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EQUALITY AND CO_2 EMISSIONS DISTRIBUTION IN CLIMATE CHANGE INTEGRATED ASSESSMENT MODELLING

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Abstract

The equity implications of alternative climate policy measures are an essential issue to be considered in the design of future international agreements to tackle global warming. This paper specifically analyses the future path of emissions and income 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 the popular regionalised optimal growth climate change model RICE99 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. As recently explained by Duro and Padilla [1]: "The inequality in per capita CO_2 emissions between countries shows different responsibilities in the generation of greenhouse gases and the contribution to climate change. Therefore, the analysis of this inequality sheds light on the debate about the different control and mitigation measures to be applied in different regions. In fact, distribution problems have become the most important issue to deal with in global climate change policy negotiations and agreements. Taking distribution problems properly into account in policy design leads to an increase in the perceived fairness of the measures and facilitates widespread participation" (p. 456).

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 atmospheric concentrations of greenhouse gases requires the participation of both developed and developing economies. The stabilization of atmospheric concentrations of greenhouse gases 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[3]. An analysis of present and future emissions distribution under different policy scenarios should also provide information about the distribution of future emission entitlements and abatement costs. Equity is a key issue to be considered in climate policies to insure a widespread participation of developing countries. Therefore, present and future equity consequences of different climate policy measures and scenarios —including different entitlements distribution criteria— should be carefully analysed and considered in order to help the design of these policies. For example, mitigation policies increasing inequalities both in income and in the contribution to the problem —emissions— could not be seen as desirable or acceptable, while policies through which these inequalities are expected to be reduced could be seen as more desirable and acceptable by many more countries.

Over the last decade, several studies have focused on the distributive analysis of CO_2 emissions and energy consumption. Sun [2] and Alcántara and Duro [3] analysed inequalities in energy intensity. Heil and Wodon [4, 5], and Padilla and Serrano [6] 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 [4] 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 [5] employed the same methodology to analyze future

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[3] Distribution of entitlements in per capita terms (see e.g., Grubb [8] ; Agarwal and Narain [9]; Meyer [10]), distribution based on current emission levels (e.g. Pearce and Warford [11]), on GNP shares (Wirth and Lashof [12]; Cline [13]) 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 [14]).

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 [6] 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 [7] 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.

On other branches of research, Miketa and Shrattenholzer [15] analyse the future differences in the allocation of emission entitlements to different regions according to two burden-sharing rules —"equal emissions per capita" and "carbon intensity" approaches— in a scenario of global carbon-emission path until the year 2050 that leads to stabilizing atmospheric CO_2 concentration at 550 ppm. Their study does not consider trade in emission permits. They use the general equilibrium model MERGE. Leimbach [16] analyses how the "equal per capita allocation principle" influences the intertemporal emission paths and the mitigation costs of different regions in the long run, in a scenario which restricts temperature change to 0.2ºC per decade and 2ºC in 2100. He takes into account the effects of emission permits trade. He uses the ICLIPS integrated assessment model. Vaillancourt and Waaub [17] analyse the consequences of two weight sets of allocation criteria (which take into account several equity criteria and regional interests) for the allocation of emissions to different regions over time to the year 2050. They assume a CO_2

concentration stabilization level at 550 ppm. They use the TIMES energy model. In Vaillancourt and Waaub [18], they also analyse the costs for each region in each case with projections to the year 2050 and consider the effects of emissions trading. They employ the MARKAL world energy model.

In this paper our original contribution will be to employ distributive analysis tools —such as the computation of inequality and concentration indexes— to analyse the distribution of emissions between different regions and groups of regions for different future scenarios involving international agreements designed to deal with the issue of climate change. To do this, we will use the popular climate change optimal growth model RICE99. To the best of our knowledge, this is the first attempt to use integrated assessment models together with distributive analysis tools 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 (Kypreos [19]), policy costs (Manne and Stephan [20]), timing of abatement (Goulder and _Mathai [21]) and scenario analyses (Turton [22]) could also be used effectively for a wider range of scientific analyses. Moreover, we investigate a much wider range of scenarios and climate policy alternatives than the previous studies that used integrated assessment models for the study of equity implications of different scenarios

The second relevant original contribution of this paper is that we connect the findings from future projections of emissions distribution to previous studies dealing with time series from historical data. Finally our paper represents the first attempt to analyse the impact of the emissions trading on the inequality measures of emissions and also analyses a wider set of scenarios than the previous studies that analyse the distributive implications of trade.

In section 2 we explain the model and scenarios. Section 3 presents our results for different scenarios of emissions reduction. Section 4 undertakes a sensitivity analysis for different parameters values. Section 5 analyses the results for different equity principles for a given level of atmospheric carbon concentration. Section 6 presents the results for different scenarios when emission trading is implemented. The paper ends with our conclusions.

2. Model and scenarios

Nordhaus and Boyer's RICE [23] is a regional dynamic general equilibrium model for the study of the economic aspects of climate change. The RICE model[4] 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 a discounted utility function.

The maximization process is subject to some constraints that capture the economic as well as environmental dynamics.

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[4] In this paper we use the original model set up. We refer to Nordhaus and Boyer [23] for parameters calibration and for a deeper explanation of equations. The Appendix 1 contains a list of variables and parameters cited in the main text.

The Resource Constraint for each region links consumption with net output *Y* and with physical investments *I*. The following equation identifies the Resource Constraint[5]:

$$C(n,t) = Y(n,t) - I(n,t) \tag{1}$$

The gross value added obtained from a Cobb Douglas production process with constant returns to scale is described by the following equation:

$$Q(n,t) = A(n,t)[K(n,t)^{\gamma}CE(n,t)^{\alpha(n)}L(n,t)^{(1-\gamma-\alpha(n))}] - p_e(t)CE(n,t) \tag{2}$$

Where A(n,t) denotes the state of the technology, K(n,t) is physical capital, CE(n,t) is carbon energy, and pe(t) is the cost of carbon energy. Apart from A(n,t) and L(n,t), all of the inputs in this value-added equation are endogenously determined. The evolution of A(n,t) represents total factor productivity (TFP) growth by production-enhancing technological change. In the model TFP growth is assumed to slow gradually over the next three centuries until eventually stopping.

There is a wedge between gross and net output production due to global warming that creates environmental damages. The environmental damage is a key variable influencing how the model captures capital accumulation by including natural resources. In RICE-99, a supply curve for carbon-energy is introduced. The supply curve allows for limited (albeit huge) long-run supplies at rising costs. Because of the optimal-growth framework, carbon-energy is efficiently allocated across time. Scarcity is only reflected in the cost of carbon.

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[5] When we introduce an emissions permit market, equation (1) should also include the revenue (expenditure) for the sale (purchase) of permits.

In the function expressing the level of emissions the green technological effect is described by:

$$E(n,t) = \zeta(n,t) CE(n,t) + ETREE(n,t) \qquad (3)$$

Where $E(n,t)$ represents the level of industrial CO_2 emissions and $ETREE(n,t)$ is a regional exogenous variable representing CO_2 land use emissions[6]. The coefficient $\varsigma(n,t)$ in (3) represents the emissions/carbon-energy ratio and captures the environmental-friendly 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.

Emissions determine atmospheric carbon concentration, atmospheric carbon concentration determines the radiative forcing, the radiative forcing is the main variable expressing the temperature increase relative to 1990 levels.

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 [6]. 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.

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[6] 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.

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. One method for overcoming the limitations of modelling is to implement a wide comparison of models. However, 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 [24], Nordhaus and Yang [25], Castelnuovo *et al*. [26], Gerlagh [27], Bosetti *et al*. [28]). Simulations run with the RICE99 model in a Business as usual scenario in which no regions take actions to reduce greenhouse gases by a sensitivity analysis for some crucial parameters do not provide significant variations in the results about emissions distribution. A Sensitivity analysis was run on the pure rate of time preference (BAU vs hyperbolic discounting with a 0.125% decline rate), on the curvature of the utility function (BAU vs decreasing elasticity of marginal utility of consumption with a 0.125% declining rate), the depreciation rate of capital (BAU vs +/- 10%) and the sensitivity of radiative forcing to atmospheric carbon concentration (BAU vs +/- 10%).

The uncertainty surrounding the future evolution of the international political framework is dealt with by an extensive analysis of scenarios. Unlike Heil and Woodon [5] (the only previous distributive analysis of future international CO_2 inequality) we run a wide range of scenarios involving possible future environmental policies.

[Table 1 about here]

As shown in Table 1, in all scenarios we assume that all Annex I countries except the USA accomplish by 2015 the 2008–2012 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 -10%" 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 [29]). The United States and developing countries observe a BAU policy. In the "Kyoto + USA" scenario, the USA joins the Kyoto -10% scenario (Galeotti [30], Cantore [31]) in 2035 and stabilizes its level of emissions at the 2025 level[7]. In the Global Kyoto scenario, from 2035 developing countries also decide to join the Kyoto -10% together with the USA (Böhringer and Löschel [32]). We also assume two 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 [33]). In the "Temp" scenario we assume a 2.5 degrees C global atmospheric constraint (van der Zwaan *et al.* [34]). 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 an emissions permits market.

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[7] 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.

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 emission target constraints for a given optimal set of strategies for all the other players and a given price of permits. In the first round, the price of permits is an arbitrary value. When all regions choose their optimal strategies, the overall net demand of permits affects the market price. If the sum of net demands in each period is close to zero, the process generates a Nash equilibrium, otherwise the price varies in proportion to the market imbalance and the process starts again (Bosetti *et al.*,[24]).

It is very difficult to implement a scenario ranking according to the likelihood of occurrence. Böhringer and Löschel [28] 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 for different scenarios of emissions reduction

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 [5] 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 [6] 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

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[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.

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 Figure 4) 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 relevant for discussions of climate distribution issues, as these discussions focus on the distribution of emissions between poor and rich countries[11]. Just for clarity, the reader should consider that the measures of inequality between different regions are computed taking the per capita values of each region, each one weighted by population in the global computation of inequality.

