{aligned} t^{nHR-CE} &= b(\theta_i, x_i^0, n_i\tilde{x}^1) + \left(x_i^1 - n_i\tilde{x}^1\right) \left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}} \right) \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} b(\theta_j, x_j^0, n_j\tilde{x}^1) - D\left(\tilde{X}\right) \right), \end{aligned}$$

where $\tilde{X} = X^0 + \left(\sum_{j\in N} n_j\right) \tilde{x}^1$.

GF-CE *For any* $i \in N$,

$$\begin{aligned} t^{GF-CE} &= b(\theta_i, x_i^0, n_i\tilde{x}^{GF} + \gamma x_i^0) + \left[\left(x_i^1 - \gamma x_i^0\right) - n_i\tilde{x}^{GF}\right] \left(\frac{D(X) - D\left(\tilde{X}\right)}{X - \tilde{X}} \right) \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} b(\theta_j, x_j^0, n_j\tilde{x}^{GF} + \gamma x_j^0) - D\left(\tilde{X}\right) \right), \end{aligned}$$

where $\tilde{X} = (1+\gamma) X^0 + \left(\sum_{j\in N} n_j\right) \tilde{x}^{GF}$ *and* $\tilde{x}^{GF} = \tilde{x}^1 - \gamma\tilde{x}^0$.

ES-CE *For any* $i \in N$,

$$t^{ES-CE} = b(\theta_i, x_i^0, x_i^1) - \frac{n_i}{\sum_{j\in N} n_j} \left(\sum_{j\in N} b(\theta_j, x_j^0, x_j^1) - D(X) \right).$$

In fact, in all four interpretations, the **C**onditionally **E**quivalent mechanism is characterized by the appropriate combination of **FARR** and **EpcPRR**.

Theorem 6

*A mechanism satisfies **HR-FARR** and **HR-EpcPRR** if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = \mathbf{t}^{HR-CE}.$$

*A mechanism satisfies **nHR-FARR** and **nHR-EpcPRR** if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = \mathbf{t}^{nHR-CE}.$$

*A mechanism satisfies **GF-FARR** and **GF-EpcPRR** if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = \mathbf{t}^{GF-CE}.$$

*A mechanism satisfies **ES-EpcPRR** if and only if*

$$\mathbf{t}\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) = \mathbf{t}^{ES-CE}.$$

Proof. We shall prove the result using the **nHR** viewpoint, but the proof technique is similar for the other "views".
It is easily checked that t^{nHR-CE} satisfies the required axioms.
Conversely, let $\left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right) \in \mathcal{P}$ and $\tilde{x}^1 \in \mathbb{R}_+$. Denote $\tilde{P} = \left(\boldsymbol{\theta}, \mathbf{x}^0, \tilde{\mathbf{x}}^1\right)$ that is

$$\tilde{P} = \left(\left(\theta_1, x_1^0, n_1\tilde{x}^1\right), \left(\theta_2, x_2^0, n_2\tilde{x}^1\right), ..., \left(\theta_n, x_n^0, n_n\tilde{x}^1\right)\right).$$

For all $k = 1, ..., n-1$, define

$$P^k = \left(\begin{array}{r} \left(\theta_1, x_1^0, x_1^1\right), ..., \left(\theta_k, x_k^0, x_k^1\right), \left(\theta_{k+1}, x_{k+1}^0, n_{k+1}\tilde{x}^1\right), ... \\ ..., \left(\theta_n, x_n^0, n_n\tilde{x}^1\right) \end{array} \right),$$

and let $P^n = P = \left(\boldsymbol{\theta}, \mathbf{x}^0, \mathbf{x}^1\right)$.
Let $\tilde{X}$, X^k and X be the emissions levels associated with $\tilde{P}$, the P^k's and P^n respectively.
By **A**nonymity and **nHR-EpcPRR,**

$$t_i(\tilde{P}) = b(\theta_i, x_i^0, n_i\tilde{x}^1) - \frac{n_i}{\sum_{j\in N} n_j}\left(\sum_{j\in N} b(\theta_j, x_j^0, n_j\tilde{x}^1) - D\left(\tilde{X}\right)\right),$$

for all $i \in N$.
Next, switching from global warming problem $\tilde{P}$ to P^1, **nHR-FARR** yields:

$$t_1\left(P^1\right) - \left(x_1^1 - n_1\tilde{x}^1\right)\left(\frac{D\left(X^1\right) - D\left(\tilde{X}\right)}{X^1 - \tilde{X}}\right) = t_1\left(\tilde{P}\right),$$

and one can check that, if $t_i\left(P^1\right) = t_i(\tilde{P})$, all $i > 1$ as required by **nHR-FARR** , we have

$$\sum_{j\in N} t_j\left(P^1\right) = \sum_{j\in N} t_j\left(\tilde{P}\right) + D\left(X^1\right) - D\left(\tilde{X}\right) = D\left(X^1\right).$$

Switching from P^k to P^{k+1} yields

$$t_j\left(P^{k+1}\right) - \left(x_j^1 - n_j\tilde{x}^1\right)\left(\frac{D\left(X^{k+1}\right) - D\left(\tilde{X}\right)}{X^{+1} - \tilde{X}}\right) = t_j\left(\tilde{P}\right),$$

all $j \leq k$ and $t_j\left(P^{k+1}\right) = t_j\left(\tilde{P}\right)$ otherwise. It follows

$$\begin{aligned} t_i\left(P\right) &= \left(x_i^1 - n_i\tilde{x}^1\right)\left(\frac{D\left(X\right) - D\left(\tilde{X}\right)}{X - \tilde{X}}\right) + t_i(\tilde{P}) \\ &= b(\theta_i, x_i^0, n_i\tilde{x}^1) + \left(x_i^1 - n_i\tilde{x}^1\right)\left(\frac{D\left(X\right) - D\left(\tilde{X}\right)}{X - \tilde{X}}\right) \\ &\quad - \frac{n_i}{\sum_{j\in N} n_j}\left(\sum_{j\in N} b(\theta_j, x_j^0, n_j\tilde{x}^1) - D\left(\tilde{X}\right)\right), \end{aligned}$$

