Measuring Benefits and Damages from CO_2 Emissions and International Agreements to Slow Down Greenhouse Warming

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SUMMARY

Recent environmental economics literature regarding global problems, like for example those associated with greenhouse gases, focuses on the emergence of international co-operation and underlying incentives. International co-operation among countries is necessary in the case of global pollution, since outcomes related to laissez-faire equilibrium are inefficient, because each country chooses its pollution behaviour ignoring the cost imposed on other countries as a result of its behaviour. Voluntary co-operation among sovereign countries has been analysed in terms of agreements of individual countries or sub-groups of countries to reduce emissions. Various models have been developed, in which a group of countries seeks to expand the agreement by self-financing welfare transfers. This implies side payments to other countries in order to induce them to restrict emissions to some desired level, so that a stable coalition is formed. This paper provides an empirical investigation related to the possibility of international agreements with respect to CO_2 emissions. Using data on GDP and CO_2 emissions for five groups of countries - Europe, Latin America, the United States and Canada, India, and China - benefit functions relating GDP to CO_2 and damage functions from the accumulation of CO_2 emissions are estimated. Benefit-cost ratios for changes in CO_2 emissions are estimated for the countries in each group; they are used as indicators of whether co-operation is possible.

NON TECHNICAL SUMMARY

In the history of international agreements on global pollution, negotiations to achieve voluntary cooperation among sovereign countries through agreements on emission control, have proven unlikely to lead to large coalitions of cooperating countries. This has been largely due to the presence of asymmetries in abatement costs and environmental damages, and to the countries' incentives to free-ride on other countries' emission abatement and to choose their pollution behaviour ignoring the costs imposed on other countries. Some recent environmental economics literature has focused on the possibility of enlarging coalitions by bribing non signatory countries through transfers. In general, the process involves a group of countries providing side payments to reluctant countries in order to induce them to reduce emissions to a desired level, so that a stable coalition is formed (e.g. Barrett , 1990, 1991; Carraro and Siniscalco, 1991, 1993, Petrakis and Xepapadeas,1996).

The ability to measure the benefits and costs from emissions when a country changes its emission policy turns out to be crucial for the empirical relevance of these theoretical models. The existing literature on the estimation of global warming damages (e.g. Nordhaus 1981,1991; Ayres and Walter, 1991; Hoel and Isaksen,1995) uses global cost measures that relate to the global climatic change, without focusing on damages corresponding to specific countries. However, global damages do not provide sufficient information when voluntary agreements are examined. The difficulties essentially arise because countries make the decision to enter into an agreement based on their own costs and benefits associated with a specific course of action. Given the asymmetries across countries, the design of international agreements on global climatic change should take into account possible differences in damages due to global warming. Similar reasoning applies to benefits from the emission of the so-called greenhouse gasses (GHGs), the most important of which is CO_2. Each country is expected to decide whether or not to participate in the agreement according to its own benefit function. Hence, heterogeneity in the benefit functions affects the emergence of the coalition.

Against this background, the present paper develops a framework for measuring costs and benefits associated with global warming at a disaggregated level. Five groups of countries (Western Europe, Latin America and the Caribbean, the United States and Canada, India, and China) are considered under the assumption that each group can act as a single decision-making unit with respect to CO_2 emissions. After having determined the benefit and the damage functions, the study focuses on benefit-cost ratios to explore whether a group of countries will agree to commit over a given time horizon to a specific emission path.

The methodological approach involves three stages. In the first step, benefits in each group of countries are estimated by specifying and estimating a benefit function. This function relates CO_2 emissions to GDP and is defined on the assumption that CO_2 emissions can be treated as a generalized input in the production of aggregated output. The benefit functions are estimated as long-run equilibrium relationships using cointegrating methodology. In the second step, damages in each group of countries are estimated by specifying and estimating a damage function that relates increases in global temperature due to CO_2 accumulation with damages measured in monetary terms. Finally, benefit-cost ratios are estimated for different scenarios of emissions. These ratios are then used as indicators of the possibility that the individual group enter into a agreement to reduce CO_2 emissions, whereby each group of countries chooses the most beneficial course of action from a limited set of predetermined alternatives. This approach is argued to be empirically relevant in negotiations to stabilise CO_2 emissions across countries with respect to a given year's emissions.

CONTENTS

1. Introduction

Recent advances in environmental economics literature regarding global problems, like for example those associated with greenhouse warming, focus on the emergence of international cooperation and underlying incentives. International cooperation among countries is necessary in the case of global pollution, since outcomes related to laissez-faire equilibria are inefficient, because each country chooses its pollution behavior ignoring the cost imposed on other countries as a result of its behavior.

Voluntary cooperation among sovereign countries has been analyzed in terms of agreements among sub-groups of countries to reduce emissions. These countries seek to expand the agreement by self-financing welfare transfers. In general the processes involves a group of countries that provides side payments to another group of countries in order to induce them to restrict emissions to some desired level, so that a stable coalition is formed. (Barrett 1990, 1991; Carraro and Siniscalco 1991, 1993; Hoel 1992; Petrakis and Xepapadeas 1996; Chander and Tulkens 1995).

Crucial however for the empirical relevance of these models, mainly in the sense of exploring the circumstances under which international agreements on this issue are really possible, is the ability to measure the benefits and costs involved when a country or a group of countries decides to change its policy with respect to CO_2 emissions.

There is a substantial body of literature dealing with the estimation of global warming damages (Nordhaus 1982, 1991; Schelling 1992; Ayres and Walter 1991; Hoel and Isaksen 1995). The basic characteristic of these studies is that they try to reach some "global" cost that relates to the global climatic change, without focusing on damages corresponding to specific countries or groups of countries. Undoubtedly the task of estimating global damages is formidable given the uncertainties and informational requirements. However while global damages might be sufficient information if the task is to determine for example some uniform carbon tax, they are not sufficient information when voluntary agreements are analyzed. This is due to the fact that when countries consider the possibility of entering into an agreement they need to make the decision based on their own costs and benefits associated with any specific course of action. Since countries are basically non-identical, with wide discrepancies among them, any attempt to analyze the possibility of international agreement on the issue of global climatic change should take into account, at least at the level of a first approximation, possible differences in damages due to global warming.

