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**International Emission Inequality:
Abatement on a Per Capita Basis with Rewards**

Amnon Levy
School of Economics
University of Wollongong

Khorshed Chowdhury
School of Economics
University of Wollongong

Jonathan Livermore
Department of Agriculture, Food and Natural Resources
University of Sydney

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Amnon Levy
School of Economics
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Khorshed Chowdhury
School of Economics
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Jonathan Livermore
Department of Agriculture, Food and Natural Resources
University of Sydney

Abstract

Greenhouse gas emission inequalities between and within five income groups of countries are computed. The revealed dominant emission 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 analyzing countries' unilateral and internationally cooperative emission abatements. The analysis suggests that the cooperative expected net benefit maximizing emission abatement can be smaller than the unilateral abatement for weak countries and also for lower and upper middle income economies with high ability and inclination to politically and economically reward other countries.

JEL Classification: O24, F51, Q54, Q56

Keywords: Emissions; Inequality; International Relations; Cooperative Abatement; Unilateral Abatement

1. Introduction

In the absence of a binding international agreement, a rationally managed country unilaterally abates greenhouse gas emissions at a level that maximizes her expected net benefit. In addition to a cleaner and healthier domestic environment and a slower process of global warming, a country's benefit from self emission reduction may include improved image and, in turn, bilateral economic and political relations. We argue that the evaluation of countries' emission abatements should be on a per capita basis. We then 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.

Studies of international greenhouse gas 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 these studies focus on aggregate levels of domestic and foreign emissions and some of their assumptions hold only if countries are identical.¹

Countries differ in population size and growth rate and in stage of economic development. Although lower middle income countries such as China and, to a lesser extent, India contributed 23.47% and 4.93% of the global carbon-dioxide emissions in 2004, the per capita emissions of these most populous countries and major

¹ For instance, in Kemfert, Lise and Tol (2004) there is no external cost effect on a country via the terms of trade and international capital dynamics when all the countries abate the same level of emissions (using their notations, $g_i(R_i - R_j) = 0$ when $R_i = R_j$).

manufacturing workshops of highly affordable, tradable 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.

To better motivate the use of per capita figures in evaluating countries' greenhouse gas 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 during the fifteen-year period for which data are available.² Section 3 highlights the possible intensification of the emission inequality between the income groups of countries under an internationally uniform abatement rate of countries' initial aggregate emissions.

Greenhouse gas 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 formulate countries' emission abatements on a per capita basis and within a framework that allows for non-uniform abatement rates. A country's costs and benefits of abatement are formulated in section 4 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 tradable output than to a high income country with a small share of tradable output. In sections 5 and 6 this influence is incorporated into the determination of the internationally cooperative and unilateral emission reductions. The analysis proposes that under such an influence the unilateral emission abatements of large, open, lower and upper middle income economies might exceed their optimal internationally

² This result is in agreement with 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 is also in agreement with 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 concern of the residents in wealthier nations who participated in the 1993 and 2003 International Social Survey Programs.

cooperative abatements. Section 7 computes and discusses the Cournot equilibrium emission abatement for a special case of a world divided into two alliances. Section 8 concludes.

2. International emission inequality and its decomposition by income

Let Q_{ik} be the annual emissions of country i affiliated to income group k , P_{ik} the population of country i affiliated to income group k , $Q_k = \sum_i Q_{ik}$ the emissions of income group k , $P_k = \sum_i P_{ik}$ the population of income group k , $Q_w = \sum_k Q_k$ the world's annual emissions, $P_w = \sum_k P_k$ the world's population, $q_k = Q_k / Q_w$ the emission share of income group k in the global emissions, $p_k = P_k / P_w$ the population share of income group k in the global population, $q_{ik} = Q_{ik} / Q_w$ the emission share of country i affiliated to income group k in the global emissions, and $p_{ik} = P_{ik} / P_w$ the population share of country i affiliated to income group k in the global population. Following Fishlow's (1972) earliest application and Bourguignon's (1979) evaluation, our computation of the international emission inequality employs a decomposition formula of Theil's (1967) entropy coefficient which is differentiable, symmetric, homogeneous of degree zero, preserving the total emission inequality between the individual countries and measuring the contributions of their income groups:

$$T_w \equiv \sum_k \sum_i q_{ik} \log \left(\frac{q_{ik}}{p_{ik}} \right) = \sum_k q_k \log \frac{q_k}{p_k} + \sum_k q_k \sum_i \frac{q_{ik}}{q_k} \log \left(\frac{q_{ik} / q_k}{p_{ik} / p_k} \right). \quad (1)$$