where $\tilde{X} = X^0 + \left(\sum_{j\in N} n_j\right)\tilde{x}^1$. ■

5 On procedural acceptability

We argue that cost shares be independent of the level of aggregation adopted to evaluate past and future emission levels. This feature seems to us particularly relevant for essentially two reasons. First, because if required transfers differ whether, say, Canada is considered at the federal level or each state is considered separately, divergent interests are likely to postpone and possibly forbid any agreement over the procedure to share the costs of climate change. Second, the problem at hand encompasses extended periods of time over which the structure of countries and political landscapes are subject to change (e.g. Europe, Yougoslavia, etc.). We thus claim that any well-defined recommendation should be insensitive to the structure of countries and their coalitions. This requirement, we name **A**ggregation **I**ndependence appears in different contexts under the name "No Merging or Splitting" (See Sprumont 2005 [33]).
As explained in Moulin and Sprumont 2007 [22], **A**ggregation **I**ndependence is closely related[8] to the "No Reshuffling" property, according to which the aggregate contribution of a group of agents should depend only on their aggregate

[8] In fact, **A**ggregation **I**ndependence implies "No Reshuffling".

consumption. This makes clear that accounting for countries characteristics is severely limited under the **A.I**; In particular, for "most" functions $b(.)$, the complex schemes considered above fail to satisfy **A**ggregation **I**ndependence.[9]

In general, there is no clear divide between surplus sharing and cost sharing. In fact, any cost-sharing mechanism where, for any agent, an increase (resp. decrease) in individual benefits yields to an equal increase (resp. decrease) in transfers can be interpreted as a surplus-sharing scheme. Yet, if **A**ggregation **I**ndependence is imposed, the set of available transfers is restricted. Thus adopting one approach or the other may not only be a question of perspective. In fact, as we shall see, the view one holds in terms of responsibility have some bite on the set of consistent mechanisms.

More precisely, we argue that, if countries are considered *not to be responsible* for what happened in the past (the **nHR,** the **GF** view), *total surplus* rather than costs should be shared. In fact, according to this view, no country should either be penalized or rewarded for its past emissions. This says that final allocation should not depend upon the x_i^0s; and to the extends that it does impact its ability in deriving benefits, one may argue that it should not depend upon the b_is either. Yet, there are several views on how this should be done. As above, we consider two in particular, as attached respectively to the **nHR** and **GF** view. In the first case, countries net payoff $b_i - t_i$ should not depend upon any country characteristics but the x_i^1s. In the second, it should depend upon the sole $x_i^{GF} = x_i^1 - \gamma x_i^0$. In both cases, payments (or financial transfers) t_i should wash out any difference streaming from the b_is, hence explicitly *depend* on it.

By contrast, countries may be held *fully responsible* for what happened in the past. Since past consumption directly impact their ability to derive benefits, this says that countries are considered to be responsible of their b_is. It follows that responsibility for the past is rather to be associated with a *cost sharing* approach. Since the cost of global warming depends upon total emissions only (and not their time profile), one may argue that contributions t_is should be related to countries cumulated emissions x_i^T. This is what we refer to as the **HR** view.

While the different concept of responsibility call to privilege either a surplus-sharing or a cost-sharing approach, the adopted approach yield in turn to different formulation of **A**ggregation **I**ndependence. In what follows, we illustrate how these considerations jointly determine the appropriate set of available schemes.

5.1 No responsibility for the past

Consider first that countries cannot be held responsible for the past. Assume that this translate into the requirement that countries net payoff $b_i - t_i$ cannot depend upon their past emissions x_i^0. If this **S**urplus-**S**haring approach is adopted, **A**ggregation **I**ndependence writes:

[9] This essentially never the case, unless benefits are linear in emissions.

Axiom 9 (AI for SS) ***A****ggregation* ***I****ndependence for* ***S****urplus* ***S****haring. Fix N, b, d and x^0.*
Let $i \in N$ and $I \subset \mathbb{N}$ such that $N \cap I = \emptyset$. Denote $N' = (N \backslash i) \cup I$.
For any $x^1 \in \mathbb{R}^N_+$, any $x'_I \in \mathbb{R}^N_+ \times \mathbb{R}^N_+$ such that

$$\sum_I x'^0_{i'} = x^0_i \quad \text{and} \quad \sum_I x'^1_{i'} = x^1_i,$$

and any $b' \in \mathcal{B}(N')$ and $d' \in \mathcal{D}(N')$ such that

$$b'(x) = (b_{N\backslash i}(x_{N\backslash i}), b_I(x'_I)) \quad \text{and} \quad \sum_{i'} d'_{i'}(X^T) = d_i(X^T),$$

we have:

$$\sum_I t_{i'}(N', \mathbf{b}', \mathbf{d}', (x'_I, x_{-I})) = t_i(N, \mathbf{b}, \mathbf{d}, x),$$

and

$$b_j - t_j(N', \mathbf{b}', \mathbf{d}', (x'_I, x_{-I})) = b_j - t_j(N, \mathbf{b}, \mathbf{d}, x) \quad \text{for all } j \in N \backslash i. \tag{1}$$

Proposition 7 *All transfer payments satisfying* ***A****ggregation* ***I****ndependence in the* ***S****urplus-****S****haring framework can be written as:*

$$b_i - t_i(N, \mathbf{b}, \mathbf{d}, x) = \gamma_i(\mathbf{b}, \mathbf{d}, X^T) - \beta(\mathbf{b}, \mathbf{d}, X^T) x^1_i$$

with β, and the γ_i's so that transfer payments sum up to $D(X^T)$.

A natural scheme consists in making γ_i dependent upon country i population as to have a constant *per capita* fixed contribution. This yields

$$b_i - t_i = \frac{n_i}{\sum_{j \in N} n_j}(B - D) - \beta\left(x^1_i - \frac{n_i}{\sum_{j \in N} n_j} X^1\right),$$

or

$$t_i\left(x^1_i\right) = b_i + \beta\left(x^1_i - \frac{n_i}{\sum_{j \in N} n_j} X^1\right) - \frac{n_i}{\sum_{j \in N} n_j}(B - D),$$

where $\left(n_i / \sum_{j \in N} n_j\right)$ is the relative population of country i and β a non-negative parameter.

