Free Trade and Global Warming:

A Trade Theory View of the Kyoto Protocol

January, 2001

Brian R. Copeland and M. Scott Taylor

Abstract: This paper demonstrates how several important results in environmental economics, true under mild conditions in closed economies, are false or need serious amendment in a world with international trade in goods. Since the results we highlight have framed much of the ongoing discussion and research on the Kyoto protocol, our viewpoint from trade theory suggests a re-examination may be in order. Specifically, we demonstrate that in an open trading world, but not in a closed economy setting: (1) unilateral emission reductions by the rich North can create self-interested emission reductions by the unconstrained poor South; (2) simple rules for allocating emission reductions across countries (such as uniform reductions) may well be efficient even if international trade in emission permits is not allowed; and (3) when international emission permit trade does occur it may make both participants in the trade worse off and increase global emissions.

Copeland: Department of Economics, University of British Columbia,
997-1873 East Mall, Vancouver, B.C. Canada V6T 1Z1
Tel: 604-822-8215; email: copeland@econ.ubc.ca

Taylor: Department of Economics, University of Wisconsin-Madison,
6448 Social Science bldg. 1180 Observatory Dr., Madison, WI, 53706.
Tel: 608-263-2515; email: staylor@ssc.wisc.edu; web: www.ssc.wisc.edu/~staylor/

Acknowledgments: We have received many helpful comments from participants in seminars at Florida International University, University of Illinois, University of Michigan, Southern Methodist University, University of Wisconsin, UC Santa Barbara, UC Santa Cruz, the NBER Summer Institute (1999), and the ESF International Dimension of Environmental Policy workshop (2000). We also gratefully acknowledge grants from the SSHRC (Copeland) and the NSF, WAGE, and IES (Taylor).

1. Introduction

Although the debate over global warming has been very contentious, there is widespread agreement among economists on the basic principles underlying the design of an effective treaty reducing greenhouse gas emissions. Every textbook on environmental economics points out that rigid rules such as uniform reductions in emissions will be inefficient because marginal abatement costs will vary across sources. Therefore, since carbon emissions are a uniformly mixed pollutant, standard analysis suggests that introducing free trade in emission permits will minimize global abatement costs and yield benefits to both buyers and sellers. And without universal participation in the treaty, it is expected that any agreement to reduce emissions will be undermined by the free rider problem as those countries outside the agreement increase their emissions in response to the cutbacks of others.

These principles are not controversial because they follow quite naturally from well-known theoretical results in environmental and public economics. The purpose of this paper is to demonstrate that while these results are true in a closed economy under mild conditions, they are either false or need serious amendment in a world of open trading nations. Since the results we highlight have framed much of the ongoing discussion and research on international environmental agreements in general, and on the Kyoto protocol in particular, our new viewpoint from trade theory suggests a re-examination may be in order.[1]

Specifically, we show that in an open trading world, *but not in a closed economy setting*: unilateral emission reductions by a set of rich Northern countries can create self-interested emission reductions by the unconstrained poor Southern countries; trade in emission permits may not be necessary for the equalization of marginal abatement costs across countries; rigid rules for emission cutbacks may well be efficient; countries holding large

[1] For a summary of the Kyoto protocol and the estimated economic impacts on the U.S. see the U.S. Administration's Economic Analysis (July 1998). Included is a list of countries pledged to cut emissions (by an average of 5%), the likely cost to the U.S. (.1% of GDP), and the time frame for the cuts (2008-2012). Recent developments in the negotiations can be found at: www.unfccc.de .

shares of emission permits may have virtually no market power in the permit market; and emission permit trading may make both participants to the trade worse off and increase global pollution. Every one of these results is inimical to conventional theory in this area.

We develop these results in a perfectly competitive general equilibrium trade model that allows for pollution. The model is static, productive factors are in inelastic supply, and emissions are a global public bad. In short, the model is deliberately conventional.

The model has three key features. First, we allow for a large number of countries that differ in their endowments of human capital. This is to rule out results that follow only from either the smallness of numbers, or the symmetry of the set-up. For some of the analysis we group these countries into an aggregate North (subject to emission limits and composed of both Eastern and Western countries) and an aggregate South (not subject to limits). West is the most human capital abundant and South the least.

Second, we allow for both trade in goods and emission permits across countries. Because one of the primary concerns in the developed world is the competitiveness consequence of a unilateral reduction in emissions, we need to address these concerns within a model allowing for goods trade. And finally, since environmental quality is a normal good, we allow for an interaction between real income levels and environmental policy. This link is important in that it generates an endogenous distribution of willingness to pay for emission reductions that will differ across countries, and allows for trading interactions to give rise to further feedback effects on emissions levels.

Within this context, we start by providing a simple decomposition of a country’s best response to a change in rest-of-world emissions into a free-riding effect, carbon leakage (a substitution effect), and "bootstrapping" (an income effect). Although this decomposition is relatively easy to obtain, it is novel to the literature. Using this decomposition, we investigate whether unilateral emission reductions by one group of countries will lead to emission increases elsewhere. The almost universal assumption in the literature is that home and rest-of-world emissions are strategic substitutes, and indeed this is true under mild conditions in our model in autarky. But we show that in an open economy, home and foreign emissions may well be strategic complements. That is, leadership by one group of countries in lowering emissions may create endogenous and self-interested emissions reductions in unconstrained countries.[2] International trade fundamentally alters the strategic interaction among countries over emission levels.

Next, we show how a wide range of treaty-imposed emission reduction rules (such as uniform reductions across countries) can yield a globally efficient allocation of abatement when there is free trade in goods. Such rules are almost never efficient in autarky. This result implies that with free trade in goods, there are an infinite number of ways to cut back on emissions efficiently, whereas in autarky there was but one. Consequently, negotiations can alter the initial allocation of permits to meet distributional concerns, to ensure participation of reluctant countries, or to satisfy political constraints. Free trade in goods will then ensure an efficient allocation of abatement, and when this occurs, we show how free trade in goods eliminates market power (at the margin) in the permit market.

Finally, when trade in goods alone cannot equalize marginal abatement costs, we show that while permit trade can play a role in minimizing the global costs of emission cutbacks, it also brings consequences not present in autarky. We illustrate how the welfare effects of permit trade now depend not only on the direct gains from permit trade, but also on the induced change in the world terms of trade for goods, and on any resulting change in emission levels in the unconstrained countries. We then demonstrate that these additional terms can be important. For example, we show that even if a permit-buying region receives all of the direct benefits of permit trade by buying permits at the seller's reservation price, the buyer may still lose from

[2] Much criticism has been leveled at the Kyoto protocol because of its failure to include significant developing country participation. For example, the U.S. Senate's Byrd-Hagel resolution requires developing countries commit to emission limits before the Senate ratifies the Kyoto protocol. Much of the analysis of the Kyoto protocol, however, fails to properly account for both income and substitution effects and how they might affect the policy response in LDCs. The income effects may be particularly important because of the very long time horizons relevant to the global warming problem.

the resulting terms of trade deterioration. As well, permit trade between two regions can lead to a terms of trade deterioration for both the buyer and seller and may raise emission levels in unconstrained countries, harming both parties to the permit trade. We have no wish to argue against emission permit trade. Our sole purpose is to demonstrate that the positive and normative consequences of emission permit trade differ greatly in open and closed economies.

The literature on global pollution abatement has proceeded in several directions. First are a large number of studies that employ computable general equilibrium models to examine the impact of unilateral or multilateral cuts on emission levels, GDP and consumption. [Jorgenson and Wilcoxen (1993), Whalley and Wigle (1991a,b), Perroni and Rutherford (1993), Ellerman et al. (1998) and Edmonds et al. (1999)]. These studies typically assume environmental policy is fixed.[3] This rules out an interaction between environmental policy, real income levels and relative prices. CGE simulations do, however, typically cover vast stretches of time over which the per capita incomes of developing countries will likely quadruple. As a result, their per capita income levels will easily exceed those of some countries already committed to emission limits. Consequently, our approach that explicitly allows for endogenous policy may provide a useful complement to these earlier analyses.[4]

In addition, CGE models in this literature typically offer a very detailed model of the energy sector, but a relatively restrictive model of trading interactions. This approach is very useful in highlighting the importance of substitutability between fuel types in the adjustment to emission reductions, but it has tended to make almost invisible the role international trade can play in meeting abatement targets. One way to meet an emissions target is to substitute among fuel types for a given slate of domestic production. Another method is to alter the mix of

[3] An exception is Perroni and Wigle (1994) but they are not concerned with global warming.

