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Equity and CO_2 Emissions Distribution in Climate Change Integrated Assessment Modelling[1]

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Abstract

Emissions distribution is a focus variable for the design of future international agreements to tackle global warming. This paper specifically analyses the future path of emissions distribution and its determinants in different scenarios. Whereas our analysis is driven by tools which are typically applied in the income distribution literature and which have recently been applied to the analysis of CO_2 emissions distribution, a new methodological approach is that our study is driven by simulations run with a popular regionalised optimal growth climate change model over the 1995-2105 period. We find that the architecture of environmental policies, the implementation of flexible mechanisms and income concentration are key determinants of emissions distribution over time. In particular we find a robust positive relationship between measures of inequalities in the distribution of emissions and income and that their magnitude will essentially depend on technological change.

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1. Introduction

The study of the international distribution of greenhouse gas emissions is essential in order to analyze the problem of climate change and design control measures. There are major differences in the per capita emissions of the different regions of the world, and this inequality between regions shows different levels of responsibility in the contribution to climate change. An analysis of this inequality therefore provides information for the debate about the different control policies to be applied in different countries.

Distribution has become an important issue when dealing with the negotiation and agreement of policies for global climate change. Properly considering this issue when designing policies leads to an increase in perceived fairness and facilitates widespread participation in policy agreements.

Rich countries are responsible for much higher emissions in absolute and per capita terms. However, the huge growth rates of CO_2 emissions in some expanding economies means that any solution designed to stabilize greenhouse emissions requires the participation of both developed and developing economies. The stabilization of concentrations of greenhouse gas emission involves limiting the level of global emissions and distributing this level between the different countries. Several approaches to the distribution of future emission "entitlements" and to the distribution of abatement costs have been argued[2]. An analysis of present and future emissions distribution should also provide information about the distribution of future emission entitlements and abatement costs.

Over the last decade, several studies have focused on the distributive analysis of CO_2 emissions and energy consumption. Sun (2002) and Alcántara and Duro (2004) analysed inequalities in energy intensity. Heil and Wodon (1997, 2000), and Padilla and Serrano (2006) use several indexes that are commonly employed in income distribution analysis to study the evolution of international inequality in CO_2 emissions. Heil and Wodon (1997) used a group decomposition of the Gini coefficient to study inequality in per capita CO_2 emissions and the contribution of two income groups to this inequality. Heil and Wodon (2000) employed the same methodology to analyze future inequality in carbon emissions using projections to the year 2100, and also considered the scenario under the impact of the Kyoto Protocol and other mitigation proposals. Padilla and Serrano (2006) employed concentration indexes and showed that inequality between rich and poor countries (concentration of emissions in richer countries) has diminished less than "simple" inequality in emissions, and showed the contribution of four income groups to inequality through a Theil index decomposition. Duro and Padilla (2006) explain the main sources of emission inequality by decomposing international inequality in CO_2 emissions into the different Kaya factors and two interaction terms, and also decompose emissions inequality between and within groups of countries. In this paper our original contribution will be to analyse the distribution of emissions for different future scenarios involving international agreements designed to deal with the issue of climate change. To do this, we will use a popular climate change optimal growth model RICE99. To the best of our knowledge, this is the first attempt to use integrated assessment models for this purpose, and it is our intuition that the optimal growth models that are typically used to investigate such traditional analyses as technological change, policy costs, timing of abatement and scenario analyses could also be used effectively for a wider range of scientific analyses. In section 2 we explain the model and scenarios, section 3 presents our results, and the paper ends with our conclusions.

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[2] Distribution of entitlements in per capita terms (see e.g., Grubb, 1990; Agarwal and Narain, 1991; Meyer, 1995), distribution based on current emission levels (e.g. Pearce and Warford, 1993), on GNP shares (Wirth and Lashof, 1990; Cline, 1992) and many combinations of these. As for the distribution of abatement costs, the proposals are mainly based on different applications of the "polluter pays" principle and indexes of ability to pay (see IPCC, 1996; pp. 103-112).

2. Model and scenarios

Nordhaus and Boyer (1999)'s RICE is a regional dynamic general equilibrium model for the study of the economic aspects of climate change. The RICE model basically considers a single sector optimal growth model by suitably incorporating the interactions between economic activities and climate. The world is divided into eight macro regions: USA, Other High Income countries (OHI), OECD Europe (Europe), Eastern European countries (EE), Middle Income countries (MI), Lower Middle Income countries (LMI), China (CHN), and Low Income countries (LI). Within each region a central planner chooses the optimal paths of fixed investment and carbon energy input that maximize the present value of per capita consumption. Nordhaus and Boyer's starting assumption is that a Social Planner optimally runs its own region, indexed by *n*, by maximizing the following discounted utility function:

$$\underset{\{C(n,t)\}_{t=1}^{T}}{Max} \sum_{t=1}^{T} \beta(t)^{t-1}\left(L(n,t)*\log(C(n,t)/L(n,t))\right) \qquad (1)$$

Where *C(n,t)* stands for consumption, β is the discount factor and *L(n,t)* is the population level. The maximization process is subject to some constraints that capture the economic as well as environmental dynamics.

The Resource Constraint for each region links consumption with net output *Y* and with physical investments *I*. The following equation identifies the Resource Constraint[3]:

$$C(n,t) = Y(n,t) - I(n,t) \qquad (2)$$

The gross value added obtained from the production process is described by the following equation:

$$Q(n,t) = A(n,t)[K(n,t)^{\gamma} CE(n,t)^{\alpha n} L(n,t)^{(1-\gamma-\alpha n)}] - p_e(n,t)CE(n,t) \qquad (3)$$

Where *A(n,t)* denotes the state of the technology, *K(n,t)* is physical capital, *CE(n,t)* is carbon energy, and $p_e(n,t)$ is the price of carbon energy. Apart from *A(n,t)* and *L(n,t)*, all of the inputs in this value-added equation are endogenously determined. Note that the evolution of *A(n,t)* accounts for productivity growth by production-enhancing technological change. In the model this index follows an exogenously determined concave path that increases over time.

There is a wedge Ω between gross and net output production due to alterations to the climate. This wedge is inversely related to and driven by the damage function *D(n,t)*:

$$Y(n,t)= \Omega(n,t)Q(n,t) \qquad (4)$$

$$\Omega(n,t)=1/D(n,t) \qquad (5)$$

$$D(n,t) =1+ \theta_{1,n}T(t) + \theta_{2,n}T(t)^2 \qquad (6)$$

Where *D(n,t)* is environmental damage[4], *T(t)* is the increase in temperature and $\theta_{1,n}$, $\theta_{2,n}$ are regionalized parameters capturing the impact of temperature. Environmental damage is a key variable influencing how the model captures capital accumulation by including environmental resources. We refer to natural resources (intended as a flow) and not to environmental capital stocks, because the basic assumptions of this model are that there is an unlimited stock of natural resources and that the demand for carbon energy is always satisfied by supply. Scarcity is only reflected in the price of carbon.