The first term on the right-hand side measures the emission inequality between the income groups and the second, the emission inequality within these groups.³

Using the World Bank's classification, countries are sorted into low income, lower middle income, upper middle income, high income/nonOECD and high

³ The equality of this decomposition to Theil's index of international emission inequality is proven as follows:

$$\begin{aligned} \sum_k q_k \log \frac{q_k}{p_k} + \sum_k q_k \sum_i \frac{q_{ik}}{q_k} \log \left(\frac{q_{ik} / q_k}{p_{ik} / p_k} \right) &= \sum_k q_k \log \left(\frac{q_k}{p_k} \right) + \sum_k q_k \sum_i \frac{q_{ik}}{q_k} \left[\log \left(\frac{q_{ik}}{p_{ik}} \right) - \log \left(\frac{q_k}{p_k} \right) \right] \\ &= \sum_k q_k \log \left(\frac{q_k}{p_k} \right) - \sum_k q_k \log \left(\frac{q_k}{p_k} \right) \underbrace{\sum_i \frac{q_{ik}}{q_k}}_1 + \sum_k \sum_i q_{ik} \log \left(\frac{q_{ik}}{p_{ik}} \right) = \sum_k \sum_i q_{ik} \log \left(\frac{q_{ik}}{p_{ik}} \right) \equiv T_w. \end{aligned}$$

income/OECD groups (see Appendix A). Table 1 summarizes our computations of the international emission inequality index and decomposition between and within the said income groups with the United Nations' data on 185 countries' carbon-dioxide emissions and populations in 1990, 1995, 2000 and 2004.⁴

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

Year	Low Income	Lower Middle Income	Upper Middle Income	High Income Non OECD	High Income OECD	Total
Population share						
2004	0.1636	0.5293	0.1426	0.0178	0.1467	1
2000	0.1605	0.5264	0.1443	0.0181	0.1508	1
1995	0.1464	0.5324	0.1474	0.0186	0.1552	1
1990	0.1456	0.5275	0.1460	0.0188	0.1621	1
Emission share						
2004	0.0240	0.3131	0.1711	0.0459	0.4459	1
2000	0.0221	0.2684	0.1798	0.0475	0.4822	1
1995	0.0283	0.2616	0.1870	0.0452	0.4779	1
1990	0.0288	0.2239	0.2164	0.0506	0.4804	1
Per capita emissions (in metric tons)						
2004	0.637	2.574	5.223	11.204	13.223	4.351
2000	0.563	2.086	5.100	10.741	13.085	4.092
1995	0.783	1.989	5.135	9.871	12.465	4.049
1990	0.799	1.716	5.995	10.864	11.984	4.044
Contribution to inequality between groups⁵						
2004	-0.0200	-0.0714	0.0136	0.0189	0.2153	0.1563
2000	-0.0190	-0.0785	0.0172	0.0199	0.2434	0.1830
1995	-0.0202	-0.0807	0.0193	0.0175	0.2334	0.1693
1990	-0.0203	-0.0833	0.0370	0.0217	0.2266	0.1817
Contribution to inequality within groups⁶						
2004	0.0072	0.0245	0.0163	0.0054	0.0177	0.0710
2000	0.0073	0.0224	0.0151	0.0064	0.0218	0.0731
1995	0.0153	0.0209	0.0187	0.0037	0.0232	0.0819
1990	0.0172	0.0259	0.0295	0.0036	0.0211	0.0972
Contribution to global inequality⁷						
2004	-0.0128	-0.0469	0.0299	0.0243	0.2330	0.2274
2000	-0.0117	-0.0561	0.0323	0.0263	0.2652	0.2561
1995	-0.0049	-0.0598	0.0380	0.0212	0.2566	0.2511
1990	-0.0031	-0.0574	0.0665	0.0253	0.2477	0.2790

⁴ 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.

⁵ Computed as $q_k \log \frac{q_k}{p_k}$.

⁶ Computed as $q_k \sum_i \frac{q_{ik}}{q_k} \log \left(\frac{q_{ik}/q_k}{p_{ik}/p_k} \right)$.