[4] Recent empirical work by Grossman and Krueger (1993, 1995), Antweiler et. al (1998) and others are highly suggestive of a strong link between income and the demand for environmental quality. In fact there is a strong cross-country link between the cuts agreed to in the Kyoto protocol and per capita income levels. See figure 1 in Frankel (1999). Each 1% increase in per capita income is associated with a 0.1% greater emission reduction from business as usual.

domestic production by substituting towards goods with a lower energy intensity and importing energy intensive goods from countries with less binding emission constraints.[5] It is exactly this margin of adjustment that generates a tendency towards equalizing marginal abatement costs worldwide via goods trade alone.

Authors in the public economics and environmental economics literature have also considered some of the issues we address but typically within models containing one private good, one public good, and no international trade [Hoel (1991), Barrett (1994), Welsch (1995), and Carraro and Siniscalco (1998)]. This literature highlights the strategic interaction among nations, the possibility of coalition formation, and the extent of free riding. However, given the absence of goods trade in these models, there are no linkages via world product markets to allow for goods trade to equalize marginal abatement costs. And as well, without goods trade, there are no terms of trade effects. As we show, this then implicitly imposes the assumption that domestic and foreign emissions are strategic substitutes, and it also rules out the possibility that terms of trade effects may undermine the direct benefits of permit trade.

Finally, there is a small literature in international trade examining the links between trading regimes and environmental outcomes but much of this literature ignores the induced policy responses that trade may create, and has not focused on the interaction between goods trade and trade in emission permits. Copeland and Taylor (1995) do allow for income-induced policy responses, but focus on the strategic interaction between rich and poor countries in the move from autarky to free trade in goods.[6]

---

[5] The key here is that researchers have typically focused their attention on disaggregating the energy sector of their model and thereby created numerous new specific factors via this disaggregation. Less emphasis has been placed on adding more international markets for goods, resources or capital. A consequence of this procedure is that the role trade can play in adjustments is reduced by assumption, and the importance of within-country substitution across energy types virtually assured. Very recent CGE work, as evidenced by the Energy Journal's (2000) special Kyoto issue, exhibits the same tendency.

[6] There is also the influential work of William Nordhaus on the optimal level and timing of emission cutbacks. Our results on free-riding, permit trade and the efficiency of cutbacks should be relevant, regardless of the precise timing or magnitude of the emission cutbacks. For the views of Nordhaus on the timing and scope of Kyoto cutbacks see Nordhaus and Boyer (2000).

While our results are in most cases significant departures from the conventional wisdom in both public and environmental economics, we owe a large intellectual debt to earlier work in trade theory. Some of our results echo classic results in the trade literature where terms of trade effects lead to surprising results when capital is mobile across countries. Important antecedents include Markusen and Melvin (1979), Brecher and Choudri (1982), and Grossman (1984). Since emissions are a factor in variable supply (unlike the fixed world capital stock in these models), and emissions are a global public bad (again unlike capital), the positive and normative consequences we find are, however, quite different. As well, while the mechanism responsible for equalizing marginal abatement costs across countries is simple and classic – it is present in the work of Samuelson (1949) on factor price equalization and Mundell (1957) on the substitutability of factor movements for goods trade – its role in maintaining production efficiency along a carbon reduction trajectory is novel.

The rest of the paper proceeds as follows. Section 2 sets out the basic model. Section 3 considers autarky and illustrates free-riding. Section 4 examines the impact of unilateral reductions and introduces both carbon leakage and bootstrapping. Section 5 considers whether cutbacks will lead to different marginal abatement costs across countries, while section 6 deals with trade in emission permits. Section 7 integrates our results from sections 4-6 to present our overall view from a trade theory perspective. Section 8 sums up our work.

2. The Model

We adapt a standard 2 good, 2 factor, K-country general equilibrium trade model to incorporate pollution emissions. Pollution is treated as a pure global public bad that lowers utility but has no deleterious effects on production. There are two goods, X and Y, and one primary factor, human capital (h) which is inelastically supplied. Endowments of human capital vary across countries, but tastes and technologies are identical across countries.[7]

[7] Introducing North-South differences in technology will have little impact on our results.

Pollution emissions are modeled as a productive factor in elastic supply. Although emissions are an undesirable joint product of output, our treatment is equivalent if there exists an abatement technology that consumes economic resources.[8] The strictly concave, constant returns to scale technologies are given by:

$$X = f(h_x, z_x) \qquad Y = g(h_y, z_y) \tag{1}$$

where h_i represents human capital allocated to industry i, z_i denotes emissions generated by industry i, f and g are increasing in both h and z, and z and h are essential for production. We assume that X (the dirty good) is always more pollution intensive than Y (the clean good). We let the clean good be the numeraire and denote the price of X by p.

Tastes over private goods are assumed to be quasiconcave, homothetic and weakly separable across the set of private goods and the public bad - emissions. Weak separability is a common assumption in the public economics literature as is homotheticity in the trade literature. Given homotheticity, we can without loss of generality represent tastes across private goods with a linearly homogenous sub-utility function denoted $q(x,y)$. Utility of the representative consumer in country k is then given by

$$u^k = u(q(x,y), Z), \tag{2}$$

where $Z = \sum_{k=1}^{K} z^k$ is world emissions and u is strictly increasing and strictly quasi-concave in q and $-Z$. We assume that X and Y are both essential goods in consumption.

Private sector behavior

Governments move first and set national pollution quotas. Pollution targets in any country are implemented with a marketable permit system: the government of country "k" issues z^k pollution permits, each of which allows a local firm to emit one unit of pollution. Permits are auctioned off to firms, and all revenues are redistributed lump sum to consumers.

---

[8] For example if pollution is proportional to output, but factors can be allocated to abating pollution, then (under certain regularity conditions) we can invert the abatement production function and write output as a function of pollution emissions and total factor use. See the appendix of Copeland and Taylor (1994).

We denote the market price of pollution permits by τ.

Given goods prices *p*, and the government's allocation of pollution permits, profit-maximizing firms maximize the value of national income and, hence, implicitly solve:

$$G(p,h,z) = \max_{x,y}\{pX + Y:\ (X,Y) \in \Theta(h,z)\}$$

where $\Theta(h,z)$ is the strictly convex technology set. $G(p,h,z)$ has all the standard properties of a national income function (See Woodland [1982], Dixit and Norman [1980]). It is increasing in *p*, *h* and *z*; convex in prices; concave in factor endowments (*h* and *z*); and linearly homogenous in both factor endowments and product prices. For given prices, *p*, the value of a pollution permit can be obtained as:

$$\tau = \partial G(p,h,z) / \partial z \equiv G_z \tag{3}$$

which represents the private sector's demand for pollution emissions. Output supplies can be obtained by differentiating with respect to product prices.

Consumers maximize utility given prices and pollution levels. Let I^k denote national income of country k. Then the indirect utility function corresponding to (2) for a representative consumer in country k is given by

$$u^k = u(I^k / \Phi(p^k), Z) \equiv u(R^k, Z) \tag{4}$$

where $\Phi(p)$ is the true price index for the private goods and $R = I/\Phi(p)$ represents "real income". Since national income is given by *G*, we can write the real income function as:

$$R(p,h,z) = \frac{G(p,h,z)}{\Phi(p)}. \tag{5}$$

The benefits of assuming separability and homotheticity are now apparent. The government's problem in choosing pollution is simplified to trading off increases in real income *R* against a worsened environment *Z*.

3. Autarky

We abstract from income distribution issues and assume that governments adopt policies that are in the best interests of their representative citizen. This allows for a direct comparison between our results and those in the existing public and environmental economics literature. We consider a non-cooperative Nash equilibrium where each government chooses its pollution target z^k to maximize the utility of its representative consumer, treating pollution in the rest of the world as fixed. For a typical country k, the problem becomes:

$$\max_{z_k} \; \{u(R^k + T, Z) : R^k = G(p^k, h^k, z^k) / \Phi(p^k),\; Z = Z_{-k} + z^k\} \tag{6}$$

where Z_{-k} is pollution from the rest of the world**,** and where for future reference, we have allowed for the possibility of an exogenous lump sum transfer T (measured in real income) to country k from the rest of the world.

The first order condition for this problem is given by:

$$u_R R_z + u_R R_p p_z + u_z = 0. \tag{7}$$

We can simplify this by noting that

$$R_p = \left(G_p - \Phi_p G / \Phi\right) / \Phi = -m / \Phi, \tag{8}$$

where m denotes net imports of the dirty good. Since in autarky, imports are zero, (7) can be rewritten as:

$$R_Z = - u_Z / u_R \equiv MD(R + T, Z) \tag{9}$$

which simply requires that the marginal benefit of polluting (the increase in real income generated by allowing firms to pollute more) be equal to the marginal damage from polluting in terms of real income (the marginal rate of substitution between environmental damage and real income). We denote marginal damage by the function MD.

An illuminating representation of (9) can obtained by using (3) and (5):

$$\tau = -u_z / u_I,$$

where u_Z/u_I is marginal damage measured in terms of the numeraire good. That is, we obtain the standard result that the government chooses the level of pollution emissions so that the equilibrium permit price is equal to the marginal damage from polluting.