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[3] When we introduce an emissions permit market, equation (2) should also include the revenue (expenditure) for the sale (purchase) of permits.

[4] Environmental damage should not be interpreted as the cost of climate change. It represents the willingness to pay to avoid deterioration by global warming.

The green technological effect is described by:

$$E(n,t) = \zeta(n,t) CE(n,t) \tag{7}$$

Where $E(n,t)$ represents the level of industrial CO_2 emissions. Notice that the coefficient $\varsigma(n,t)$ in (7) represents the emissions/carbon-energy ratio and captures the second form of technological change of the RICE99 model: emission-reducing technological change. This index of carbon intensity is exogenously determined and follows a negative exponential path over time. It represents the assumption of a costless improvement in green technology gained by agents over time. Total emissions will be derived from the sum of industrial emissions and emissions from land use.

$$TE(n,t) = E(n,t) + ETREE(n,t) \tag{8}$$

Where $TE(n,t)$ are total emissions and $ETREE(n,t)$ is a regional exogenous variable representing CO_2 land use emissions[5].

The RICE99 model is our tool for investigating the relationship between income distribution and emissions distribution. We will use techniques derived from the inequality literature such as those in Padilla and Serrano (2006). The main difference is that whereas Padilla and Serrano base their analysis on historical data, in this paper we will analyse projections of results derived from a popular climate change optimal growth model.

The main difficulty we faced was uncertainty. Projections of relevant economic and environmental variables over time strongly depend on the assumptions and calibration of the model and on the political and social evolutions derived from the future international setting. The best method for overcoming the limitations of modelling is to implement sensitivity analyses and adopt a wide comparison of models. Whereas the major differences in the features of the most used climate change models mean they are extremely difficult to compare, a sensitivity analysis should involve a large number of relevant parameters (discount rate, elasticity of the marginal utility of consumption, total factor productivity and all other calibrated variables) that could affect the distribution of emissions and income over time. This procedure is extremely time consuming and does not guarantee information of any added value. We believe it is more reasonable to work with the highly popular DICE/RICE family of climate change models that have been widely used in science to tackle the "hot" topics of global warming (Toth 1995, Nordhaus and Zhang 1996, Castelnuovo *et al*. 2003, Gerlagh 2004, Bosetti *et al*. 2005).

The uncertainty surrounding the future evolution of the international political framework is dealt with by an extensive analysis of scenarios. Unlike Heil and Woodon (1997) (the only previous distributive analysis of future international CO_2 inequality) we run a wide range of scenarios involving possible future environmental policies.

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[5] Other GHG are included in the RICE99 model by an exogenous variable O(t) affecting radiative forcing and temperature increase together with the accumulated CO_2 atmospheric concentration.

Table 1 Scenario descriptions

Scenario	Description
BAU	Business as usual. No policy.
Kyoto no trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario". No market of pollution permits.
Kyoto trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario". Since 2015 market of pollution permits.
Kyoto + USA no trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario" for OHI, WE and EE. From 2035 USA is obliged to maintain the level of emissions as in 2025. No market of pollution permits.
Kyoto + USA trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario" for OHI, WE and EE. From 2035 USA is obliged to maintain the level of emissions as in 2025. Since 2015 market of pollution permits.
Global Kyoto no trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario" for OHI, WE and EE. From 2035 USA and non Annex I regions are obliged to maintain the level of emissions as in 2025. No market of pollution permits.
Global Kyoto trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 "Kyoto forever scenario" for OHI, WE and EE. From 2035 USA and non Annex I regions are obliged to maintain the level of emissions as in 2025. No market of pollution permits. Since 2015 market of pollution permits.
Temp no trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 2.5 degree global atmospheric constraint. No market of pollution permits.
Temp trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 2.5 degree global atmospheric constraint. Since 2015 market of pollution permits.
Conc no trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 550 ppm global atmospheric constraint.No market of pollution permits.
Conc trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 550 ppm global atmospheric constraint. Since 2015 market of pollution permits.
Conc Sov no trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 550 ppm global atmospheric constraint. The burden among regions is shared according to the sovereignty rule. No market of pollution permits.
Conc Sov trading	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. From 2025 a 550 ppm global atmospheric constraint. The burden among regions is shared according to the sovereignty rule. Since 2015 market of pollution permits.

As shown in Table 1, in all scenarios we assume that all Annex I countries except the USA accomplish the 2015 Kyoto emissions target. Scenarios differ for different assumptions concerning post Kyoto agreements. We ran scenarios implying emission stabilizing policies and global atmospheric constraints. For emission stabilizing policies we assume 3 cases: in the first, the "Kyoto forever" scenario, Annex I regions (excluding the United States) are subject to a further 10% reduction in emissions in 2025 and are then obliged to maintain the same emissions cap forever (Bosetti and Buchner 2005). The United States and developing countries observe a BAU policy. In the "Kyoto + USA" scenario, the USA joins the Kyoto Protocol (Galeotti 2003, Cantore 2006) in 2035 and stabilizes its level of emissions at the 2025 level[6]. In the Global Kyoto scenario, from 2035 developing countries also decide to join the Kyoto Protocol together with the USA (Böhringer and Loschel 2003). We also assume 3 cases for the global atmospheric constraints: in the "CONC" scenario from 2025 we assume a cost effective 550 ppm global atmospheric constraint for all regions (Gerlagh 2005). In the TEMP scenario we assume a 2.5 degree global atmospheric constraint (van der Zwann *et al.* 2002). In the CONC SOV scenario (Böhringer and Welsch 2006) we assume that a 550 ppm global atmospheric constraint is accomplished in accordance with the polluter pays principle assuming that each

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[6] The State of California's recent decision to join the Kyoto Protocol after the Bush administration had rejected it makes the Kyoto + USA scenario more realistic.

region's reduction in emissions must be proportional to the BAU level of emissions[7]. For each scenario we assume two kinds of cases: "trading" and "non trading". In the former we assume efficiency in the accomplishment of the emissions cap through an emissions permit market that guarantees regions the lowest abatement costs. In the latter we assume the absence of *where flexible* mechanisms.

Technically an emissions permit market is introduced in the context of an open loop Nash equilibrium. Each region maximizes its utility subject to the climate module and the economic and emissions target constraints for a given optimal set of strategies for all the players and a given price of permits. In the first round, the price of permits is set at an arbitrary level. When all regions have made their optimal choices, the overall net demand of permits is computed at the given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained, otherwise the price is revised in proportion to the market imbalance and the process starts again. (Bosetti *et al.*, 2005).