In accordance with **G**rand-**F**athering, one could consider that the x^0_is constitute a natural benchmark for the "needs" of the respective countries; and that countries are responsible for x^{GF}_i. This may yield one to propose

$$b_i - t_i = \frac{n_i}{\sum_{j \in N} n_j}(B - D) - \beta\left(x^{GF}_i - \frac{n_i}{\sum_{j \in N} n_j} X^{GF}\right),$$

or

$$t_i\left(x^{GF}_i\right) = b_i + \beta\left(x^{GF}_i - \frac{n_i}{\sum_{j \in N} n_j} X^{GF}\right) - \frac{n_i}{\sum_{j \in N} n_j}(B - D).$$

Interestingly enough, neither **E**galitarian **E**quivalent mechanisms nor **C**onditionnally **E**quivalent mechanisms appear to satisfy **A**ggregation **I**ndependence in the **S**urplus-**S**haring framework, unless the function $b(.)$ displays (at least some) linearity in its argument.

5.2 Historical Responsibility

We assume that if countries are held responsible for past-emissions, a **C**ost-**S**haring approach is adopted. In this context, **A**ggregation **I**ndependence writes:

Axiom 10 (AI for CS) ***A****ggregation* ***I****ndependence for a* ***C****ost-****S****haring. Fix* N, b, d *and* x^0.
Let $i \in N$ *and* $I \subset \mathbb{N}$ *such that* $N \cap I = \emptyset$. *Denote* $N' = (N \backslash i) \cup I$.
For any $x^1 \in \mathbb{R}^N_+$, *any* $x'_I \in \mathbb{R}^N_+ \times \mathbb{R}^N_+$ *such that*

$$\sum_I x'^0_{i'} = x^0_i \quad \textit{and} \quad \sum_I x'^1_{i'} = x^1_i,$$

and any $b' \in \mathcal{B}(N')$ *and* $d' \in \mathcal{D}(N')$ *such that*

$$b'(x) = (b_{N\backslash i}(x_{N\backslash i}), b_I(x'_I)) \quad \textit{and} \quad \sum_{i'} d'_{i'}(X^T) = d_i(X^T),$$

we have:

$$\begin{aligned} &\sum_I t_{i'}(N', \mathbf{b}', \mathbf{d}', (x'_I, x_{-I})) = t_i(N, \mathbf{b}, \mathbf{d}, x), \\ \textit{and} \quad & \\ &t_j(N', \mathbf{b}', \mathbf{d}', (x'_I, x_{-I})) = t_j(N, \mathbf{b}, \mathbf{d}, x) \qquad \textit{for all } j \in N\backslash i. \end{aligned} \tag{2}$$

Proposition 8 *All transfer payments satisfying* ***A****ggregation* ***I****ndependence in the* ***C****ost-****S****haring framework can be written as:*

$$t_i(N, \mathbf{b}, d, x) = \alpha(\mathbf{b}, d_i, X^T)x^0_i + \beta(\mathbf{b}, d_i, X^T)x^1_i + \gamma_i(\mathbf{b}, d_i, X^T)$$

with α, β, *and the* γ_i*'s so that transfer payments sum up to* $D(X^T)$.

Proof. Fix N, b, d and x^0 and let $x^1 \in \mathbb{R}^N_+, I, b', d'$ and x'_I as in the definition of **AI**. Because $t_j(N', b', d', (x'_I, x_{-I})) = t_j(N, b, d, x)$ for any $j \in N\backslash i$, transfers t_j are necessarily independent of the coalition structure, $N\backslash j$. Also, t_j's dependence in x^0 (resp. x^1) is limited to x^0_j and X^0 (resp. x^1_j and X^1). Similarly, t_j's dependence in d is limited to d_j and D. Thus, for any $j \in N\backslash i$:

$$t_j(b', d_j, D', X^0, x^0_j, X^1, x^1_j) = t_j(b, d_j, D, X^0, x^0_j, X^1, x^1_j).$$

Moreover, because x^0 (and, consequently, X^0) and D are taken to be exogenous, we lighten notations and simply write $t_j(b, d_j, X^T, x_j)$. The result follows almost immediately[10] from Expression 2 and a result in Aczél (Chap. 7, Theorem 1). ■

[10] A bit of manipulation must be done to handle the fact that X^0 is exogenous.

Various natural payment schemes are available.
First of all, since GHG have almost no decay, one may ask that past and future emissions be treated symmetrically. This view, which is congruent with **H**istorical **R**esponsibility yields

$$\alpha = \beta = \frac{D(X_T) - \sum_{i \in I} \gamma_i(N, \mathbf{b}, D(X_T))}{X_T},$$

and a two-part tariff scheme: a personalized lump sum, as indicated by the γ_i's followed by a uniform rate per unit of emissions (past or future):

$$t_i(N, \mathbf{b}, D, \mathbf{x}) = \beta(\mathbf{b}, D, X^T) x_i^T + \gamma_i(\mathbf{b}, D, X^T)$$

In particular, choosing $\gamma_i = b_i D(X_T) / \left[\sum_j b_j(x_j)\right]$ amounts to splitting the costs proportionally to each country's benefit $b_i(x_i)$. Similarly, choosing $\gamma_i = n_i D(X_T) / \sum_j n_j$, leads to *per capita* equal sharing of the total environmental damage, irrespective of emission levels.

Again, neither **E**galitarian **E**quivalent mechanisms nor **C**onditionnally **E**quivalent mechanisms appear to satisfy **A**ggregation **I**ndependence. If the later property is imposed, it is to us an open question to understand what are the "appropriate" weights in the two formulas provided above. This together with the more general issue of the "bite" of **AI** (how much is lost in terms of "efficiency" and/or "fairness" when it is imposed), is left for future research.

6 Some Figures

As already mentioned, global warming hits very differently the various regions of the globe. Some pacific islands may well disappear in the short run, while having had almost no emissions. Even if global warming were not linked with anthropomorphic activities but a purely natural catastrophe, it appears a mankind duty to provide help to the hurt populations. We take the view that no one bears any responsibility for the place where he/she was born; and as a consequence, "full insurance" should be provided in order to allow the countries to cover the damages that follow from global warming. Yet the associated costs will have to be shared across the countries. It is the purpose of the present paper to understand how this ought and should be done.