The optimum is illustrated in Figure 1. Real income is on the vertical axis and world emissions on the horizontal axis. Indifference curves slope upward since emissions are

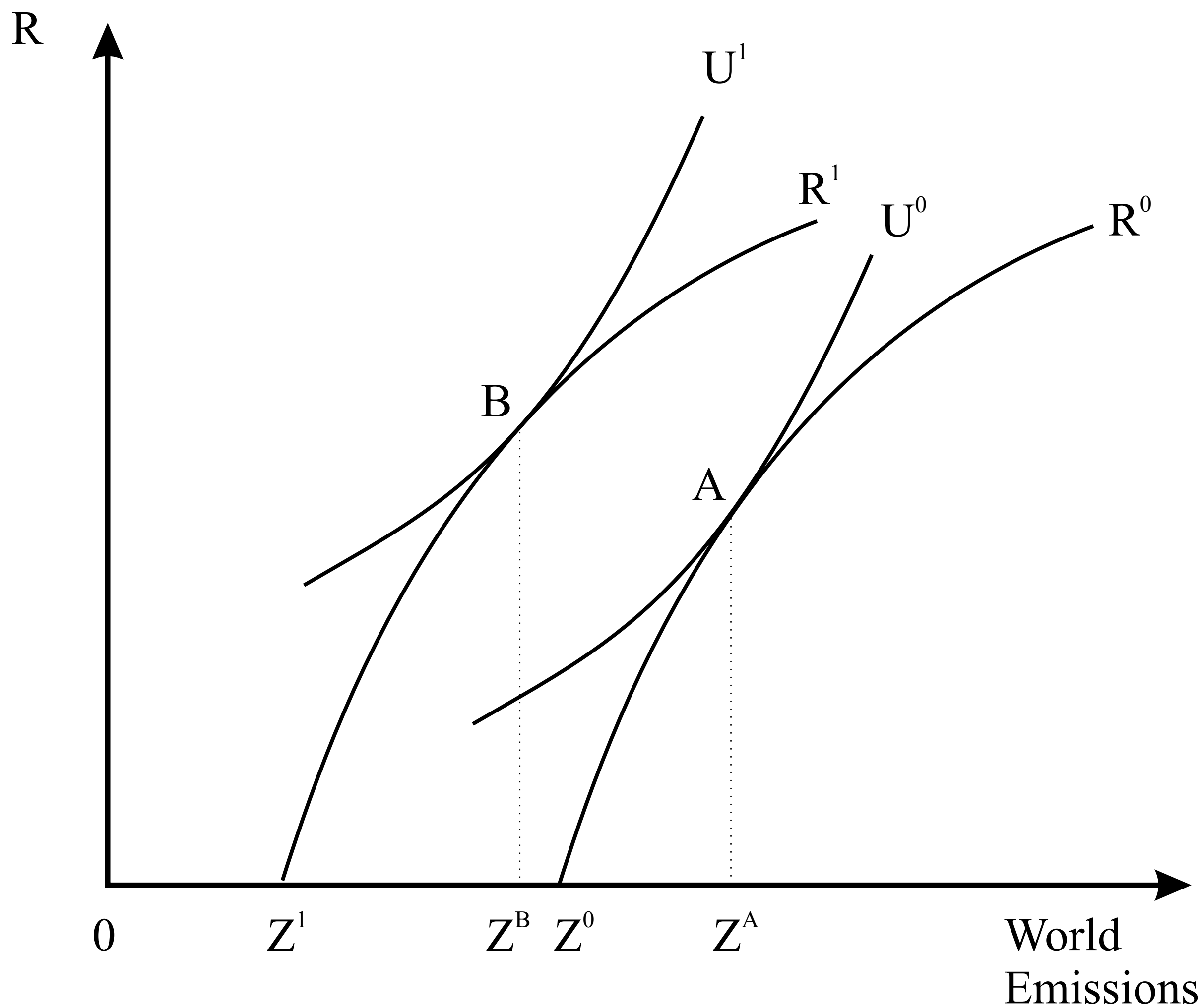

Figure 1.
Domestic response to foreign
emission reductions in autarky

harmful, and they are convex since the utility function is quasi-concave. To plot real income as a function of world emissions, note that if country k does not pollute at all, then world emissions are Z^o, and at this point country k real income is zero, since we have assumed that emissions are an unavoidable aspect of production. As country k increases its emissions, real income begins to rise, yielding the concave function R^o as illustrated (concavity is proven in the appendix). Consequently the domestic optimum is at point A, where the indifference curve is tangent to the income constraint. This corresponds to condition (9). World emissions at this point are Z^A, with domestic emissions given by the gap $z^k = Z^A - Z^o$.

Free Riding

We can now examine country k's response to changes in rest-of-world emissions. Starting from an initial optimum at A, a fall in rest-of-world emissions shifts country k's real income frontier to the left as shown. The slope of the real income frontier is unaffected and the economy moves to B where country k emits more, but total world emissions have fallen.[9]

Proposition 1. Suppose there is no international trade. If the environment is a normal good, domestic and foreign emissions are strategic substitutes; that is, any country's best response to rest-of-world emissions is negatively sloped. Nevertheless, unilateral emission reductions in one or more countries lead to a fall in global pollution.

Proof: See appendix.

The intuition behind the result is straightforward. Rest-of-world emission reductions create a welfare gain for country k, and consumers will want to allocate some of this gain to private goods consumption. To do this, country k's regulators translate the gift of a cleaner environment into real goods by emitting more pollution. This is the free rider effect in Fig. 1.

[9] For a similar result within a partial equilibrium setting see Chapter 6 of Cornes and Sandler (1996).

4. Free Riding, Carbon Leakage and Bootstrapping

We now turn to the effects of emission reductions in the presence of international trade. Much of the discussion of the role of goods trade in the Kyoto protocol concerns the impact of emission cutbacks on carbon leakage. Carbon leakage occurs when non-participant countries increase their dirty goods production (and emissions) in response to price effects created by cutbacks elsewhere. A commonly cited estimate is that carbon leakage will offset 25% of the original cut in Annex I countries. This suggests that unilateral emission cutbacks in an open economy must then be doubly deleterious, as both free-riding and carbon leakage would combine to raise emissions elsewhere. For example, one prominent researcher in this area, Scott Barrett, sums up the prevailing view this way:

> "Free-riding will be exacerbated by a different but related problem: leakage. If a group of countries reduce their emissions, world prices will change. Comparative advantage in the pollution-intensive industries will shift to the non-participating countries. These countries will thus increase their output-and increase their emissions, too – as a direct consequence of the abatement undertaken by participating countries. An effective climate change agreement must plug this leak." (Barrett, 1997)

In this section, we show that once we examine the full implications of both endogenous policy (which is necessary for free riding) and endogenous world prices (which is necessary for carbon leakage), there is an additional substitution effect and an additional income effect that were unaccounted for in conventional analyses. Once we factor these new motives into our calculus, the strategic interaction between countries becomes far richer.

We begin by decomposing the impact of a fall in rest-of-world emissions on country k emissions into three effects: free-riding, carbon leakage, and bootstrapping. The first order condition for emissions in free trade has the same form as (7), with p interpreted as the world price. Assuming that country k is a price taker in world markets, we have $p_z = 0$, and hence (7) reduces to (9).[10] Although the conditions determining pollution in trade and autarky have the

[10] A small country has no incentive to manipulate its terms of trade via emissions choice, but retains its incentive to control emissions in general. This is because its marginal impact on world prices is a function

same form, note that goods prices are determined by domestic demand and supply in autarky, but by the rest of the world in free trade. Hence the solution to its optimization problem (6) in free trade can be written as

$$z^k = z^k(Z_{-k}, p, T).$$

That is, the domestic country's optimal emissions level depends on rest-of world emissions, goods prices p, and any income transfers T. To determine the effect of a change in rest-of-world emissions, we differentiate with respect to Z_{-k} to obtain:

$$\frac{dz^k}{dZ_{-k}} = \frac{\partial z^k}{\partial Z_{-k}} + \frac{\partial z^k}{\partial p}\frac{dp}{dZ_{-k}}. \tag{10}$$

As well as the direct strategic effect ($\partial z^k/\partial Z_{-k}$), which we analyzed in autarky, there is also the impact of the change in world goods prices induced by the change in rest-of-world emissions, captured by the second term above. The price change term, in turn, can be decomposed into substitution and income effects; and using this in (10) yields our decomposition:

Proposition 2. In free trade, country k's best response to a cut in rest-of-world emissions reflects the relative strength of free-riding, carbon leakage and bootstrapping effects:

$$\frac{dz^k}{dZ_{-k}} = \frac{\partial z^k}{\partial Z_{-k}} + \left[\left.\frac{\partial z^k}{\partial p}\right|_u - \frac{\partial z^k}{\partial T}\, m / \Phi(p)\right]\frac{dp}{dZ_{-k}}. \tag{11}$$

Proof: See Appendix.

