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ECONOMIC IMPACTS OF CARBON REDUCTION SCHEMES: SOME GENERAL EQUILIBRIUM ESTIMATES FROM A SIMPLE GLOBAL MODEL

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Abstract

The possibility that over the next decade or two a major global initiative will be adopted to reduce (or, at least, slow the rate of growth of) carbon emissions because of concerns over global warming is now taken sufficiently seriously for economists to study the consequences. Teh focus of most work thus far has been the global costs of such a measure, while noting the incentives, especially for smaller countries, to free ride. Typically, no explicit treatment of benefits is offered.

This paper presents preliminary results fom a computable general equilibrium model with a stylized treatment of preferences towards reduced global carbon use, and compares them with those from a corresponding model with no representation of benefits. Results suggest that the inclusion of the benefit sidca substantially affect the assessment of the welfare consequences of alternative global and unilateral carbon reduction initiatives.

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Over the last several years, expert bodies and international forums have issued various calls for dramatic cuts (of up to 50%) in carbon emissions over the next decades to reduce the severity of the greenhouse effect. The policies to be used to implement these cuts, however, have not usually been specified in such calls. And the effects of such cuts on resource allocation and income distribution have not usually been considered or assessed in any detail. These unknowns pose challenges to the economics profession. Policies to implement carbon reduction schemes must be designed, and the economic impacts of alternative policies assessed.

The purpose of this paper is to illustrate how applied general equilibrium (AGE) modelling can be used to explore the economic implications of policies directed towards controlling greenhouse, particularly carbon, emissions. The appeal of the AGE approach in this context lies in its ability to capture far reaching interactions and feedbacks that the implementation of carbon reduction initiatives of the severity proposed imply. More particularly, however, AGE models can handle simultaneously the effects of trade, tax policies, and quota type instruments; and can incorporate public goods. Policies aimed at curtailing carbon emissions will almost certainly take the form of restrictions on trade, or the imposition of taxes or quotas; the abatement (or reduction in the growth) of carbon emissions is by its nature a global public good. AGE models give economists an appropriate conceptual framework within which to analyze quantitatively the impact of carbon reduction policies.

The AGE approach will be exemplified here by a model originally due to Whalley and Wigle (1991), which has been extended in Piggott, Whalley and Wigle (PWW) (1991a). It should be noted that there are now a number of other AGE models constructed to analyse greenhouse policies (e.g., Jorgenson and Wilcoxen (1990), Nordhaus (1991), Perroni and Rutherford (1991), Burniaux et al. (1991)).

These and other modelling efforts are surveyed in Dean et al. (1990) and Winters (1991). Two important differences between the PWW model and many of the others are that, firstly, PWW have no dynamics in their model; and secondly, they give some representation to the benefits of carbon emission reduction. The elimination of dynamics is just a simplification: for our purposes, little is added by an explicit intertemporal specification. The representation of benefits in the model allows a variety of issues to be analysed which cannot be addressed in a model confined to the cost side.

Results reported in the present paper focus on national carbon taxes[1] (that is, taxes where the revenue is returned to the jurisdiction levying the tax). They suggest the following:

1. If national carbon taxes are introduced on a co-ordinated global basis, then the form of the tax (whether it is levied on consumption or production) plays a crucial role in determining the gainers and losers from such a policy.

2. If single regions undertake cuts in consumption or production, then other regions will face a change in world prices that lead them to increase their own consumption or production. The net global reduction in carbon emissions may be very small, and may even be negative.[2] This raises the question of whether unilateral action such as that undertaken by Sweden has any appreciable effect on global carbon emissions.

3. Terms-of-trade effects can be important in determining the overall outcome when one region cuts its consumption or production.

4. Inclusion of a representation of benefits has a substantial impact on the pattern of gainers and losers, and the extent of gain or loss.

2. A Numerical General Equilibrium Model for Analysing Carbon Reduction Initiatives

The model described here is originally due to Whalley and Wigle (1991), and has been extended by Piggott, Whalley and Wigle (1991a).[3] It incorporates trade, production, and consumption of both energy and non-energy products for a number of countries (or groups of countries) over a single forty-year projection period of 1990-2030,[4,5] which is treated for analytical convenience as a single period; i.e. the model incorporates no explicit dynamics. The model also does not incorporate existing taxes on energy products, although these vary by region, and would affect results. To further keep the model manageable, we do not identify fuel types within the broader category of carbon-based energy products, even though various elements within this category (oil, coal, natural gas) have different carbon content.

