International Emission Inequality
and Per Capita Abatement Schemes

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Abstract
Carbon-dioxide emission inequalities between and within five income groups of countries are computed. The revealed dominant inequality between the high income groups and the low and middle income groups and its likely intensification by an internationally uniform abatement rate constitute a case for using per capita figures in assessing countries’ unilateral and internationally cooperative abatements. Our analysis suggests that the cooperative expected net benefit maximizing abatement can be smaller than the unilateral abatement for weak countries and for countries with high ability and inclination to politically and economically reward other countries.

JEL Classification: F
Keywords: National Emissions; International Inequality; International Relations; Cooperative Abatement; Unilateral Abatement
1. Introduction

In addition to a cleaner and healthier domestic environment and a slower process of global warming, a country’s benefit from self reduction of carbon-dioxide emissions may include improved image and, in turn, bilateral economic and political relations. Studies of international carbon-dioxide emissions have considered the effect of international economic relations – trade, in particular. For example, Barrett (1997) has studied the role of trade sanctions in deterring free riding. Using a general equilibrium model with a game theoretic component, Alpay (2000) has shown under which conditions trade can stimulate environmental protection. Eyckmans and Tulkens (2003) have introduced a world model for simulating cooperative game theoretic aspects of global climate negotiations. Kemfert, Lise and Tol (2004) have focused on how international trade changes optimal emission reduction and incentives to cooperate on emission reduction. Their modelling of a country’s cost of emission reduction has attempted to capture the domestic costs of self emission reduction, the effect of international variation in the level of stringency of emission reduction policy on the country’s terms of trade and capital flow, and the negative external effect on the country’s export of a slowing international economic growth that is due to foreign emission reduction.

The models used in the aforesaid studies focus on aggregate levels of domestic and foreign emissions and some of their assumptions hold only if countries are identical. Countries differ in population size and growth rate and in stage of economic development. Although lower middle income countries such as China and India contributed 23.47% and 4.93% of the global carbon-dioxide emissions in 2004, the per capita emissions of these populous large producers of highly affordable traded goods were 19% and 6%, respectively, of those of high income countries such as Canada and the United States. These differences and inequities are not captured by models focusing on countries’ aggregate levels of emissions. We therefore focus our analysis on per capita emission abatement. We demonstrate that if other countries’ assessments of, and reactions to, a country’s commitment to per capita emission abatement are influenced by relative per capita output and its traded component, the optimal cooperative per capita abatement can be smaller than the unilaterally optimal one for some countries.

To motivate the use of per capita figures in evaluating countries’ carbon-dioxide emission abatement, Section 2 investigates, in a manner that takes into account
population shares, the contributions of emission disparities between and within income groups of countries to the international emission inequality since 1990 – the post Cold War and transition period to global market economy. The investigation reveals a stable dominance of inequality between the income groups over the inequality within these groups. This finding does not lend support to the environmental Kuznets curve hypothesis. It can be supported by Dunlap, Gallup and Gallup’s (1993) finding that nine out of the fourteen items in the Health of the Planet Survey that measure environmental concern are negatively correlated with GNP per capita. It can also be supported by Franzen’s (2003) finding that the increase in real per capita income between 1993 and 2000 did not lead to a further increase in the environmental concerns of the residents of wealthier nations who participated in the 1993 and 2003 International Social Survey Programs.

To further motivate the use of per capita figures in evaluating countries’ carbon-dioxide emission abatement, Section 3 highlights the possible intensification of the emission inequality between the income groups of countries under an internationally uniform abatement rate of national aggregate emissions. Carbon-dioxide emissions are byproducts of production and consumption activities. From a global welfare perspective, an intensification of the already large international per capita emission disparities is not desirable. Therefore, we construct in Section 4 and Section 5 an emission-abatement scheme with non-uniform abatement rates based on per capita figures.

Section 4 formulates a country’s costs and benefits of abatement in a way that highlights the possible effects of the country’s and her counterparts’ per capita emissions, incomes and domestically consumed output. In particular, the assessment of, and reaction to, a country’s commitment to emission abatement by other countries are considered to be influenced by per capita income and traded and non-traded output composition. A higher degree of tolerance is assumed to be revealed toward a low income country with a large share of traded output than to a high income country with a small share of traded output. Section 5 incorporates this influence into the determination of an internationally cooperative emission-reduction scheme.

For comparison, section 6 incorporates the said influence into the determination of unilateral emission reductions. The comparison reveals that in the presence of such an influence the unilateral emission abatements by some countries can exceed their optimal internationally cooperative abatements. Section 7 further computes and
discusses the Cournot equilibrium emission abatement for a special case – a world divided into two alliances.