We refer to the first term on the right hand side of (11) as the free rider effect, and the next two terms as the carbon leakage and bootstrapping effects, respectively. We illustrate them with the aid of Figure 2, which assumes that country k is a dirty good exporter. Initially world emissions are Z^o. The corresponding real income frontier is $R(p^o,Z^o)$ and the initial domestic

of its share of world output (which is vanishingly small), while the marginal cost of extra emissions depends on the total quantity of world emissions (since this determines marginal damage). A proof of this result, within a specific context, is given in Copeland and Taylor (1995) (see footnote 25 in particular).

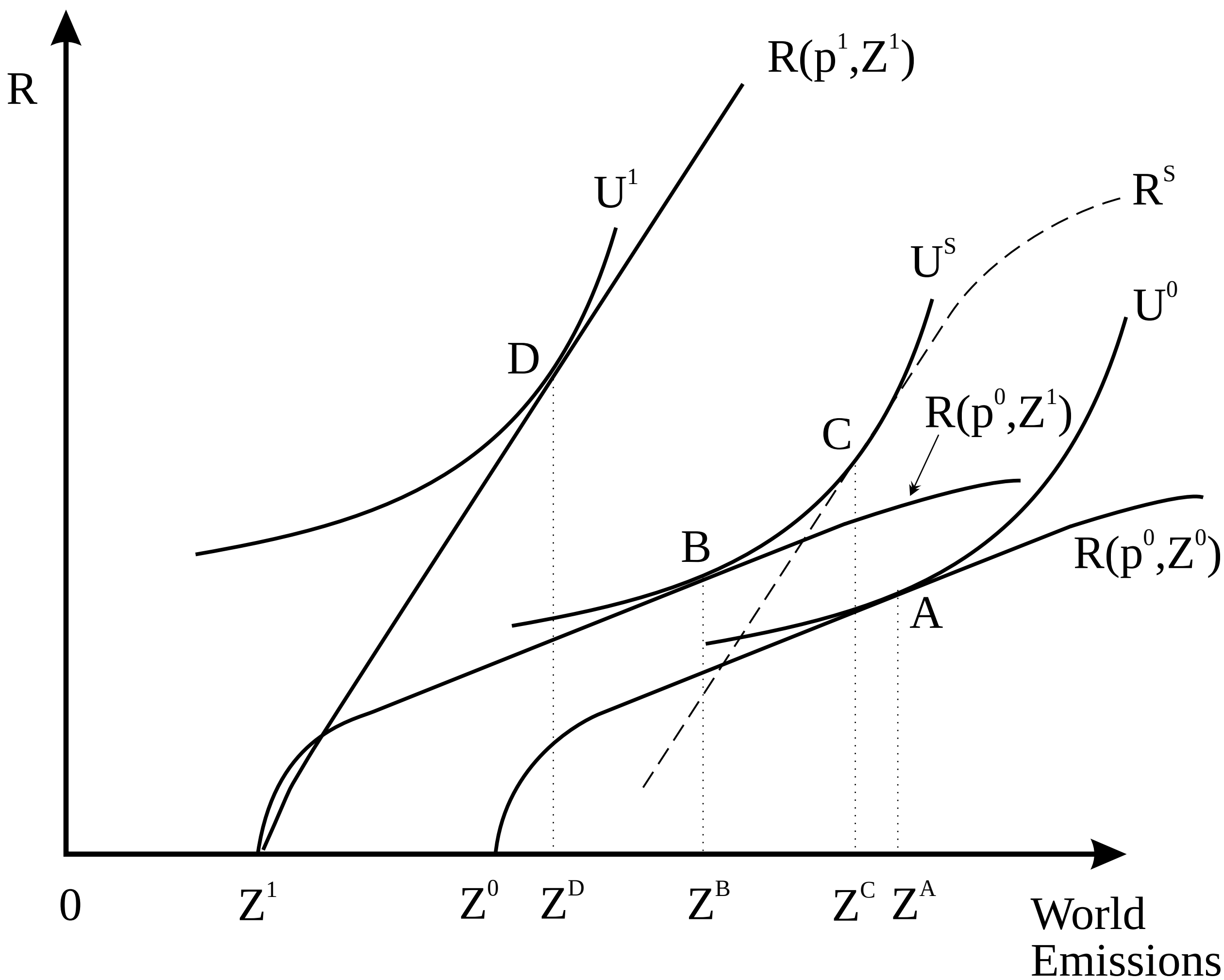

Figure 2.
Domestic response to foreign
emission reductions in an open economy

optimum at point A.[11] A reduction in rest-of-world emissions to Z^1 in free trade both shifts the real income frontier to the left and change its slope (as we explain below), yielding the new real income frontier $R(p^1,Z^1)$ and a new domestic optimum at point D.

The free rider effect is the pure strategic effect of the foreign emission reduction, holding the world price *p* constant, and is illustrated in Figure 2 as the movement from A to B. If we hold the world price *p* fixed, the fall in foreign emissions from Z^o to Z^1 shifts the real income frontier to the left from $R(p^o,Z^o)$ to $R(p^o,Z^1)$. Along this frontier, home chooses B, which corresponds to an increase in its emissions (since $z^k{}_B = Z^B - Z^1 > Z^A - Z^o = z^k{}_A$). To sign this effect, differentiate (9) with respect to Z_{-k}, holding p constant, to obtain:

$$\frac{\partial z^k}{\partial Z_{-k}} = -\frac{MD_z}{\Delta} < 0, \qquad (12)$$

where $\Delta = MD_Z + MD_R R_Z - R_{ZZ} > 0$. As in autarky, the free-rider effect raises emissions.

Next, consider the price change induced by the foreign emission reduction. An increase in the price of the dirty good makes the real income frontier steeper for a dirty good exporter, yielding the new frontier $R(p^1,Z^1)$.[12] We define carbon leakage as the pure substitution effect of this price change. To isolate carbon leakage, we take the new frontier, and eliminate the real income gain due to the price change by shifting the frontier vertically downward until we obtain the hypothetical (thin dashed-line) frontier R^S which is tangent to the indifference curve U^S at point C.[13] The movement along the indifference curve from B to C is the pure substitution effect of the price change: this is carbon leakage. In Fig. 2, carbon leakage yields $Z^C - Z^B$ additional units of emissions. To solve for this effect, differentiate (9)

---

11 In free trade, the real income frontier is still concave, but contains a linear segment. This corresponds to the range of emission levels for which the economy is fully diversified and produces both goods. The slope of the real income frontier is given by $R_Z = \tau/\Phi(p)$. If both goods are produced, factor prices (w,τ) are completely determined by the zero profit conditions: $c^x(w,\tau)=p$ and $c^y(w,\tau)=1$; and so τ does not vary with z if a country is small. When emissions z are either very high or very low the economy specializes in either X or Y, and the real income frontier becomes strictly concave because of diminishing returns.

12 Real income rises for a dirty good exporter and falls for a dirty good importer, and so the new real income frontier must intersect the old one, as illustrated (since the country is a dirty good importer for low z^k and a dirty good exporter for high z^k).

13 We have only drawn the upper part of this frontier to avoid clutter.

with respect to p, holding utility constant:[14]

$$\left.\frac{\partial z^k}{\partial p}\right|_u = \frac{R_{zp}}{\Delta} = \frac{\tau}{p\Delta\Phi}[\varepsilon_{\tau p} - \theta_{x^c}], \quad (13)$$

where $\varepsilon_{\tau p} = pG_{zp}/\tau$ is the elasticity of producer demand for emissions τ with respect to p, and $\theta_{x^c} = px^c/G < 1$ is the share of spending on X. The two terms in (13) reflect substitution effects in production and consumption, respectively. In general, either effect can dominate.

Finally, the price change that created carbon leakage also raises real income for a dirty good exporter. The pure income effect of the price change is the movement from C to D: this is what we call bootstrapping. Because environmental quality is a normal good, country k emissions must fall via the income effect (from Z^C to Z^D in Fig. 2) and we have:

$$-\frac{\partial z^k}{\partial T}\, m / \Phi(p) = \frac{MD_R}{\Delta} m / \Phi(p) < 0 \quad \text{if } m < 0. \quad (14)$$

Conversely, for a dirty good importer ($m > 0$), an increase in the price of the dirty good lowers real income, and the bootstrapping effect tends to increase emissions.

Combining the three terms in (11), it is clear that country k's response to a rest-of-world emission reduction is ambiguous in trade, whereas it was unambiguously positive in autarky. The reason is simply that the same change in world prices that creates a substitution effect on the production side also creates an income effect (bootstrapping) and a substitution effect on the consumption side as well. As a result, it is possible in trade – but not in autarky – that South may lower emissions in the face of unilateral Northern cuts.