In the model, the world is divided into six regions, indicated in Table 1. These are the European Community, North America, Japan, other OECD, oil exporters (including all OPEC countries and major non-OPEC energy exporters), and a residual rest of the world, representing most developing countries (those who are not oil exporters) along with the centrally planned economies. Nested CES functions are used to represent production and demand in each region; the nesting structures are set out in Table 2. Each region is endowed with four non-traded primary factors: (i) primary factors, exclusive of energy resources; (ii) carbon-based energy resources (deposits of oil, gas and coal); (iii) other energy resources (hydro-electric and nuclear capacity); and (iv) sector-specific skills and equipment in the energy-intensive manufacturing sector. Both energy resources are treated as able to be converted into the relevant energy products through a refining/extraction process which uses other resources (primary factors). There are three internationally traded commodities: carbon-based energy products, energy-intensive manufactures, and other goods (all other GNP). Details of trade patterns are reported in Whalley and Wigle (1991). However, given the aggregation in the present model, direct trade in carbon-based energy products amounts to EC and JPN imports from the oil exporting region. Energy-intensive manufactures, other goods, and the composite energy product (carbon-based and non-carbon-based energy) enter final demands.

For each of the five produced goods in each region (listed in Table 1), production is represented by nested CES functions. Carbon-based and non-carbon-based energy products use the respective energy resources and primary factors. Non-carbon-based energy products are non-traded, since hydro-electric, solar and nuclear power are not traded in significant quantities between the regions as defined. A domestic energy composite is produced by a third (energy conversion) industry, using the two energy products as inputs. The two final goods (energy-

Table 1: Regions in the Global Equilibrium Model Used to Evaluate Incentives to Participate in Carbon Reduction Initiatives

1. EUROPEAN COMMUNITY (of the 12) [EC]*

2. NORTH AMERICA (U.S., Canada) [NAM]

3. JAPAN [JPN]

4. OTHER OECD [ODV]

   Austria, Switzerland, Finland, Iceland, Norway, Sweden, Australia, New Zealand

5. OIL EXPORTERS (OPEC countries, plus major non-OPEC exporters) [OEXP]

   Algeria, Libya, Nigeria, Tunisia, Mexico, Venezuela, Indonesia, Iran, Iraq, Kuwait, Saudi Arabia, United Arab Emirates

6. REST OF THE WORLD (Developing Countries and Centrally Planned Economies) [ROW]

   This is a residual category containing all other countries including USSR, Eastern Europe, China, Brazil, India, and other developing countries not in category 5.

* Abbreviations in square brackets are those used in the results tables to follow.

Table 2: Production and Demand Structures in the Global General Equilibrium Model Used to Evaluate Carbon Reduction Initiatives

A. Factors and Goods in Each Region

Endowments	Produced Goods
Carbon-Based Energy Resources (CR)	Carbon-Based Energy Products (CP)
Non-Carbon-Based Energy Resources (ER)	Non-Carbon-Based Energy Products (EP)
Sector-Specific Factors in Energy-Intensive Manufacturing (SF)	Composite Energy (E)
Other Primary Factors (PF)	Energy-Intensive Goods (EI)
	Other Goods (OG)

B. Structure of Production in Each Region
(CES* functions used at each stage; figures in parentheses give assumed elasticities of substitution)

Stage 1: Production of Energy Products

```
      PF     CR                        PF    ER
        \   /  (1.0)                     \  /  (1.0)
 CP      \ /  CO2 (0.0)                   EP
```

Stage 2: Production of Composite Energy

```
      CP    EP
        \  /  (1.0)
         E
```

Stage 3: Production of Energy-Intensive and Other Goods

```
      E     SF    PF          E     PF
       \    |    /  (0.7)      \   /  (0.7)
           EI                   OG
```

C. Structure of Final Demands
(Nested CES* functions used; figures in parenthesis give assumed elasticities of substitution)

```
        /  \  (1.0)
  CO2      GOODS
           / | \  (0.5)
         EI OG  E
```

* CES denotes "constant elasticity of substitution."

intensive manufactures and other goods) use primary factors and the composite domestic energy product as inputs. Perfect competition is assumed throughout in all regions and for all sectors.

For the two nontraded goods (non-carbon energy products and composite energy) there is domestic market clearing separately within each economy. Since prices in this system are treated as completely flexible, they will adjust to the levels required to clear the relevant international and domestic markets.

Counterfactual analyses with the model for any hypothesized policy change involve the computation of a new equilibrium model solution. Policy evaluation with the model is based on a comparison between counterfactual model solutions and the base data to which the model has been calibrated.