Interestingly enough, since our solution concept supposes "complete coverage", we can abstract from the exact distribution of damages. In fact, we posit total damages D to amount to a given fraction of world GDP and focus upon the way these costs are re-distributed across countries.

The above is illustrated by using CAIT[11], a database of the World Resources Institute (See [7]). GDP and Population refer to year 2004. Cumulative emissions (X^0) are provided for the period 1950-2000. Current emissions (X^1) are those of 2000. The database contains 185 countries. However, GDP was not provided neither for Barbados nor for Bosnia. Therefore, both were dropped from

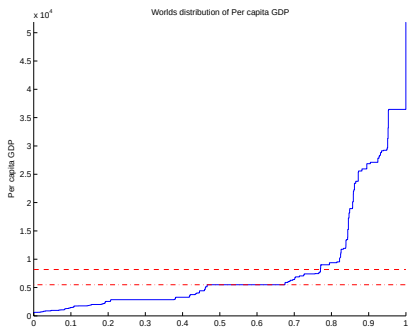
[11] Climate Analysis Indicator Tools: http://cait.wri.org/

the analysis. For all other countries, GDP and cumulated and current emissions figures are available. Although some complementary data were missing, the analysis is performed for these 183 countries. We proceed in three steps. First, an overview of the issue at hand is provided through basic statistics. Then the benefit function is estimated. Finally, on the basis of this estimate, the different transfer schemes are computed. The whole exercise is performed for various damage levels but for a damage function which is assumed to be linear.

6.1 Distribution of wealth and distribution of emissions

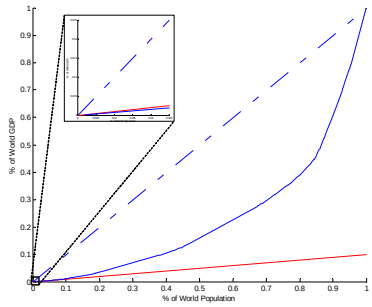
In order to appreciate the working of the different schemes, it may be useful to consider first the distribution of the different characteristics at hand. We provide here a broad overview. More descriptive statistics are provided in appendix, together with a detailed analysis.

According to the data set, in 2004, global GDP amounted to US $: 51 804 billions for a world population estimated at 6.33 billion. Average *per capita GDP* was thus US $: 8 186. Yet, the yearly income of the median individual, which is Chinese, amounted to US $: 5 490, about US $ 15 a day. The poorest country (in *per capita* terms) is Malawi with a *per capita GDP* of US $: 591. The *per capita GDP* of the richest, Luxembourg, is about 88 times higher. More precisely, it amounts to US $ 51 892. These figures are row estimates in that they do not account for within country heterogeneity. Yet they provide an interesting benchmark to recognize the challenge at stake.



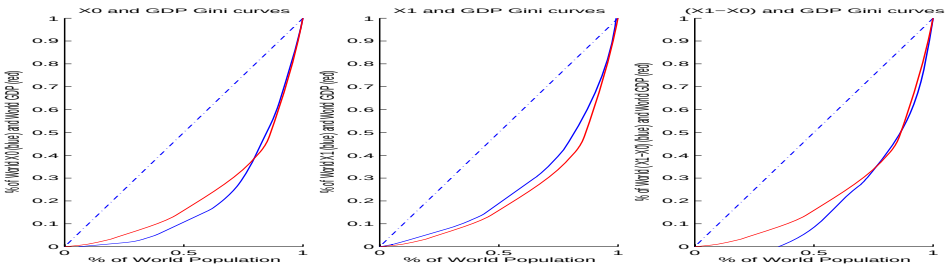
If damages of global warming amount to 10%, 1% or 0.1% of *global GDP* and the costs where equally split (on a per capita basis), the required yearly contribution would amount to respectively, US $: 819, US $: 82 and US $: 8 *per capita.* The highest figure exceeds the *per capita GDP* of the nine poorest countries, whose joint population exceeds 180 million people (0.7% of world population). The median figure amount to about 14% of the *per capita GDP* of the poorest country, Malawi, where 12.6 million people would live with on average US $: 1.6 a day. The lowest figure corresponds still for the inhabitants

of Malawi to a relative loss of *GDP* which is 14 times higher than the global average relative loss.



Gini Curve and Equal Sharing of Damages when $D = 10\%$ of World GDP.

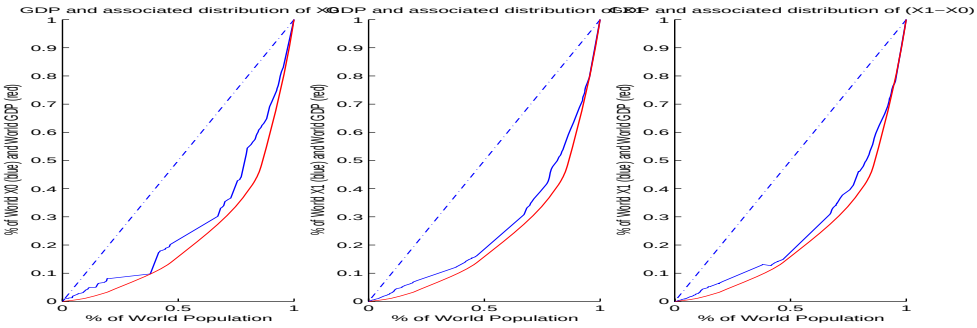
As compared to the *per capita GDP* distribution, the distribution of current *per capita* emissions x^1/n is *more* egalitarian. The ranking of cumulated *per capita* emissions x^0/n and *per capita GDP* is less clear since both curve cross. However, on the basis of their Gini coefficient x^0/n is *less* egalitarian than the *per capita GDP* distribution. The distribution of *per capita* emissions as accounted for according to the **G**rand-**F**athering view $\left(x^1 - x^0\right)/n$ displays one interesting feature. Even if the emission "rights" associated to **G**rand-**F**athering are very limited (as for current figure where they amount to 50% of current emissions), a consistent fraction appear to emit little enough to be considered as having *negative* emissions.