Conditions for Strategic Complements

Notice that in Figure 2, the domestic country's emissions have fallen in response to the foreign cutback since domestic emissions are $z^k{}_D = Z^D - Z^1 < Z^A - Z^o = z^k{}_A$. To determine when this can occur, we compare the strength of the three effects:[15]

---

[14] We allow for a hypothetical change in income to ensure consumers stay on the same indifference curve.

[15] Cornes and Sandler (1996, ch. 8) demonstrates that with an impure public good and sufficient complementarity between the public good and one of the private goods, an agent may view others

Proposition 3. With free trade in goods, if foreign emission cutbacks raise the price of the dirty good, then country k will view rest-of-world emissions as a strategic complement if

$$\left(\theta_x \varepsilon_{MD,R} + \theta_{x^c}\right) | \varepsilon_{p,z_{-k}} | > \varepsilon_{\tau p} | \varepsilon_{p,z_{-k}} | + \varepsilon_{MD,z} , \qquad \text{(C1)}$$

where $\varepsilon_{MD,z} \geq 0$ and $\varepsilon_{MD,R} > 0$ are the elasticities of marginal damage with respect to emissions and real income, respectively; $\theta_X = - pm/G$ is the share of exports of X in income (this is negative if X is imported); and $\varepsilon_{p,z_{-k}} < 0$ is the elasticity of the price of the dirty good with respect to a change in rest-of-world emissions.

Proof: Follows from (11).

To understand what (C1) requires, consider a dirty good exporter. The combined income and substitution effect in the demand for environmental quality created by the change in world prices is captured by the left side of (C1). The income effect is clear; the substitution effect arises because as *p* rises, consumers would like to substitute towards the cheaper good (environmental quality). The government responds by tightening environmental policy and reducing emissions. The strength of this substitution effect depends on the share of the dirty good in consumption spending ($\theta_{X^c} < 1$). Working against these forces is the right side of (C1). This is composed of a producer substitution effect reflecting the shift in producers' demand for emissions when the price of the dirty good rises, $\varepsilon_{\tau p}$, and the free rider effect.

Note that the substitution effect in production and consumption always work against each other, but as long as the dirty good is produced, the producer effect dominates because $\varepsilon_{\tau p} \geq 1$.[16] Hence $\varepsilon_{\tau p} > \theta_{X^c}$ and the net marginal benefit of polluting rises with an increase in

---

contributions to the public good as a strategic complement. Our result here is entirely different: the public good (the environment) and other goods are substitutes, and trade introduces asymmetries across agents so that some agents view contributions by others as strategic substitutes while others view them as strategic complements.

[16] If the economy is diversified, then $\varepsilon_{\tau p} > 1$ follows from the magnification effect of the Stolper-Samuelson theorem (see Jones, 1965). If the economy is specialized in X, then $\varepsilon_{\tau p} = 1$.

the price of the dirty good. This leads the domestic country to substitute towards more emissions and this is why we refer to this combined substitution effect as carbon leakage.[17] If instead the economy is specialized in the clean good, then there is no substitution effect on the producer side, the consumption effect dominates and the net marginal benefit of polluting falls with an increase in the price of dirty goods. In this case, carbon leakage is negative.

Therefore it is apparent that whether emissions rise or fall depends on both the magnitude of the various elasticities, and also the pattern of production and trade. For a diversified or specialized dirty good exporter, income effects must be significant for emissions to fall. For a specialized dirty good importer, income effects must be *small* for emissions to fall. To see this, consider the case where country k is specialized in production and marginal damage is insensitive to changes in aggregate emissions (i.e., $MD_Z = 0$). Then we have:

Corollary 3.1. Suppose country k is specialized in producing only one good in trade, marginal damage does not vary with emissions (i.e., $MD_Z = 0$), and a rest-of-world cutback raises the world price of the dirty good, $dp/dZ_{-k} < 0$. Then:

(i) if $m(\varepsilon_{MD,R} - 1) < 0$, country k and rest-of-world emissions are strategic complements;

(ii) if $m(\varepsilon_{MD,R} - 1) > 0$, country k and rest-of-world emissions are strategic substitutes.

With $MD_Z = 0$, there is no free rider effect. For a dirty good exporter ($m < 0$) specialized in X production, domestic and foreign emissions are strategic complements if the income elasticity of marginal damage with respect to emissions is greater than 1. In contrast, for a dirty good importer specialized in clean good production, domestic and foreign emissions are strategic complements if the income elasticity of marginal damage with respect to emissions is *less* than 1. This is because if the country is specialized in clean good production,

[17] Definitions of carbon leakage differ across papers. In models with exogenous policy only the producer substitution effect is operative and this alone would represent carbon leakage.

then as discussed above, carbon leakage tends to reduce emissions. And if the income effect is weak, then carbon leakage dominates bootstrapping, and emissions fall in response to the foreign cutback. In this case, domestic and foreign emissions are also strategic complements, but for entirely different reasons than for a dirty good exporter.

Therefore while Figure 2 shows how dirty good exporters may reduce emissions because of strong income effects, the key to the possibility of strategic complements is that international markets create asymmetries across countries that did not exist in autarky. This is reflected in the fact that the sign of net imports, m, appears in the results above. Consequently, whenever cutbacks affect world prices, international trade will introduce striking possibilities not present in autarky. For example, if income effects are strong and if South is a dirty good exporter, then when North cuts unilaterally, South benefits from a positive terms of trade effect. If (C1) holds, Southern emissions will fall. In contrast, under these same conditions, if South cuts emissions, then North suffers from a terms of trade loss and raises its emissions. In this case, the asymmetry introduced by a natural trading pattern suggests that the North can play an important leadership role in emission reductions.

While the strength of these endogenous policy responses is unclear, it is important to recognize that free-riding is itself an endogenous policy response. And while the slow graduation of developing countries into the emission-cutting Annex I group may seem unlikely at present, it is unwise to rule out such possibilities *a priori* especially when the policy experiment under consideration involves extremely large time horizons and potentially large changes in income. At the very least, the inclusion of the additional substitution effect in consumption always works to dampen potential increases in emissions in unconstrained countries, while bootstrapping in turn dampens carbon leakage in dirty good exporters.

5. Emission Reductions and Efficiency

International environmental agreements often exhibit rigid burden-sharing formulas such as equiproportionate reductions in pollutants. This feature is present in the Kyoto

Protocol where industrialized countries face roughly similar percentage reductions in emissions. An almost universal critique of these agreements by economists is that emission cutbacks following rigid rules are not cost minimizing. For example, one prominent researcher in this area, Michael Hoel, sums up the prevailing view this way:

> "International cooperation often takes the form of an agreement among cooperating countries to cut back on emissions by some uniform percentage compared with a specific base year. However, it is well-known from environmental economics that equal percentage reductions of emissions from different sources produces an inefficient outcome because the same environmental goals can be achieved at lower costs through a different distribution of emission reductions...This is true whether 'sources' are interpreted as different firms or consumers within a country, or as different countries...Uniform percentage reductions are therefore not a cost-efficient way to achieve our environmental goal." (Hoel, 1991, pp. 94-95)

In this section we demonstrate that the equiproportionate rule and many other rigid rules will often be efficient in a world with free international trade in goods, even if there is no provision for international trade in emission permits. In contrast, such rules are almost never efficient in autarky. Therefore, free trade in goods makes it much easier to design an international environmental treaty leading to an efficient allocation of abatement globally.

Autarky

We start by demonstrating the inefficiency of such rules in autarky. Suppose there is a binding global treaty fixing total global emissions. Since all countries are by assumption part of the global treaty, this effectively eliminates the unconstrained South from our analysis. To proceed, we divide the constrained countries into two regions: East and West. East and West are each composed of any number of identical countries, with regions differing in only their levels of human capital.[18] West has greater human capital than East and we indicate Eastern variables with an asterisk (*) when necessary. Our main result in this section is that if there is no free

---

[18] The case with K heterogeneous countries is algebraically intensive and leads to no new insights. When we consider permit trade in the next section, we will reintroduce the unconstrained South.

trade in goods, then arbitrary allocations of permits across countries will almost always yield an outcome below the Pareto frontier.