The base-case equilibrium solution for the model represents an assumed future evolution of the global economy over a forty-year period between 1990-2030. This is based on an assumption of continuing growth in OECD countries at annual rates reflecting the late 1980s, unchanged energy use, and consumption and production of other goods. Hicksian neutral (factor augmenting) growth is assumed to occur in each of the regions in the model at average annual rates reported in the 1989 World Development Report, which are assumed to apply over the entire period under consideration. The Oil Exporting region is assumed to grow at 2.5 percent, the Rest of the World at 2.7 percent, and the remaining regions at 2.3 percent. Each region's endowment of non-produced factors in the model thus reflects the present value of their resources (at constant prices) over the entire forty-year period. We assume that a 5 percent real discount rate applies for all years in the period considered in the model. The model is then solved to yield a forty-year base line solution representing an equilibrium in the world economy in the absence of any response to global warming over the period 1990-2030 (in discounted present value terms at 1990 prices, and in $US billion). Policy experiments are then evaluated relative to this base line, with a comparison of base and counterfactual equilibria.

The structure of the regional economies in the base data used in the model largely corresponds to data available for 1982, projected forward to 1990. Data for regional population and GNP in 1982 are obtained from the 1987 World Tables. Value-added, production and trade in energy-intensive manufactures (primary metals, glass, ceramics, and other basic manufactured products) are obtained from Nguyen et al. (1990). These are identified as those industries having the highest energy input requirements. Input ratios from Whalley and Wigle (1991) are used to infer energy input requirements for energy-intensive and other industries.

Production, consumption and trade in carbon-based energy products and non-carbon-based energy (for 1982) come from U.N. Energy Statistics. Raw data are in (metric) kilotons of coal equivalent. The carbon content of production and consumption for the regions in the model are determined using the same conversion coefficients as those in Whalley and Wigle (1991). To convert production data into value terms, we use price information from World Resources 1990-1991.

To incorporate the benefit side of slowed global warming, we have modified the preference functions for each of the regions identified in the earlier Whalley-Wigle model so as to include not only goods directly consumed, but also an argument reflecting the level of global carbon emissions. This, in effect, involves an additional nesting level within the utility function U_i, as depicted in Table 2. For each region, goods consumed, G_i, are region-specific, but the global CO_2 emission level is common to all regions. G_i is a composite of the goods identified in Table 2

i.e. $G_i = G_i(EI_i, OG_i, E_i)$. Hence, through each region's utility function, U_i externality effects associated with global warming are directly incorporated in the model.

$$U_i = U_i(G_i, CO_2) \qquad i=1,\dots 6 \qquad (1)$$

While this change in the model is conceptually straightforward, and parallels the analysis of public goods in the public finance literature (see Atkinson and Stiglitz (1979)), there are major problems with numerical specification of these preference functions in a model such as this. As is by now well-known, there are no widely agreed estimates as to how large or small the benefits from a slowing global warming are. There are suggestions, such as those by Nordhaus (1991) and Schelling (1991), that the benefits of slowing global warming are likely to be quite small. Nordhaus puts these at no more than three-quarters of one percent of GDP for the United States over a seventy-five year period, whereas Schelling suggests that these are so imperceptibly small and likely to take place over such a long period of time (say, seventy-five years) that they would be little noticed by most individuals. On the other hand, economists such as Cline (1991) have argued that with a possible sextupling in levels of atmospheric carbon dioxide by the end of the next century, the potential costs are so large that some emission reduction should be undertaken immediately. He emphasizes how most debate on the global warming has focused on the consequences of a doubling of atmospheric CO_2 by the middle of the next century, for which temperature rise could be modest, rather than on the larger increases in CO_2 content which would follow out into the next century and for which the consequences are potentially more alarming.

At this point, the sum of marginals benefits from CO_2 reduction is equal to marginal cost. Regional marginal valuations of CO_2 emissions are determined by

assuming that the income elasticity of demand for CO_2 abatement is 1.5, and by taking into account regional population levels in 1990.

Our specification of preferences towards global warming would undoubtedly be more convincing if there were a clearer consensus on the size of possible benefits from slowing global warming on the demand side. At the same time, the profile of the policy debate on the issue is such that it still seems worthwhile to make calculations based on various assumptions, even if these are sometimes strong.