⁷ Computed as $q_k \log \frac{q_k}{p_k} + q_k \sum_i \frac{q_{ik}}{q_k} \log \left(\frac{q_{ik}/q_k}{p_{ik}/p_k} \right)$.

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 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 risen 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 risen, 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. Inequitability of a uniform abatement rate of countries' aggregate emissions

Greenhouse gas emissions are byproducts of production and consumption activities. 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. Moreover, it is possible that the poorer the country the higher her full marginal mitigation and adaptation costs of emission reduction. In comparison to rich countries, production and consumption activities in poor countries are more painfully forgone. In addition, the rich countries' technological and innovative edge moderates their production and consumption loss.

Hence, an intensification of the international per capita emission disparities is not desirable from a global welfare perspective.

PROPOSITION 1: *If the rate of population growth is negatively correlated with affluence, then the poor countries' rates of abatement of per capita emissions are larger than those of rich countries under a uniform abatement rate of countries' initial aggregate emissions.*

Proof: Under a uniform abatement rate ($0 < \alpha < 1$) of countries' initial aggregate emissions $\{Q_{ik}^0\}$, the rate of abatement of per capita emissions for a country i affiliated to income group k , whose population is growing at a rate g_{ik} , is given by

$$\varphi_{ik} = 1 - \frac{[(1-\alpha)Q_{ik}^0]/[(1+g_{ik})P_{ik}^0]}{Q_{ik}^0/P_{ik}^0} = 1 - \frac{1-\alpha}{1+g_{ik}}. \text{ Consequently, } \frac{\partial \varphi_{ik}}{\partial g_{ik}} = \frac{(1-\alpha)}{(1+g_{ik})^2} > 0. \blacksquare$$

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 risen. The population share of the lower middle income group has slightly risen 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.

The hypothesis of a negative correlation between population growth rate and affluence is further assessed 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 one percent level of significance:

$$\hat{g}_{(1990-2004)i} = 0.106575 - 0.00000261 PCGDP_{1990i} \quad (2)$$

(14.6522) (2.9132)

In view of the estimated negative correlation between population growth rate and income and Proposition 1, it is expected that an application of a uniform abatement rate of countries' initial aggregate emissions intensifies the per capita emission disparity and the associated consumption gap between the 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 costs and expected benefits of countries' emission abatements and, subsequently, in the derived internationally cooperative and, for comparison, unilateral expected net benefit maximizing abatements.

4. Country's costs and benefits of abatement

Country i 's total cost of reducing its per capita greenhouse gas 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:

$$MAC_i = c_i [(\hat{e}_i - e_i)P_i]^2 \quad (3)$$

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 maximal value $c > 0$ with the country's level of economic development as some production and consumption activities are less painfully forgone and as technological absorptive and innovative capacities are improved. Taking the pre abatement per capita income ($y \geq 1$) as an indicator of the country's level of economic development, we let c_i be given by:

$$c_i = c / y_i. \quad (4)$$

A reduction of domestic emissions increases the residential value of country i . Due to trans-boundary externalities, this 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 ($j \neq i = 1, 2, 3, \dots, N$) counterpart's emissions 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^{exp} denoting country i 's expectations about any country j 's per capita emissions, country i 's expected appreciation of domestic residence is:

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

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:

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

where γ_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. However, country i cannot equally impress all her counterparts. A less committed country may regard country i as environmentally responsible and a non-opportunistic trading partner, whereas a more committed country might deem country i environmentally irresponsible and an opportunistic trading partner. Hence, country i may economically and politically be rewarded by the former, but sanctioned by the latter. As a higher degree of tolerance is likely to be revealed toward a low income country producing tradable goods, the sanctions and rewards might be responsive to the portion of the per capita income generated by export oriented industries. We therefore assume that country i expects her economic and political relations with any other country to change with the relative stringency of their emission-abatement policies devaluated by their non-export income. More specifically, we assume that country i expects the loss of bilateral relations (LBR) with country j to diminish from a maximal nominal level $LBR_{ji}^{\text{max}} \geq 0$ 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:

$$E(LIR_i) = \sum_{j \neq i}^N \left\{ LBR_{ji}^{\max} - r_{ji} \left[\frac{(\hat{e}_i - e_i)/(s_i y_i)}{(\hat{e}_j - e_j^{\text{exp}})/(s_j y_j)} \right] \right\}. \quad (7)$$