We first find the Pareto frontier. To find the set of efficient permit allocations in autarky, a planner chooses the allocation of permits across countries, and uses international lump sum transfers to satisfy distributional concerns. For any weight λ on West's utility, the planner solves:

$$\max_{z,T}\left\{\lambda u\left(\frac{I}{\Phi(p)},Z\right)+(1-\lambda)u^*\left(\frac{I^*}{\Phi(p^*)},Z\right)\right. \qquad (15)$$
$$\left. s.t.\ Z=z+z^*,\ \ I=G(p,h,z)-T,\ I^*=G^*(p^*,h^*,z^*)+T\right\}$$

where 0 < λ < 1. The first order conditions for this problem imply:

$$\lambda\frac{\partial u}{\partial I}=(1-\lambda)\frac{\partial u^*}{\partial I^*} \qquad (16)$$

$$\frac{\partial G(p,h,z)}{\partial z}=\frac{\partial G(p^*,h^*,z^*)}{\partial z^*} \qquad (17)$$

The first condition, (16), requires equalization of the shadow value of income across regions given the weights placed on each region's welfare. The second condition requires that general equilibrium marginal abatement costs be equalized across regions.[19]

Figure 3 illustrates the efficient allocation of total emissions *Z* (ignore for the moment the dashed lines MAC^T and MAC^{*T}). We have normalized the width of the graph to 1, and plotted the marginal abatement cost curves from (17); these autarky curves are labelled MAC^A and MAC^{*A}. The intersection of these curves at B determines the efficient shares of emissions allocated to West (S^B), and East ($1-S^B$).

Given our assumptions on preferences and technology, the intersection at B is unique, and moreover, because *G* is homogeneous of degree 1 in (*h*,*z*) we can write (17) as

$$\frac{\partial G(p,h/z,1)}{\partial z}=\frac{\partial G(p^*,h^*/z^*,1)}{\partial z^*} \qquad (18)$$

[19] Recall ∂G/∂z is the general equilibrium demand for emissions – or in the parlance of environmental economics, the marginal abatement cost. These first order conditions are sufficient given the concavity of the objective function and also render unique solutions under standard conditions.

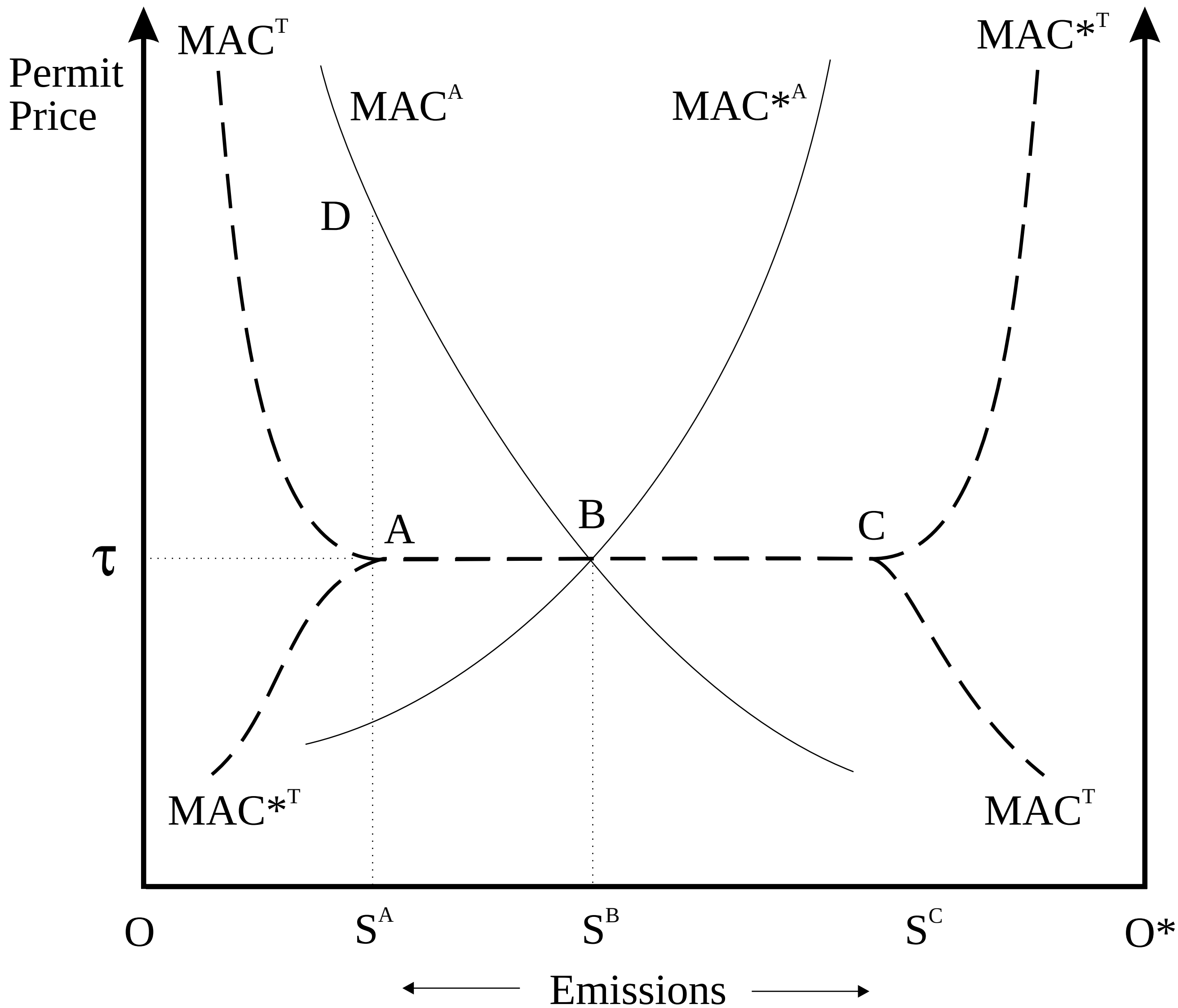

Figure 3.
Marginal abatement cost curves
and efficiency

The solution to (18) requires identical relative factor supplies ($h/z = h^*/z^*$) across regions. To see this, note that since we have identical homothetic tastes over consumption goods and identical technologies, then if $h/z = h^*/z^*$, goods prices are the same across regions ($p=p^*$); and hence $h/z = h^*/z^*$ must solve (18). Thus we conclude that for efficiency, West's share of permits $S(Z)$ must be equal to its share of human capital:

$$S(Z) = \frac{h}{h + h^*} \tag{19}$$

What is striking about this rule is that for any level of world emissions Z, there is only one efficient allocation of emissions across countries, regardless of the weight λ placed on West in the solution to the planner's problem (15). Efficiency requires that we distribute permits to ensure that countries are at most scalar multiples of each other. Movements along the Pareto frontier require adjustments in lump sum transfers alone. Any attempt to address distributional issues by reallocating emission permits will be inefficient. To sum up, we have

Proposition 4. Suppose that preferences and technology satisfy (1) and (2), and that there is no trade in goods or pollution permits. Then there is only a single emission reduction path $S(Z)$ which is efficient. Along this path, each country's share of emission permits must equal its share of human capital.

Proof: See appendix.

Proposition 4 establishes that unless emissions are originally allocated so that regions are identical up to a scaling factor and cutbacks maintain this condition, then global abatement costs will not be minimized as cutbacks proceed. If lump sum transfers and international permit trading are ruled out, West and East must make equity/efficiency tradeoffs when they decide on permit allocations and hence are unlikely to end up on the efficient path.

Free Trade in Goods and Marginal Abatement Cost Equalization

With free trade in goods, the situation is radically different: there are *infinitely many* efficient emission reduction paths. Even if lump sum transfers and emission permit trading are unavailable, arbitrary rules for allocating rights across countries may well be efficient.

To understand this result, suppose we start at point B in Figure 3 and introduce free trade in goods. Since relative factor endowments were equal at B, opening up to trade will have no effect.[20] Point B was efficient in autarky and is efficient in free trade as well. Now suppose we move to the left of point B in Fig. 3 and allocate a slightly smaller share of the world's emission rights to the West. In autarky, this was not efficient because we moved down East's marginal abatement cost curve and up West's. In trade this new allocation is efficient.

To demonstrate this result, assume for the moment that goods prices p are unaffected by this reallocation of permits across regions. Then both before and after the reallocation of emission rights, factor prices τ and w in both West and East are fully determined by the zero profit conditions.[21] Consequently emission permit prices are unaffected by the reallocation of permits across countries. Instead, the entire burden of the adjustment falls on the composition of output in West and East and not in the price of emissions. West absorbs the extra permits by increasing clean good production and reducing dirty good production, and thereby begins to export the clean good. East does the reverse. But since both regions employ the same techniques of production, West's production expansion in Y (and contraction in X), must exactly mirror changes in the East. Consequently, world supply of both goods is unaffected.

On the demand side, a reallocation of permits from West to East raises income in the West and reduces it in the East. But because preferences are identical and homothetic,[22] demand will be unaffected by the reallocation of permits. Since neither world demand nor world supply is affected by the reallocation of permits, equilibrium goods prices are unaffected, and hence by our argument above, permit prices do not change.

---

[20] Autarky goods prices are equalized when $h/z = h^*/z^*$, and there is no incentive to trade at point B.

[21] See footnote 11.