Our procedure is to assume that calls for emission reductions voiced at various international conferences are consistent with a global optimal allocation on a full participatory basis if they were implemented. Taking this as our reference point, we evaluate the incentives for regions or countries to participate in various arrangements. The call for emission reductions emerging from the 1988 Toronto conference of a 20 percent emission reduction by the year 2005, and a 50 percent emission reduction to follow to stabilize CO_2 content provides the basis for our preference parameterization; namely, that a 50 percent carbon emission reduction by all regions corresponds to a global full participation global externality correcting intervention. Using this strong assumption we are then able to analyze what the incentives are for various countries to participate in reduction initiatives of different forms.

The parameterization of this extended version of the Whalley-Wigle model is based on standard calibration (see Mansur and Whalley 1984), with the preference parameters towards climate change being correspondingly generated. Counterfactual analysis then allows us to compute new equilibria under carbon emission reductions of various forms, given various assumptions as to what form of region participation is involved.

3. Results

In this paper, various model results are reported which are intended to illustrate the application of an applied general equilibrium model to the global warming issue.

We have used the model to evaluate possible international incidence, trade, and welfare effects which would follow the introduction of alternative carbon tax schemes. The results that follow evaluate a target of a 50 percent cut in carbon emissions relative to the base line model solution over the period 1990-2030. This target is met either by all countries simultaneously, or by a single country (or region) acting unilaterally. The policy instrument used is in all cases a national carbon tax (or taxes), levied on either consumption or production. A 50 percent cut in emissions from the base line is on the high side of the range of targets currently used by other modellers evaluating carbon tax proposals, but corresponds approximately to that called for in the 1988 Toronto Conference statement.

In all our model runs, we endogenously determine the ad valorem carbon tax rate, which, in this structure, applies to all fuels at the same rate. However, the rate may vary somewhat across regions.

The carbon tax variants we consider are as follows:

1. **Production-based carbon taxes collected by national governments. The emission target assumed is a 50 percent reduction in each region's production of carbon-based energy. Under this scheme, tax rates will vary by region.**
2. **Consumption taxes collected by national governments. The emission target assumed is a 50 percent reduction in each region's consumption of carbon-based energy. Under this scheme, tax rates will vary by region.**

These tax schemes are each evaluated using the general equilibrium model in counterfactual mode. The model is first calibrated to reproduce the original (benchmark) data as a base line equilibrium solution over the period 1990-2030, and with no policy changes in effect. The model is then re-solved with a carbon tax in place. The impacts of any of the tax schemes are determined by comparing the original (benchmark), and the new (or counterfactual) equilibria.

The left panel of Table 3 reports our estimates of the gains or losses for the regions identified in the model under each of the tax options, when they are undertaken on a co-ordinated global basis, that is, with all regions fully participating. The welfare measures capture the combined gains or losses to regions from the production and sale of carbon-based products, as well as the consumption side gains associated with price changes. They also capture the economy-wide effects of energy price changes as they feed through the model. In the model variant in which the benefits from carbon emission reduction are captured, the value of the benefits are included in the results.

The right side of Table 3 reports some trade impacts flowing from the implementation of these policies. While the trade patterns of all three traded goods in the model change substantially with the introduction of globally co-ordinated carbon taxes, the direction of trade also alters in a number of cases for energy intensive goods. These changes in direction are reported, together with the terms-of-trade index.

Table 3: Welfare and Trade Effects of a Global Scheme of National Carbon Taxes to Implement a 50% Cut in Carbon Emissions

Region		WELFARE EFFECTS (BASE = 100)		TRADE EFFECTS	
		Model Variant with No Representation of Benefits from Carbon Reduction	Model Variant with Benefits from Carbon Reduction Incorporated	Direction of Trade in Energy Intensive Goods	Terms-of-Trade Index (Laspeyres) (Base = 100)
EC	Production tax	96.1	103.0	Export _ Import	46
	Consumption tax	99.0	104.0	Export _ Import	433
NAM	Production tax	95.7	102.9	Export _ Import	45
	Consumption tax	96.5	103.2	Export _ Import	428
JPN	Production tax	96.4	103.1	Export _ Import	46
	Consumption tax	100.6	104.6	Export _ Import	435
ODV	Production tax	97.7	103.6	No change	84
	Consumption tax	98.0	103.7	No change	127
OPEC	Production tax	104.4	105.9	No change	221
	Consumption tax	81.2	96.1	Import _ Export	23
ROW	Production tax	92.9	100.2	Import _ Export	71
	Consumption tax	93.3	100.4	Import _ Export	125
WORLD	Production tax	95.6	102.3		
•	Consumption tax	95.6	102.3		

• Percentage change in sums of money-metric utilities

As can be seen from Table 3, the implications of a globally co-ordinated initiative of this kind are large. Consider first the welfare impacts generated by a model variant in which the benefits of reduced carbon emissions have not been incorporated. World welfare is estimate to have fallen by 3.4 percent as a result of these taxes.