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 greenhouse gas emissions is:

$$\begin{aligned} ENB_i &= E(ADR_i) + E(MGW_i) - E(LIR_i) - MAC_i \\ &= (\alpha_i + \gamma_i)(\hat{e}_i - e_i)P_i + \sum_{j \neq i}^N (\beta_{ji} + \gamma_j)(\hat{e}_j - e_j^{\text{exp}})P_j \\ &\quad - \sum_{j \neq i}^N LBR_{ji}^{\max} + \sum_{j \neq i}^N r_{ji} [(s_j y_j)/(s_i y_i)] \left[\frac{\hat{e}_i - e_i}{\hat{e}_j - e_j^{\text{exp}}} \right] - (c/y_i)(\hat{e}_i - e_i)^2 P_i^2. \end{aligned} \quad (8)$$

5. Cooperative emission abatement

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

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

$\sum_{j=1}^N ENB_j$ 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:

$$\begin{aligned}
& (\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^o)} + P_i \sum_{j \neq i}^N (\beta_{ij} + \gamma_j) \\
& - \frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i}^N r_{ij}[(s_i y_i)/(s_j y_j)](\hat{e}_j - e_j^o) = 2(c/y_i)(\hat{e}_i - e_i^o)P_i^2
\end{aligned} \tag{9}$$

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:

$$(\hat{e}_i - e_i^o) = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^o)} + P_i \sum_{j \neq i}^N (\beta_{ij} + \gamma_j) - \frac{\sum_{j \neq i}^N r_{ij}[(s_i y_i)/(s_j y_j)](\hat{e}_j - e_j^o)}{(\hat{e}_i - e_i^o)^2}}{2(c/y_i)P_i^2} \tag{10}$$

PROPOSITION 2. *In a cooperatively optimal scheme country i reduces, maintains, or*

increases its emissions if $\left[(\alpha_i + \gamma_i) + \sum_{j \neq i}^N (\beta_{ij} + \gamma_j) \right] P_i + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^o)}$ *is larger,*

equal to, or smaller than $\frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i}^N r_{ij}[(s_i y_i)/(s_j y_j)](\hat{e}_j - e_j^o)$.

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_{ij}) and inclination ($(s_i y_i)/(s_j y_j)$) of country i to economically and politically reward other countries, the smaller 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 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, but diminishes with the erosion of her 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 greenhouse gas emissions at a level that maximizes her expected net benefit *per se*. In this unilateral framework, 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:

$$(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^{\text{exp}})} = 2(c/y_i)(\hat{e}_i - e_i^*)P_i^2. \quad (11)$$

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:

$$\hat{e}_i - e_i^* = \frac{(\alpha_i + \gamma_i)P_i + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^{\text{exp}})}}{2(c/y_i)P_i^2}. \quad (12)$$

By ignoring the effects of her emissions on any other country's residential environment (trans-boundary pollution) 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 which is larger than her allotted abatement had the aforementioned internationally cooperative scheme (that maximizes the sum of the member countries' expected net benefits) been implemented. As indicated in the previous section, a country i with high ability (r_{ij}) and inclination ($((s_i y_i)/(s_j y_j))$) to economically and politically reward other countries $j \neq i = 1, 2, 3, \dots, N$ might be awarded with a relatively low per capita emission

abatement. Large, open, lower and upper middle income economies might have such ability and inclination. Furthermore, a powerful country i (one that can inflict a large loss of bilateral relations – LBR_{ij}^{\max} – on some other countries j) that strongly evaluates her own benefit from improved global environment (has a large γ_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 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*

$$\left\{ P_i \sum_{j \neq i}^N (\beta_{ij} + \gamma_j) + \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^o)} \right\} \\ = \left\{ \sum_{j \neq i}^N \frac{r_{ji}[(s_j y_j)/(s_i y_i)]}{(\hat{e}_j - e_j^{\text{exp}})} + \frac{1}{(\hat{e}_i - e_i^o)^2} \sum_{j \neq i}^N r_{ij}[(s_i y_i)/(s_j y_j)](\hat{e}_j - e_j^o) \right\}$$