Emissions Gini Curve (blue) and *GDP* (red) Gini Curve – Left X^0 - Center X^1 - Right $\left(X^1 - X^0\right)$

To assess the risdistributive effects of a taxation scheme based upon x_0, x_1 or made according to the **G**rand-**F**athering view, one should however consider the distribution of emissions "associated" to the *GDP* distribution. As appears clearly in the figure below, the (cumulative) distribution of emissions appear to be above the *GDP Gini curve,* whatever the "view" which is considered.

This says that, distributing costs according to emissions _ as when a taxation scheme is adopted _ tend to be *regressive.* Of course a more precise assessment of the effects of taxation requires a study on a per country basis. Again a more detailed analysis is provided in appendix.



GDP distribution (red) and associated distribution of emissions (blue) – Left X^0 - Center X^1 - Right $\left(X^1 - X^0\right)$.

It is pretty clear that a *regressive* scheme is likely to be problematic. This is not only true from a normative point of view. Remind indeed that a simple egalitarian split may already fail feasibility as a result of a *per capita* contribution exceeding *per capita* GDP in the poorest countries. Even if taxation schemes yield less striking outcomes, their regressivity makes them unlikely implementable, for they will generate fierce resistance if not conflicts. Thus, even if income redistribution may be considered as a distinct issue, it cannot be completely ignored. This is to say, whatever the view in terms of responsibility, *some* redistribution as to be performed. We attempt however to distinguish as much as possible our cost-sharing problem from the question of income redistribution. One of the merits of the axiomatic approach is precisely to make clear the principles that govern the design of the various possible schemes. In particular, when compared to **E**galitarian **E**quivalent mechanisms, **C**onditionally **E**quivalent mechanism appear not to accomodate in terms of responsability

Note that, even when ignoring the feasibility issue and focussing on the sole cost-sharing problem, it make sense to require that burden of global warming be shared according, not only the costs of countries emissions but also the benefits theses countries have been able to derive from it. This says that the relationship between countries' emissions and GDP is to be assessed. This is the purpose of what comes next.

6.2 Estimation of the benefit function

Clearly, emissions are linked to energy use and the later to development. A simple regression confirms this view without no ambiguity:

$$\ln b_i = \underset{(58.875)}{7.794407} \; \underset{(3.097)}{+0.070877} \ln x_i^0 + \underset{(21.013)}{0.676069} \ln x_i^1 + \epsilon_i.$$

Yet, neither x^0 nor x^1 are perfectly correlated with GDP. In fact, the ratio (*Standard Deviation / Mean*) of x^0/GDP and x^1/GDP amount respectively to 1.91 and 0.85. Of course, standard deviation is a measure of dispersion which is very sensitive to outliers and there are some. However, the ratio (*Mean Absolute Deviation / Mean*), which is less so gives also pretty pretty high figures (0.98 and 0.58 for x^0/GDP and x^1/GDP respectively). This stress the importance of other determinants for GDP, hence the usefulness of acquiring a more complete picture of its generation process. It also underlines the relevance of accounting for other characteristics than the sole emissions in the design of the cost-sharing scheme.

A fundamental determinant of GDP is naturally the population n_i. In principle, the "heating degree days" dH_i and the "cooling degree days" dC_i provide us with the fundamental indicators for the "energy needs". Absent other geographical factor, dH_i appear actually to reflect the global distribution of wealth, which is relatively more concentrated in colder countries. In fact we obtain:

$$\begin{aligned}\ln b_i \quad = \quad & \underset{(15.678)}{4.832184} + \underset{(6.063)}{0.344913} \ln n_i + \underset{(3.035)}{0.026649} \ln\left(1 + n_i\ dH_i\right) - \underset{(2.940)}{0.042805} \ln\left(1 + n_i\ dC_i\right) \\ & + \underset{(2.635)}{0.739785} \ln\left(1 + x_i^0/n_i\right) + \underset{(11.791)}{0.787448} \ln\left(1 + x_i^1\right) + \varepsilon_i. \end{aligned} \tag{3}$$

The R^2 associated to this linear regression is 0.9159. Postponing for the time being the search for a better estimate[12] we set the function b to

$$b\left(\theta_i, x_i^0, x_i^1\right) = A\left(\theta_i\right)\left(1 + \frac{x_i^0}{n_i}\right)^{\alpha_0}\left(1 + x_i^1\right)^{\alpha_1}$$

where $\alpha_0 = 0.739785$ and $\alpha_1 = 0.787448$; the function $A\left(\theta_i\right)$ stands for

$$A\left(\theta_i\right) \equiv A\left(n_i, dH_i, dC_i, \varepsilon_i\right) = A\left(n_i\right)^{\alpha_n}\left(1 + n_i\ dH_i\right)^{\alpha_{dH}}\left(1 + n_i\ dC_i\right)^{\alpha_{dC}}\varepsilon_i,$$

where $A = \exp\left(4.832184\right) = 125.4847$, $\alpha_n = 0.344913$, $\alpha_{dH} = 0.026649$, $\alpha_{dC} = -0.042805$ and where ε_i is the residual of (3).
Note in particular that residuals are considered to be a characteristic countries are not responsible for.

6.3 Redistributive effects of the cost-sharing mechanisms

We are now ready to explore the working of the different cost-sharing schemes.
We consider first "**T**axation", then "**E**galitarian **E**quivalent" mechanisms, "**C**onditionally **E**quivalent" mechanisms and finally a sample of mechanisms that satisfy "**A**ggregation **I**ndependence".