In a BAU scenario the concentration of income and the CO_2 pseudo Gini index are both decreasing (see Figures 1 and 2). That is, the concentration of income and CO_2 emissions in rich regions decreases over time. The result is confirmed in those scenarios assuming a modest reduction in emissions only for developed countries ("Kyoto – 10%", "Kyoto – 10% + USA") or a relatively balanced reduction in

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[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.

emissions in developed and developing countries ("Conc" 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 [6] of historical emissions data, in our analysis involving future projections we are able to can confirm that inequality in income distribution is positively related to inequality in emissions distribution from a "between group perspective".* However, the "Global Kyoto" scenario shows a remarkable increase in emissions inequality, and the "Temp" scenario shows almost not change at the end the period. These scenarios also show a mildly lower reduction in income inequalities, which is explained by the stronger mitigation effort for poor regions they involve. As a result, in these scenarios, which involve a strong and disproportionate abatement effort for developing countries, there is 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, major environmental policies involving a strong effort by developing countries break this relationship*. In short, the application of the RICE99 model allowed us to conclude that mitigation policies such as the stated in the "Global Kyoto no trading" and "Temp no trading" scenarios could break the relationship between the concentration of income and the emissions per capita. Politics 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 and figures 1,2,3 about here]

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, that is, emissions are less unequally distributed than 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 CO_2 pGini index minus the GDP Gini index.

This index shows the degree to which the inequality in the "responsibilities" in the contribution to the problem is greater or lower than income inequality under the different scenarios taken into account[12]. In all scenarios we always find a negative Kakwani index. That is, *RICE99 clearly indicates that the concentration of emissions would be smaller than the concentration of income, that is, the concentration of emissions is "progressive" whatever the design of the future international agreements (see Figure 4).* Therefore, in richer countries emissions are less

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[12] Moreover, other things equal, a policy whose emissions allocation strongly increased this "regressivity" or decreased this "progressivity" could be considered to penalise developing countries more than a policy which did not lead to this result —as far as emissions trade or other flexibility mechanisms or economic compensations were not considered in the analysis.

concentrated than income. This result can again be compared to that found by Padilla and Serrano [6] 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 2) and $\zeta(n,t)$ (emissions/carbon energy ratio, see equation 3) 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 about here]

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 [35]). 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 of 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 [6] to check the consistency between past and future paths of emissions and income distribution in different scenarios.

First, in the BAU, Kyoto – 10%, Kyoto – 10% + USA and Conc we find contiguity between Padilla and Serrano results' [6] and our own. In both studies there is a decrease in the simple emissions inequality of both the Between group and the Within group components. 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 [6] 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 findings 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.

Third, in contrast to Padilla and Serrano's analysis [6] 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 [13]. As Tables 3–8 show, this result is strongly driven by an increase in Within group

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

inequality in the Low Income Group, which is determined by the outstanding growth in China in comparison with that experienced by other low income regions.

[Table 3 about here]

4. Results for different equity principles in a 550 ppm global atmospheric scenario.

We have verified that our results are robust across emissions reducing scenarios — except in those implying a strong and disproportionate abatement effort for developing countries. Now, we investigate how the distribution of emissions can be affected when we consider the same global emissions reduction target but the abatement burden is shared among regions according to different equity principles. We consider as benchmark the "Conc" scenario in which we introduced a global upper bound of 550 ppm atmospheric carbon concentration and a cost effective abatement burden sharing.

As summarized in the table 11 we consider three alternative equity principles: the sovereignty rule (CONCSOV), the equality principle rule (CONCEQUAL) as implemented in Cantore [36] and the Brasilian proposal (CONCBRAS) rule representing a very interesting policy proposal[14]. The sovereignty rule is a policy option in which the abatement burden is shared across regions according to the future evolution of BAU emissions. With the Brasilian proposal rule the abatement

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[14] Equity principles are 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.

burden is shared according to the historical responsibility of countries in generating atmospheric carbon concentration according to the Den Helzen and Schaeffer [37] research study[15]. With the equalitarian rule an upper bound of emissions is introduced to countries in order to reach an equal level of emissions per capita according to their future level of population[16].

As we can see from Figure 13, the sovereignty rule and the Brasilian proposal generate a redistribution of emissions: past and future responsibility of rich countries in generating atmospheric carbon concentration induces their higher abatement effort and a redistributive effect.

Redistribution is particularly strong in the equalitarian scenario. An equal emissions per capita scenario would imply a 0 value of the Gini index. As can be noticed from Figure 13, the pseudo Gini inequality index is slightly higher than 0. In the LI region the emissions per capita upper bound is not binding and is higher than the optimal level of emissions per capita. "CONCEQUAL" and "CONCBRAS" scenarios lead to the greatest reduction in CO_2 and —although less remarkable— income inequalities, as well as the lowest reduction in the progressivity of emissions distribution.

In spite of the fact that the application of equity principles generates a strong redistribution of emissions, we always confirm that the Between group component of inequality is predominant (Table 12), the Kakwani index is always negative (Figure 14) and the inequalities in the distributions of emissions and income appear to be

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[15] In Den Helzen and Schaeffer [37]the historical responsibility of countries from 1751 to 1990 is shared with a different regional aggregation than the one of RICE99. For this reason we take data about the historical responsibility for Annex I and non Annex I countries from the Den Helzen and Schaeffer study and we share the abatement burden by applying the same reduction percentage to Annex I regions (USA, OHI, Europe, EE) and non Annex I regions (MI, LMI, China and LI) in RICE99.

[16] When we introduce the equalitarian principle the optimal level of emissions per capita can be lower than the upper bound for some regions over time. In this case the level of atmospheric carbon concentration is slightly lower than 550 ppm as in the other scenarios.

decreasing and correlated (figures 12 and 13). The magnitude of variations of income inequality is not very relevant. However, it can be noticed that CONCBRAS and especially CONCEQUAL are the scenarios in which income inequality decreases most. In these cases, climate change policies could make a (modest) contribution to the reduction of problem of inequality in income distribution. This may be clearer in the case of considering flexible mechanisms such as emissions trading (see next section).

[Figures 5, 6, 7 about here]

[Table 4, 5 about here]

5. Results for different scenarios of emissions reduction: the implementation of flexible mechanisms.

Finally, unlike Heil and Wodon [5] we also analyze the role of flexible mechanisms in income and emissions distributions in the context of emissions stabilizing policies. Some other studies have also analysed some equity implications of emissions trading for future paths of income and emissions. Vaillancourt and Waaub [18] employed an energy model (MARKAL) for analysing implications in terms of the different percentage of emissions allocated to different regions and the different reduction cost ranges for different regions under different allocation criteria for years 2010 and 2050. Leimbach [16] employed an integrated assessment model (ICLIPS) for analysing the implications of carbon emissions trading and equal per capita allocation principle in terms of the different losses in per capita consumption for 4 scenarios (restricted vs. unrestricted trade; and 2025 vs. 2100 as year in which equal per capita distribution takes full effect). Both studies show that emissions trading could both increase efficiency as well as lead to different per capita abatement costs in different regions, with negative abatement costs for some developing regions, which may gain from international emissions trade. This is especially evident in the case analysed by Leimbach [16], which implies a per capita equity criteria in the distribution of emission rights. Here we will employ the RICE99 model to study how the possibility of emissions trade can, under different policy scenarios, lead to a different evolution of inequality both in emissions and income over the period 1995–2100.

Our results show that, when we investigate scenarios involving different emissions reductions, trading does not significantly influence emissions and income distribution for most of the scenarios considered. Emissions trading is a crucial mechanism governing the efficiency of policy implementation and compliance costs but for two of the considered scenarios its impact on inequality indexes are almost negligible ("Kyoto – 10%" and "Kyoto – 10% + USA" scenarios), while for other two there are some small differences in emissions inequalities ("Temp" and "Conc" scenarios). The only exception is the "Global Kyoto" scenario (see Figures 8–12). 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. Trade has also a small impact on income inequality, which decreases more when emissions trade is allowed. Flexible mechanisms allows to alleviate the impacts of disproportionate mitigation efforts required to developing countries in this scenario.

As those scenarios involving a 550 ppm global atmospheric constraint with different equality principles results are quite interesting. In contrast to the Global Kyoto scenario for the CONCSOV, CONCBRAS and CONCEQUAL scenarios we find that trading increases inequality in the distribution of emissions as developed countries are buyers in the emissions permits market (see Figures 13, 14, 15).

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 especially 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 too relevant in terms of inequality evolution for most of the scenarios considered in this section.

As proof of the fact that the impact on emissions distribution is more relevant than that on GDP distribution, in the scenario CONCEQUAL involving the widest emissions redistribution, the highest impact is associated to United States that are heavily penalised and that can gain by trading of permits in terms of more output (+17% in 2105) by producing a 5 times higher level of emissions[17]. In the CONCEQUAL scenario together with CONCBRAS and CONSOV, emissions trading generates a modest income inequality increase. In these cases trading creates a mechanism in which the flow of money from rich (buyers) to poor countries (sellers)

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[17] Roson and Bosello [38] find by a RICE-type model only a - 6% variation of an equity index for GDP due to the implementation of an emissions permits market in 2050.

deriving from the permits market is more than compensated by cost savings that are mainly concentrated in developed regions.

[Figures 8,9,10,11,12, 13, 14, 15 about here]

6. Results for different parameters values: a sensitivity analysis

As we said previously our results are robust to sensitivity analyses run on crucial scalars like the pure rate of time preference, the depreciation rate of capital, the elasticity of marginal utility of consumption and the sensitivity of radiative forcing to atmospheric carbon concentration. However regional parameters rather than world scalars could also play a role in affecting the distribution of emissions.

For this reason, we analyse the TFP parameter (A(n,t) in the production function equation 2), the carbon intensity parameter (ζ(n,t) in the emissions equation 3) and population (L(n,t) in the production function equation 2). As those parameters are different for each region we simplify the scenarios implementation by assuming the same percentage of increase/reduction of parameters for all regions in a specific macro-region. In particular, we assume increases/decreases of the TFP and population parameters for Poor countries and increases/decreases of the carbon intensity parameters for the Rich macroregion. Of course, this analysis includes only the investigation of a small set of parameters and macroregions, but we deem this experiment as meaningful to verify the stability of model results by varying crucial parameters affecting the growth path.