It is very difficult to implement a scenario ranking according to the likelihood of occurrence. Böhringer and Loschel (2003) attempted to consider the most likely scenarios according to expert opinions, but there are still major doubts in terms of the political variables that will affect future international evolution[8]. Our strategy is to consider a wide spectrum of possible scenarios and assess the consequences derived from each. The following section summarizes the results.

3. Results

A number of interesting results can be derived from our analysis of the 1995-2105 period, which can be compared with those found by Padilla and Serrano (2006) for historical data for the 1971-1999 period and by Heil and Wodon (2000) for their projection of future emissions for the 1993–2100 period. However, there are some differences with respect to the data employed by Padilla and Serrano (2006) that should be taken into account. They used IEA data on CO_2 emissions from fuel combustion. This data does not include land use emissions, which are much more important in poor countries. This explains why the inequality and concentration indexes for CO_2 emissions found in their study are greater than the ones found here. These differences in data also explain why the Kakwani index (see below) is much lower in our study.

As a first step we compare the Gini index for Gross Domestic Product (GDP) representing the concentration of income between regions (GDP Gini index)[9] and the pseudo Gini index for CO_2 emissions (CO_2 pGini index or CO_2 concentration index), which measures inequality in the distribution of emissions between regions ranked according to their level of income per capita, i.e. the degree of concentration of emissions in richer countries[10]. We consider that the CO_2 p-Gini concept is more relevant for discussions of climate distribution issues, as these discussions focus on the distribution of emissions between poor and rich countries[11].

In a BAU scenario the concentration of income and the CO_2 pseudo Gini index are both decreasing (see Figures 1 and 2). The result is confirmed in those scenarios assuming a modest

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[7] The Conc Sov scenario is implemented in two steps. We first calculate the global reduction derived from the cost effective scenario Conc. Then for each period and region we impose an emissions constraint that is proportional to the global reduction according to the equity rule.

[8] Modelling and estimating CO_2 emissions and income projections over the next century is a difficult challenge, so caution is required in the interpretation of the results.

[9] The GDP Gini index shows inequality in income distribution. This index is computed through the Lorenz curve, the curve that shows the degree of income inequality, i.e., the percentage of income received by different percentages of population, ordered in increasing value of per capita income.

[10] The CO_2 pGini index is computed through the concentration curve of emissions, curve that shows the percentage of emissions that concentrate different shares of population, ordered in increasing value of per capita income (and not according to per capita emissions as would be the case if we computed the Gini index)

[11] However, for the 8 regions considered in this study there is very little difference (less than 1%) between CO_2 p-Gini and CO_2 Gini, which shows the importance of per capita income differences in explaining the differences in per capita emissions.

reduction in emissions only for developed countries ("Kyoto", "Kyoto + USA") or a relatively balanced reduction in emissions in developed and developing countries (CONC and CONC SOV, see Table 2). However, even in the cases in which inequality reduction is greater there are still considerably high levels of inequality in emissions and GDP. *As in Padilla and Serrano's study (2006) of historical emissions data, in our analysis involving future projections we are able to make the important confirmation that inequality in income distribution is positively related to inequality in emissions distribution from a "between group perspective"*. However scenarios involving a strong and disproportionate abatement effort for developing countries show an ambiguous relationship between the CO_2 pseudo Gini index and the GDP Gini index (see Figure 3). Whereas income concentration is still decreasing, global environmental constraints could require a major effort to reduce emissions in developing countries implying a higher concentration of emissions activities in Annex I regions. *The general finding is that the concentrations of emissions per capita and income per capita are positively correlated. However, our intuition is that major environmental policies involving developing countries could break this relationship*. Political and marginal abatement costs could play a crucial role in determining the future link between emissions and income distribution respectively for emission stabilizing policies and global atmospheric constraints.

Table 2 **Percent of emissions reduction (Policy vs BAU scenario) in 2100. Annex I vs non Annex I regions. No trading scenarios.**

Kyoto		Kyoto + USA		Global Kyoto		Temp		Conc		Conc SOV	
Annex I	Non Annex I	Annex I	Non Annex I	Annex I	Non Annex I	Annex I	Non Annex I	Annex I	Non Annex I	Annex I	Non Annex I
-7.00	-0.11	-9.00	-0.10	-9.00	-51.19	-49.70	-67.37	-29.53	-43.21	-38.92	-39.11

Figure 1 **GDP Gini index.**

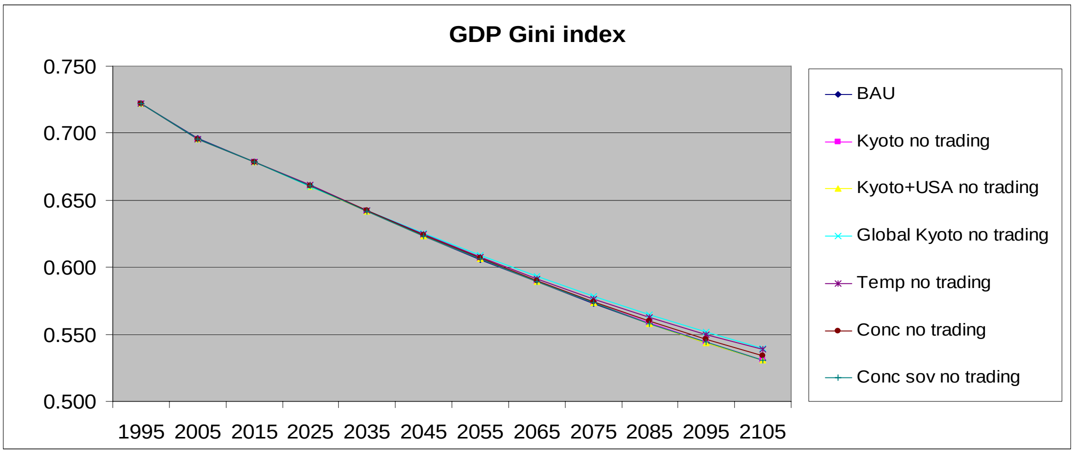


Figure 2 CO_2 pGini index.