Similar reasoning applies to benefits from the emissions of CO_2 and the other greenhouse gasses. Since it is common, in analyzing global pollution problems, to treat emissions as a productive input in a benefit function relating gross output in a country to emissions (e.g. Welsch 1993, Dockner and Van Long 1993, Hoel and Isaksen 1995, Petrakis and Xepapadeas 1996), each country or group of countries should examine its participation in the international agreement based on its own benefit function. Again asymmetries in the benefit functions could be important in the emergence of the international agreement.

In the context described above the present paper seeks to provide an empirical investigation related to the possibility of international agreements with respect to reduction of CO_2 emissions,[1] with the purpose of slowing down global warming. Five groups of countries are considered, under the assumption that each group can act as a single decision-making unit with respect to CO_2 emissions. The first two groups - Western Europe, and the United States and Canada - are at the upper end of the development ladder, while the other three - Latin America, India, and China - belong to the lower end.

The methodological approach involves three stages. First a benefit function is estimated for each group of countries. This function which is regarded as a long-run equilibrium relationship, relates CO_2 emissions with GDP in each group and is defined on the assumption that CO_2 emissions can be treated as a generalized input in the production of aggregate output. Benefit functions are estimated as cointegrating relationships. The concept of a long-run benefit function obtained by using the cointegration approach, provides a more solid framework for analyzing a long-term problem such as global warming, and constitutes an advancement towards a more realistic quantification of the whole issue. At the second stage damages in each country are estimated by specifying and estimating a damage function that relates increases in global temperature due to CO_2 accumulation with damages measured in monetary terms in each country. Damage functions are differentiated among groups on the basis of fundamental parameters such as the growth of GDP and the discount rate. At the final stage benefit-cost ratios are estimated for specified scenaria of CO_2 emissions. These ratios are used as indicators of the possibilities of the individual countries entering into an international agreement to reduce CO_2 emissions.

This approach does not involve comparison of a non-cooperative equilibrium with a cooperative equilibrium in order to examine the size and the stability of the coalition, as in the theoretical models. The paper seeks mainly to provide a sound quantitative basis for the problem, and at a second stage examines the issue of agreements, along the lines of a cost-benefit type of approach, where the group of countries has to choose the most beneficial course of action - which is not necessarily the optimal - from a limited set of predetermined alternatives.

2. The Benefit Function

It is assumed that benefits from the use of combustion fuels in production activities, that result in anthropogenic CO_2 emissions, can be reflected in a benefit function which takes the form $Y_i = B_i(E(t)_i, t)$, where Y_i is the total product produced in each group $i = 1,\ldots,n$ during a certain time period - that is GDP- which accounts for the benefits, and E_i are CO_2 emissions in the same group generated during the production of aggregate output. Hence (CO_2) emissions are used as a generalised input in the production process. Finally t is assumed to reflect technical change.[2]

Following standard economic theory assumptions, the benefit function should satisfy:

$$\frac{\partial B_i}{\partial E_i} > 0, \frac{\partial B_i}{\partial t} > 0, \frac{\partial^2 B_i}{\partial E_i^2} < 0, \frac{\partial B_i}{\partial E_i} \to \infty, \text{as } E_i \to 0$$

2.1 Data

The five groups of countries used for the estimation of the benefit functions are defined as follows:

Group 1: Western Europe. This group includes the following countries:

Austria, Belgium, Luxembourg, Denmark, Finland, France, Federal Republic of Germany, West Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Malta, Spain, Netherlands, Norway, Portugal, Sweden, Switzerland, United Kingdom.

Group 2: Latin America & Caribbean

Group 3: United States & Canada.

Group 4: India.

Group 5: China.

For groups 1, 2 and 3 data cover the period 1952-1992. For groups 4 and 5 the sample range is smaller, covering the period 1960-1992.The unequal samples are due to data limitations.[3]

The International Financial Statistics Yearbooks and the Penn World Tables (Mark 5) prepared by Summers and Heston (1991) were the data sources for the construction of the

GDP time series in each group of countries. In the former, GDP was given for each country as a percentage change over the previous year, while in the latter GDP was given for each country in millions of international dollars for the year 1988 using 1985 as the base year for all the countries. All GDP figures are expressed in millions of international dollars. [4]

The main data source used for the CO_2 emission series was the data reported in Halvorsen *et al.* (1989). In this source CO_2 emissions are calculated for the period 1952-1986. The series were extended to cover the period 1987-1992 using fossil fuels consumption data from the United Nations series "Energy Statistics Yearbook" in which consumption is expressed in thousand metric tons of coal equivalent (Ktce). From the fossil fuel consumption data, carbon dioxide emissions are estimated by applying emission coefficients for three different types of fuels: solids (coal), liquids (oil) and natural gas.[5] All emissions data is expressed in thousand tons of carbon.[6] The time series of GDP and CO_2 emissions in each country group are presented in Figures 1 and 2.