We mainly focus on the Poor macro-region including China and LI because as outlined by Nordhaus [39]: “Many elements, particularly the assumptions for developing economies and economies in transition, are difficult to validate or estimate and are subject to large and growing projection errors as they run further into the future” (p. 125). The choice to run a sensitivity analysis to the carbon intensity parameter for the rich countries derives from the recent USA’s policy proposal to reduce carbon intensity (-18%) rather than the absolute value of emissions. Therefore we are interested in verifying how significant variations of the carbon intensity parameter for rich countries can affect the distribution of emissions over time.

The summary of the scenarios is included in Table 6 and results are presented in the table 7. We assume wide variations of the three parameters in the range [+30%, - 30%] to verify how robust our findings are.

Results are quite consistent. An increase/decrease of the TFP parameter for developing countries decreases/increases inequality in the distribution of output and emissions. This finding is quite intuitive. A faster growth for poor regions shrinks the gap in the level of output per capita and emissions per capita between rich and poor regions.

An increase/decrease of the population path increases/decreases inequality in the distribution of income and emissions in the first decades even if outcomes are more ambigous over time. In the first decades, an increase in population for developing countries increases the output levels, but output per capita and emissions per capita decrease as the elasticity of output to population is lower than 1.

An increase/decrease in the carbon intensity of rich countries increases/decreases the inequality in the distribution of emissions. An increase in the carbon content for each unit of consumed energy increases aggregate emissions levels for rich regions and consequently the level of emissions per capita being the population path as unchanged over time. When we vary the carbon intensity parameter we do not register significant variations of income distribution (Figure 7) as technological change is costless and benefits are enjoyed only in the medium-long term due to lower environmental damage.

A more general conclusion that we notice from our results is that we can confirm the results coming from the previous section:

- Inequalities in the distributions of income and emissions are decreasing and appear to be correlated;
- The Between group component of inequality in the distribution of emissions is predominant (Table 8);
- The Kakwani index is always negative (Figure 16).

Therefore, strong parameters variation does not affect the RICE99 findings on future emissions and income distribution under different mitigation policy scenarios presented in the previous section.

[Figure 16, 17, 18 about here]

[Tables 6, 7, 8 about here]

A final test that we want to run is to verify if our results also hold when we consider Purchase Parity Power (PPP) values rather than Market Exchange Rates (MER) to express output. The problem has been widely debated in climate change economics literature by those researchers claiming that MER values may lead to an upward bias of emissions and level of temperature (Manne et al. [40]). Nordhaus and Boyer, when they set up the RICE99 model criticize the PPP approach and provide strong motivations to support the MER approach.[18].

However in our context PPP values to express output could be useful to interpret meaningfully results coming from the elaboration of the Kakwani index. Our intuition is that the investigation of the effects deriving from PPP on our findings about equity could provide useful additional information and test robustness of the results obtained with MER values. To transform GDP values we follow a suggestion from Nordhaus and Boyer who claim [23]: "If users would like to convert the data to PPP income levels, the levels of output can of course be scaled by a factor to represent living standards at a particular time" (chapter 3, p. 5). In other words the authors suggest to assume equal growth rates in a MER and PPP environment and to scale results from simulations expressed in MER values to PPP values. To scale our results we follow the procedure adopted by Manne et al. [40] who calculate the PPP/MER ratio for each region on the basis of the following hyperbolic function:

$$(4) \qquad \frac{PPP}{MER}(n,t) = \frac{k(t)}{GDPpercapita(n,t)}$$

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[18] They claim [23]: "While it is common practice to use output measured at international or purchasing-power parity (PPP) exchange rates, this is inappropriate in the current context for three reasons. First, since historical output data at market exchange rates is more readily available than at PPP rates, we rely on these data to make projections about future growth in output and carbon intensity. In order for the output levels we project to be consistent with our projected output and carbon intensity growth rates, we define them as output at market exchange rates. Second, in the context of optimizing a country's consumption path, it should use its internal prices rather than the world average price level. Third, international trading in carbon emissions permits will take place at market exchange rates, so output needs to be measured in market exchange rates for consistency in measurement between trade flows and economic production as well as between the marginal cost of carbon abatement and the international carbon permit price.

We calibrate the value of K(t) since 1995 to 2085 by matching the PPP/MER ratio arising from the CPI baseline (von Vuuren et al. [41]) when we consider the world level of GDP per capita. We apply the PPP/MER regional ratios on the levels of output that we obtained through our sensitivity analysis in each scenario. Not surprisingly and in line with results of Manne et al. [40] the highest PPP/MER ratios are associated to China and Low Income Countries (the figure 18 presents MER GDP per capita, PPP GDP per capita and emissions per capita in a BAU scenario). When we consider PPP values, though all the inequality indices are confirmed to show a decreasing path over time, we observe a strong redistribution of the GDP Gini index towards poor regions, whereas the emissions pseudo Gini index and the ranking of regions in terms of GDP per capita influencing the decomposition of the Theil index are substantially unaffected.

Therefore the most interesting variation concerning the PPP context if compared to the MER context that we examined before concerns the Kakwani index. In particular for every scenario we notice an upward shift of the Kakwani index that remains negative only in the short term (see figure 17). Our results show that when we consider the distribution of income the choice between PPP values and MER values matters. These results complement those of Nordhaus and Boyer claiming that the introduction of PPP values "has little substantive effect" on the level of income and those of Manne and Richels [40] claiming that "Employing a computable general equilibrium model designed to examine a variety of issues in the climate debate, we find that there is a difference, but that it is only minor" on the level of emissions.

When we consider equity issues we cannot reach unambiguously the same conclusions.

7. Conclusions

In this paper we investigate how future scenarios involving different climate policies could affect emissions and income distribution over time. In spite of the limits of our investigation deriving from restrictive model assumptions and calibration and from the acknowledgment that in our study inequality refers to a cross country concept by hypothesising homogenous consumers and polluters within each region, we find a set of interesting findings derived from simulations.

First, we find a robust correlation between measures of inequality in income and emissions distribution. This result agrees with previous analogous studies. Of course, environmental policies could have an impact on the robustness of this finding. Specifically, we have shown that international climate agreements that penalise heavily developing countries could provide a contextual reduction of equality together with a redistribution of emissions towards developed countries. In these cases, evidence of a strong relationship between the evolution of inequalities in income and emissions distributions appears ambiguous, but the Between group component and consequently the differences in GDP per capita between rich and poor regions continue to be the most important determinants of emissions distribution. Moreover, as stated by Vaillancourt and Waaub [18] "the fact that the climate policies should not accentuate the inequalities between the developed countries and the developing countries is well accepted overall" (p. 497). Therefore, the policy scenarios leading to these results (Global Kyoto) can hardly be justified on equity grounds.

Another important implication for policy-making of the strong correlation between the inequalities in income and emissions per capita is that international policies oriented by the equity perspective of approaching to an equal per capita emissions rights criteria —a fair share of atmosphere— and so aiming at reducing the inequality in the distribution of emissions, would be more feasible if there were a reduction in income inequality between rich and poor countries. Global policies aimed at improving income equality would lead to reduce emissions inequality.

The great current inequalities involve that short-term measures focused on reducing emissions in rich countries might still be effective for controlling the evolution of global emissions for some years. Nevertheless, 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. This result reinforces the need to take into account the distribution consequences of the different policy alternatives in order to facilitate the participation of developing countries in the global policy measures.

Second, unlike previous studies, we provide an examination of the "progressivity" of future emissions distribution in comparison to income concentration through the Kakwani index. Mitigation policies involving a strong mitigation effort by developing regions might lead to a strong reduction of this "progressivity". This, other things equal and in the absence of flexible mechanisms and/or economic compensations to poor countries, could be considered as an undesirable result, as they lead to a negative redistribution of the assimilative capacity of the atmosphere by requiring a relatively disproportionate effort by poorer countries.

However, emissions distribution will also 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 this "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. Of course, it should be noticed that achieving a more equal distribution of emissions is not the only relevant goal because of the different efforts and/or benefits implied by the different allocation of the assimilative capacity of the atmosphere it implies. Therefore the reduction of "progressivity" in emissions distribution could also be seen as a consequence of the improvement in other important goals, such as reducing emissions and/or income inequality. These are complex trade off that policy makers should manage carefully and for which science could provide answers through multicriteria analysis or social choice tools.

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 and when we consider PPP values for GDP rather than MER The evaluation if PPP values or MER values is more appropriate to run equality analyses is beyond the aims of our paper, but we deem very important to underline that results are quite sensitive to this methodology adopted for the GDP measurement. Our elaborations clearly show that in a PPP context the distribution of emissions will remain "progressive" only in the short run and stimulate further research on the discrepancy arising between results in fields of research outside equity and climate change issues.

Third, a sensitivity analysis on different parameter values of the model shows the consistency of the results.

Fourth, the consideration of different equity criteria for a given level of global emissions reduction lead to different results in terms of the evolution of emissions inequality, while the consequences on income inequality are much lower.

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 emissions trade is irrelevant, for others we find that the purchase/sale of permits could determine a significant redistribution of emissions among countries. Policy makers should take into account this important aspect when designing policies: the results confirm that increasing the perceived fairness and so obtaining widespread acceptability of international agreements will be needed in order to achieve any relevant objective, and this requires achieving a more equitable distribution over time through those agreements.

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Appendix 1.

List of variables.