2. International emission inequality and its decomposition by income

To motivate the use of per capita figures in assessing countries’ carbon-dioxide emission abatement this section investigates the emission disparities between and within income groups of countries. Following Fishlow’s (1972) earliest application, our computation of the international emission inequality employs a decomposition formula of Theil’s (1967) entropy coefficient. With $q_k$ denoting the emission share of income group $k$ in the global emissions, $p_k$ the population share of income group $k$ in the global population, $q_{ik}$ the emission share of country $i$ affiliated to income group $k$ in the global emissions, and $p_{ik}$ the population share of country $i$ affiliated to income group $k$ in the global population, the Theil index of the international emission inequality is

$$\sum_k \sum_i q_{ik} \log \left( \frac{q_{ik}}{p_{ik}} \right) = \sum_k q_k \log \frac{q_k}{p_k} + \sum_k q_k \sum_i \frac{q_{ik}}{q_k} \log \left( \frac{q_{ik}}{q_k} \frac{p_k}{p_{ik}} \right).$$

(1)

As shown by Bourguignon (1979), this index is differentiable, symmetric and homogeneous of degree zero. The decomposition formula on the right-hand side indicates the contributions of the income groups of countries in a manner that preserves the total emission inequality between the individual countries computed with the left-hand-side formula. The first term on the right-hand side measures the emission inequality between the income groups of countries and the second, the emission inequality within these groups.

Using the World Bank’s classification, countries are sorted into low income, lower middle income, upper middle income, high income/nonOECD and high income/OECD groups (see Appendix A). Table 1 summarizes our computations of the international emission inequality index and decomposition between and within the

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1 The equality of this decomposition to total international emission inequality is proven as follows:

$$\sum q_k \log \frac{q_k}{p_k} + \sum_k q_k \sum_i \log \left( \frac{q_{ik}}{q_k} \frac{p_k}{p_{ik}} \right) = \sum q_k \log \frac{q_k}{p_k} + \sum_k q_k \sum_i \frac{q_{ik}}{q_k} \left[ \log \frac{q_{ik}}{p_{ik}} - \log \frac{q_k}{p_k} \right]$$

$$= \sum_k q_k \log \frac{q_k}{p_k} - \sum_k q_k \log \frac{q_k}{p_k} \sum_i \frac{q_{ik}}{q_k} + \sum_k \sum_i q_{ik} \log \frac{q_{ik}}{p_{ik}} = \sum_k \sum_i q_{ik} \log \frac{q_{ik}}{p_{ik}}.$$
said income groups with the United Nations’ data on 185 countries’ carbon-dioxide emissions and populations in 1990, 1995, 2000 and 2004.\(^2\)

Table 1. Income groups’ carbon-dioxide emissions: share, per capita and inequality

<table>
<thead>
<tr>
<th>Year</th>
<th>Low Income</th>
<th>Lower Middle Income</th>
<th>Upper Middle Income</th>
<th>High Income Non OECD</th>
<th>High Income OECD</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>0.1636</td>
<td>0.5293</td>
<td>0.1426</td>
<td>0.0178</td>
<td>0.1467</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>0.1605</td>
<td>0.5264</td>
<td>0.1443</td>
<td>0.0181</td>
<td>0.1508</td>
<td>1</td>
</tr>
<tr>
<td>1995</td>
<td>0.1464</td>
<td>0.5324</td>
<td>0.1474</td>
<td>0.0186</td>
<td>0.1552</td>
<td>1</td>
</tr>
<tr>
<td>1990</td>
<td>0.1456</td>
<td>0.5275</td>
<td>0.1460</td>
<td>0.0188</td>
<td>0.1621</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Population share</th>
<th>Emission share</th>
<th>Per capita emissions (in metric tons)</th>
<th>Contribution to inequality between groups</th>
<th>Contribution to inequality within groups</th>
<th>Contribution to global inequality</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>0.0240</td>
<td>0.3131</td>
<td>0.5274</td>
<td>-0.0200</td>
<td>0.0072</td>
<td>-0.0128</td>
</tr>
<tr>
<td>2000</td>
<td>0.0221</td>
<td>0.2684</td>
<td>0.5100</td>
<td>-0.0190</td>
<td>0.0073</td>
<td>-0.0117</td>
</tr>
<tr>
<td>1995</td>
<td>0.0283</td>
<td>0.2616</td>
<td>0.5135</td>
<td>-0.0202</td>
<td>0.0153</td>
<td>-0.0049</td>
</tr>
<tr>
<td>1990</td>
<td>0.0288</td>
<td>0.2239</td>
<td>0.2164</td>
<td>-0.0203</td>
<td>0.0083</td>
<td>-0.0031</td>
</tr>
</tbody>
</table>

The largest contributor to the international emission inequality has been the high income/OECD group. Its contribution has been about eight times that of the second largest contributor – the high income/nonOECD group. Despite having the largest

\(^2\) Annual figures on carbon-dioxide emissions and populations are extracted from the Millennium Development Goals Database, and from the UNSD Demographic Statistics, United Nations Statistics Division.

\(^3\) Computed as \(q_k \log \frac{q_k}{p_k}\).

\(^4\) Computed as \(q_k \sum_i \frac{q_{ik}}{q_k} \log \left( \frac{q_{ik}}{q_k} \right) \left( \frac{p_{ik}}{p_k} \right)\).