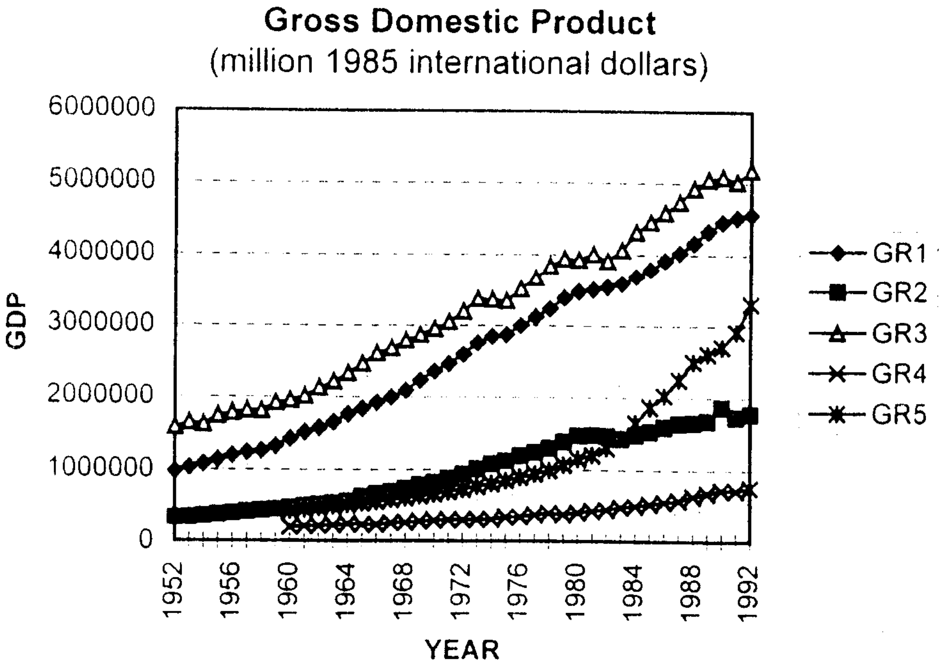

Figure 1: Gross Domestic Product

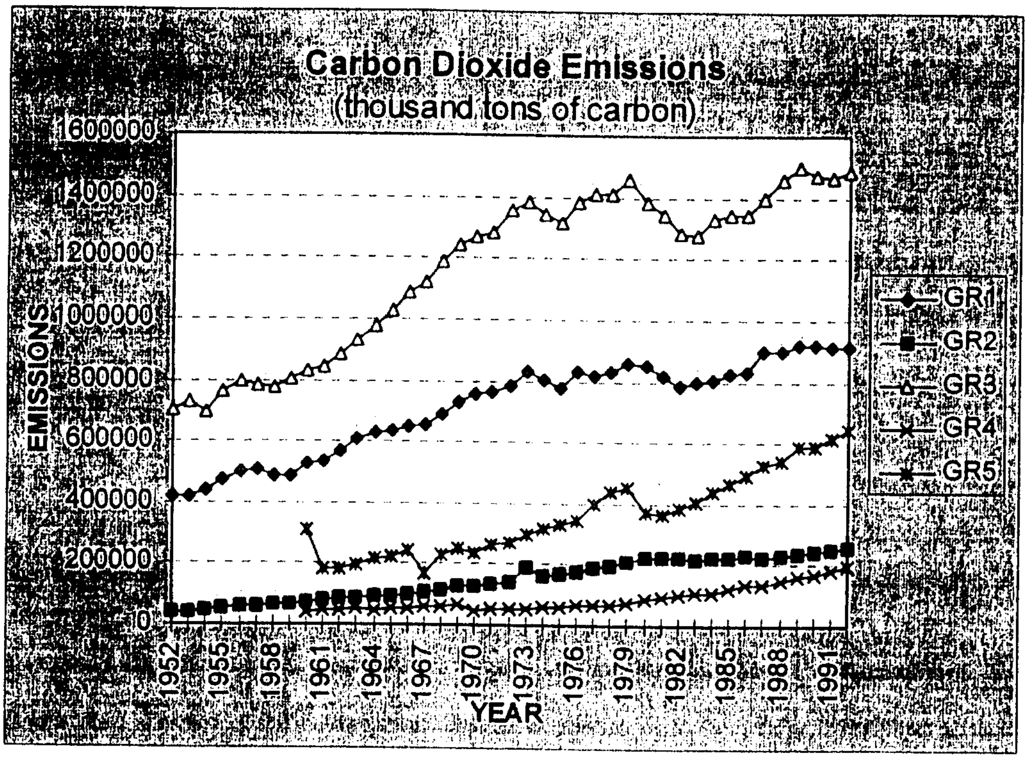

Figure 2: Carbon Dioxide Emissions

It is clear from the above figures that the two groups with largest GDP, group 1 and group 3, are also responsible for the largest part of CO_2 emissions. Using the emissions for year 1990 as a benchmark, total emissions of the five groups amount to approximately 3.4 billion tons of carbon (GtC), while total emissions from fossil fuel burning amount to approximately 5.4 (GtC).[7]

2.2 Estimation and Results

As stated in the introduction the approach to analysing the possibility of obtaining agreements to reduce CO_2 emissions relies on comparing costs and benefits associated with these emissions, to the benefit function. The benefit function is the relevant concept for estimating benefits associated with a specific emission path. Thus countries in our model use the benefit function to calculate benefits from emissions. Since the time horizon for a global warming problem is quite large, Cline (1992) suggests that the atmospheric build-up of carbon is likely to continue for the next two to three centuries, and thus the appropriate concept for the benefit function should be a long-run concept. That is, faced with such a long time horizon countries should calculate benefits using a long-run equilibrium benefit function, instead of a short-run one that will reflect short-term adjustment towards equilibrium.

A large body of literature has been developed related to the estimation of long-run equilibrium relationships in the context of cointegration (e.g., Phillips and Loretan 1991, Banerjee *et al.* 1993). Let y_t denote $\ln(GDP)_t$, and e_t denote $\ln(CO_2)_t$. The functional form for the equilibrium relationship expressing the benefit function is assumed to be linear in logarithms:

$$y_t = a + b\, e_t + \varepsilon_t \ , t = 1,\ldots,n \qquad (1)$$

where $(y_t\ , e_t)$ are assumed to be integrated processes of order one , I(1), and the error term is assumed to be integrated of order zero, I(0). In this model the parameters a and b describe a hyperplane towards which the vector process $(y_t\ , e_t)$ tends over time. In relationship (1) a linear trend can be added which can be interpreted as reflecting technical change:

$$y_t = a + b\, e_t + gt + \varepsilon_t \ , t = 1,\ldots,n \qquad (1)'$$

Thus relationship (1)′ can be regarded as an equilibrium relationship that shifts in time as it is affected by technical change.

Following standard approaches in this type of analysis the order of the integration of the logarithms of the GDP, CO_2 series is examined using the Augmented Dickey-Fuller (ADF) test. The test was applied to the levels and to the first differences of the series. The results are presented in table 1.

Table 1. ADF tests on the levels and on the first differences of the series ln(GDP) and ln(CO_2)

GROUPS	ln(GDP)		ln(CO_2)	
	ADF statistic levels	ADF statistic 1st differences	ADF statistic levels	ADF statistic 1st differences
GROUP 1	-0.437970 (-3.5279)**	-4.770107 (-4.2165)*	-2.542745 (-2.9378)**	-4.129486 (-3.6117)*
GROUP 2	-0.198574 (-3.5279)**	-3.634017 (-3.5312)**	-1.209400 (-3.5279)**	-5.712381 (-4.2165)*
GROUP 3	-1.150617 (-3.5279)**	-4.750704 (-4.2165)*	-1.031687 (-3.5279)**	-4.661005 (-4.2165)*
GROUP 4	-1.668336 (-3.5614)**	-5.160489 (-4.2949)*	-1.080318 (-3.5670)**	-4.427310 (-4.2949)*
GROUP 5	-0.710693 (-3.5614)**	-3.916989 (-3.5670)**	-3.430098 (-3.5614)**	-5.890066 (-4.2949)*

MacKinnon critical values for rejection of hypothesis of a unit root are given in parentheses.
* refers to 1% critical level while ** refers to 5% critical level.