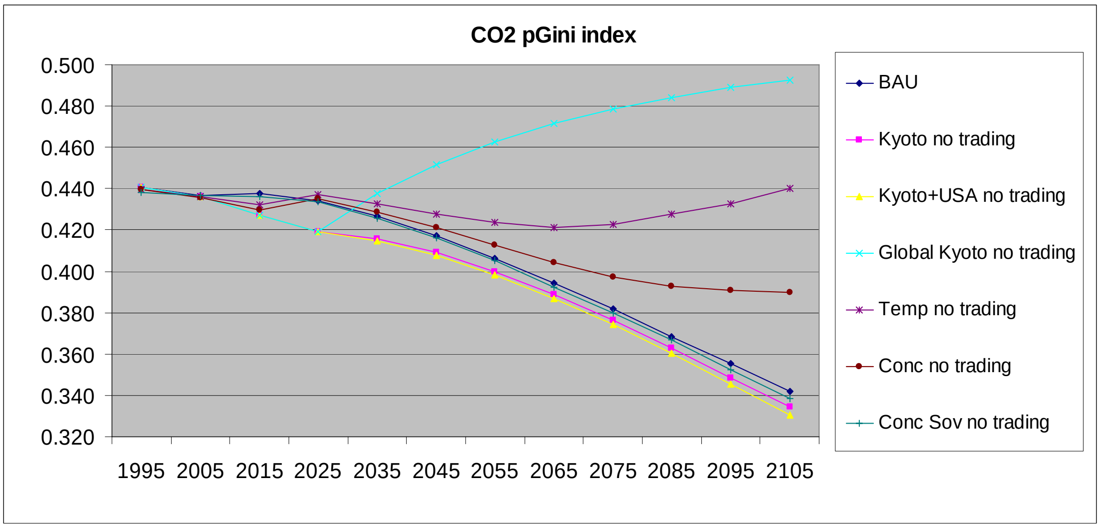
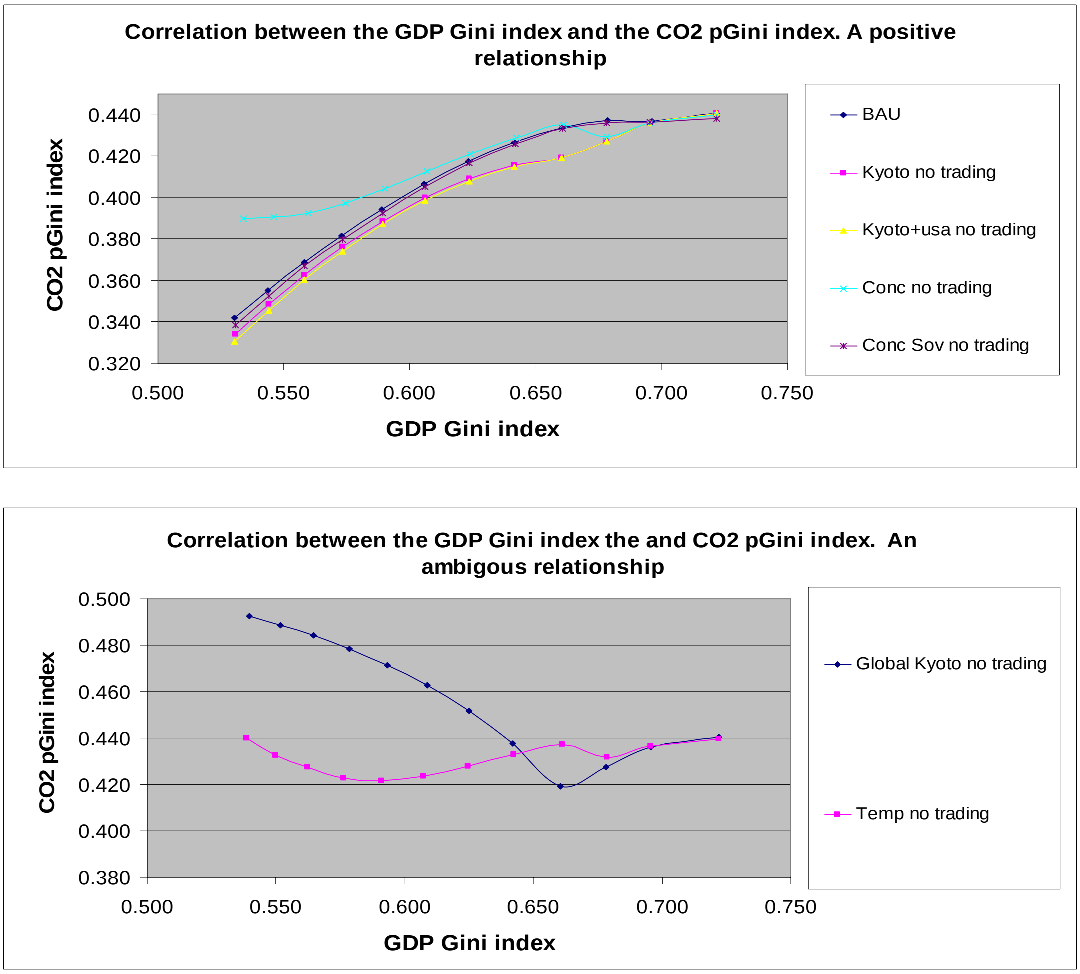
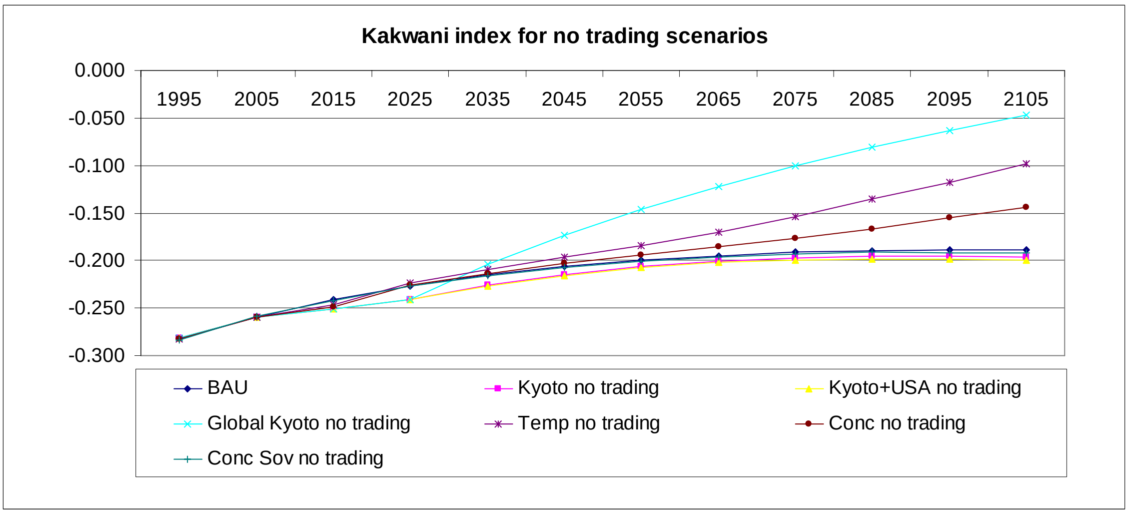


Figure 3 The relationship between the GDP Gini and the CO_2 pGini index.