\(^5\) Computed as \(q_k \log \frac{q_k}{p_k} + q_k \sum_i \frac{q_{ik}}{q_k} \log \left( \frac{q_{ik}}{q_k} \right) \left( \frac{p_{ik}}{p_k} \right)\).
internal emission inequality, the lower middle income group has had, as in the case of the low income group, an overall moderating effect on the international emission inequality due to a dominant negative contribution to inequality between groups. Yet the aggregate contribution of inequality between the five income groups to the international emission inequality has been about twice as large as the contribution of the inequality within these groups during the entire observed period. This result is attributed to the very large contribution of the high income/OECD group to the emission inequality between groups, while modestly contributing to emission inequality within groups, and to the low emission inequalities within the other income groups.

Furthermore, the emission share of the high income/OECD group has been about three times this group’s population share. In contrast, the emission share of the low income group has declined from 0.2 to 0.146 of its population share, and the emission share of the lower middle income group, to which more than half of the world’s population and the largest workshop economies – China and India – are affiliated, has only increased from less than 0.5 of its population share to about 0.6 over the observed period. Although the per capita emissions of the high income/OECD group have been the highest and steadily increasing, they declined from about seven times the per capita emissions of the most populous group of lower middle income countries in 1990 to five times in 2004.

3. In-equitability of a uniform abatement rate of national emissions
To further motivate the use of per capita figures in evaluating countries’ carbon-dioxide emission abatement this section highlights the possible intensification of the emission inequality between the income groups of countries under an internationally uniform abatement rate of national aggregate emissions. Carbon-dioxide emissions are byproducts of production and consumption activities. Production and consumption activities are more painfully forgone in poor countries than in rich countries. As can be seen from Table 1, affluence is indeed positively correlated with per capita emissions, and the recorded emission inequality and per capita disparity between the five income groups of countries are already large. An intensification of the international per capita emission disparities is not desirable from a global welfare perspective. The following proposition says that an enforcement of an internationally
uniform abatement rate of national aggregate emissions might result in an intensification of the per capita emission inequality between rich and poor countries.

**PROPOSITION 1:** If population-growth rate is negatively correlated with affluence, then the enforcement of an internationally uniform abatement rate of national aggregate emissions renders poor countries’ rates of abatement of per capita emissions larger than those of rich countries.

Proof: Under an internationally uniform abatement rate \( 0 < \alpha < 1 \) of national aggregate emissions, the rate of abatement of per capita emissions for country \( i \) affiliated to income group \( k \) with initial national emissions \( Q^0_{ik} \) and a population growing at a rate \( g_{ik} \) from an initial size \( P^0_{ik} \) is

\[
\begin{align*}
\varphi_{ik} &= 1 - \frac{[(1-\alpha)Q^0_{ik}]/[(1+g_{ik})P^0_{ik}]}{Q^0_{ik} / P^0_{ik}} = 1 - \frac{1-\alpha}{1+g_{ik}}. \\
\text{In which case, } & \quad \frac{\partial \varphi_{ik}}{\partial g_{ik}} = \frac{(1-\alpha)}{(1+g_{ik})^2} > 0. \quad \blacksquare
\end{align*}
\]

As can be seen from Table 1, during the observed period 1990-2004 the population shares of the two high income groups have steadily declined, most profoundly in the case of the high income/OECD group. In contrast, the population share of the low income group has steadily increased. The population share of the lower middle income group has slightly increased and the population share of the upper middle income group has slightly declined. These findings reveal that the population growth rate of the low income group has been the highest and followed, in order, by those of the lower middle income group, upper middle income group, high income/nonOECD group and high income/OECD group.

We further assess the hypothesis of a negative correlation between population growth rate and affluence by regressing the 185 countries’ population growth rate over the period 1990-2004 onto their 1990’s per capita gross domestic product \( (PCGDP_{1990i}) \). As can be seen from the following estimated form (t-ratios computed with White heteroskedasticity-consistent standard errors and reported in parentheses), the ordinary least squares estimation results indicate that this hypothesis is not rejected at the one percent level of significance:

\[
\begin{align*}
\hat{g}_{(1990–2004)i} &= 0.106575 - 0.00000261 \text{PCGDP}_{1990i}. \quad (2)
\end{align*}
\]
In view of the estimated negative correlation between population growth rate and income and Proposition 1, it can be expected that an application of an internationally uniform abatement rate of national emissions will intensify the per capita emission disparity and the associated consumption gap between rich and poor countries. This expectation lends support to the consideration of a non-uniform rate of per capita emission abatement in formulating international abatement schemes. This aspect is featured in our formulation of the national costs and expected benefits of emission abatements and in the derived internationally cooperative expected net-benefit maximizing abatement.