The results of the above table indicate that the series are integrated of order one. To test for the existence of a cointegrating relationship either of the form (1) or (1)′ the error term should be integrated of order zero. The standard methods test the null hypothesis of no cointegration against the alternative, that the variables are cointegrated and are residual based. We perform two types of tests on relationship (1). The first is a standard ADF unit root test on the errors obtained by ordinary least squares estimation of relationship (1), which tests the null hypothesis of no cointegration. The second is the Hansen (1992) approach which is based on the fully modified estimates of cointegrating vectors developed by Phillips and Hansen (1990). Three test statistics are obtained L_c, *MeanF*, and *SupF*. The L_c tests the null hypothesis of cointegration against the alternative of no cointegration (Haug 1996). The *MeanF* and *SupF* test again the null of cointegration against the alternative of structural changes in the cointegrating relationship. In particular *SupF* tests the null against the alternative of a sudden structural break, while *MeanF* tests against slowly changing coefficients. These tests are useful for our analysis since structural breaks might be expected given the shocks that the world economy has undergone in the last forty years. The ADF and the Hansen test statistics are presented in tables 2 and 3 below.

Table 2. Test for cointegration using ADF

GROUPS	ADF test statistic
GROUP 1	-1.668884 (-1.9495)**
GROUP 2	-3.099958 (-2.6227)*
GROUP 3	-1.195976 (-3.5279)**
GROUP 4	-2.067285 (-1.9521)**
GROUP 5	-2.255748 (-1.9521)**

MacKinnon critical values for rejection of hypothesis of a unit root are given in parentheses.
* refers to 1% critical level while ** refers to 5% critical level.

Table 3. Hansen statistics for parameter stability

GROUP	TEST STATISTICS
GROUP 1	Lc = 0.23367081 MeanF = 5.7561036 SupF = 41.206965
GROUP 2	Lc = 0.79632852 MeanF = 8.9715753 SupF = 13.047507
GROUP 3	Lc = 0.22637541 MeanF = 8.6646120 SupF = 20.593692
GROUP 4	Lc = 0.29664321 MeanF = 5.7795486 SupF = 11.551668
GROUP 5	Lc = 1.2481505 MeanF = 4.770503 SupF = 16.14708

CRITICAL VALUES*

1% Significance level: Lc = 0.898 , MeanF = 6.78 , SupF = 16.2

5% Significance level: Lc = 0.575, MeanF = 4.57, SupF = 12.4

Source: Hansen (1992)

The ADF statistics indicate the null of no cointegration should be rejected in all cases except group 3, while the Hansen statistics indicate rejection of the null of cointegration in all cases except in group 5. Furthermore the *MeanF* and *SupF* statistics indicate that the relationships might not be stable over the sample period. According to the residual-based tests conducted above, it can be concluded that in groups 1,2,4, and 5 the series are cointegrated while in group 3 they are not.

The instabilities detected by the Hansen tests could suggest the possibility of structural breaks. A structural break in the model would be reflected in changes in the intercept or the slope of the cointegrating equation, and could explain the indication of no cointegration between variables of group 3 according to the ADF test.[8] For this reason the next step is to check for parameter constancy and this is done by the application of the Scaled Recursive Chow Test (SRCT). According to this test, as described by Charemza and Deadman (1992), if RSS is the residual sum of squares for the model fitted by OLS for the period t-1, and if RSS* is the residual sum of squares for the model fitted for the period t, then the SRC test statistic is calculated as:

$$\mathrm{Chow}_t = \frac{(\mathrm{RSS}^* - \mathrm{RSS})}{\mathrm{RSS}/(t-k)}$$

In this test the null hypothesis of no structural change in the model between periods t-1 and t is tested against the alternative that a structural change has occurred. This statistic has an *F* distribution with 1 and t-k degrees of freedom. Values of the statistic greater than the *F* critical values lead to the rejection of the null hypothesis. The statistic and the critical values of *F* are functions of time so we can divide the Chow value by its 5% critical value from the tables of F to get a scaled recursive Chow test for each recursion. Hence the statistic Chow/

$F_{0.05}(1, t-k)$ should be less than unity under the null hypothesis of no structural break at the given year.

The test was conducted for all 5 groups and the results are presented in table 4.

Table 4. Structural breaks according to the Scaled Recursive Chow Test

GROUPS	TIMING OF THE BREAK
GROUP 1	1st break in 1975
	2nd break in 1986
GROUP 2	1st break in 1965
	2nd break in 1975
GROUP 3	1st break in 1978
	2nd break in 1981
GROUP 4	1st break in 1970
GROUP 5	No break detected

For groups 1 to 3 the results indicate one break that can be attributed to the first oil crisis and a second one which can not be clearly attributed to a specific event but seems to reflect adjustments within the group. The results for groups 4 and 5 should be interpreted with caution given the smaller time horizon used for these countries. However the combination of the results of the Hansen and the SRC tests indicate that the model used to describe the relationship between GDP and CO_2 emissions has to be re-specified in order to take into account the possibility of structural changes. These structural changes are modelled as level shifts of the cointegrating relationships by introducing dummy variables taking values 0 or 1, depending on the timing of the break. In the model a linear time trend is also introduced along with the dummy variables, in the fashion of (1)′. Thus the cointegrating relationship accounts both for structural breaks and for exogenous technological change and can be defined as:

$$y_i = a + a_1 D_{1t} + a_2 D_{2t} + be_i + gt + \varepsilon_t \ , t = 1,\dots,n$$
$$D_{1t} \begin{matrix} = 0 & if & t \le \tau_1 \\ = 1 & if & t > \tau_1 \end{matrix} \ , \quad D_{2t} \begin{matrix} = 0 & if & t \le \tau_2 \\ = 1 & if & t > \tau_2 \end{matrix} \tag{2}$$

Thus it is assumed that the structural change is reflected in changes in the intercept which can be interpreted as the efficiency parameter of the benefit function, while the slope coefficient indicating the elasticity of CO_2 emissions with respect to output is held constant.