[22] The assumption of identical homothetic preferences simplifies the exposition here. But it is not necessary to ensure that a continuum of allocations of permits will be efficient.

This means that marginal abatement cost curves in free trade (given by the dashed lines MAC^T and MAC^{*T} in Fig. 3) each have flat segments which overlap. Consequently movements to the left or right of B do not disturb the equality of emission permit prices across countries and so production efficiency is maintained. This argument will work for any reallocation of permits between the two regions as long as each region continues to produce both goods. For very skewed allocations of permits, at least one region will specialize in production and permit prices are no longer tied down by goods prices. Once this occurs, then permit prices will differ across regions and marginal abatement cost curves are no longer flat and diverge, as illustrated.

We conclude that there is a continuum of efficient allocations between regions, that is:

Proposition 5. Suppose preferences and technology satisfy (1) and (2), X is always strictly more pollution intensive than Y, and there is free international trade in goods but not in pollution permits. Then there are infinitely many emission reduction paths $S(Z)$ that are efficient.

Proof: See appendix.

A simple example highlighting the difference between free trade and autarky arises if elasticities of substitution are unity in both production and consumption. In autarky, uniform reductions in emissions are never efficient unless regions are identical up to a scaling factor. In contrast, if there is free trade in goods, uniform reductions in emissions are *always* efficient whenever we start from an equilibrium with diversified production.

Proposition 6. Assume elasticities of substitution are unity in both production and consumption. If there is free trade in goods but no international trade in emission permits then equiproportionate reductions is always an efficient path starting from any allocation where both goods are produced in each country.

Proof: See Appendix.

Propositions 4-6 and the analysis in Fig. 3 are important in several respects. First, they demonstrate that even without trade in emission permits, a treaty implementing rigid emission allocations across countries can obtain a globally efficient allocation of abatement.

Second, reallocations of permits and lump sum transfers can be perfect substitutes along the range S^AS^C in Fig. 3. For example, suppose West is given a share of permits S^B in Fig. 3, and there are no lump sum transfers. This yields some utilities U in the West and U^* in the East. This same distribution of utilities can be implemented by giving West any share of permits in the range (S^BS^C) to the right of point S^B and requiring a lump sum transfer from West to East. Or West could be given a smaller share of permits and in return for a transfer from the East. This gives countries a great deal of flexibility in implementing emission reduction agreements. If the political process focuses on choosing emission allocation rules that seem "fair", then they also have a good chance of being efficient as well.

Third, our results indicate that the costs of cutbacks depend critically on the role that international trade in goods can play in diffusing the costs of abatement across countries. As an example, referring to Figure 3, suppose West reduces emissions from S^B to S^A. If adjustment via trade in goods is not taken into account, then conventional measures of abatement cost would yield the area BDS^AS^B under the autarkic marginal abatement cost curve. If instead international trade in goods can play a major role in diffusing the costs of cutbacks across countries, West's abatement would cost the much smaller area BAS^AS^B under the perfectly elastic free trade marginal abatement cost curve. We highlight this point below:

Corollary 5.1. Consider a small open economy facing fixed goods prices and with technology given by (1). Then as long as the economy is diversified in production, the marginal abatement cost curve is infinitely elastic.

Proof: Follows from the proof of Prop. 5. The marginal abatement cost is equal to the permit price, which is determined independently of the level of emissions by the zero profit conditions.

That is, although the marginal abatement cost curve slopes down in autarky, it is flat in free trade: the adjustment to changes in the level of allowable emissions takes place via output changes and not via factor price changes. Although this result may seem surprising, it is consistent with recent evidence on the adjustment of economies to changes in factor supplies. Empirical work suggests that a surprising amount of adjustment to factor supply shocks in open economies occurs through changes in the composition of output and not factor prices.[23]

Our results in this section can also be useful in interpreting the wide variance in the estimates presented in the CGE literature.[24] Missing from this literature is an appreciation for how large an impact different assumptions on tradability can be to the ultimate results. For example, Manne and Richels (1991) use the GLOBAL-2100 model which appears to have no trade in final goods across regions. They find enormous differences across countries in the carbon tax implied by cutbacks (because everyone moves up their old autarky demand curve) and equally enormous losses in GDP. In contrast, Whalley and Wigle (1991a) adopt a trade model with two final and homogenous (across countries) goods. They find almost no variance in carbon taxes across countries because trade patterns adjust greatly. While much emphasis has been placed on obtaining better elasticity estimates and disaggregating the energy sector of these models, virtually no attention has been paid to the importance of assumptions made on the relative number of international versus domestic markets. This key factor determines the

---

[23] This is far from a settled empirical question, and much empirical work in this area is ongoing. However, some evidence supports such an adjustment mechanism. Card (1990) in his study of the Mariel Boatlift found that an immigration-induced increase of 7% in the Miami labour market had virtually no effect on wages. Card and Dinardo (2000) conclude that the labour markets absorb immigrants primarily via output changes and not by wage changes.

[24] The editors of the special Kyoto issue of the Energy Journal, warn “the reader is cautioned not to view the wide range of model results here as an expression of hapless ignorance on the part of analysts, but a manifestation of the uncertainties inherent…”, p. viii, special Kyoto Issue, Energy Journal (2000)

extent of linkage between trading economies, and has a strong bearing on the results we ultimately find.

Our result on marginal abatement cost equalization has one further implication. Free trade in goods undermines market power in the emission permit market. That is:

Proposition 7. Consider any allocation of permits between two large regions West and East that generates emission permit trade in autarky. Then, starting from a free permit-trade equilibrium, both West and East can gain by manipulating the permit market via small changes in their emission permit purchases or sales. If instead there is free trade in goods, and the original allocation of permits between West and East lies anywhere in the interior of S^AS^C in Figure 3, then, starting from a free permit-trade equilibrium, neither West nor East can gain via small changes in their permit purchases or sales.

Proof: See appendix.

The first part of Proposition 7 generalizes the influential result of Hahn (1984) to a general equilibrium setting. Hahn showed that a dominant firm could exploit its monopoly or monopsony power in the permit market by reducing its permit trading below the competitive level and preventing marginal abatement costs from being equated across firms. As a result, an efficient allocation of abatement costs cannot be attained with an arbitrary initial allocation of permits. In our simple general equilibrium model, a large region has an incentive to behave in exactly the same way as Hahn's dominant firm. Thus, without free goods trade, concerns about market power in the permit market are justified.

Once we introduce free trade in goods, the ability of a large country to manipulate the permit market is severely constrained. To understand the intuition for this result, recall that if there is no goods trade and West reduces its imports of permits, then the supply of permits rises in the East. This pushes down East's price of dirty goods and puts downward pressure on the permit price, benefiting the permit-importing West. In contrast, if West reduces its permit imports when there is free trade in goods, then the ensuing increase in dirty good production in East is simply exported to West, and no goods price decline occurs (neither goods supply or demand is affected). Consequently, there is no downward pressure on the permit price. That is, competition via free trade in the goods market prevents both goods and permit prices from changing.[25]

6. Permit Trade

We now consider situations where free trade in goods is not enough to equalize marginal abatement costs across countries. Since many CGE models, and almost all closed economy models predict unequal marginal abatement costs, permit trade has been suggested as a means to ensure global efficiency while providing benefits to all. Many authors claim that standard gains-from-trade results should apply to permit trade within open economy settings. For example, Jeffrey Frankel of the Brookings Institution writes:

> "The economic theory behind the gains from trading emission rights is analogous to the economic theory behind the gains from trading commodities. By doing what they each do most cheaply, both developing and industrialized countries win." (Frankel, 1999, p.4).

As we demonstrate below, however, while permit trade does indeed benefit all countries in autarky, it can be welfare-reducing to some countries if they are already trading goods. This is because trade in pollution permits can change world goods prices. This must necessarily worsen at least one country's terms of trade, and can change the level of pollution generated by unconstrained countries. Hence the positive and normative consequences of permit trade are radically different in an open economy than in a closed economy.

---

[25] We have focused on marginal incentives to manipulate the permit market: these are present in autarky but absent with free goods trade. However, non-marginal incentives to manipulate the permit market may persist with free goods trade – this would require a large scale intervention in the permit market to force the world out of the range $S^A S^C$ in Fig. 3. One can show that such interventions are qualitatively different than in both autarky and in Hahn’s analysis: large expansions rather than small contractions of permit trade would be needed to exploit market power.

To examine permit trade we combine elements of our analysis from both Section 4 and 5. We now reintroduce our unconstrained Southern region, and keep our two constrained regions: West and East. For simplicity, we assume countries within each region are identical.[26] As before, we assume a treaty limits emission levels in both West and East, but we now allow for West-East permit trade as well. The South's level of emissions is chosen as shown in Section 4. To generate a basis for permit trade we assume that the allocation of permits is to the left of point S^A in Fig. 3 with West specialized in producing the clean good Y, while East remains diversified.[27] Letting τ be the permit price in the West and τ^* be the permit price in the East, we have $\tau > \tau^*$ and West will import permits from East.