4. National costs and expected benefits of abatement
Country $i$’s total cost of reducing its per capita carbon-dioxide emissions from the present level $\hat{e}_i$ to $e_i$ includes the full costs (including production loss) of enforcement of, and adaptation to, the new lower domestic emission level. We assume that these mitigation and adaptation costs ($MAC$) convexly rise with the country’s aggregate level of emission abatement. Namely,

$$MAC_i = c_i[(\hat{e}_i - e_i)P_i]^2$$

where $P_i$ denotes country $i$’s population and $c_i$ is a positive scalar indicating the gradient of country $i$’s marginal $MAC$. We further assume that the marginal $MAC$’s gradient declines from a maximum level $c > 0$ with the country’s degree of economic development as some production and consumption activities are less painfully forgone. Taking the pre abatement per capita income ($y_i > 0$) as an indicator of the country’s level of economic development, we let $c_i$ be given by

$$c_i = c / y_i.$$  

(4)

A reduction of domestic emissions increases the residential value of country $i$. Due to trans-boundary externalities, the appreciation of domestic residence ($ADR_i$) also depends on the emissions abated by other countries. We take $ADR_i$ to be linear (for tractability) in country $i$’s emission abatement, $(\hat{e}_i - e_i)P_i$, and in each of her $j$ $(j \neq i = 1, 2, 3, \ldots, N)$ counterpart’s emission abatement, $(\hat{e}_j - e_j)P_j$. The average external effect of any country $j$’s emission abatement on $ADR_i$ depends on the directional alignment of $i$ and $j$ with dominant winds, on the distance between $i$ and $j$ and on the structure of the surface separating $i$ from $j$. Due to these intervening
factors, the average external effect \((\beta_{ji} \geq 0)\) is likely to be smaller than the average internal effect \((\alpha_i > 0)\) of \(i\)'s emission abatement. With \(e_j^{\text{exp}}\) denoting country \(i\)'s expectations about any country \(j\)'s per capita emissions, country \(i\)'s expected appreciation of domestic residence is

\[
E(ADR_i) = \alpha_i (\hat{e}_i - e_i) P_i + \sum_{j \neq i}^N \beta_{ji} (\hat{e}_j - e_j^{\text{exp}}) P_j. \tag{5}
\]

By reducing her emissions, country \(i\) also contributes to the aggregate international effort of moderating the global accumulation of greenhouse gases and, in turn, global warming. We take country \(i\)'s expected benefit (in nominal units) from the aggregate international effort to moderate global warming \((MGW)\) to be given by

\[
E(MGW_i) = \gamma_i \left[ (\hat{e}_i - e_i) P_i + \sum_{j \neq i}^N (\hat{e}_j - e_j^{\text{exp}}) P_j \right]. \tag{6}
\]

where \(\gamma_i\) is a positive scalar indicating a fixed (for tractability) marginal benefit to country \(i\) from the aggregate effort to moderate global warming.

As other countries’ environment and terms of trade depend on country \(i\)'s commitment to emission reduction, there are international benefits to country \(i\) from impressing her counterparts of being environmentally responsible and non-opportunistic trading partner. We argue that country \(i\) cannot equally impress all her counterparts. A less committed country regards country \(i\) as environmentally responsible and a non-opportunistic trading partner, whereas a more committed country deems country \(i\) environmentally irresponsible and an opportunistic trading partner. Hence, country \(i\) is economically and politically rewarded by the former, but sanctioned by the latter. We further argue that a higher degree of tolerance is revealed toward a low income country producing traded goods and hence the sanctions and rewards are responsive to the portion of the per capita income generated by export oriented industries. Therefore, country \(i\) can expect her economic and political relations with any other country to change with the relative stringency of her emission-abatement policy devaluated by her relative non-export income. More specifically, we assume that country \(i\) expects the loss of bilateral relations \((LRB)\) with country \(j\) to diminish from a maximal nominal level \(LRB_{ji}^{\text{max}} \geq 0\) with her ratio of per capita abatement to per capita non-export income, relative to that of country \(j\). The maximal loss depends on the nature of the initial bilateral relations, relative size and
international influence of $i$ and $j$. Consequently, country $i$’s expected aggregate loss of international relations ($LIR$) is

$$E(LIR_i) = \sum_{j \neq i} N \max_{j} LBR_{ji} - r_{ji} \left[ \left( \frac{\hat{e}_i - e_i}{(s_j y_j)} \right) \left( \frac{\hat{e}_j - e_j^{exp}}{(s_j y_j)} \right) \right].$$  \hspace{1cm} (7)

The scalar $0 \leq s_i \leq 1$ denotes country $i$’s non-export income share. The scalar $r_{ji} \geq 0$ and the ratio $(s_j y_j)/(s_i y_i)$ indicate, respectively, country $i$’s assessment of country $j$’s ability and inclination to reward country $i$’s commitment to per capita domestic emission-reduction with more favorable economic and political relations. A negative (positive) $E(LIR_i)$ reflects country $i$’s overall expectation to be rewarded (sanctioned) for her relatively strong (weak) commitment to emission abatement with more (less) favorable international economic and political relations.