Next a test for cointegration among the variables y_t and e_t is conducted for all groups since the model has been re-specified. Since the structural break is treated as known the null hypothesis of no cointegration can be tested using OLS residual based tests.[9] In testing we use the ADF test statistic and the Phillip's Za, Zt test statistics. Due to the well known problems associated with the OLS estimators of cointegrating regressions (e.g. Phillips and Durlauf 1986) we estimate in addition Park's (1992) canonical cointegrating regression (CCR) estimators and the Saikkonen (1991) estimator. The results are presented in table 5.

Table 5. Estimates of the benefit functions

GROUP$^+$	a	b	D_1	D_2	g	ADF	Z_a , Z_t	$\bar{R}^2$
Group 1								
OLS	5.368	0.649	0.0249	-0.072	0.0277	-4.413	-31.142	0.99
	(9.716)	(15.295)	(2.075)	(-6.482)	(21.427)	-2.532**	-19.795**	
CCR	4.991	0.678	0.0297	-0.0678	0.0268			
	(9.547)	(16.771)	(2.522)	(-5.781)	(20.694)		-5.172	
Saikkon.	4.744	0.697	0.2092	-0.6208	0.0263		-3.566**	
	(9.109)	(17.317)	(2.013)	(-5.951)	(22.516)			
Group 2								
OLS	7.371	0.496	0.111	0.129	0.015	-3.244	-34.501	0.99
	(13.746)	(10.002)	(4.757)	(6.097)	(7.166)	-2.533**	-19.795**	
CCR	7.358	0.496	0.119	0.128	0.0158			

	(13.169)	(9.626)	(4.703)	(5.757)	(7.260)		-4.649	
Saikkon	6.468	0.576	0.0828	0.014	0.0124		-3.566**	
	(11.246)	(10.910)	(3.862)	(6.014)	(6.850)			
Group 3								
OLS	7.047	0.534	0.035	0.032	0.0188	-3.413	-19.645	0.999
	(11.635)	(11.848)	(3.150)	(2.154)	(13.189)	-2.532**	-13.877*	
CCR	6.452	0.581	0.0396	0.0174	0.0174			
	(5.148)	(6.241)	(1.881)	(5.847)	(5.847)		-3.467	
Saikkon	7.471	0.502	0.0373	0.0226	0.0201		-2.937*	
	(11.983)	(10.795)	(3.319)	(1.597)	(13.674)			
Group 4								
OLS	6.849	0.497	0.153		0.0126	-3.707	-19.312	0.992
	(4.663)	(3.541)	(2.095)		(1.392)	-2.532**	-13.877**	
CCR	6.103	0.572	0.195		0.00796			
	(2.665)	(2.628)	(1.673)		(0.560)		-3.845	
Saikkon	0.155	0.468	7.201		0.0166		-2.937**	
	(1.788)	(3.778)	(5.525)		(2.071)			
Group 5								
OLS	10.668	0.231			0.0792	-2.593	-9.281	0.993
	(7.995)	(2.213)			(19.291)	-1.952*	-12.929*	
CCR	11.028	0.204			0.0788			
	(13.347)	(3.176)			(23.087)		-2.455	
Saikkon	11.047	0.201			0.0813		-2.949*	
	(8.036)	(1.861)			(17.994)			

† Saikkonen estimators include one lag and one lead
** 1% critical value
*5% critical value
t-statistics in parentheses

The above results indicate that exogenous technical change has been significant in determining GDP and that the elasticity of CO_2 emissions is less than one, indicating strictly concave benefit functions. This result is in accordance with the assumptions of the theoretical models. Furthermore all the chosen dummy variables were significant, indicating the existence of structural breaks. Given the above results the benefit function for each group, using CCR estimators, is defined as:

Group 1: $Y=(141.585)E^{0.678}\exp(0.0268t)$

Group 2: $Y=(2008.212)E^{0.496}\exp(0.0158t)$

Group 3: $Y=(671.155)E^{0.581}\exp(0.0174t)$

Group 4: $Y=(1565.562)E^{0.468}\exp(0.0166t)$

Group 5: $Y=(61574.309)E^{0.201}\exp(0.0788t)$

Note should also be made of the relatively high elasticities of groups 1 and 3, which indicate a relatively higher degree of efficiency in transforming energy to output, and the high rate of technical change indicated in group 5.

3. The Damage Function

The increase in the amount of GHGs in the atmosphere is regarded as responsible for global warming. GHGs, the most important of which is CO_2, are emitted at a rate higher than the physical process can remove. The result is expected to be global warming which is likely to produce potentially disastrous climatic changes. Since GHGs are accumulated in the atmosphere and the effects of global warming would affect all countries, it is not a country's own emissions that are responsible for the damage suffered in this same country from the climate change, but rather the total amount of accumulated emissions. In order to specify damages from global warming, it is assumed that the damage function in each group is a function of the climatic change, which is in turn a function of the concentration of CO_2, and takes the form:

$$D_i = D_i(T(t),t)\,,\ \frac{\partial D}{\partial T} > 0\,,\ T(t) = T(M(t))$$

where

$T(t)$ = the increase in the average global temperature due to greenhouse warming above its preindustrial level.

$M(t)$= anthropogenic atmospheric concentration of CO_2, above its preindustrial level.[10]

To estimate such a damage function we first need to describe the relationship between CO_2 emissions and the climate development. According to Nordhaus (1991) to find the impact of an increase in GHGs concentration on climate, we have to take into account the temperature adjustment process, because the average climate responds slowly to the increase in radiative inputs. For this purpose the following simplified two-box diffusion model is used.

$$T(t) = \sigma\left[\lambda h(M(t)) - T(t)\right] \qquad (3)$$

$$M(t) = \beta E(t) - \delta M(t) \qquad (4)$$

where

E(t): anthropogenic emissions of CO_2 equivalent GHGs, $E(t) = \sum_{i=1}^{m} E_i$, for i=1,...,n groups of countries.

σ: the delay parameter of temperature in response to radiative increase (per year). We use a value of 0.025 (Hoel and Isaksen 1995).

β: fraction of CO_2 equivalent emissions that enter the atmosphere. We set $\beta=0.5$ according to Nordhaus's (1991) estimation.