C (n,t)=consumption expressed in *trillions of 1990US$*
L (n,t)= population expressed in *millions*.
Q (n,t)=Gross production expressed in *trillions of 1990 US$*
Y(n,t) = Production net of environmental damage expressed in trillions of 1990 US$.
CE (n,t)= Carbon energy expressed in *gigatons*
I (n,t)= fixed investments expressed in *trillions of 1990 US$.*
E = Total industrial CO_2 emissions emissions expressed in *gigatons.*
ETREE (n,t)= Land use carbon emissions expressed in *gigatons.*
p_e (n,t) = Cost of one unit of carbon energy expressed in thousands of $ per ton

List of parameters
α (n) = Elasticity of output to carbon energy (regional parameter)
γ = Elasticity of output to capital (scalar)
ζ (n,t)= Exogenous technical change effect of energy on CO_2 emissions
A(n,t)= total factor productivity

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Tables

Table 1 Scenarios description

Scenario	Description
BAU	Business as usual. No policy.
Kyoto – 10% no trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 “Kyoto – 10% forever scenario”. No market of pollution permits.
Kyoto – 10% trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 “Kyoto – 10% forever scenario”. Since 2015 market of pollution permits.
Kyoto – 10% + 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 – 10% 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 – 10% + USA trading	In 2015 Kyoto emission constraint for OHI, Western Europe and Eastern Europe regions. Further 10% emissions reduction in 2025. From 2025 “Kyoto – 10% 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 – 10% 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 – 10% 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.

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Table 2. Percent of emissions reduction (Policy vs BAU scenario) in 2105. Annex I vs non Annex I regions. No trading scenarios.

Kyoto – 10%		*Kyoto – 10% + USA*		*Global Kyoto*		*Temp*		*Conc*	
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*

Table 3. Decomposition of the Theil index. Business as usual (BAU) scenario in 2055.

	Theil	Theil Between	Theil Within	Contribution Between (%)	Contribution Within (%)	Contribution Within (%) High income	Contribution Within (%) Medium income	Contribution Within (%) Low income
BAU	0.310	0.259	0.051	83.632%	16.368%	7.933%	1.893%	6.542%
Kyoto no trading	0.303	0.250	0.054	82.260%	17.740%	9.430%	1.548%	6.763%
Kyoto -10% + USA	0.300	0.248	0.053	82.407%	17.593%	9.176%	1.568%	6.850%
Global Kyoto no trading	0.407	0.334	0.073	81.991%	18.009%	7.989%	2.248%	7.773%
Temp no trading	0.342	0.292	0.050	85.335%	14.665%	7.209%	2.895%	4.561%
Conc no trading	0.322	0.272	0.050	84.464%	15.536%	7.621%	2.322%	5.593%

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Table 4. Summary of the equity principles.

Conc	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. Since 2025 a 550 ppm global atmospheric constraint.
CONCSOV	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. Since 2025 a 550 ppm global atmospheric constraint. The global burden is shared according to the future responsibility of countries in generating emissions
CONCBRAS	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. Since 2025 a 550 ppm global atmospheric constraint. The global burden is shared according to the past responsibility of countries in generating emissions
CONCEQUAL	Kyoto commitment for OHI, Western Europe and Eastern Europe in 2015. Since 2025 a 550 ppm global atmospheric constraint. Equal per capita emissions per region.

Table 5. Decomposition of the Theil index in a Between and a Within component for different equity principles in 2055.

	Between	***Within***	***Theil index***
Conc	0.272	0.050	0.322
CONCSOV	0.258	0.050	0.308
CONCEQUAL	0.041	0.032	0.073
CONCBRAS	0.223	0.058	0.281

Table 6. Summary of the sensitivity analysis for parameters.

$A (n,t)$ – China and LI countries	+ 30% (TFP + 30%)	+20% (TFP + 20%)	+10% (TFP + 10%)	-10% (TFP - 10%)	-20% (TFP - 20%)	-30% (TFP - 30%)
$\zeta (n,t)$ – USA, OHI countries and Europe.	+ 30% (PHI + 30%)	+20% (PHI + 20%)	+10% (TFP + 10%)	-10% (PHI -10%)	-20% (PHI - 20%)	-30% (PHI - 30%)
$L (n,t)$ China and LI	+ 30% (POP + 30%)	+20% (POP + 20%)	+10% (POP + 10%)	-10% (POP -10%)	-20% (POP - 20%)	-30% (POP - 30%)

countries						

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Table 7. Sensitivity analysis. Value of the GDP Gini index and emissions pseudo Gini index compared to the BAU scenario.

	GDP Gini index	***CO_2 pseudo Gini index***
TFP + 30%	-13.203	-21.215
TFP + 20%	-8.885	-14.586
TFP +10%	-4.477	-7.479
TFP - 10%	4.523	8.196
TFP - 20%	9.051	16.730
TFP - 30%	13.497	25.573
PHI + 30%	0.032	10.004
PHI + 20%	0.023	6.833
PHI + 10%	0.013	3.481
PHI - 10%	-0.005	-3.300
PHI - 20%	-0.015	-6.872
PHI - 30%	-0.025	-10.377
POP + 30%	-1.798	-1.152
POP + 20%	-1.093	-0.606
POP + 10%	-0.482	-0.167
POP - 10%	0.320	0.197
POP - 20%	0.406	-0.032
POP - 30%	0.182	-0.687

Table 8. Sensitivity analysis. Decomposition of the Theil index in a between and a within component in 2055.

	Between	*Within*	*Theil index*
TFP + 30%	0.144	0.056	0.199
TFP + 20%	0.176	0.054	0.230
TFP +10%	0.214	0.052	0.267
TFP - 10%	0.313	0.049	0.363
TFP - 20%	0.375	0.048	0.423
TFP - 30%	0.447	0.047	0.494
PHI + 30%	0.336	0.054	0.390
PHI + 20%	0.310	0.053	0.363
PHI + 10%	0.285	0.052	0.337
PHI - 10%	0.235	0.050	0.285
PHI - 20%	0.212	0.049	0.261
PHI - 30%	0.190	0.048	0.237
POP + 30%	0.263	0.053	0.316
POP + 20%	0.263	0.052	0.315
POP + 10%	0.262	0.052	0.313
POP - 10%	0.257	0.050	0.307
POP - 20%	0.252	0.049	0.301
POP - 30%	0.245	0.049	0.293