In view of the said costs and expected benefits, country $i$’s expected net benefit ($ENB_i$) from reducing her carbon-dioxide emissions is

$$ENB_i = E(ADR_i) + E(MGW_i) - E(LIR_i) - MAC_i$$

$$= (\alpha_i + \gamma_i)(\hat{e}_i - e_i)P_i + \sum_{j \neq i} N (\beta_{ji} + \gamma_j)(\hat{e}_j - e_j^{exp})P_j$$

$$- \sum_{j \neq i} N \max_{j} LBR_{ji} + \sum_{j \neq i} r_{ji}[(s_j y_j)/(s_i y_i)] \left[ \frac{\hat{e}_i - e_i}{\hat{e}_j - e_j^{exp}} \right] - (c / y_j)(\hat{e}_j - e_j)^2 P_j^2.$$  \hspace{1cm} (8)

### 5. Cooperative emission abatement

The cooperatively optimal abatement of per capita emissions by country $i$ is

$$\hat{e}_i - e_i^o = \arg \max \sum_{j=1}^{N} ENB_j.$$  \hspace{1cm} If $(c / y_j)P_i^2 > 1/\left[ \sum_{j \neq 1} N r_{ji}[(s_j y_j)/(s_i y_i)](\hat{e}_j - e_j)/(\hat{e}_i - e_i)^3 \right],

\sum_{j=1}^{N} ENB_j$ is concave in $(\hat{e}_i - e_i)$ and there exists an interior solution for which the marginal expected global benefit from country $i$’s optimal per capita emission abatement is equal to this country’s marginal cost:

$$(\alpha_i + \gamma_i)P_i + \sum_{j \neq i} r_{ji}[(s_j y_j)/(s_i y_i)](\hat{e}_j - e_j) \left( \frac{\hat{e}_j - e_j}{(\hat{e}_i - e_i)^3} \right) + P_i \sum_{j \neq i} (\beta_{ji} + \gamma_j)$$

$$- \frac{1}{(\hat{e}_i - e_i)^2} \sum_{j \neq i} r_{ji}[(s_j y_j)/(s_i y_i)](\hat{e}_j - e_j^o) = 2(c / y_i)(\hat{e}_i - e_i^o)P_i^2$$  \hspace{1cm} (9)
Though not a closed-form solution, it is useful, for a comparison with the non-cooperative emission abatement, to express country $i$’s cooperatively optimal per capita emission abatement as:

\[
(\hat{e}_i - e_i^o) = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j \neq i} r_{ji}[(s_j y_j)/(s_j y_i)](\hat{e}_j - e_j^o) + P_i \sum_{j \neq i} (\beta_j + \gamma_j) - \sum_{j \neq i} r_{ji}[(s_j y_i)/(s_j y_j)](\hat{e}_j - e_j^o)}{2(c_i y_i)P_i^2}
\]

(10)

**PROPOSITION 2.** In a cooperatively optimal international abatement scheme country $i$ reduces, maintains, or increases its emissions if

\[
\left[ (\alpha_i + \gamma_i) + \sum_{j \neq i} (\beta_j + \gamma_j) \right] P_i + \sum_{j \neq i} r_{ji}[(s_j y_j)/(s_j y_i)](\hat{e}_j - e_j^o)
\]

is larger, equal to, or smaller than

\[
\frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i} r_{ji}[(s_j y_i)/(s_j y_j)](\hat{e}_j - e_j^o).
\]

Proof: Since the denominator of the term on the right hand side of (10) is positive, the sign of $\hat{e}_i - e_i^o$ is equal to the sign of the numerator. ■

Proposition 2 says that the larger the ability ($r_{ji}$) and inclination ($((s_j y_i)/(s_j y_j))$) of country $i$ to economically and politically reward other countries, the smaller is her cooperatively optimal per capita emission abatement. Moreover, with sufficiently large such ability and inclination, country $i$’s per capita emissions increase when an international abatement scheme that maximizes the sum of the member countries’ expected net benefits is implemented. Equation (10) also indicates that country $i$’s cooperatively optimal abatement rises with her own and counterparts’ marginal benefits from improved domestic residential environments and moderated global warming and with her improved international relations, and decreases with the erosion of the counterparts’ relative abatement and subsequent bilateral relations with her. Country $i$’s cooperatively optimal abatement also decreases with the gradient of her marginal mitigation and adaptation costs.
6. Unilateral emission abatement

In the absence of an international agreement, a rationally managed country unilaterally abates carbon-dioxide emissions at a level that maximizes her expected net benefit \textit{per se}. The country ignores the effect of her emission abatement on other countries’ environment and loss of international relations. As $ENB_i$ is concave in $(\hat{e}_i - e_i)$, there exists an interior $\hat{e}_i - e_i^* = \arg\max ENB_i$. It equates country $i$’s marginal expected self benefit from abatement to her marginal cost of abatement:

$$\left(\alpha_i + \gamma_i\right)P_i + \sum_{j\in i} \frac{r_{ji}[(s_jy_j)/(s_jy_i)]}{(\hat{e}_j - e_j^{\exp})} = 2(c/y_i)(\hat{e}_i - e_i^*)P_i^2.$$  \hspace{1cm} (11)

Consequently, the unilateral expected net benefit maximizing abatement of per capita emissions is equal to the ratio of the sum of country $i$’s marginal benefits from improved international relations and domestic residential environment and moderated global warming to the increment in her marginal mitigation and adaptation costs:

$$\hat{e}_i - e_i^* = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j\in i} r_{ji}[(s_jy_j)/(s_jy_i)]}{2(c/y_i)P_i^2}.$$  \hspace{1cm} (12)