In the next step, we make a more in-depth investigation of the magnitude of changes in income and emissions distribution. This issue has major implications in terms of the "regressivity" of emissions distribution over time. Distribution of CO_2 emissions is "progressive" when it shows a pGini of CO_2 emissions (index computed by ranking regions by level of income per capita) which is lower than the concentration of income. For this purpose we calculate the Kakwani index. The Kakwani index computes the extent to which inequality in the distribution of emissions between richer and poorer countries is greater than inequality in the distribution of income. In other words, the Kakwani index computes the level of "progressivity" or "regressivity" of the distribution of emissions. This index is equal to the difference between the CO_2 pGini index and the GDP Gini index. In all scenarios we always find a negative Kakwani index. *RICE99 clearly indicates that the concentration of emissions would be smaller than the concentration of income, that is, CO_2 concentration is "progressive" whatever the design of the future international agreements (see Figure 4).* Therefore, in richer countries emissions are less concentrated than income. This result can again be compared to that found by Padilla and Serrano (2006) which found a positive Kakwani index for several years. The more "progressive" concentration of emissions found in our study is basically the result of differences in the data employed, which in our case includes land use change emissions. These emissions are much more important in poor countries, thus attenuating CO_2 inequality between countries. The authors find a positive or close to zero Kakwani index in the 1971–1999 period except in the mid 1980s when the oil crisis reduced emissions in developed countries. RICE99 is a deterministic optimal growth model and does not assume energy market crises. The results of our simulations show that a "progressive" distribution of emissions could also be obtained in a deterministic framework in which no crises induce a rise in fossil fuel prices and lower emissions by developed countries as far as all emission sources are considered in the analysis. This result strictly depends on the calibrated values of the regional parameters *A* (total factor productivity, see equation 3) and *ζ(n,t)* (emissions/carbon energy ratio, see equation 7) which respectively regulate the output convergence among regions and environmentally friendly technological change. RICE99 provides the insight that the evolution of future industrial and environmental technology will be crucial in determining the relationship between emissions and income distribution. However the results also show that in every scenario the gap between the GDP Gini index and the CO_2 pGini index will diminish over time. This decrease in "progressivity" in emissions distribution will be higher in such scenarios as the "Global Kyoto" assuming a major abatement effort in developing countries and consequently a higher redistribution of emissions towards developed economies.

Figure 4 Kakwani index.



Previous findings can be further investigated by analyzing the determinants of emissions distribution over time. Specifically, the decomposition of inequality index is a useful tool for achieving this. We use the Theil index rather than the Gini index. As the inequality literature shows, the Gini index of inequality can be decomposed into a "between group", a "within Group" and a residual component whose interpretation has been widely debated in income distribution literature (Lambert, 1993). To yield a clearer interpretation, we use the Theil index for our CO_2 inequality decomposition analysis. The Theil index can be simply decomposed into "between group" and "within group" inequality components. Our aim is to verify the proportion representing the between group component and consequently the emissions inequality between different income groups in countries in terms of the overall inequality in emissions distribution. We aggregate RICE99 regions as 3 groups: High Income (USA, OHI and Western Europe), Medium Income (Eastern Europe, MI and LMI) and Low Income Countries (China and LI).

We find an interesting set of results that can be compared in turn to those found by Padilla and Serrano (2006) to check the consistency between past and future paths of emissions and income distribution in different scenarios.

First, in the BAU, Kyoto, Kyoto + USA, Conc, Conc Sov we find contiguity between Padilla and Serrano results' (2006) and our own. In both studies there is a decrease in the simple emissions inequality of the between group and the within group. Again, the results seem to change significantly when environmental policies determine a strong imbalance in the effort to reduce emissions (Temp and Global Kyoto Scenario). In this case the Theil index together with its decomposition factors (the between and the within group components) are increasing.

Second, we find that in each scenario the between group component is the most important over time and its contribution is always higher than 75%. *This means that RICE99 shows that whatever the future set of climate agreements the between group component and inequality in the distribution of emissions between rich and poor regions will be the most important driving forces and will explain more than ¾ of future emissions inequality. This result strongly supports that offered by Padilla and Serrano (2006) and shows that the between group component, which has already played a crucial role in the past, will continue to explain most inequalities in emissions in the future.* Moreover these findings are also confirmed in those scenarios (Global Kyoto and Temp) that we previously claimed did not generate a clear positive relationship between income and emissions distribution. These finding also show that when the path of inequality in income does not provide strong evidence to govern the path of emissions distribution over time, emissions distribution is still mainly explained by differences in income between regions. Income distribution will also still be the main determinant if political variables play a complementary role in determining the path of emissions distribution over time.

Third, in contrast to Padilla and Serrano's (2006) analysis of past emissions, this study does not provide robust evidence of an increasing percentage of the between group component over time, but this could in part depend on the different group aggregation and on the assumptions and calibration of the RICE99 model [12]. As Tables 3-9 show, this result is strongly driven by an increase in within group inequality in the Low Income Group, which is determined by the outstanding growth in China in comparison with that experienced by other poor regions.

Table 3 Decomposition of the Theil index. Business as usual (BAU) scenario.

BAU	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.351	0.297	0.054	84.685%	15.315%	9.428%	3.636%	2.251%
2005	0.344	0.288	0.056	83.715%	16.285%	9.026%	3.137%	4.122%
2015	0.348	0.292	0.056	83.940%	16.060%	8.548%	2.706%	4.806%
2025	0.346	0.291	0.055	84.092%	15.908%	8.274%	2.379%	5.255%
2035	0.337	0.284	0.053	84.192%	15.808%	7.973%	2.158%	5.677%
2045	0.325	0.273	0.052	84.025%	15.975%	7.885%	2.000%	6.091%
2055	0.310	0.259	0.051	83.632%	16.368%	7.933%	1.893%	6.542%
2065	0.293	0.244	0.050	83.050%	16.950%	8.073%	1.827%	7.050%
2075	0.276	0.227	0.049	82.305%	17.695%	8.281%	1.797%	7.617%
2085	0.258	0.210	0.048	81.427%	18.573%	8.544%	1.796%	8.233%
2095	0.241	0.194	0.047	80.445%	19.555%	8.854%	1.821%	8.880%
2105	0.224	0.178	0.046	79.394%	20.606%	9.207%	1.868%	9.531%

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[12] Their study uses individualized data for 113 countries and small groups of countries and divides them into four income groups, while here we have projections for 8 regions which we group into three income groups.

Table 4 Decomposition of the Theil index. Kyoto no trading scenario.