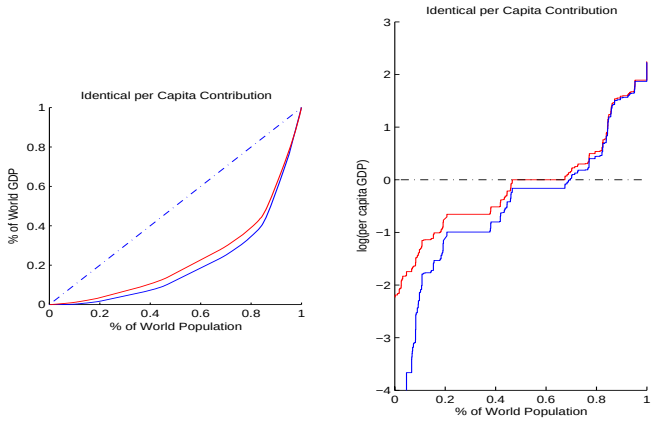
6.3.1 Taxation

The External Shock view The **E**xternal **S**hock view is an interesting benchmark in that allows us to distinguish between the question of solidarity from

[12] See appendix for a discussion of the estimation.

the question of responsibility. In fact, remind that, according to the **E**xternal **S**hock view, mankind bears absolutely no responsibility in climate change. The cost-sharing mechanism follows from countries' solidarity in facing an exogenous adverse event.

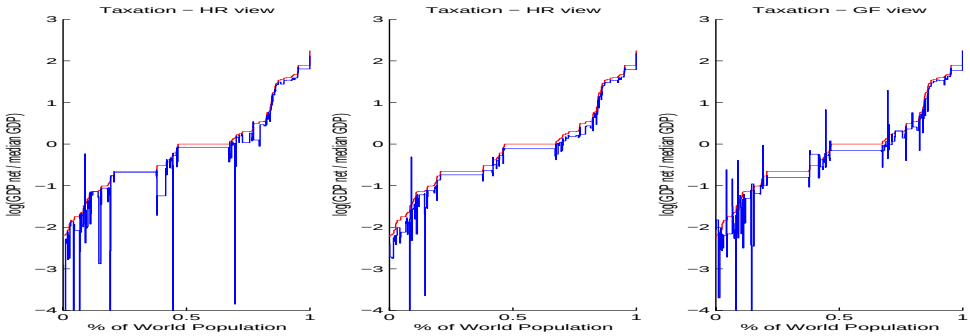
In this contest, consider two natural scheme. Assume first that there is a unique "*per capita* contribution" which total amount exactly cover damages D. This yields the following ex-post Gini curve for the GDP distribution:



Ex-ante (red) and ex-post (blue) curves for the GDP distribution

Clearly, the scheme is highly regressive (ex-post Gini curve is below the ex-ante Gini curve). Remind also that it may not feasible if damages are "high enough". In fact, if damages were to exceed the 7.22% of world GDP, the required contribution would wash out the whole GDP of the poorest country.
Another natural scheme consists in setting a "*per capita* contribution" proportional to *per capita GDP*. By definition, such a scheme has no redistributive impact. However, it is clearly inappropriate if anthropomorphic emissions have some responsibility in climate change. This is now what we turn to consider.

Taxation along the HR, nHR and GF views There are clear differences across the taxation schemes associated to the different views. In particular, as may be observed by comparing the left-hand side and the right-hand side of the figure below, **G**rand-**F**athering tend to be disadvantageous for growing countries like India and China, for which current emissions are relatively higher than cumulated emissions. The converse holds true for a country like Indonesia for which the relative contribution of cumulated emissions is 4.8 times higher than its current relative contribution.



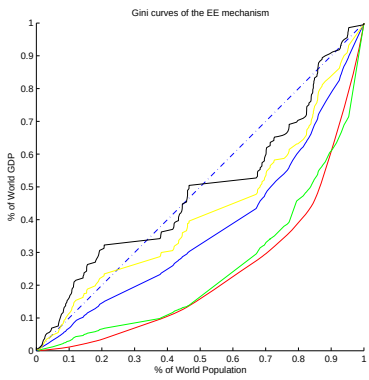
Ex-ante (red) and ex-post (blue) curves for the GDP distribution

On the whole however, none of the taxation scheme appear to sensibly modify the global distribution of income. The ex-post gini curves appear sensibly identical, although, they all tend to be regressive.

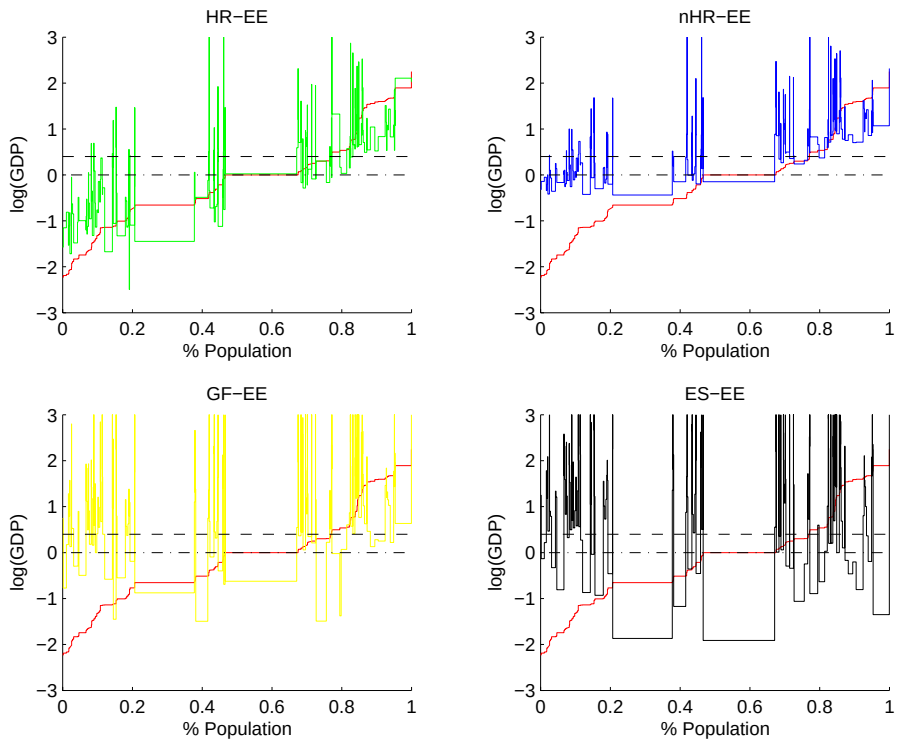
6.3.2 Egalitarian Equivalent mechanisms

The various versions of the **E**galitarian **E**quivalent mechanism are computed for reference vectors equal to the *average* values of the characteristics countries are not considered to be responsible for. Moreover, the pollution "rights" associated to the Grand-Fathering mechanism is set up at $\gamma = 0.5\left(X^1/X^0\right)$.