Figures

Figure 1. CO$_2$ pGini index

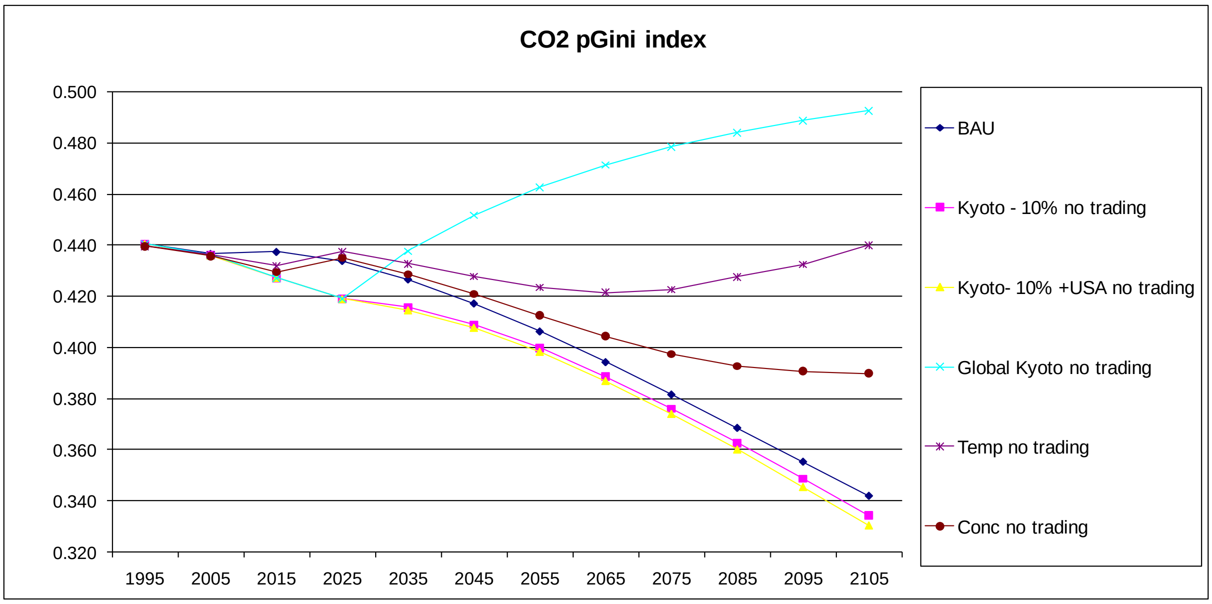


Figure 2. GDP Gini index

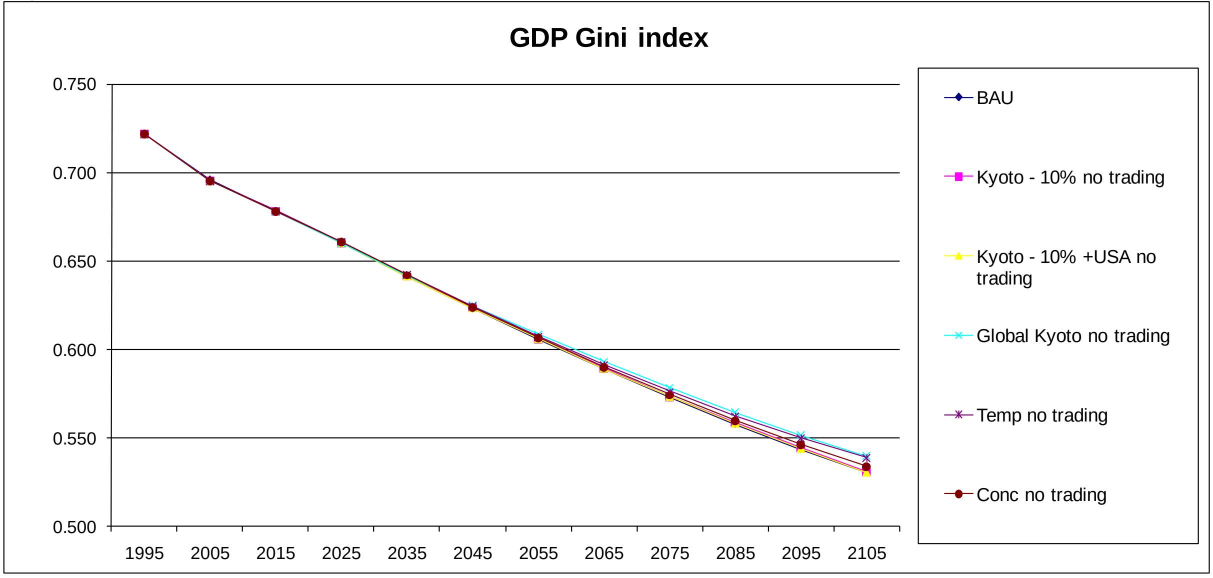
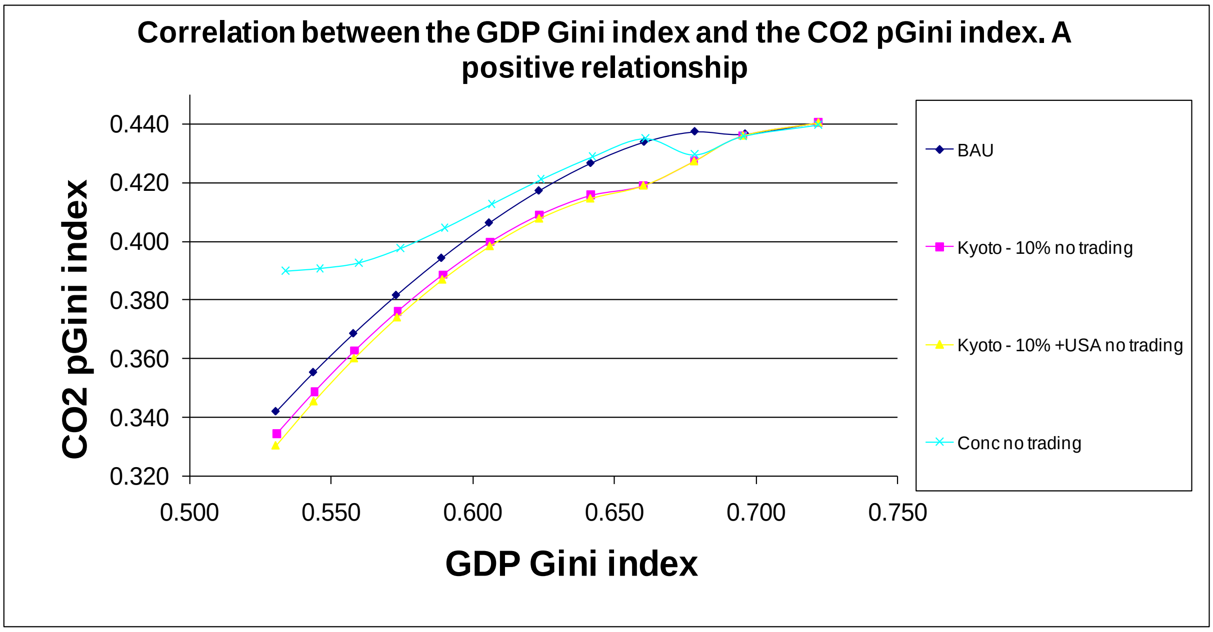


Figure 3. The relationship between the GDP Gini and the CO$_2$ pGini index.



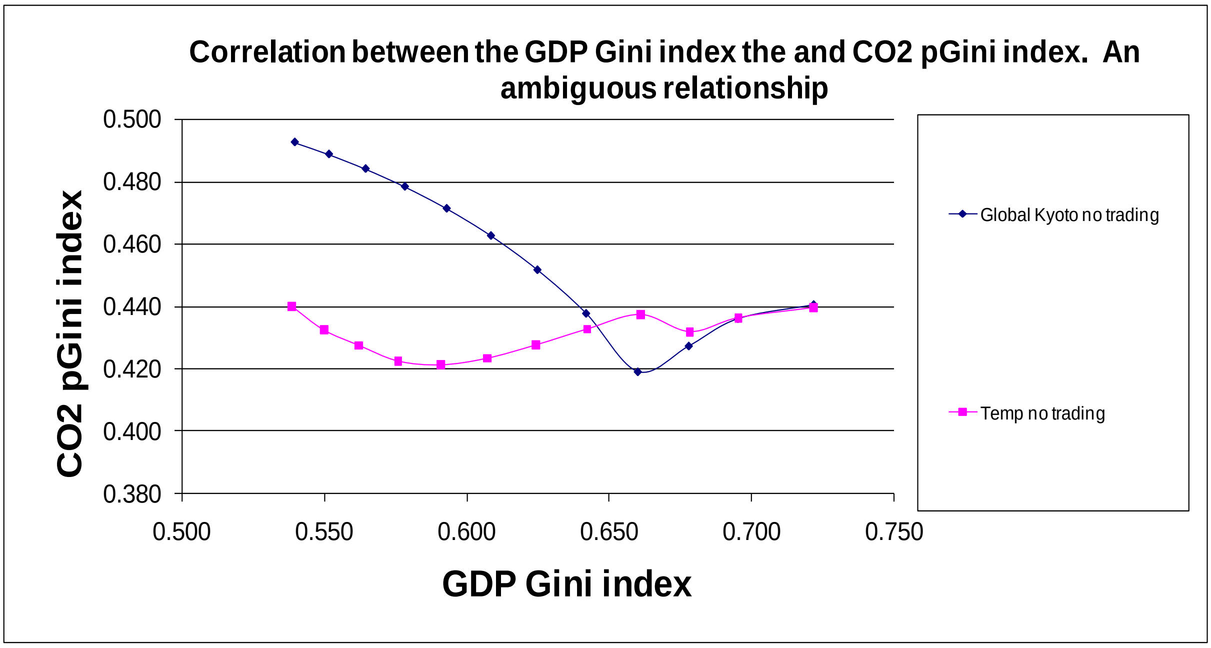


Figure 4. Kakwani index.

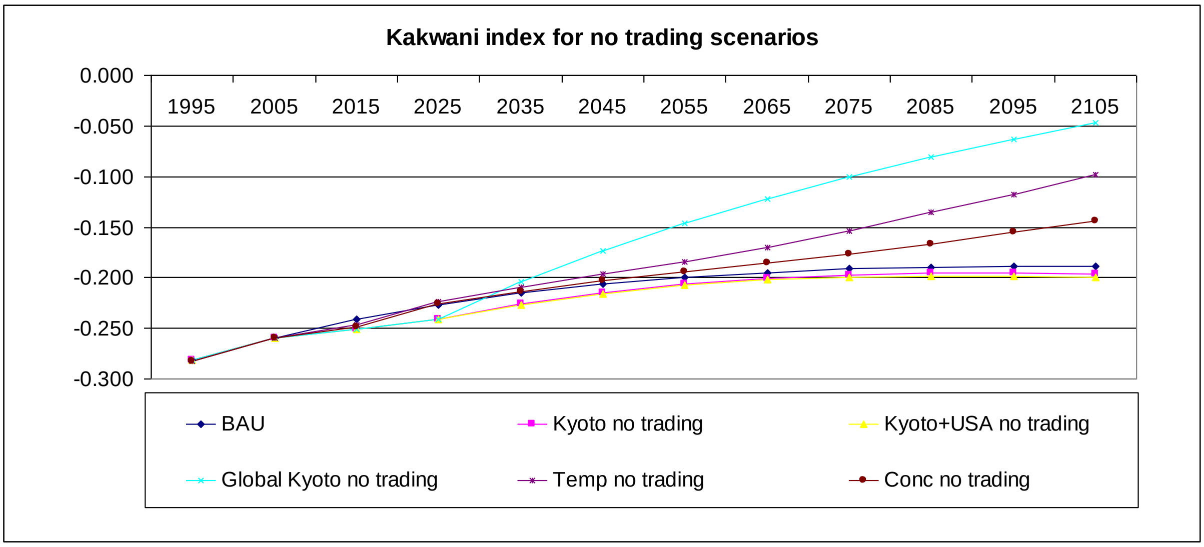


Figure 5. Income Gini index for different equity principles.

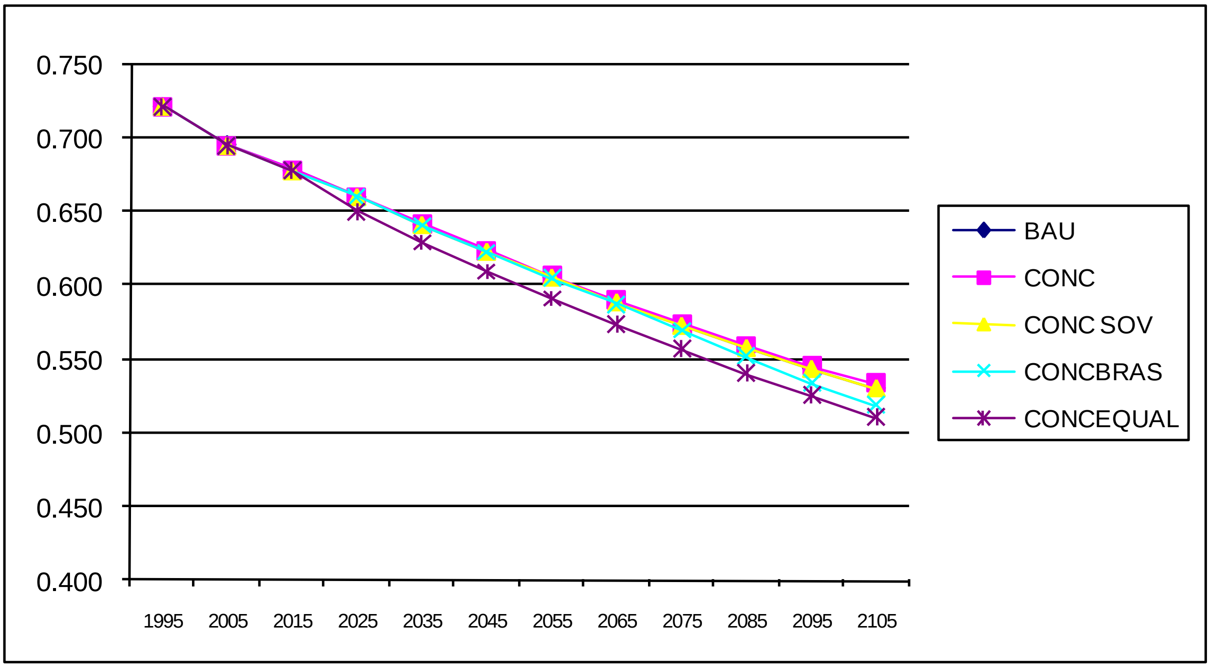


Figure 6. Emissions pseudo Gini index for different equity principles.