Kyoto no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.351	0.297	0.054	84.686%	15.314%	9.428%	3.636%	2.250%
2005	0.344	0.287	0.056	83.655%	16.345%	9.059%	3.147%	4.139%
2015	0.339	0.275	0.064	81.099%	18.901%	11.412%	2.400%	5.089%
2025	0.333	0.265	0.067	79.808%	20.192%	12.573%	1.937%	5.682%
2035	0.327	0.266	0.061	81.315%	18.685%	10.883%	1.795%	6.008%
2045	0.317	0.260	0.057	82.049%	17.951%	9.935%	1.668%	6.348%
2055	0.303	0.250	0.054	82.260%	17.740%	9.430%	1.548%	6.763%
2065	0.288	0.236	0.052	82.080%	17.920%	9.217%	1.436%	7.267%
2075	0.270	0.220	0.050	81.584%	18.416%	9.216%	1.338%	7.862%
2085	0.252	0.204	0.048	80.816%	19.184%	9.381%	1.264%	8.539%
2095	0.234	0.187	0.047	79.814%	20.186%	9.682%	1.224%	9.280%
2105	0.216	0.170	0.046	78.631%	21.369%	10.082%	1.230%	10.056%

Table 5 Decomposition of the Theil index. Kyoto + USA no trading scenario.

Kyoto + USA no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.351	0.297	0.054	84.686%	15.314%	9.428%	3.636%	2.250%
2005	0.344	0.287	0.056	83.655%	16.345%	9.059%	3.147%	4.139%
2015	0.339	0.275	0.064	81.098%	18.902%	11.412%	2.400%	5.089%
2025	0.333	0.265	0.067	79.808%	20.192%	12.574%	1.937%	5.682%
2035	0.324	0.264	0.060	81.434%	18.566%	10.690%	1.812%	6.064%
2045	0.314	0.258	0.056	82.183%	17.817%	9.710%	1.687%	6.420%
2055	0.300	0.248	0.053	82.407%	17.593%	9.176%	1.568%	6.850%
2065	0.284	0.234	0.050	82.248%	17.752%	8.915%	1.458%	7.379%
2075	0.266	0.218	0.048	81.788%	18.212%	8.834%	1.364%	8.014%
2085	0.247	0.200	0.047	81.071%	18.929%	8.881%	1.295%	8.753%
2095	0.228	0.183	0.045	80.129%	19.871%	9.024%	1.264%	9.583%
2105	0.209	0.165	0.044	79.008%	20.992%	9.244%	1.280%	10.468%

Table 6 Decomposition of the Theil index. Global Kyoto no trading scenario.

Global Kyoto no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.351	0.297	0.054	84.686%	15.314%	9.428%	3.635%	2.251%
2005	0.343	0.287	0.056	83.652%	16.348%	9.060%	3.147%	4.141%
2015	0.339	0.275	0.064	81.096%	18.904%	11.413%	2.399%	5.091%
2025	0.332	0.265	0.067	79.817%	20.183%	12.564%	1.937%	5.683%
2035	0.361	0.294	0.068	81.269%	18.731%	10.186%	2.045%	6.501%
2045	0.386	0.316	0.070	81.800%	18.200%	8.842%	2.150%	7.208%
2055	0.407	0.334	0.073	81.991%	18.009%	7.989%	2.248%	7.773%
2065	0.425	0.348	0.076	82.023%	17.977%	7.420%	2.330%	8.226%
2075	0.440	0.361	0.079	81.984%	18.016%	7.026%	2.397%	8.594%
2085	0.452	0.371	0.082	81.913%	18.087%	6.745%	2.449%	8.894%
2095	0.463	0.379	0.084	81.830%	18.170%	6.540%	2.489%	9.141%
2105	0.472	0.386	0.086	81.746%	18.254%	6.388%	2.519%	9.347%

Table 7 Decomposition of the Theil index. Temp no trading scenario.

Temp no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.349	0.296	0.053	84.838%	15.162%	9.406%	3.622%	2.134%
2005	0.344	0.289	0.055	84.108%	15.892%	8.989%	3.103%	3.800%
2015	0.345	0.284	0.061	82.271%	17.729%	10.439%	2.838%	4.452%
2025	0.353	0.299	0.053	84.871%	15.129%	8.065%	2.542%	4.522%
2035	0.349	0.297	0.052	85.177%	14.823%	7.657%	2.514%	4.652%
2045	0.345	0.294	0.051	85.307%	14.693%	7.406%	2.624%	4.663%
2055	0.342	0.292	0.050	85.335%	14.665%	7.209%	2.895%	4.561%
2065	0.342	0.292	0.050	85.327%	14.673%	6.990%	3.352%	4.330%
2075	0.349	0.297	0.051	85.329%	14.671%	6.701%	4.003%	3.967%
2085	0.362	0.309	0.053	85.353%	14.647%	6.323%	4.813%	3.511%
2095	0.380	0.324	0.056	85.383%	14.617%	5.891%	5.682%	3.044%
2105	0.398	0.339	0.058	85.350%	14.650%	5.506%	6.445%	2.699%

Table 8 Decomposition of the Theil index. Conc no trading scenario.

Conc no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.349	0.296	0.053	84.765%	15.235%	9.419%	3.628%	2.188%
2005	0.343	0.288	0.055	83.894%	16.106%	9.027%	3.117%	3.963%
2015	0.341	0.279	0.062	81.743%	18.257%	10.820%	2.687%	4.750%
2025	0.348	0.294	0.054	84.494%	15.506%	8.173%	2.449%	4.884%
2035	0.341	0.289	0.052	84.685%	15.315%	7.825%	2.317%	5.173%
2045	0.332	0.281	0.051	84.653%	15.347%	7.672%	2.273%	5.402%
2055	0.322	0.272	0.050	84.464%	15.536%	7.621%	2.322%	5.593%
2065	0.311	0.262	0.049	84.185%	15.815%	7.613%	2.472%	5.730%
2075	0.303	0.254	0.049	83.883%	16.117%	7.603%	2.741%	5.773%
2085	0.298	0.249	0.049	83.619%	16.381%	7.550%	3.150%	5.681%
2095	0.297	0.248	0.049	83.445%	16.555%	7.417%	3.714%	5.424%
2105	0.303	0.253	0.050	83.389%	16.611%	7.174%	4.436%	5.001%

Table 9 Decomposition of the Theil index. Conc Sov no trading scenario.