Two features can be observed. First, they all display a high "variability": more precisely, countries with almost similar *per capita* GDP levels *ex-ante* may well end up with very different *per capita* GDP level ex-post. Second, they may be ranked unambiguously in terms of redistribution. More precisely, the **HR-EE** mechanism leave almost unchanged the wealth distribution, except for the first decile which ends up better ex-post than ex-ante. The less responsibility, the more redistributive the mechanism.



Gini curves associated with the various **E**galitarian **E**quivalent mechanisms.



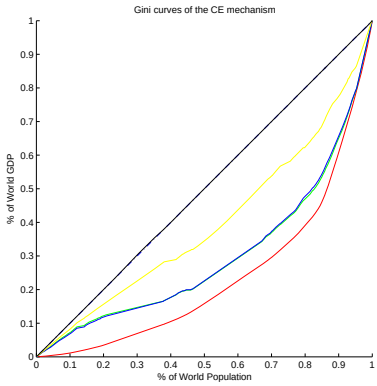
GDP distribution associated with the various **E**galitarian **E**quivalent mechanisms

6.3.3 Conditionnally Equivalent mechanisms

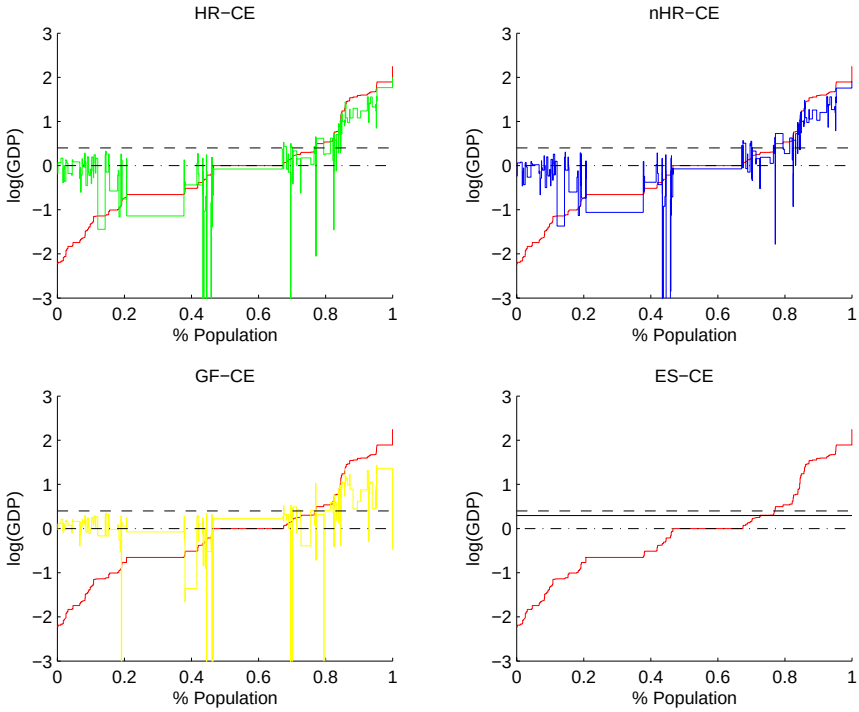
The various versions of the **C**onditionnally **E**quivalent mechanism are computed for reference vectors equal to the *average* values of the characteristics countries are considered to be responsible for. Again, the pollution "rights" associated to the **G**rand-**F**athering mechanism is set up at $\gamma = 0.5\left(X^1/X^0\right)$.

All schemes operate a strong redistribution in favor of the two lowest deciles of the GDP distribution. The **ES-CE** yields to the egalitarian outcome. The **GF-CE** mechanism is also fairly redistributive. **HR-CE** and **nHR-CE** are very similar. They leave roughly unchanged the upper par of the distribution.

Although **CE** schemes display some "variability", they appear to provide more reasonable outcomes than **EE** schemes. This may follow from the very fact that it is easier to define a reasonable reference for emissions than provide a reference profile for other countries characteristics.



Gini curves associated with the various **C**onditionally **E**quivalent mechanisms.



GDP distributions associated with the various **E**galitarian **E**quivalent mechanisms.

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7 Appendix

7.1 Descriptive Statistics

Standard descriptive statistics for our data set (an extraction of CAIT) are provided in the following table.

	Average	Median	Std. Err.	Min	Max
Population (in thousands)	34588	7781	128339	2	1296157
GDP (in million US$)	283082	27454	1037354	8	10703900
Per capita GDP (in US$)	8922	5234	9584	591	51927
X^0 (in MtCO2)	5991	871	19473	-828	186669
Per capita X^0 (in Tons CO2)	221	134	346	-241	3386
X^1 (in MtCO2)	182	28	661	0	6868
Per Capita X^1 (in Tons CO2)	6	4	6	0	43
Heating d^o days	1078	118	1512	0	6681
Cooling d^o days	1648	1242	1311	0	4064

The great *heterogeneity* of countries' characteristics is to be stressed. The country with the largest population, China is more than 600000 times bigger than the less populated, Niue, with about 2000 inhabitants. When accounting for land use change, *four* countries appear to have *negative* cumulated emissions over the period 1950-2000: Uruguay, Vietnam, Swaziland and Gambia with respectively, -827.7, $-551.2, -36.1$ and -2 MtCO2. This contrasts with the European Union (25) whose cumulated emissions are estimated to 176560.6 MtCO2 and with the United States of America for which the figure amounts to 186669.1 MtCO2. In terms of current emissions, Niue or the Cook Islands appear to have almost no emissions while, in 2000, both the EU and China appear to have emitted around 5000 MtCO2 while the US was about to reach 7000 MtCO2 (6867.9 exactly). There is no need to underline the differences across countries in terms of temperature; not to mention other characteristics we have not been able to account for.