δ : rate of removal of CO_2 equivalent emissions from the atmosphere (per year). Nordhaus (1991) estimated it to be equal to 0.005 (representing residence time of 200 years).

λ: factor of proportionality between radiative forcing and the long-run temperature response, λ is set at 0.75 which means that an increase in radiative forcing of $1 W/m^2$ gives a long-run temperature increase equal to 0.75 degrees (Celsius). This relation is based on the "best estimate" of climate sensitivity to radiative forcing as given in Houghton *et al.* (1992).

$h(M)$: the increase in radiative forcing from CO_2 since its preindustrial level (measured in W/m^2).The h function for CO_2 takes the form $6.3\ln\left(\frac{M}{M_0}\right)$, where M_o is the atmospheric concentration of CO_2 in pre-industrial time (Wigley 1987, IPCC-I 1990). For the present time the ratio M/M_o is set to 1.25 (Cline 1991).

We assume, following Hoel and Isaksen (1995), that the damage can be specified by the following functional form:

$$D_i\left(T(t),t\right) = A_i T(t)^{\alpha} \exp(\theta_i t)$$

where

α : curvature of the damage function for climate change, this is set equal to 1.5 across all groups to allow for convexity in the damage function. This assumption is in line with the estimates of Cline (1992).

θ_i : expresses how the monetary damage of a climatic change develops overtime for a constant climate in a specific country. We consider this parameter as a group specific parameter, and we use Cline's (1992) assumption to regard this parameter as proportional to gross product. Thus θ_i gives the growth rate of the gross product of the group i. Or, $\theta_i = \eta_i + \gamma_i$, where η_i is the rate of population growth, and γ_i is per capita growth of the gross product of group i.

Regarding the value of A_i, we have that in global models of greenhouse damages, this value taken together with α=1.5 means that a temperature increase of 3 degrees is assumed to account for damages of x% of the world GDP. So to find the value A will take we first need to specify the value of x. There have been different estimates of the value of x starting 1/4%

(Nordhaus 1991) to values in excess of 2.4% (Ayres and Walters 1991). We use the assumption that x=2%, which is in accordance with Cline and results in a global value of A=115 billions dollars (Hoel and Isaksen 1995). We then determine group A_i by taking the ratio A_i/A to be the same as the group's GDP to the world GDP.

Solution of differential equation (4) determines the concentration of CO_2 emissions as a function of the emissions and the rest of the parameters, or $M(t) = M(t; \sum_i E_i(t), \beta, \delta)$. Substituting this solution in (3) and solving again the differential equation we obtain temperature increase with respect to the preindustrial level as a function of emissions, or $T(t) = T(t; \sum_i E_i(t), \beta, \delta, \sigma, \lambda, M_0)$.

Using the definition of the damage function, total damages at t=0 of a given path of CO_2 emissions $p_{ij} = \left\{E_{ij}(t)\right\}_{t=0}^{t=\bar{T}}$ is determined, for group i as the present value of the stream of annual damages:

$$TD_i = \int_0^{\bar{T}} e^{-r_i t} D_i\left(T(t), t\right) dt \qquad (5)$$

where r_i is the discount rate for group i which weights environmental damages suffered by future generations. The issue of selecting an appropriate discount rate for public projects has received excessive attention in the economic literature over several decades. Different concepts have been proposed including the government or the private borrowing rates or some weighted average of them, the shadow price of capital, or the social time preference rate. It has been suggested (Lind 1990) that the choice of the discount rate should depend on the policy problem and the time profile of the costs and benefits. The basic feature of the problem we analyse is that it is a long-term one involving intergenerational choices with benefits accruing with a considerable lag, a feature justifying the use of discount rates relatively lower compared to short-term projects where capital is displaced (Scheraga 1990). In our calculations the groups' discount rate is approximated by the social time preference rate defined as:

$$r_i = \rho_i + \omega_i \gamma_i \qquad (6)$$

where

ω_i : is the elasticity of the marginal utility of per capita consumption for group i. It reflects government's attitude towards income distribution and possible values could range from 0 to 3. The value of ω will be lower the less the government's concern about income distribution (Brent 1990).

ρ_i : is the pure rate of time preference of group i reflecting society's concern about future generations compared to present generations. The higher the value of ρ the higher the premium on current generation's consumption. As suggested by Squire and van der Tak (1975) the value of ρ should lie between 0 and 5%.

γ_i : is per capita growth of the gross product of group i as specified above.

The social time preference rate defined in (6) has been traditionally associated with a single country. In our case however it needs to be interpreted in the groups' context. Since groups are fairly homogeneous this seems to be a justifiable approach.

In estimating the damage function for each group the parameter values shown in table 6 have been used.

Table 6. Parameter values for damage function estimation

GROUPS	η	γ	θ	ω	ρ	r
GROUP 1	0.2%	2.3%	2.5%	1.5	0.005	0.0395

GROUP 2	1.8%	-0.2%	1.6%	1.0	0.015	0.013
GROUP 3	0.8%	2.6%	3.4%	1.5	0.005	0.044
GROUP 4	1.7%	3.6%	5.3%	1.0	0.015	0.051
GROUP 5	1.3%	8.2%	9.5%	1.0	0.015	0.097

In choosing the distributional parameters ω, and pure time preference parameters ρ that determine the social time preference rate, we assumed that in groups 1 and 3, which are at the higher end of the development ladder, the distributional parameter is relatively higher and the pure time preference parameter relatively lower. This could reflect a greater concern about income distribution and future generations in these groups.

4. Benefit-Cost Ratios of Changing Emissions and International Agreements

Having determined the benefit and the damage functions, one approach would be to determine the emission path that will maximise the present value of benefits less damages over the chosen planing horizon subject to the differential equations describing the climate change and any capacity constraints.[11] Co-operative and non co-operative solutions can then be derived to characterise the optimal emissions path under co-operative or laissez-fair equilibrium.[12] Then conditions can be derived for agreements that could achieve the co-operative solution or some other desired outcome.[13]

In our approach to the problem of international agreements to reduce CO_2 emissions, however, we do not seek optimal emission paths, but rather try to explore whether a group of countries will agree to commit over a given time horizon to a specific emission path. This approach could be empirically-relevant in agreements to stabilise CO_2 emissions with respect to a given year's emissions, e.g. 1990. The problem is approached in terms of a cost-benefit type of exercise where a group of countries has two choices over alternative paths of CO_2 emissions.