Conc Sov no trading	Theil	Theil Between	Theil Within	Contribution between (%)	Contribution within (%)	Contribution within (%) High income	Contribution within (%) Medium income	Contribution within (%) Low income
1995	0.347	0.294	0.053	84.645%	15.355%	9.531%	3.609%	2.214%
2005	0.344	0.288	0.056	83.772%	16.228%	9.028%	3.118%	4.082%
2015	0.346	0.291	0.056	83.948%	16.052%	8.603%	2.702%	4.747%
2025	0.345	0.290	0.055	84.061%	15.939%	8.318%	2.479%	5.141%
2035	0.336	0.283	0.053	84.165%	15.835%	7.979%	2.191%	5.666%
2045	0.324	0.272	0.052	84.016%	15.984%	7.926%	2.002%	6.056%
2055	0.308	0.258	0.050	83.828%	16.172%	7.897%	1.921%	6.354%
2065	0.290	0.241	0.049	83.137%	16.863%	8.029%	1.883%	6.952%
2075	0.273	0.225	0.048	82.372%	17.628%	8.449%	1.826%	7.353%
2085	0.256	0.209	0.047	81.701%	18.299%	8.423%	1.961%	7.916%
2095	0.237	0.191	0.046	80.583%	19.417%	8.879%	1.905%	8.633%
2105	0.222	0.177	0.045	79.583%	20.417%	9.241%	2.047%	9.130%

Finally, unlike Heil and Wodon (1997) we also analyze the role of flexible mechanisms in income and emissions distributions. Trading does not widely influence emissions and income distribution. Emissions trading is a crucial mechanism governing the efficiency of policy implementation and compliance costs but in our analysis it does not generally provide significant insights into equity issues. The only exceptions are the Global Kyoto and Conc Sov scenarios (see Figures 5-10). Whereas in the Global Kyoto scenario, when we implement trading, non Annex I regions buy a huge quantity of permits and we observe a redistribution of emissions towards poor countries, in the Conc Sov scenario Annex I regions are mostly permit buyers and trading generates a redistribution of emissions towards developed regions. *In other words the magnitude and the sign of the impact of trading on emissions distribution essentially depend on the structure of marginal costs for each country, on the level of global abatement reduction and on how the abatement effort is shared among regions*. However the magnitude of the impacts of environmental constraints on the economic variables does not appear to be relevant.

Figure 5 Non trading vs trading. Kyoto scenario.

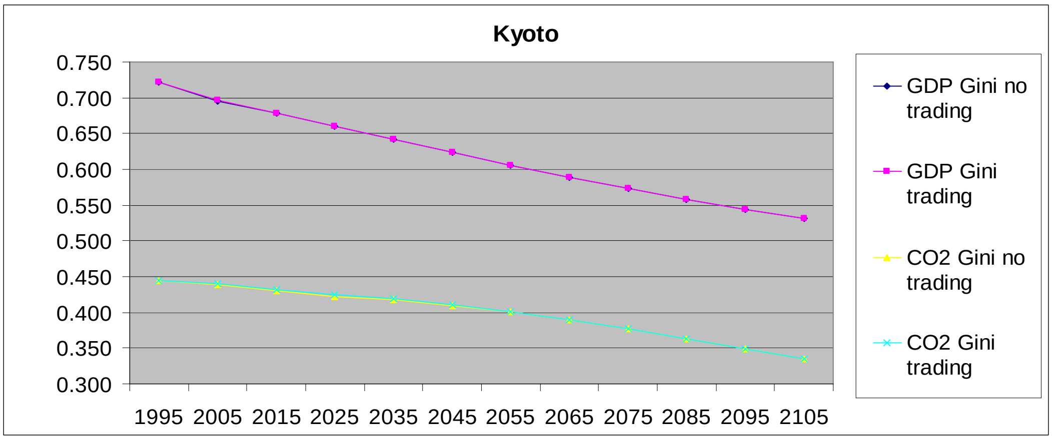


Figure 6 Non trading vs trading. Kyoto + USA scenario.