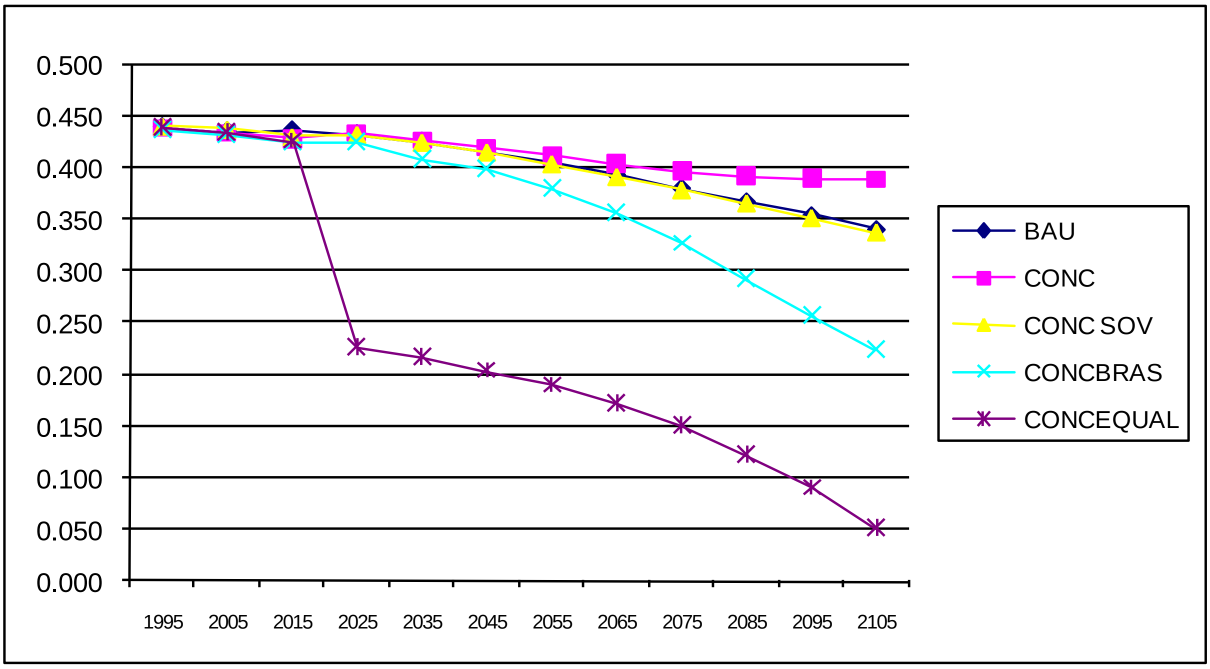


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Figure 7. Kakwani index for different equity principles.

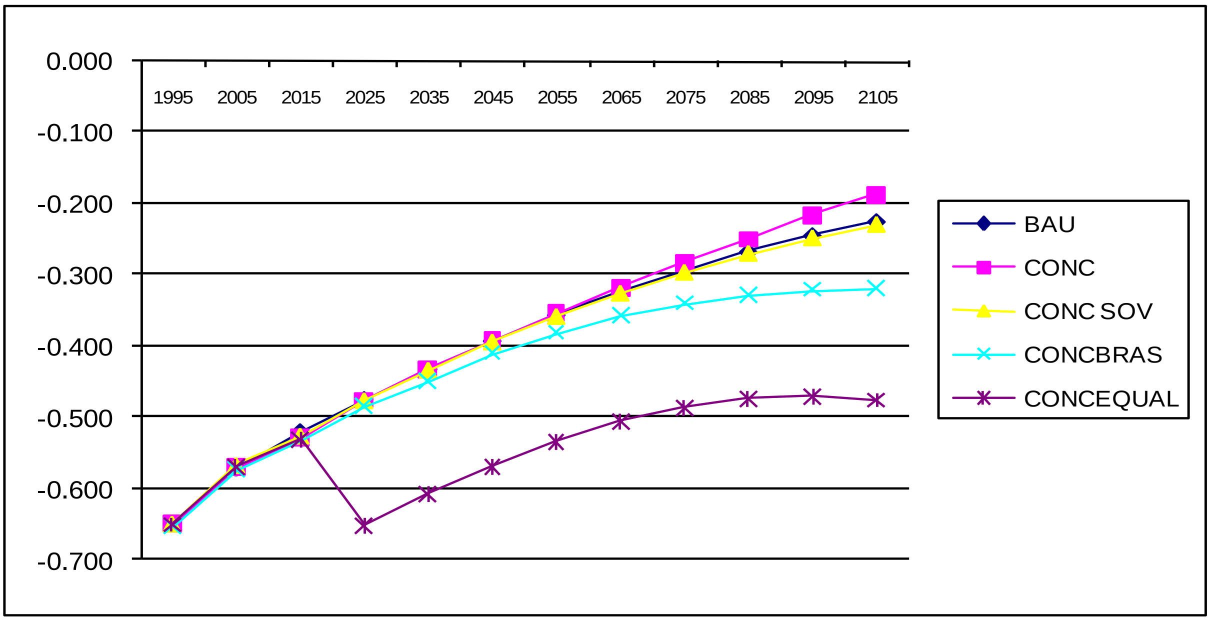

Figure 8. Non trading vs trading. Kyoto – 10% scenario.

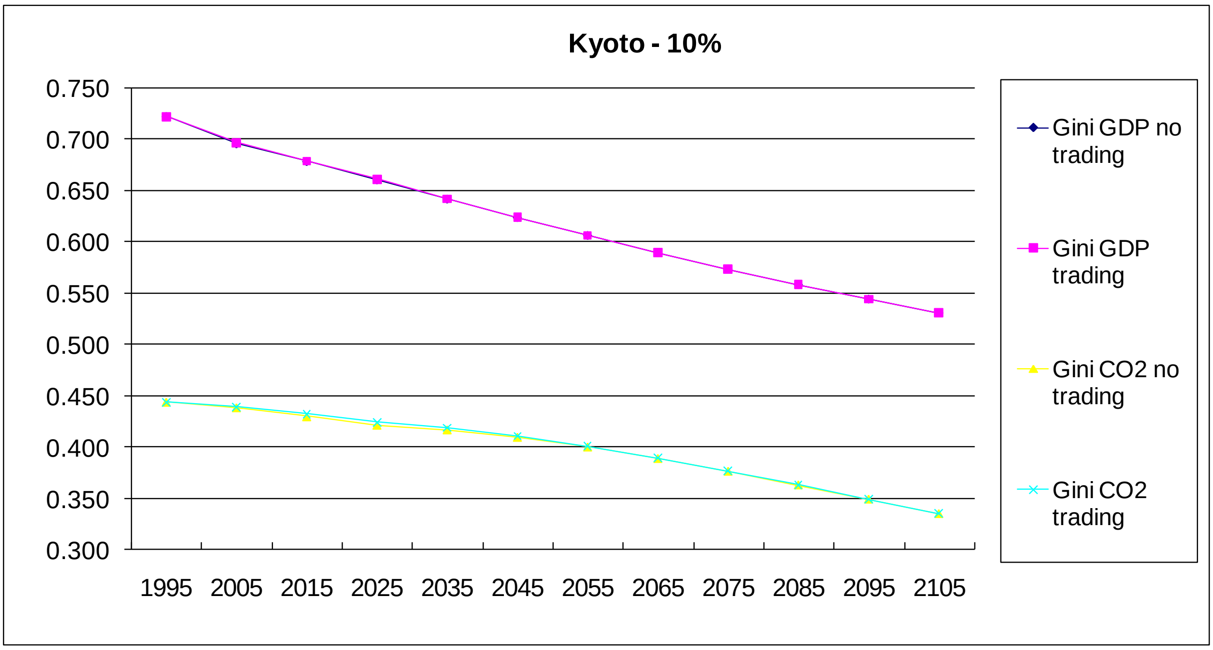

Figure 9. Non trading vs trading. Kyoto – 10% + USA scenario.

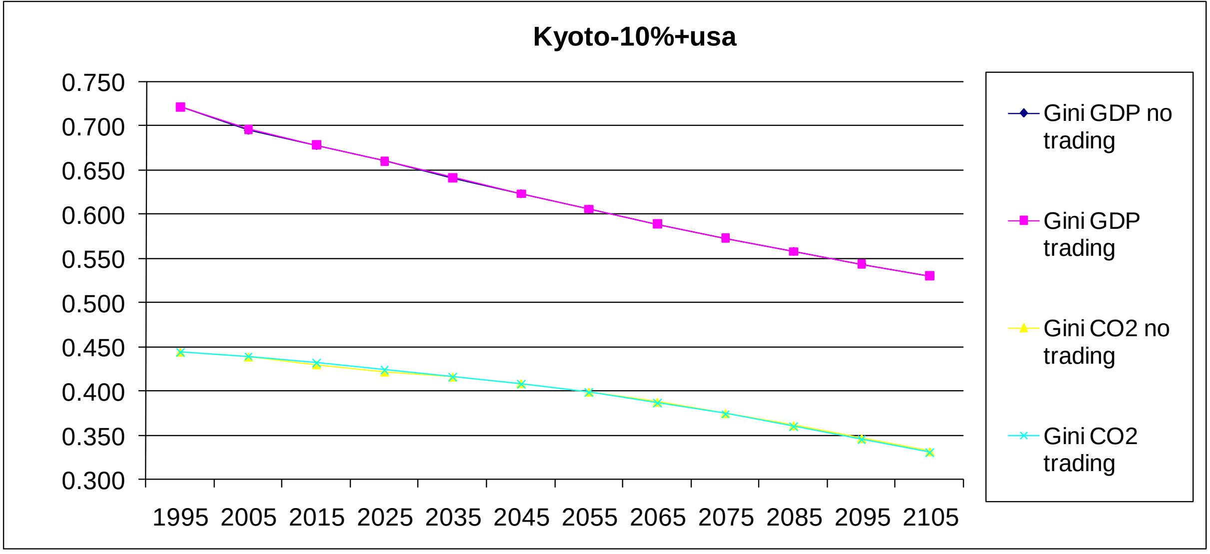

Figure 10. Non trading vs trading. Global Kyoto scenario.