Given the benefit function, total benefits for group i at t=0, from a given CO_2 path, $p_{ij} = \left\{ E_{ij}(t) \right\}_{t=0}^{t=\bar{T}}$ are determined as the present value of annual benefits, and defined as:

$$TB_i \middle| p_{ij} = \int_0^{\bar{T}} e^{-r_i t} B_i \left(E_{ij}(t), t \right) dt \qquad (7)$$

where the path p_{ij} could be for example emissions increasing at a rate equal to the rate of increase up to 1992, or emissions constant at the 1990 level.

On the other hand given the specification of the damage function, total damages for the same path p_{ij} for the given group i will be a function of the emissions of group i and the emissions of all the other groups $h \neq i$ which follow emission paths p_{hv}. Thus total damages for group i are defined as:

$$TD_i \middle| p_{ij\,hv} = \int_0^{\bar{T}} e^{-r_i t} D_i \left(\left(E_i \middle| p_{ij} \right) + \sum_{h \neq i} \left(E_h \middle| p_{hv} \right) \right) dt \qquad (8)$$

where $v = \left(v_1, \ldots v_{i-1}, v_{i+1}, \ldots v_v \right)$.

Define the benefit cost ratio for group i, when the group follows path j and the rest of the countries follow paths $v = \left(v_1, \ldots v_{i-1}, v_{i+1}, \ldots v_v \right)$ as:

$$BC_{i,jv} = \frac{\left(TB_i \middle| p_{ij} \right)}{\left(TD_i \middle| (p_{ij}, p_{-iv}) \right)} \qquad (9)$$

Consider now the case of the choice between two alternatives: (i) Path 1: Commitment to an emission path which will keep emissions constant at the 1990 levels, and (ii) Path 0: An emission path with emissions growing at the average rate of the sample period for the given group.

We assume that the objective of the agreement is to have the groups committed to emissions path such that (a) the increase in global temperature will not exceed 3°C over an 100 year time horizon, (b) the agreed emission paths will result in the highest possible benefit-cost ratios for the groups in the agreement relative to the alternative emission paths that do not violate condition (a).

It should be stressed that we do not consider optimality issues or coalition stability issues regarding any specific agreement. The goal is to examine, based on group specific benefit and damage functions, whether groups of countries can agree on CO_2 emissions paths on the basis of two simple requirements. The first seeks not to allow emission paths that will result in temperature increases above 3°C. This temperature increase has been regarded as a benchmark for global damage calculations and, given the uncertainties associated with damages, emission paths that will result in higher temperatures might not be properly reflected in the estimated damage functions,[14] something that reduces the validity of benefit costs calculations. The second requirement aims at emission paths, within the physical temperature constraints, that will produce the highest possible benefits per unit of damages due to global warming. In the framework defined above the choice is over paths 0 or 1.

We define a specific path, that corresponds to an agreement about a certain choice of emission paths, to be *desirable* for a group *i*, if the temperature constraint is satisfied and the benefit-cost ratio for the group under the path of agreement is higher then the benefit-cost ratios corresponding to the cases where the group does not follow the path of the agreement and the rest of the groups follow any possible course of action. For emission path choices 0 and 1, this condition can be written as:

$$\begin{array}{l} BC_{i,1v_1} > BC_{i,0v_k},\ v_1 = (1,1,1,1),\ v_k = (k_1,k_2,k_3,k_4) \\ \text{where } (k_1,k_2,k_3,k_4) \text{ permutations of } (0,1) \end{array} \qquad (10)$$

That is, in deciding about entering into the agreement each group will have to calculate its benefit-cost ratio for every possible course of action by the other groups. This happens because of the well known free riding incentive. Although it might be beneficial for a group to enter the agreement, it might be even more beneficial not to enter the agreement while having everybody else in the agreement We call the agreement *strongly desirable* if (10) is satisfied for all i.

In the empirical investigation of the desirability of the agreement to stabilise emissions at the 1990 levels we consider only a subset of potential combinations of courses of actions based on the fact that due to their level of economic development and their political power, groups 1 and 3 are of crucial importance to any agreement. Thus we compare to the benchmark case of no agreement to stabilise emissions at the 1990 levels, the cases of full agreement and the three cases in which groups 1 and 3 decide to reduce emissions either unilaterally or together. That is, we do not consider the possibility of either group 1 or 3 free riding on the other less-developed groups, although we consider the possibility of free riding against each other with the other groups out of the agreement. The results for a 100 year time horizon are shown in table 7.[15]

Table 7. Benefit-cost ratios for different emission paths

Temperature Increase (°C)	Emission Path	GROUPS 1	2	3	4	5
3.21	a. (0,0,0,0,0)	130.59	259.14	69.00	36.00	36.69
0.88	b. (1,1,1,1,1)	160.29	182.81	110.76	51.34	58.66
2.61	c. (1,0,1,0,0)	88.82	329.25	58.32	46.67	46.17
2.99	d. (1,0,0,0,0)	77.88	281.70	74.46	39.98	39.76
2.82	e. (0,0,1,0,0)	148.44	300.37	53.76	42.61	42.29

Path (a) and marginally path (b) violate the temperature restriction. Of the remaining paths, path (b) where all groups cooperate in keeping emissions to the 1990 levels, seems to be preferable to paths (c) and (d) for all groups except 2, Latin America. Group 2 would prefer path (c) in which group 1 (Europe) and group 3 (USA and Canada) are the only groups that restrict their emissions. This conflict could be resolved either by having all groups agree on path (c), which is however less desirable for all the rest of the groups to path (b), or by providing transfer payments to group 2, either related directly to the CO_2 reductions or related to a linked issue,[16] in order to restrict emissions.

It should be noticed finally that the above analysis relies on the assumption that countries evaluate their participation or not in an agreement on emission paths, based on "objective" assessment of the global warming damages, and not on perceived assessments. If for example perceived damages are much lower than objective damages then the whole analysis needs to be carried out in a different framework.

5. Concluding Remarks

The purpose of the paper was to develop a framework for measuring costs and benefits associated with global warming on a disaggregated level and then explore the implications of the quantification of costs and benefits on choices of groups of countries to agree on specific paths of CO_2 emissions.