$$\text{then } (\hat{e}_i - e_i^*) \stackrel{<}{=} (\hat{e}_i - e_i^o).$$

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' abatement levels are perfect ($e_j^{\text{exp}} = e_j^*$), the solution of the N equation-system (12) is the Cournot equilibrium of the N countries' emission-abatement levels. In order to shed light on the properties of the Cournot equilibrium levels of abatement let us consider the analytically tractable case of a world divided into two alliances (e.g., an alliance of low and middle income countries producing tradable primary and manufactured goods versus the rest of the world). In this case, the expected-net-benefit maximizing per capita emissions are

$$e_1^* = \hat{e}_1 - \frac{(\alpha_1 + \gamma_1)P_1 + \frac{r_{21}(s_2 y_2 / s_1 y_1)}{(\hat{e}_2 - e_2^{\text{exp}})}}{2(c / y_1)P_1^2} \quad (13)$$

for alliance 1, and by symmetry,

$$e_2^* = \hat{e}_2 - \frac{(\alpha_2 + \gamma_2)P_2 + \frac{r_{12}(s_1y_1/s_2y_2)}{(\hat{e}_1 - e_1^{\text{exp}})}}{2(c/y_2)P_2^2} \quad (14)$$

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:

$$\hat{e}_1 - e_1^* = 0.5 \frac{[0.5(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)P_1P_2 + (c/y_2)r_{21}(s_2y_2/s_1y_1)P_2^2 - (c/y_1)r_{12}(s_1y_1/s_2y_2)P_1^2]}{(c/y_1)(\alpha_2 + \gamma_2)P_2P_1^2} + 0.5 \left\{ \left[\frac{0.5(\alpha_1 + \gamma_1)(\alpha_2 + \gamma_2)P_1P_2 + (c/y_2)r_{21}(s_2y_2/s_1y_1)P_2^2 - (c/y_1)r_{12}(s_1y_1/s_2y_2)P_1^2}{(c/y_1)(\alpha_2 + \gamma_2)P_2P_1^2} \right]^2 + 2 \frac{(\alpha_1 + \gamma_1)P_1r_{12}(s_1y_1/s_2y_2)}{(c/y_1)(\alpha_2 + \gamma_2)P_2P_1^2} \right\}^{0.5} \quad (15)$$

The quantity and properties of $(\hat{e}_2 - e_2^*)$ are obtained by symmetry.

Equation (15) reveals that in the Cournot equilibrium, the per capita emission abated by alliance 1 $(\hat{e}_1 - e_1^*)$ rises with the marginal improvement in its own environment stemming from its own abatement (α_1) , with its marginal benefit from the combined effort of curbing global warming (γ_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

$$\frac{\partial(\hat{e}_1 - e_1^*)}{\partial\{r_{12}[(s_1y_1)/(s_2y_2)]\}} = -0.5[1/((\alpha_2 + \gamma_2)P_2)]\{1 + [1 - 2(\alpha_1 + \gamma_1)/((c/y_1)P_1)]\Delta^{-0.5}\} \quad (16)$$

and

$$\begin{aligned}
\frac{\partial(\hat{e}_1 - e_1^*)}{\partial P_2} = & 0.5[(((c/y_2)r_{21}(y_2/y_1)/((c/y_1)(\alpha_2 + \gamma_2)P_1^2)) + (r_{12}(s_1y_1/s_2y_2)/((\alpha_2 + \gamma_2)P_2^2)))] \\
& + 0.25\Delta^{-0.5}\{((c/y_2)r_{21}(s_2y_2/s_1y_1)/((c/y_1)(\alpha_2 + \gamma_2)P_1^2)) \\
& + [1 - 2(\alpha_1 + \gamma_1)/((c/y_1)P_1)][r_{12}(s_1y_1/s_2y_2)/((\alpha_2 + \gamma_2)P_2^2)]\}
\end{aligned} \tag{17}$$

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 rise with the population of alliance 2 and decline with alliance 1's ability to reward alliance 2 (r_{12}). 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 greenhouse gas emission abatements was motivated by the outcomes of our preliminary investigation of the international carbon-dioxide emission inequality and by the inequity of an internationally uniform abatement rate of countries' aggregate emissions. Using a decomposable inequality indicator that takes into account population shares, our investigation revealed 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 is expected that the emission inequality between the income groups of countries will be aggravated by an internationally uniform abatement rate. Consequently, a country's costs and benefits of abatement were 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 were assumed to influence the assessment of, and reaction to, a country's commitment to emission abatement by other countries. This influence was incorporated into the determination of a country's internationally cooperative and unilateral emission abatements. The analysis revealed 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 large, open, lower, or upper, middle income economy that has high ability and inclination to reward other countries with improved bilateral economic and political relations.