While the world welfare change is approximately the same under production and consumption based taxes, effects by region differ dramatically. North America loses 3.5 percent of income under a national consumption tax, while the ROW loses 7 percent of income under such a tax. Oil exporters gain substantially from a national production-based tax, while they lose dramatically from a national consumption-based tax.

These results, therefore, strongly underline the point we emphasize above; namely, that the form any carbon tax takes will have major implications for the international incidence effects of the tax. Under a national production-based tax, energy producers collect tax revenues; hence oil exporters gain. Under a national consumption tax, oil importers collect revenues, and hence Europe gains, North America loses only marginally, while oil exporters lose.

The welfare losses we have been discussing are in model terms the costs of introducing a distortion, or distortions, into an otherwise undistorted competitive market system. The policy proposal itself, however, is motivated by concerns that there is market failure in the form of an externality, in that carbon emissions, while imposing an economic cost, are not priced. It is possible to interpret carbon tax proposals as alternative formulations of a Pigovion tax, designed to correct this market failure. Given the parameterization procedures on the benefit side outlined in section 2, a single-rate tax which reduced carbon emissions by 50 percent globally, would indeed be a perfect example of such a tax in the model variant in

which the benefits of carbon emission reductions have been introduced. In this model variant, such a tax, instead of introducing a distortion, would be removing a distortion, and world welfare would rise rather than fall.

The taxes considered in this paper are not exactly of this form, since each region is required to meet the 50 percent reduction target, and the tax rates required to achieve this will vary across regions. But they are fairly close to such a tax. So, it is to be expected that world welfare will rise under such a policy, as reported in Table 3.

It is, however, of greater interest to note that, with one exception, all regions gain from both these reduction initiatives. The exception is that oil exporting nations lose from a globally co-ordinated consumption tax. This results from the dramatic terms-of-trade loss experienced by the oil exporters under such a policy. The significant net benefits accruing globally from such a cut reflect the falling marginal benefit schedule from emission reductions (given the preferences), and the rising marginal cost schedule of reductions (due to emission reduction interventions of increasing severity).

We now turn to trade effects, reported on the right side of Table 3. Here we emphasize those cases where the direction of trade changes, and report the terms-of-trade index change. Both Europe and Japan become net importers of energy-intensive products, where previously they were net exporters. A change also occurs for oil exporters from a net import to a net export position.

The dramatic terms-of-trade changes reflect principally changes in the price of carbon fuels. They serve to emphasize the different international incidence impacts of production and consumption based taxes. However, it should be remembered that pre-intervention quantity weights are used in the calculation of these indices, and that carbon energy production and consumption in the new equilibrium is only half its baseline value.

Table 4 reports the welfare and terms-of-trade effects of national production taxes designed to unilaterally cut production in a single region by 50 percent. The model variant with the benefit side incorporated is used here, and in all subsequentresults. Unilateral cuts of 50 percent involve losses by the regions making such cuts, except for NAM. North America, the costs of reducing energy production are relatively low because of the high productivity of mobile

Table 4: Welfare and Terms-of-trade Effects of Unilateral Production Tax Policies to Cut Carbon Emissions by 50% (Base = 100)

Region	50% National Cuts By					
	EC	NAM	JPN	ODV	OEXP	ROW
			WELFARE EFFECTS			
EC	99.9	100.7	100.0	100.1	100.6	101.4
NAM	100.2	100.0	100.0	100.1	100.7	101.7
JPN	100.2	100.6	100.0	100.1	100.5	101.3
ODV	100.2	100.8	100.0	99.7	100.7	101.7
OEXP	100.5	101.8	100.0	100.2	98.0	104.3
ROW	100.2	100.6	100.0	100.1	100.5	99.1
WORLD*	100.2	100.6	100.0	100.1	100.4	101.0
			Terms-of-trade EFFECTS			
	EC	NAM	JPN	ODV	OEXP	ROW
EC	97.3	90.5	99.9	99.1	91.9	79.5
NAM	97.3	90.4	99.9	99.1	91.8	79.3
JPN	97.3	90.6	99.9	99.1	92.0	79.6
ODV	99.6	98.4	100.0	99.9	98.7	96.1
OEXP	102.8	110.6	100.1	100.1	108.9	126.2
ROW	99.0	96.4	100.0	99.7	96.9	91.6