By ignoring the effects of her emissions on any other country’s residential environment and suffering from global warming, country $i$ understates the benefits stemming from her emission abatement. Furthermore, by ignoring the effect of her abatement on any other country’s loss of bilateral relations with her, country $i$ understates other countries’ incentives to reduce emissions. This latter argument can explain the counterintuitive outcome, indicated in Proposition 3, of a unilateral emission abatement by country $i$ that is larger than her abatement under the aforementioned internationally cooperative scheme. As indicated in the previous section, a country $i$ with high ability ($r_{ij}$) and inclination (($s_jy_i)/(s_jy_j)$) to economically and politically reward other countries ($j \neq i = 1,2,3,\ldots,N$) might be awarded with a relatively low per capita emission abatement. Furthermore, a powerful country $i$ (one that can inflict a large loss of bilateral relations – $LBR_{ij}^{\text{max}}$ – on some other countries $j$) that strongly evaluates her own benefit from improved global environment (has a large $\gamma_i$), might coerce weaker countries into abating greater quantities of emissions than the cooperatively optimal ones by adhering to a punitive policy (low $r_{ij}$). The possibility that for some countries the cooperative expected net-

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benefit-maximizing abatement of per capita emissions is smaller than the unilateral expected net-benefit-maximizing abatement is indicated in the following proposition.

**PROPOSITION 3:** If

\[
\left\{ \begin{array}{c}
P_i \sum_{j \neq i} (\beta_{ij} + \gamma_j) + \sum_{j \neq i} r_{ji}[(s_jy_j)/(s_iy_i)] \\
\geq \left\{ \frac{N}{j \neq i} r_{ji}[(s_jy_j)/(s_iy_i)] + \frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i} r_{ji}[(s_jy_j)/(s_jy_j)](\hat{e}_j - e_j^o) \right\}
\end{array} \right.
\]

then

\[
(\hat{e}_i - e_i^*) < (\hat{e}_i - e_i^o).
\]

Proof: By comparing the numerators of equations (10) and (12). ■

7. Cournot equilibrium levels of abatement

If each country’s expectations about the other countries’ per capita emission abatements are perfect \((e_j^{\exp} = e_j^*)\), the solution of the N equation-system (12) is the Cournot equilibrium of the N countries’ per capita emission-abatement levels. In order to shed light on the properties of the Cournot equilibrium levels of abatement, we consider the analytically tractable case of a world divided into two alliances (e.g., low and middle income countries producing traded primary and manufactured goods versus the rest of the world). In this case, the expected-net-benefit maximizing per capita emissions are

\[
e_j^* = \hat{e}_j - \frac{(\alpha_j + \gamma_j)P_j + r_{2j}(s_jy_j/s_iy_i)}{(\hat{e}_j - e_j^{\exp})} \frac{(s_jy_j)}{(2(c/y_j)^2)P_j^2} \]

(13)

for alliance 1, and by symmetry,

\[
e_j^* = \hat{e}_j - \frac{(\alpha_j + \gamma_j)P_j + r_{2j}(s_jy_j/s_iy_i)}{(\hat{e}_j - e_j^{\exp})} \frac{(s_jy_j)}{(2(c/y_j)^2)P_j^2} \]

(14)

for alliance 2. As shown in Appendix B, the solution to this system of reaction equations yields the following Cournot equilibrium per capita emission abatement for alliance 1:
\[ \hat{e}_1 - \hat{e}_1^* = 0.5 \left[ \frac{(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)}{(c/y_1)(\alpha_2 + \gamma_2)} P_2 + \frac{(c/y_2)r_{21}(s_1y_2/s_1y_1)P_2^2}{(c/y_1)(\alpha_2 + \gamma_2)} - \frac{(c/y_1)\eta_2(s_1y_1/s_2y_2)P_2^2}{(c/y_1)(\alpha_2 + \gamma_2)} \right] \\
+ 0.5 \left[ 0.5(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)P_1P_2 + \frac{(c/y_2)r_{11}(s_1y_2/s_1y_1)P_1^2}{(c/y_1)(\alpha_2 + \gamma_2)} - \frac{(c/y_1)\eta_2(s_1y_1/s_2y_2)P_1^2}{(c/y_1)(\alpha_2 + \gamma_2)} \right]^{0.5} \]

\[ \hat{e}_2 - \hat{e}_2^* = 0.5 \left[ \frac{(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)}{(c/y_1)(\alpha_2 + \gamma_2)} P_1 + \frac{(c/y_2)r_{22}(s_1y_2/s_1y_1)P_1^2}{(c/y_1)(\alpha_2 + \gamma_2)} - \frac{(c/y_1)\eta_2(s_1y_1/s_2y_2)P_1^2}{(c/y_1)(\alpha_2 + \gamma_2)} \right] \\
+ 0.5 \left[ 0.5(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)P_2P_1 + \frac{(c/y_2)r_{12}(s_1y_2/s_1y_1)P_2^2}{(c/y_1)(\alpha_2 + \gamma_2)} - \frac{(c/y_1)\eta_2(s_1y_1/s_2y_2)P_2^2}{(c/y_1)(\alpha_2 + \gamma_2)} \right]^{0.5} \]

The quantity and properties of \((\hat{e}_2 - \hat{e}_2^*)\) are obtained by symmetry.