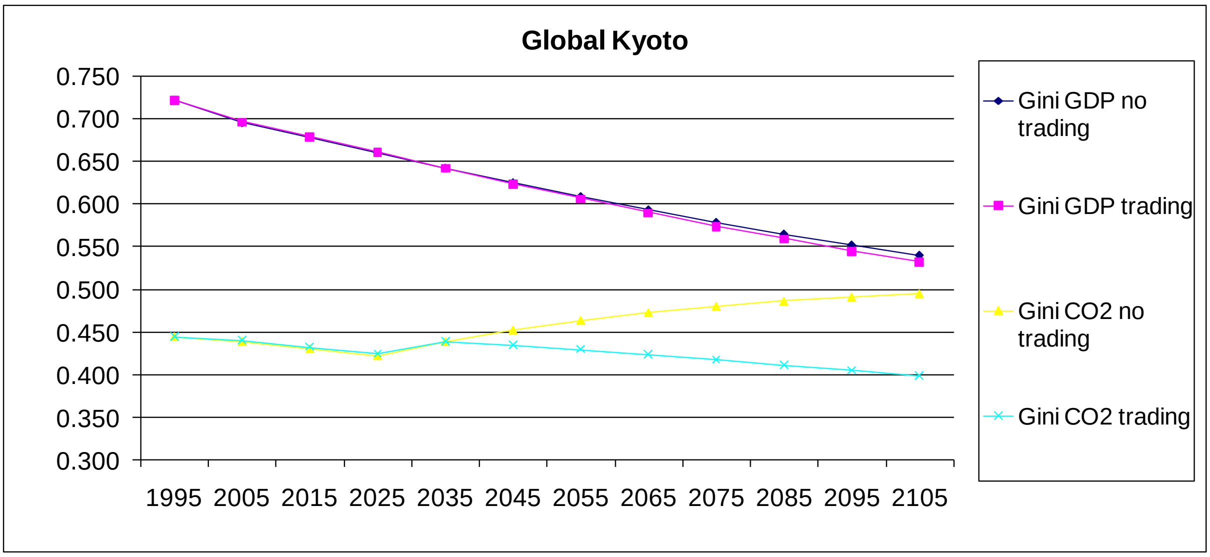

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Figure 11. Non trading vs trading. Temp scenario.

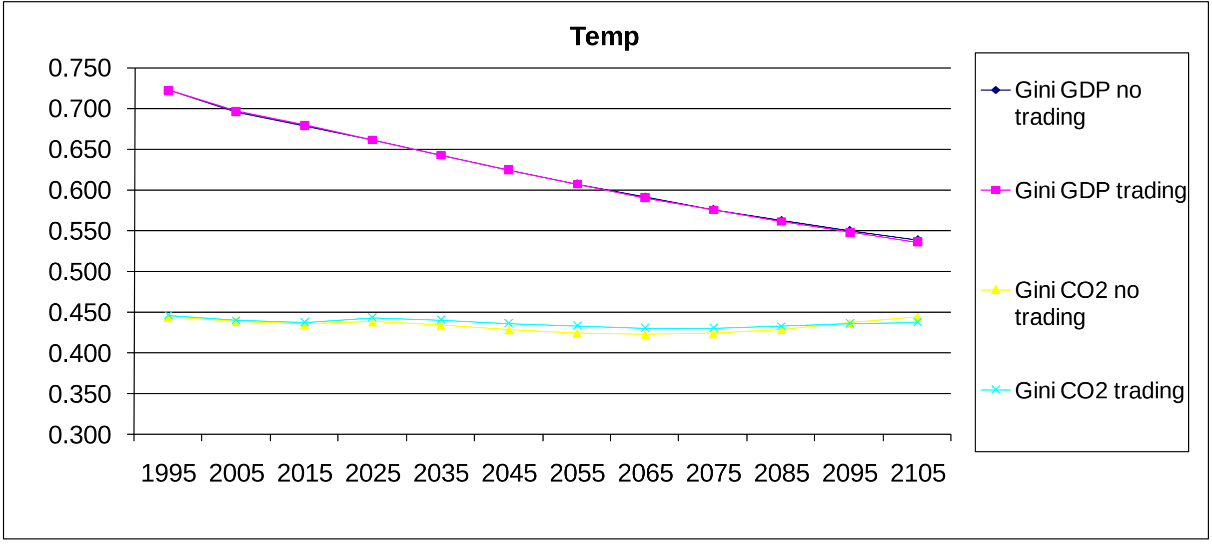

Figure 12. Non trading vs trading. Conc scenario.

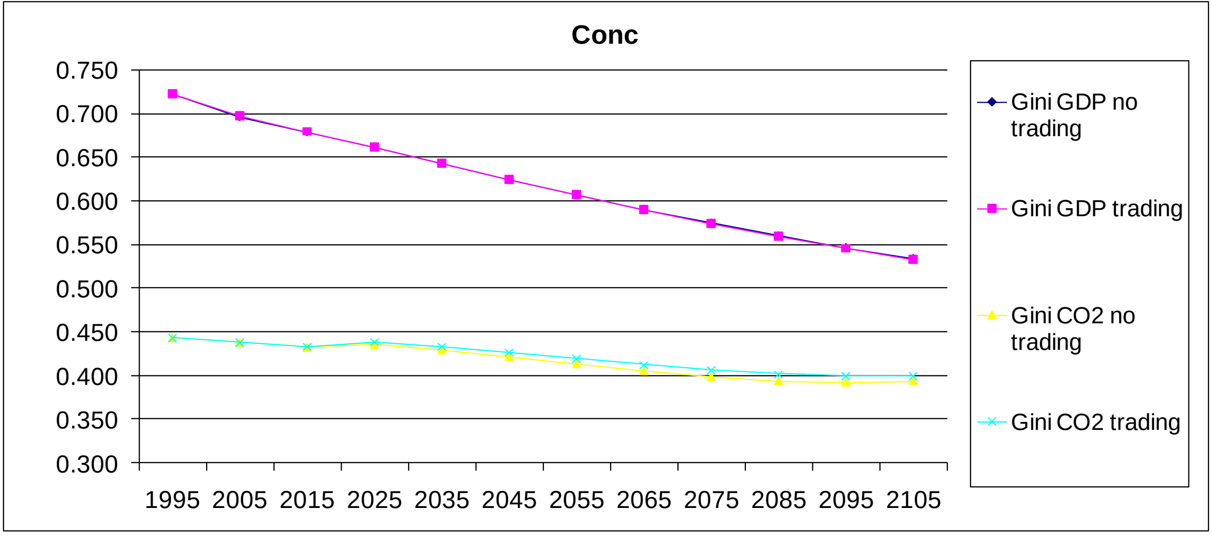

Figure 13. Non trading vs trading. CONCSOV scenario.

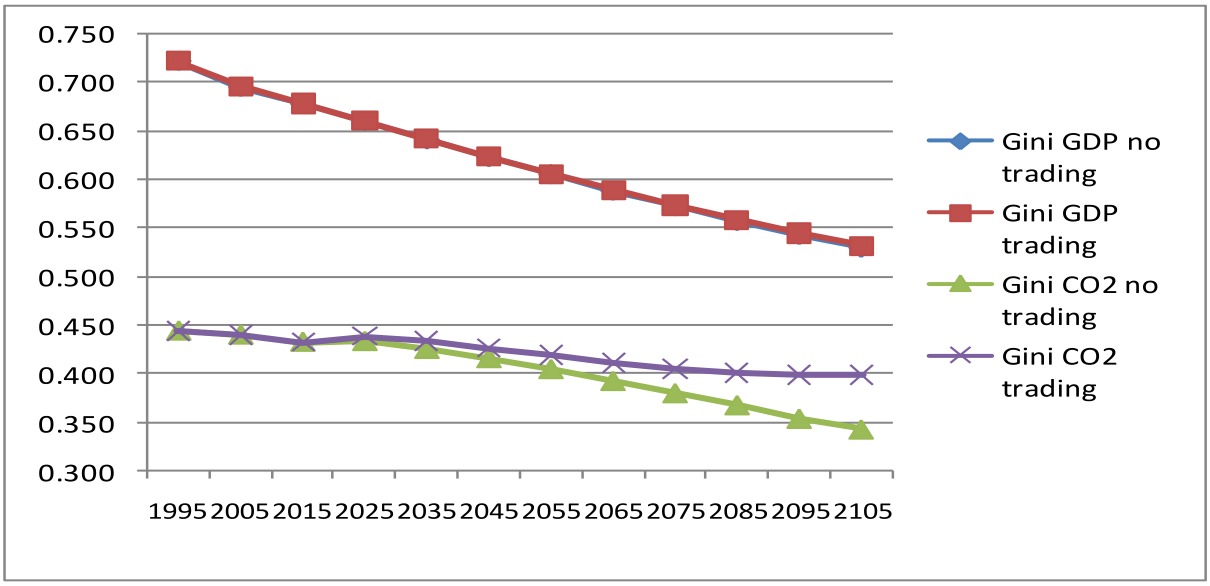

Figure 14. Non trading vs trading. CONCBRAS scenario.