Benefit functions are estimated as long-run equilibrium relationships using cointegration methodology. We believe that this approach could provide reliable estimates of a long-run relationship between GDP and CO_2 emissions, including structural breaks and estimates of technical change, which is the relevant concept for analysing long-term problems such as global warming. Damage functions are differentiated among groups on the basis of the size of the group, discount rates and GDP growth. Benefits and damages are combined in order to provide simple decision rules about choices of emission paths. Considering two emission paths, stabilisation to 1990 levels and continuation of emissions at the prevailing rates, we combine a natural constraint, not exceeding 3^{o}C over an 100 year period for any set of emission paths for each group, with an economic requirement, choice of the action with the higher benefit cost ratio, in order to explore what type of agreement might prevail. It seems that if group 2 is properly compensated to agree to stabilise its emissions, the rest of the groups would find the stabilisation alternative attractive.

Of course the present analysis should be regarded as a first step in the attempt to quantify properly the issues related to global warming and international agreements. Damage function estimation on a disaggregated level can be improved by considering in more detail the size and the importance of the economic sectors which are affected by global warming, such as agricultural production, value of land lost due to the rise in sea level, cost of relocating people from affected areas and so on.

On the issue of the desirability of a certain type of agreement, more choices could be considered. The emission paths choices need not have constant or constantly growing emission paths, since this can be handled with the proper numerical simulations. Most importantly given the estimated benefit and damage functions, which in our case satisfy the concavity-convexity assumptions of economic theory, cooperative and non-cooperative solutions can be derived and issues of coalition stability can be explored on a sound empirical basis.

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ENDNOTES

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[1] CO_2 is not the only one of the so-called greenhouse gasses (GHGs); others are methane, nitrous oxide, chlorofluorocarbons (CFCs). However we focus on CO_2 since on the one hand it is the most important GHG, contributing approximately 80% to the global mean greenhouse forcing (Nordhaus 1991), and on the other CO_2 emissions are closely connected to combustion of fossil fuels, which is closely connected to economic activity (Halvorsen *et al.* 1989), and thus can be used as a generalised input in the aggregate benefit function for each country.

[2] In our approach benefits from CO_2 emissions are separable from the damages caused by these emissions. For an alternative approach where there is a feedback from climatic change to production, that affects multiplicatively the benefit function see Kverndokk (1993, 1994).

[3] The rest of the world is considered exogenous. This approach was taken because of severe problems in obtaining reliable series of data for the countries of Central and Eastern Europe and the countries of the former Soviet Union.

[4] A common currency, the international dollar, is used to make comparison possible across countries. In this international dollar currency, relative prices of individual goods are set at the average of relative prices for the same goods in all countries, and the level of prices is normalised so that the GDP of the USA is the same in international dollars as in American dollars.

[5] The following CO_2 emission coefficients were used:

	Natural gas	Liquids	Solids
Kt Carbon/Ktce	0.39934	0.57579	0.69653

[6] The method for estimating CO_2 emissions is consistent with the one used by Halvorsen *et al.* (1989) to obtain the CO_2 emissions for the period 1952-1986.

[7] Emissions due to deforestation should be added to the 5.4 GtC, bringing annual global emissions into the range of 6-7 GtC (Cline 1991).

[8] Regarding the ADF test Gregory *et al.* (1996) have shown that its power falls sharply in the presence of a structural break. So there is a case where the model is indeed cointegrated but there is a structural break in the cointegrating vector, and the standard ADF test may not reject the null hypothesis. In this case the researcher will falsely conclude that there is no long-run relationship, while in fact one exists (Gregory and Hansen 1996).

[9] An alternative approach would have been to treat the break as unknown and use the Gregory and Hansen (1996) approach to test for the null of cointegration and the timing of the break simultaneously.

[10] Atmospheric concentration is measured in the same units as emissions. The result is equivalent to measurement of the concentrations in parts per million (ppm) since 1gigaton of emissions can be transformed to ppm by multiplying by the coefficient 6.84/44.

[11] See Nordhaus (1982, 1991).

[12] See for example Hoel (1991) or Welsch (1993) for static approaches, or Dockner and Van Long (1993) or Xepapadeas (1995) for dynamic approaches.

[13] See Barrett (1990, 1991); Carraro and Siniscalco (1991, 1993); Hoel (1992); Petrakis and Xepapadeas (1996); Chander and Tulkens (1995).

[14] In a sense we consider that the damage function is adequately defined only locally with respect to temperature changes.

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[15] In all scenaria the rest of the world emissions including deforestation emissions are considered to increase at an exogenous rate of 1%.

[16] See Cesar and de Zeeuw (1996) for the analysis of the linkage of issues in international environmental agreements.

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(xv) Paper presented at the Human Capital and Mobility Program "Designing Economic Policy for Management of Natural Resources and the Environment" Second Workshop FEEM, GRETA, University of Crete, Venice, May 12-13, 1995

(xvi) Paper presented at the International Workshop on "The Political Economy of Economic Policy - The Organization of Government" European Science Foundation and Fondazione Eni Enrico Mattei, Castelgandolfo (Rome), September 5-10, 1995

(xvii) This paper was presented at the Workshop on "Corporate Governance and Property Rights" organized by the Corporate Governance Network and by Fondazione Eni Enrico Mattei, Milan, 16-17 June 1995

(xviii) This paper was presented at the International Workshop on "Creation and Transfer of Knowledge: Institutions and Incentives" organized by the Fondazione Eni Enrico Mattei and the Beijer International Institute of Ecological Economics, Castelgandolfo (Rome), September 21-23, 1995

(xix) This paper was presented at the International Workshop on "Environment and Transport in Economic Modelling" organized by the Department of Economics - Ca' Foscari University, Venice for the "Progetto Finalizzato Trasporti 2" CNR and in cooperation with Fondazione Eni Enrico Mattei, Venice, November 9-10, 1995

(xx) This paper was presented at the Conference on "Technology, Employment and Labour Markets" organized by the Athens University of Economics and Business and Fondazione Eni Enrico Mattei, Athens, May 16-18, 1996

(xxi) This paper was presented at the Conference on "Applications of Environmental Accounting", sponsored by the Fondazione Eni Enrico Mattei and the State Science and Technology Commission of the People's Republic of China, Beijing China, March 11-13, 1996

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