Equation (15) reveals that in the Cournot equilibrium, the per capita emission abated by alliance 1 \((\hat{e}_1 - \hat{e}_1^*)\) rises with the marginal improvement in its own environment stemming from its own abatement \((\alpha_1)\), with its marginal benefit from the combined effort of curbing global warming \((\gamma_1)\), with alliance 2’s ability to reward commitment, weighted by its relative non-export per capita income \((r_{21}(s_2y_2/s_1y_1))\), and with alliance 2’s marginal mitigation and adaptation costs’ gradient \((c_2 = c/y_2)\). In the Cournot equilibrium, alliance 1’s per capita emission abatement declines with its own marginal mitigation and adaptation costs’ gradient \((c_1 = c/y_1)\) and with the size of its own population \((P_1)\). In order to assess the effect of alliance 1’s ability to reward alliance 2 and the effect of alliance 2’s population size on alliance 1’s emission-abatement level in a Cournot equilibrium it is important to note that

\[ \frac{\partial(\hat{e}_1 - \hat{e}_1^*)}{\partial \eta_2(s_1y_1/(s_2y_2))} = -0.5\left[ \frac{1}{((\alpha_2 + \gamma_2)P_2)} \right] \left\{ 1 + \frac{1}{((\alpha_1 + \gamma_1)/(c/y_1)P_1)} \right\} \Delta^{0.5} \]  

(16)

and

\[ \frac{\partial(\hat{e}_1 - \hat{e}_1^*)}{\partial P_2} = 0.5\left[ \frac{((c/y_2)r_{21}(y_2/y_1)((c/y_1)(\alpha_2 + \gamma_2)P_2^2)) + (\eta_2(s_1y_1/s_2y_2)/((\alpha_2 + \gamma_2)P_2^2))} \right] \\
+ 0.5\Delta^{-0.5}\left[ \frac{((c/y_2)r_{21}(s_2y_2/s_1y_1)((c/y_1)(\alpha_2 + \gamma_2)P_1^2))}{((\alpha_2 + \gamma_2)P_1^2)} \right] \\
+ \left[ 1 - 2(\alpha_1 + \gamma_1)/(c/y_1)P_1 \right] \frac{\eta_2(s_1y_1/s_2y_2)/((\alpha_2 + \gamma_2)P_2^2)} \]  

(17)

where \(\Delta > 0\) is the discriminant indicated in the second term on the right-hand side of equation (15). As long as the population of alliance 1 \((P_1)\) is not very small, \([1 - 2(\alpha_1 + \gamma_1)/(c/y_1)P_1]>0\). In which case the per capita emissions abated by alliance 1 in a Cournot equilibrium increase with the population of alliance 2 and
decrease with alliance 1’s ability to reward alliance 2 \( (\eta_2) \). The emission-abatement moderating effect of the latter factor is increased by alliance 1’s relative non-export per capita income \( (s_1y_1 / s_2y_2) \). Recalling that \( \partial(\hat{e}_1 - e^*_1) / \partial\{r_21[(s_2y_2)/(s_1y_1)]\} > 0 \), the total effect of alliance 1’s relative non-export per capita income \( (s_1y_1 / s_2y_2) \) on alliance 1’s emission reduction is negative.

8. Conclusion

The use of per capita figures in our comparison of internationally cooperative and unilateral abatements of carbon-dioxide emissions is motivated by the outcomes of our investigation of the international carbon-dioxide emission inequality and by the in-equitability of an internationally uniform abatement rate of national aggregate emissions. Using a decomposable inequality indicator that takes into account population shares, our investigation reveals a stable dominance of the emission inequality between five income groups of countries over the inequality within these groups during the post Cold War and transition period to global market economy. As the populations of poor countries grow in a higher rate than the populations of rich countries, it can be expected that the emission inequality between the income groups of countries will be aggravated by an internationally uniform abatement rate of national aggregate emissions. Consequently, a country’s costs and benefits of abatement are formulated in a manner that highlights the effects of the country’s and her counterparts’ per capita emissions, incomes and domestically consumed output. As countries’ environment and terms of trade depend on the commitment of each other to emission reduction, there are international benefits to a country from impressing her counterparts of being environmentally responsible and non-opportunistic trading partner. Per capita output and its traded component are assumed to influence the assessment of, and reaction to, a country’s commitment to emission abatement by other countries. This influence is incorporated into the determination of a country’s internationally cooperative and unilateral emission abatements. The analysis reveals that under such an influence the unilateral emission abatement might exceed the internationally cooperative abatement not only in the case of a weak country, but also in the case of a country that has high ability and inclination to reward other countries with improved bilateral economic and political relations.
Appendix A: Income Groups
The classification of countries into income groups is based on World Bank list of economies, July 2009.