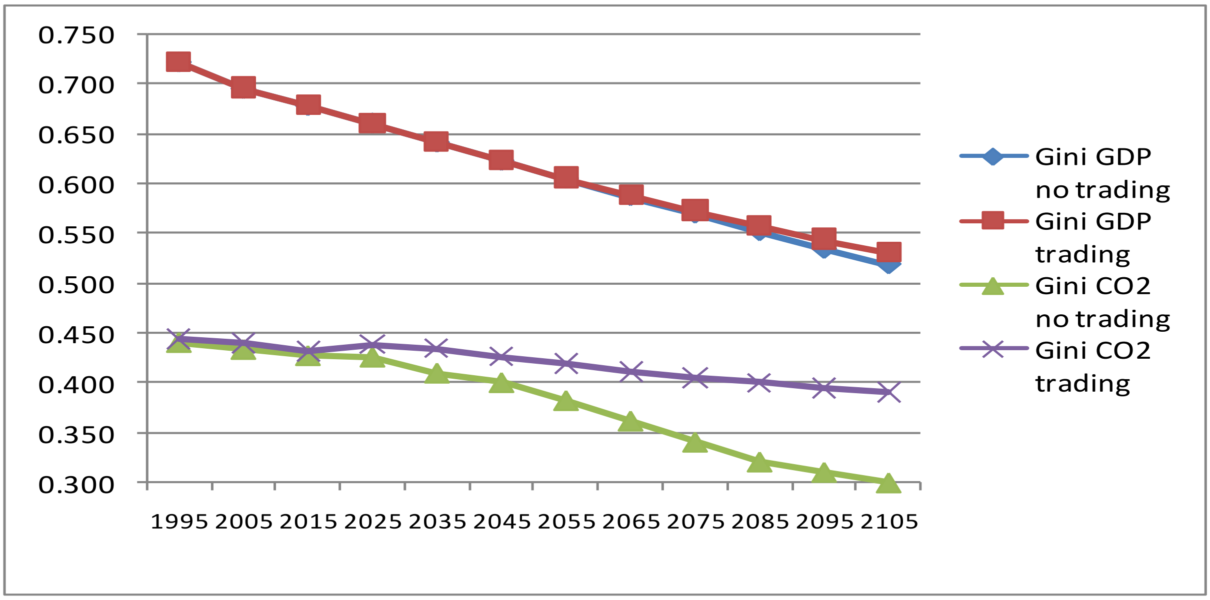

Figure 15. Non trading vs trading. CONCEQUAL scenario.

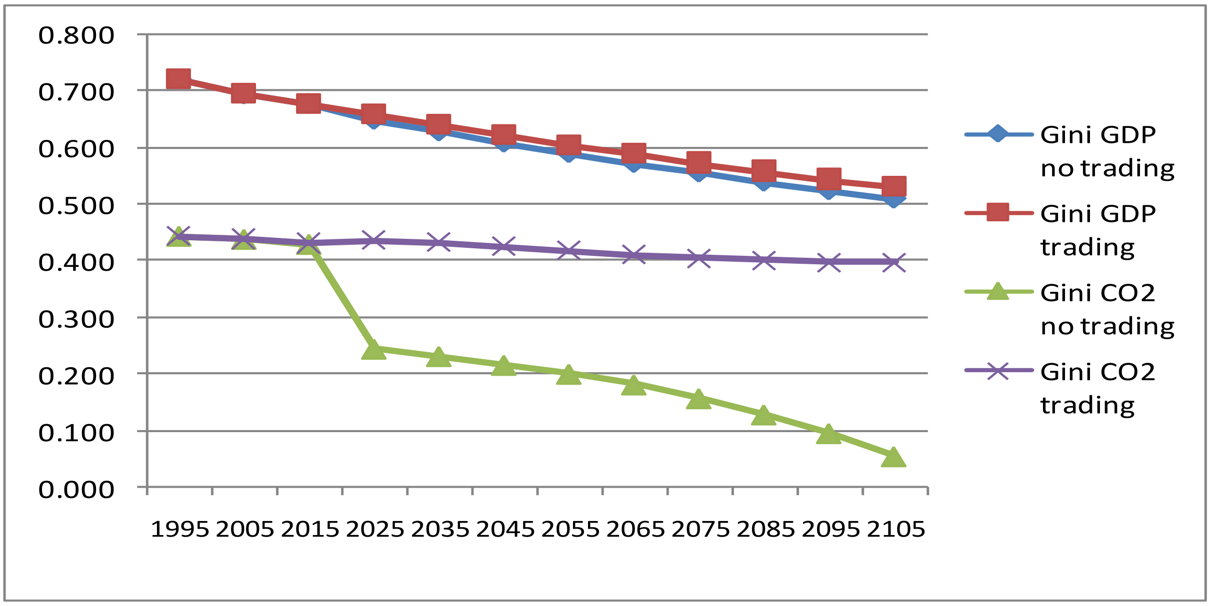

Figure 16. The sensitivity analysis. The Kakwani index: MER values for GDP.

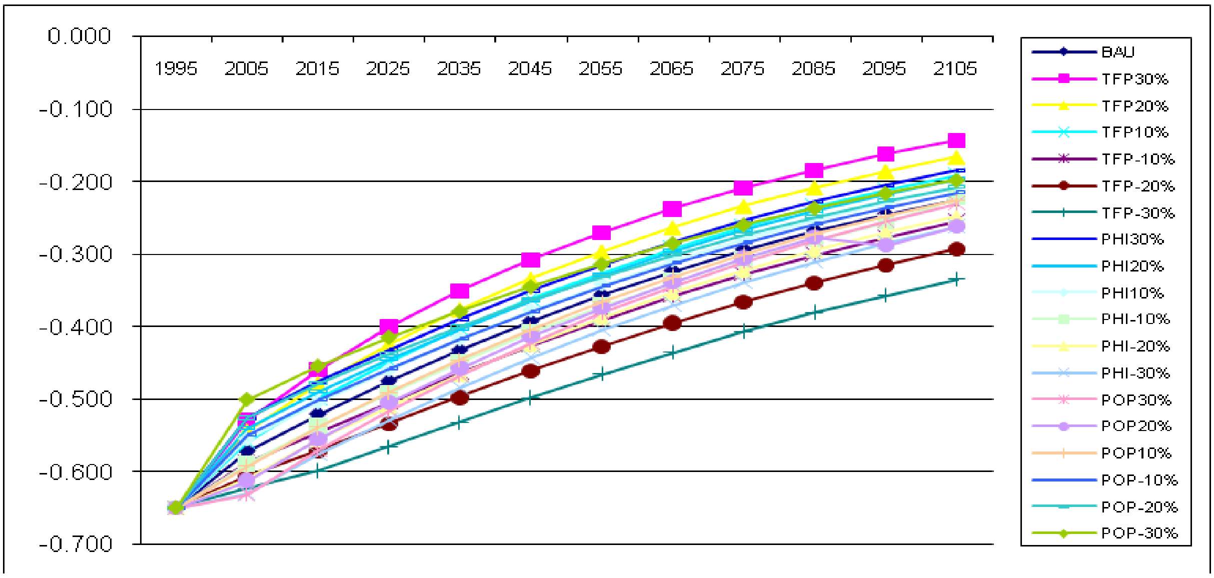

Figure 17. Kakwani index: PPP values for GDP.

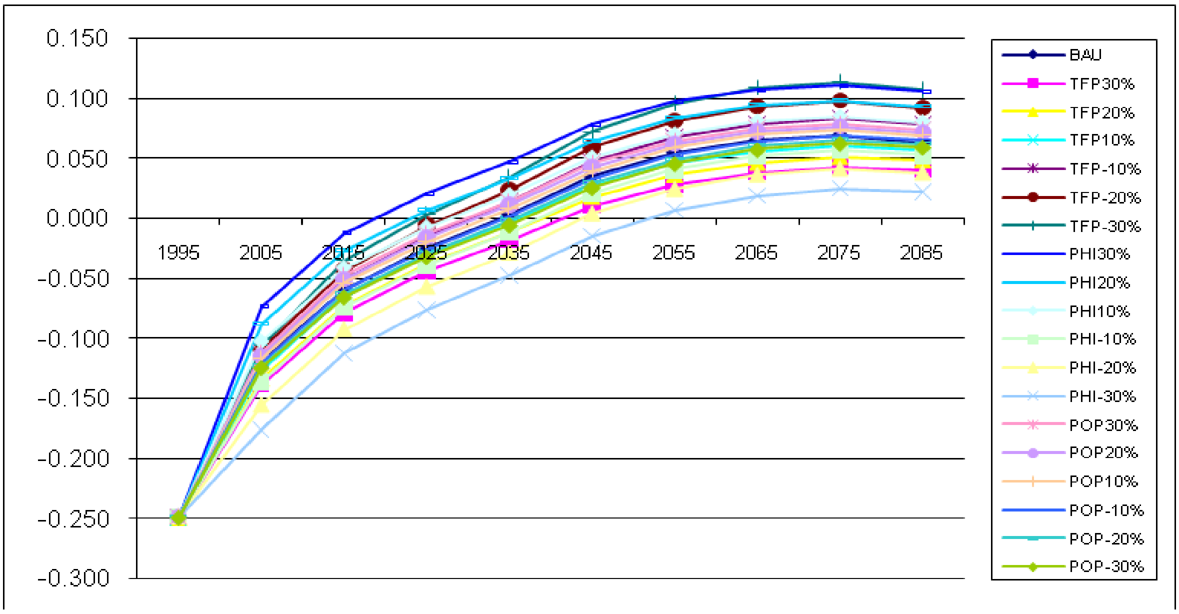

Figure 18.

RICE99. MER GDP per capita, PPP GDP per capita (thousands of 1995$ per capita) and emissions per capita (Gigatons/billions of people) and emissions per capita in a BAU scenario.