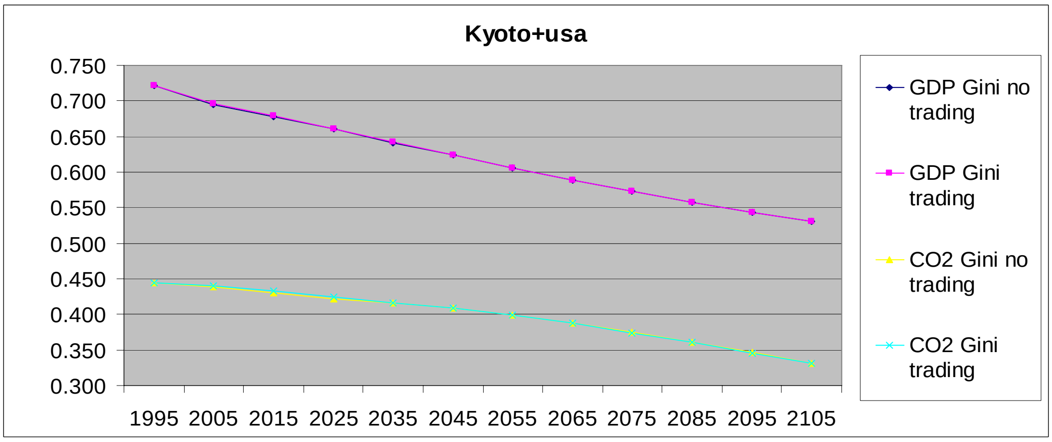


Figure 7 **Non trading vs trading. Global Kyoto scenario.**

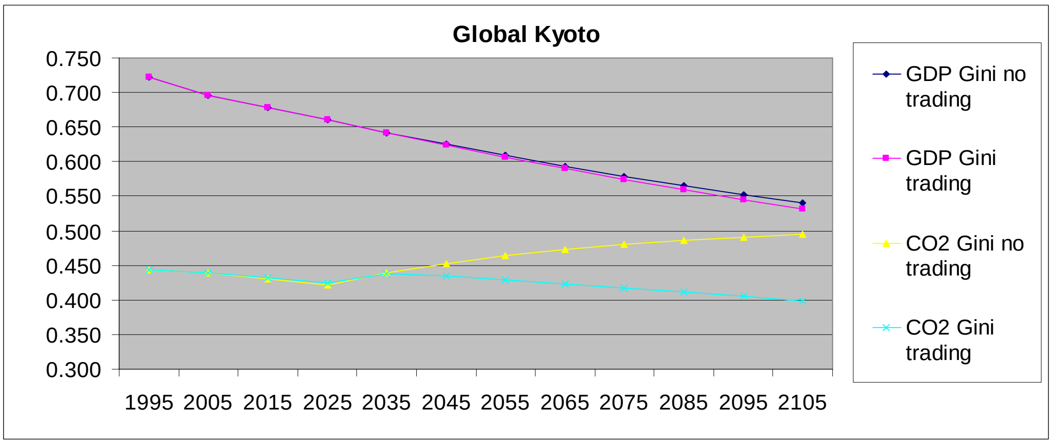


Figure 8 **Non trading vs trading. Temp scenario.**

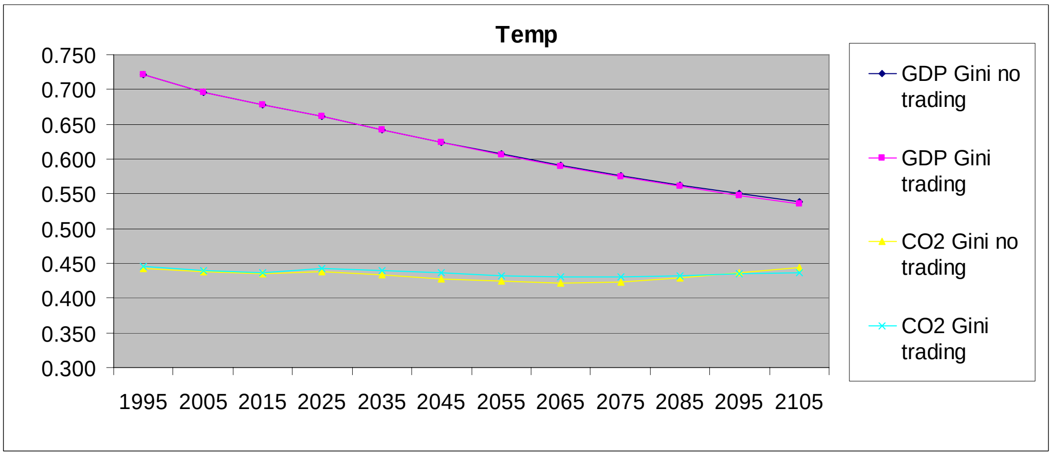


Figure 9 **Non trading vs trading. Conc scenario.**

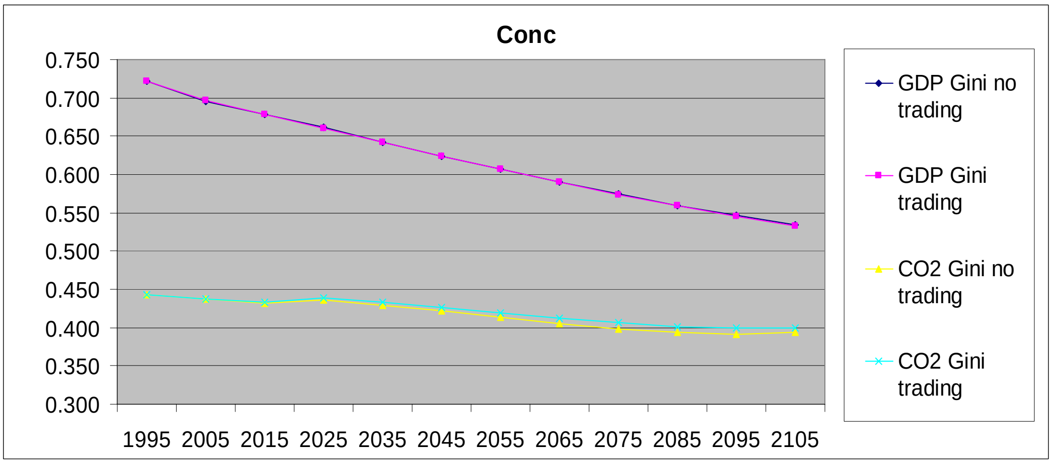
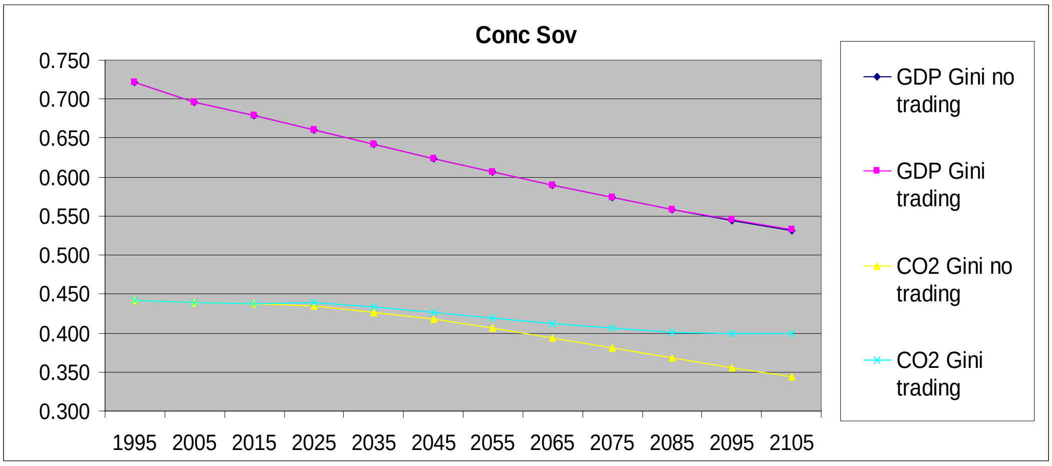


Figure 10 **Non trading vs trading. Conc Sov scenario.**



4. Conclusions

In this paper we investigate how future scenarios involving different climate policies could affect emissions distribution over time. We find a set of interesting findings derived from simulations run with a popular optimal growth model of climate change that we briefly summarize.

First, we find a robust correlation between measures of inequality in income and emissions distribution. An important implication for policy-making is that future international policies aimed at reducing inequality in the distribution of emissions would be more feasible if there were a reduction in income inequality between rich and poor countries. This result agrees with previous analogous studies. Of course, environmental policies could have an impact on the robustness of this finding. Specifically in this paper we have shown that international climate agreements that penalise heavily developing countries could provide a contextual reduction of equity together with a redistribution of emissions towards developed countries. In these cases evidence of a strong relationship between inequality in income and emissions distribution appears ambiguous, but the between group component and consequently the differences in GDP between rich and poor regions continue to be the most important determinants of emissions distribution. Short-term measures focused on reducing emissions in rich countries might be effective for controlling the evolution of global emissions, although in the medium and long term the expected economic growth of developing economies (which will reduce income and emission inequalities) means that effective climate measures require the participation of developing economies.

Second, unlike previous studies, we provide a more complete explanation of the "progressivity" of emissions distribution in comparison to income concentration through the Kakwani index. Emissions distribution will be governed by changes in green technology in different countries. A lower technological gap for abatement activities between developed and developing countries could lead to an increase in the concentration of emissions in rich regions and to a decrease of "progressivity". On the other hand, a reduction in "progressivity" could also be induced by a reduction in the gap between countries in terms of industrial technology enhancing productivity inputs and determining a lower concentration of income over time. For both changes to industrial and green technology, diffusion caused by spillover effects will be crucial for influencing technological differences between developing and developed countries and consequently the "progressivity" of emissions distribution over time. Moreover, this "progressivity" in the concentration of emissions with respect to income inequality is expected to experience a considerable reduction during the period considered due to the reduction in emissions from land use change in poorer countries.

Finally, we showed that emissions distribution could depend not only on climate policies but also on the flexible mechanisms aimed at guaranteeing efficiency in the accomplishment of emissions constraints. Whereas for some scenarios the impact of an emissions permit is irrelevant, for others we find that the purchase/sale of permits could determine a significant redistribution of emissions among countries. Policy makers focused on achieving more equitable emissions distribution over time through international agreements (which are needed in order to increase the perceived fairness and widespread acceptability of these agreements) should take into account this important aspect when designing policies.

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