Appendix A: Income Groups

(Based on World Bank list of economies, July 2009)

Low Income: Afghanistan, Bangladesh, Benin, Bhutan, Bolivia, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Haiti, Kenya, Korea, Democratic People's Republic of, Kyrgyzstan, Lao People's Democratic Republic, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Myanmar, Nepal, Niger, Pakistan, Rwanda, Senegal, Sierra Leone, Tajikistan, Togo, Uganda United Republic of Tanzania, Uzbekistan, Viet Nam, Yemen, Zambia, Zimbabwe

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),

$$\hat{e}_1 - e_1^* = \frac{(\alpha_1 + \gamma_1)P_1 + \frac{r_{21}(s_2 y_2 / s_1 y_1)}{(\hat{e}_2 - e_2^{\text{exp}})}}{2c_1 P_1^2} \quad (\text{B1})$$

and

$$\hat{e}_2 - e_2^* = \frac{(\alpha_2 + \gamma_2)P_2 + \frac{r_{12}(s_1 y_1 / s_2 y_2)}{(\hat{e}_1 - e_1^{\text{exp}})}}{2c_2 P_2^2}. \quad (\text{B2})$$

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

$$\hat{e}_1 - e_1^* = \frac{\theta_1 P_1 + \frac{r_{21}(\tilde{y}_2 / \tilde{y}_1)}{\theta_2 P_2 + \frac{r_{12}(\tilde{y}_1 / \tilde{y}_2)}{(\hat{e}_1 - e_1^{\text{exp}})}}}{2c_1 P_1^2} \quad (\text{B3})$$

In turn,

$$2c_1 P_1^2 (\hat{e}_1 - e_1^*) - \theta_1 P_1 = \frac{2c_2 P_2^2 r_{21}(\tilde{y}_2 / \tilde{y}_1)(\hat{e}_1 - e_1^*)}{\theta_2 P_2 (\hat{e}_1 - e_1^*) + r_{12}(\tilde{y}_1 / \tilde{y}_2)} \quad (\text{B4})$$

By rearranging terms,

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

Consequently,

$$(\hat{e}_1 - e_1^*)^2 - \frac{[0.5\theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\tilde{y}_2 / \tilde{y}_1) P_2^2 - c_1 r_{12}(\tilde{y}_1 / \tilde{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2} (\hat{e}_1 - e_1^*) = \frac{\theta_1 P_1 r_{12}(\tilde{y}_1 / \tilde{y}_2)}{2c_1 \theta_2 P_2 P_1^2} \quad (\text{B6})$$

The roots of (A6) are:

$$\hat{e}_1 - e_1^* = 0.5 \frac{[0.5\theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\tilde{y}_2 / \tilde{y}_1) P_2^2 - c_1 r_{12}(\tilde{y}_1 / \tilde{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2} \pm 0.5 \sqrt{\left[\frac{0.5\theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\tilde{y}_2 / \tilde{y}_1) P_2^2 - c_1 r_{12}(\tilde{y}_1 / \tilde{y}_2) P_1^2}{c_1 \theta_2 P_2 P_1^2} \right]^2 + 4 \frac{\theta_1 r_{12}(\tilde{y}_1 / \tilde{y}_2)}{2c_1 \theta_2 P_2 P_1^2}} \quad (\text{B7})$$

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:

$$\hat{e}_1 - e_1^* = 0.5 \frac{[0.5\theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\tilde{y}_2 / \tilde{y}_1) P_2^2 - c_1 r_{12}(\tilde{y}_1 / \tilde{y}_2) P_1^2]}{c_1 \theta_2 P_2 P_1^2} + 0.5 \sqrt{\left[\frac{0.5\theta_1 \theta_2 P_1 P_2 + c_2 r_{21}(\tilde{y}_2 / \tilde{y}_1) P_2^2 - c_1 r_{12}(\tilde{y}_1 / \tilde{y}_2) P_1^2}{c_1 \theta_2 P_2 P_1^2} \right]^2 + 4 \frac{\theta_1 r_{12}(\tilde{y}_1 / \tilde{y}_2)}{2c_1 \theta_2 P_2 P_1^2}} \quad (\text{B8})$$

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