* Percentage change in sum of regional money-metric utilities

Table 5: Impacts on Global Carbon Emissions of National Tax Policies to Cut Emissions by 50% (Base = 100)

by	Unilateral cuts with no restraint by other regions		Unilateral cuts with other regions constrained to baseline levels	
	Production cuts	Consumption cuts	Production cuts	Consumption cuts
EC	97.4	98.0	96.4	92.9
NAM	91.1	96.0	88.1	86.9
JPN	100.0	99.4	99.9	97.8
ODV	99.2	99.7	98.8	98.8
OEXP	92.6	99.6	89.8	97.3
ROW	81.5	91.6	76.8	76.1

factors of production elsewhere in the economy, while their high marginal valuation of the benefits of reduced global carbon use result in benefits outweighing costs.[6] Unilateral cuts also benefit all other regions. But the benefits come not only from shared benefits in emission reductions of the country or region making the cuts, but also from terms-of-trade and other effects. Regions cutting production allow other regions to increase production, as well as raising the world price of energy so as to benefit other energy exporters.

The lower part of Table 4 reports the terms-of-trade changes for all regions associated with unilateral production cuts. In all cases, the movements are strongest for the oil exporters, whose terms of trade improve in every case. In corresponding simulations involving consumption taxes (not reported here), the converse result occurs.

The results of Table 4 suggest that the net impact on global carbon emissions of unilateral cuts might be much less than the reduction in emissions by the region undertaking the cut, because changes in world prices resulting from the unilateral cut induce other regions to increase their production or consumption. This issue is investigated further in Table 5. Reductions in global carbon emissions from unilateral 50 percent production and consumption cuts are reported, and compared with the percentage global reduction which would have been achieved had other regions not changed their production or consumption levels. The results clearly show substantial production and consumption spillovers take place.[7]

4. Conclusion

This paper has attempted to illustrate how applied general equilibrium (AGE) models may be used to shed light on the economic impacts of policies designed to curtail global warming. Using a model originally developed by Whalley and Wigle (1990, 1991), and subsequently extended by Piggott, Whalley and Wigle (1991a,b), the impacts of policies designed to implement a 50 percent cut in carbon emissions are investigated.

We stress that in considering major policy initiatives of this kind, it is essential to adopt a technique that is able to capture the interactions and feedbacks between industries and regions that would occur were such policies actually implemented. Applied general equilibrium (AGE) models are able to do this, and in addition are able to focus on relevant aspects of trade and taxation policy, and to incorporate public goods, of which slowed global warming is an example.

Results reported in the paper focus on national carbon taxes. They indicate that the base of the tax (production or consumption) is crucial in determining regional welfare changes, but less important in the determination of global welfare change. Where unilateral cuts in production or consumption are undertaken, other regions will tend to respond by increasing their production or consumption, so that the net impact on global carbon emissions may be much smaller than the cut. Terms-of-trade effects can also be important in determining the pattern of welfare gains and losses resulting from such carbon reduction initiatives.

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ENDNOTES

1 For an analysis of global taxes, and detailed discussion of international carbon tax incidence, see Whalley and Wigle (1991).

2 The possibility that carbon emission reduction in one region may actually increase global emissions arises because the carbon efficiency of production techniques may vary across regions. In the present model, there are no systematic regional variations in carbon efficiency, and the negative result does not occur.

3 See also the presentation in Whalley and Wigle (1990) for earlier calculations made using an even more simplified version of this model.

4 This has been chosen somewhat arbitrarily to capture the initial period and subsequent intermediate term during which a carbon tax would have its largest effects, since with discounting the significance in present value terms of later-year effects recedes. It is relatively easy to run the model for a longer projection period (say, 80 or 100 years), and were this done we believe that the main themes of our results would remain.

5 A weakness of this 40-year projection period approach is that in the base year data used for these projections, most carbon energy trade takes place in oil rather than in other carbon-based fuels. If, as some expect, trade in oil is slowly replaced by trade in coal into the next century, the data used here may be misleading since the countries who are potential future coal exporters (U.S.S.R, Australia, China) are quite different from current oil exporters (OPEC countries, Mexico).

6 Although 50 percent unilateral cuts are generally losing propositions for the region undertaking the cut, substantial unilateral cuts can lead to welfare gains, especially for the wealthier regions. Piggott et al. (1991b) explore this issue in greater detail.

7 This issue is investigated in more detail by Piggott, et al. (1991a).

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