Lower Middle Income: Albania, Angola, Armenia, Aruba, Azerbaijan, Cameroon, Cape Verde, China, Cote d'Ivoire, Djibouti, Ecuador, Egypt, El Salvador, Georgia, Guatemala, Guyana, Honduras, India, Indonesia, Iran (Islamic Republic of), Iraq, Jordan, Kiribati, Liberia, Maldives, Moldova, Mongolia, Nicaragua, Nigeria, Papua New Guinea, Paraguay, Philippines, Samoa, Solomon Islands, Sri Lanka, Sudan, Swaziland, Syrian Arab Republic, Thailand, The former Yugoslav Republic of Macedonia, Timor-Leste, Tonga, Tunisia, Turkmenistan, Ukraine, Vanuatu

Upper Middle Income: Algeria, Argentina, Belarus, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Fiji, Gabon, Grenada, Jamaica, Kazakhstan, Latvia, Lebanon, Libyan Arab Jamahiriya, Lithuania, Malaysia, Mauritius, Mexico, Namibia, Palau, Panama, Peru, Poland, Russian Federation, Serbia and Montenegro, Seychelles, South Africa, Suriname, Turkey, Uruguay, Venezuela

Higher Income–nonOECD: Antigua and Barbuda, Bahamas, Bahrain, Barbados, Bermuda, British Virgin Islands, Brunei Darussalam, Cayman Islands, China-Hong Kong Special Administrative Region, China-Macao Special Administrative Region, Croatia, Cyprus, Czech Republic, Equatorial Guinea, Estonia, Faeroe Islands, French Guiana, French Polynesia, Greenland, Hungary, Israel, Kuwait, Malta, Netherlands Antilles, New Caledonia, Oman, Qatar, Romania, Sao Tome and Principe, Saudi Arabia, Singapore, Slovakia, Slovenia, Trinidad and Tobago, United Arab Emirates

Higher Income-OECD: Australia, Austria, Belgium, Belize, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Korea (Republic of), Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States
Appendix B: The Cournot equilibrium

Recall (13), (14) and (4),

\[
\hat{e}_1 - e_1^* = \frac{(\alpha_1 + \gamma_1) P_1 + r_{21}(s_1 y_2 / s_1 y_1) e \hat{P}_2 - e_S}{2c_1 P_1^2} \tag{B1}
\]

and

\[
\hat{e}_2 - e_2^* = \frac{(\alpha_2 + \gamma_2) P_2 + r_{12}(s_1 y_2 / s_2 y_2) e \hat{P}_2 - e_S}{2c_2 P_2^2} \tag{B2}
\]

Let \( \theta_1 = \alpha_1 + \gamma_1, \theta_2 = \alpha_2 + \gamma_2, \bar{y}_1 = s_1 y_1 \) and \( \bar{y}_2 = s_2 y_2 \) and substitute the right hand side of (B1) into (B2):

\[
\hat{e}_1 - e_1^* = \frac{2c_1 P_1^2}{2c_2 P_2^2}
\]

In turn,

\[
2c_1 P_1^2 (\hat{e}_1 - e_1^*) - \theta_1 P_1 = \frac{2c_2 P_2^2 r_{21}(\bar{y}_2 / \bar{y}_1)(\hat{e}_1 - e_1^*)}{\theta_2 P_2 (\hat{e}_1 - e_1^*)} + r_{12}(\bar{y}_1 / \bar{y}_2)
\]

By rearranging terms,

\[
2\theta_2 P_2 c_1 P_1^2 (\hat{e}_1 - e_1^*)^2 - \theta_1 \theta_2 P_1 P_2 + 2c_2 P_2^2 r_{21}(\bar{y}_2 / \bar{y}_1) - 2c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_2^2 (\hat{e}_1 - e_1^*) = 0 \tag{B5}
\]

Consequently,

\[
(\hat{e}_1 - e_1^*)^2 = \frac{[0.5 \theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\bar{y}_2 / \bar{y}_1) P_2^2 - c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2}
\]

The roots of (A6) are:

\[
\hat{e}_1 - e_1^* = 0.5 \left[\frac{[0.5 \theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\bar{y}_2 / \bar{y}_1) P_2^2 - c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2}\right]^{1/2} + 0.5 \left[\frac{[0.5 \theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\bar{y}_2 / \bar{y}_1) P_2^2 - c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2}\right]^{1/2}
\]

As the discriminant in (B7) is positive and larger than the absolute value of the coefficient of \( (\hat{e}_1 - e_1^*) \) in (B6), only the following root is considered to be relevant:

\[
\hat{e}_1 - e_1^* = 0.5 \left[\frac{[0.5 \theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\bar{y}_2 / \bar{y}_1) P_2^2 - c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2}\right]^{1/2} + 0.5 \left[\frac{[0.5 \theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\bar{y}_2 / \bar{y}_1) P_2^2 - c_1 r_{12}(\bar{y}_1 / \bar{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2}\right]^{1/2}
\]

(B8)
References