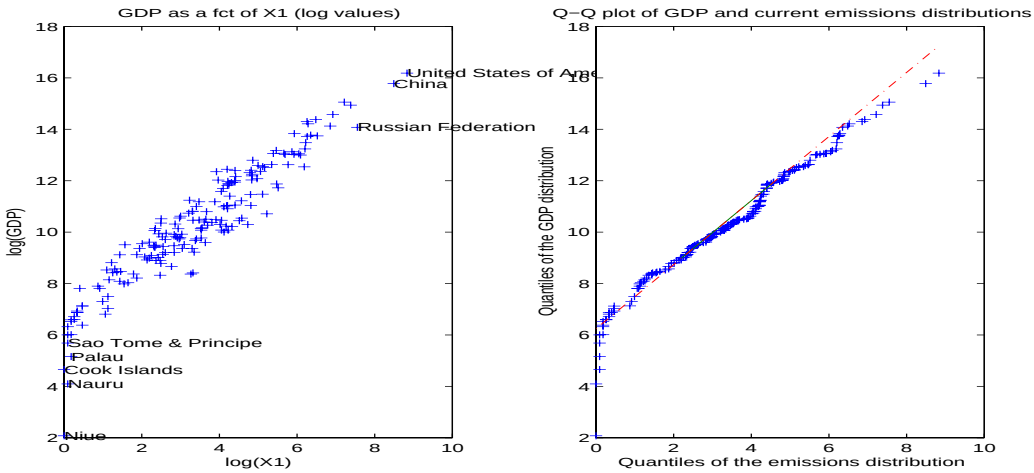
This is true even when considering *per capita* values. As already mentioned the GDP of the richest country, Luxembourg is 88 times higher than the GDP of the poorest countries, Malawi. Guyana and Belize that whose cumulated emissions in *50* years amounts respectively to 2146.4 and 3390.1 tons CO2 *per capita* compares with difficulty with Swaziland (-32.3 tons CO2 *per capita*), in spite of the relatively low GDP of the three countries (respectively 4108, 6334 and 4258 US$). This heterogeneity is not limited to past events. In 2000, on a *per capita* basis, people in Qatar actually emitted more than *100* times more than people in Burundi.

One of the consequence of the uneven distribution of characteristics across countries is that the average (or median) of countries' per capita value may markedly differ from world average (or median). The average over countries' *per capita* GDP is only slightly higher than the world average (8922 as compared to 8186 US$; an overestimation of about 9%). The average over countries' *per*

capita cumulated emissions (221 tons CO2 p.c.) is more than 25% higher than the world average (173 tons CO2 p.c.). This is also the case for current emissions (respectively 6.74 and 5.27 tons CO2 p.c.).
This uneven distribution of characteristics explains in turn the intrinsic difficulty to define "representative" values hence "reference vectors" that do not penalize exaggeratedly "outliers". We shall return to this point later.

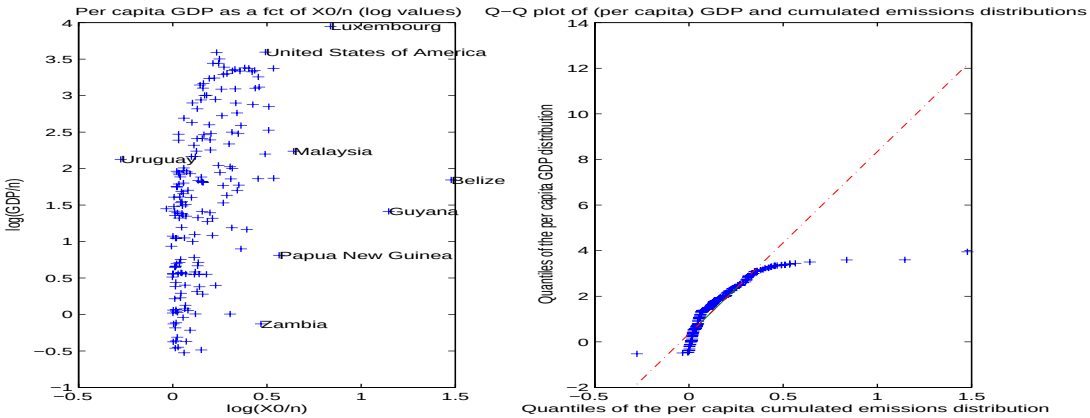
7.2 Relation across variables

As evidenced by the Q-Q plot below, the current emissions x^1 constitutes a remarkable indicator of countries' GDP. Apart from the five smallest countries (in terms of GDP), that is Niue, Nauru, Cook Islands, Palau and Sao Tome & Principe _ all island nations _ the alignment of the distribution of $\ln\left(1+x_i^1\right)$ and $\ln\left(GDP_i\right)$ is "almost perfect". For the seven largest countries (in terms of GDP), that is France, United Kingdom, Germany, India, Japan, China and the United States of America, the functional relationship between emissions and GDP seems to slightly differ. However, even for these extreme points, countries ranking according to x_i^1 and to GDP_i appear to be quite congruent. In fact, in 2000, the seven largest emitters were Brazil, Germany, Japan, India, Russian Federation, China and the United States of America.



Per capita cumulated emissions x^0/n can be expected to somewhat reflect the countries' development as measured by *per capita* GDP. However, the relationship between both variables appear to be relatively weak. A few outliers can be identified, in particular, Uruguay, which is credited with *negative* cumulated emissions (once accounted for land-variation effects), and Zambia, Papua New Guinea, Malaysia, Guyana and Belize, which appear to be high emitters given their GDP per capita. The Q-Q plot makes it clear the distribution of both variables seems to coincide for intermediate values only. This suggests that a better econometric model might be found while splitting our data set into three categories (poor, intermediate and rich countries). This is also a reminder that

the set of explanatory variables considered here remains very limited. In fact, a better indicator of *per capita* GDP would probably consists in considering *per capita* cumulated emissions *without* incorporating the effects of land-use variations.



Interestingly, although not surprisingly, the distributions of both the (*per capita)* current and cumulated emissions appear to be very similar, once a bunch of countries are excluded. These "outliers" include in particular oil producers and countries where deforestation is a serious concern. This may explain similar patterns of outcomes when either the **HR** or **nHR** view is considered, although, on a country basis, they yield different outcomes.