Aggregating across Western countries, we write Western national income as GDP less the value of permit imports, or:

$$I = G(p, h, z + z^I) - \tau^I z^I \tag{20}$$

where z^I denotes net imports of pollution permits, and τ^I as the price at which permits are traded internationally. To facilitate the exposition, we consider a small movement towards full free trade in permits.[28] Differentiating (4) and using (20) we obtain the welfare effect on a representative Western consumer:

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[(\tau - \tau^I) - m\frac{dp}{dz^I} - MD\frac{dZ}{dz^I}\right]. \tag{21}$$

The welfare impact of permit trade depends on the sign and relative magnitude of three effects. The first bracketed term in (21), $\tau - \tau^I$, represents the direct gains from permit trade for given goods prices. Since we are considering only small trades, the price at which permits

---

[26] Although this is not required for our results, it simplifies matters by tying regional measures of welfare to country-specific measures.

[27] This will occur if West's h/z ratio is sufficiently. Although the pattern of production and trade affects who gains or loses from permit trade, this is immaterial to our focus which is to identify the sources of welfare changes and discuss their possible magnitude. Interested readers can refer to our discussion paper NBER 7657 for other cases.

[28] The trade and capital mobility literature has many results true for marginal movements of capital but false for completely free trade in capital. These differences, which arise from the existence of a fixed distortion such as a tariff, do not apply here.

are traded will be determined by bargaining between each country buyer and each country seller (which we do not model here). Individual rationality puts bounds on the price: $\tau^* \leq \tau^I \leq \tau$. Therefore, the direct gains from permit trade are always non-negative.

The second term in (21) is the terms of trade effect created when permit trade alters production in both West and East. Note that whenever permit prices differ across countries, a reallocation of permits must alter world production patterns. Consequently, a necessary consequence of permit trade is a change in the world production of goods. The sign and magnitude of this terms of trade effect is, however, at issue as we discuss below.[29]

The final term in (21) represents the change in world pollution created by emission permit trade. Recalling our analysis in Section 4, a change in world prices created by permit trade will alter emission levels in unconstrained Southern countries by altering their real income frontier. Therefore, emission permit trade between the West and East will have effects on emissions in the South via this world pollution effect. This is different than the standard "leakage" argument. Here “leakage” occurs when permit trade between the East and West alters world prices but the aggregate North is holding its emissions constant.

Permit trade in Autarky

First, suppose there is no goods trade. Then imports are zero ($m = 0$), and there is no effect on global pollution ($dZ/dz^I = 0$). This follows from our analysis in Fig. 1: in autarky, optimal domestic emissions depend on aggregate global emissions, not the distribution of emissions across countries. While autarky prices in West and East will change as permit trade alters local production patterns, these changes are irrelevant to the choice of emissions by the

---

[29] A permit trade between one Western country and one Eastern country will have almost no effect on world prices. We are modeling here the simultaneous trade between many Western and many Eastern countries, and this will have world price effects. Some/many estimates from the CGE literature predict extremely large permit trade under the Kyoto protocol together with large world price effects. Although results differ across models, a not uncommon finding is that emission permits will constitute Russia’s largest export, and the value of U.S. permit imports will exceed the cost of imports from Japan and several other OECD countries combined. See the contributions in the Energy Journal’s 2000 Special Kyoto Issue.

unconstrained South. Therefore only the direct gains from trade remain in (21) and we have:

Proposition 8. Suppose all countries are initially in autarky (with no trade in any goods or factors), and there are no distortions (except possibly that the aggregate level of allowable emissions may be too high or low). Then trade in emission permits between countries constrained by emission limits cannot harm any country.

Proof: see appendix

That is, the standard claims about the benefits of permit trade are true in our model if there is no international trade in goods.

Permit trade with free goods trade: Terms of trade effects

Let us now consider how free trade in goods affects permit trade. It is illuminating to start with the case where there is free goods trade between East and West, but no trade with the South. In this case, permit trade does not affect global pollution, and (21) reduces to:

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[(\tau - \tau^I) - m\frac{dp}{dz^I}\right]. \tag{22}$$

The direct gains from permit trade must now be weighed against a terms of trade effect in the goods market. If West is specialized in clean good production, then a permit flow from East to West must increase Northern Y output and reduce Northern X output. Hence p rises and West's terms of trade deteriorate (since it imports X). If West buys permits at their domestic opportunity cost ($\tau = \tau^I$), then all of the direct gains from permit trade go to the East, and it is clear from (22) that the West will lose from this trade since it is left with only a terms of trade deterioration. More surprising, though, is that West can receive *all* of the direct benefits from permit trade and still lose. Nothing perverse is required for this to happen; it can happen in a simple Cobb-Douglas economy.

Proposition 9. The West can lose from permit trade even if it receives all of the direct gains from permit trade by buying permits at the current Eastern market price: $\tau^I = \tau^*$.

Proof. See Appendix.

Proposition 9 raises several issues. First, why would West agree to a permit trade that ultimately ends up being harmful? The key is that "West" doesn't agree to these trades, but rather small Western firms do. Individual firms rationally do not take into account the effect of their purchases of permits on the terms of trade since they are price takers. It is true that the governments of all Western countries may anticipate the terms of trade deterioration and perhaps join with other Western countries to block such trades.[30] But this is our point: free trade in emission permits need not benefit all countries.

A second issue raised by the proposition concerns the magnitude of terms of trade effects. Aren't the terms of trade effects likely to be small in relation to the direct gains? The answer given in Proposition 9 is clearly no, but there is a more general reason why as well. Recall that it is the difference in the (value) marginal product of emissions across countries creating the incentive for permit trade. But moving permits across countries alters world output to the extent that marginal products of emissions differ. Therefore the cause of permit trade is intimately tied to the magnitude of its consequence on world product markets. While it is possible by judicious choice of elasticities to make one effect or the other dominant, there is little reason to believe terms of trade effects will be small *a priori*.[31]

---

[30] This possibility may indeed be highly relevant as negotiations continue over the role of emission permit trading in the Kyoto protocol with at least one major group of countries in the West (the European Union) proposing quantitative restrictions on international emission trading.

[31] Some CGE models predict large distributional consequences of permit trade. For example, in McKibben et al. (1999), Japan loses approximately $16 billion (in terms of real income) when free trade in permits is introduced. The proximate cause is that the price of oil rises with permit trade, and Japan is a large oil importer.

Permit-trade-induced carbon leakage

Now suppose there is global free trade in goods; that is, the unconstrained country, South, is involved in goods trade with East and West as well. For concreteness, suppose that in such a trading equilibrium, South is specialized in producing the dirty good X and that it exports to both East and West.[32] We maintain our assumption that West specializes in the clean good, and that East is diversified in production. When necessary we will superscript variables with W, E, or S respectively. Because our interest is in isolating the impact of adding a third and unconstrained country we eliminate all West-East distributional issues by adopting the fiction of a representative Northern consumer straddling the two regions. If this representative consumer is made worse off by permit trade, then for some West-East division of the direct permit trade gains, both regions will lose as well. In obvious notation, income for our Northern consumer becomes:

$$I = G^W\left(p, h^W, z^W + z^I\right) + G^E\left(p, h^E, z^E - z^I\right).$$

A permit sale from East to West reduces X production in East and increases Y production in West. Both effects raise the price of X. The effect on our representative Northern consumer is:

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[(\tau^W - \tau^E) - m\frac{dp}{dz^I} - MD\frac{dZ}{dz^S}\frac{dz^S}{dp}\frac{dp}{dz^I}\right], \tag{23}$$

The first term represents the direct gains from permit trade. The second is the terms of trade effect. Since p rises and $m > 0$, the terms of trade effect works against the direct gains from permit trade. In fact, as we confirm in Prop. 10 below, both West and East may now lose from permit trade via this effect alone; that is, both permit buyers and sellers may lose even if emissions in the unconstrained region do not change. By trading permits, the two regions increase their production efficiency and this increases the joint supply of their export good, which in turn worsens their terms of trade.

[32] This will be the case if South's h/z ratio is sufficiently low, West's is sufficiently high, and East's is somewhere in between (but not too low). As we noted before, other trade patterns are possible and the possibility of immiserizing trades can arise in these other scenarios as well.

The final term in (23) captures what we call permit-trade-induced carbon leakage. To examine this last term, note that the unconstrained Southern response can be found by combining the substitution and income effects we derived in Section 3. That is, combine (13) and (14), and simplify to take account of South being specialized in X. This yields:

$$\frac{dz^S}{dp} = \frac{\tau(1 - \theta^S_{x^c})(1 - \varepsilon^S_{MD,R})}{p\Phi\Delta}. \tag{24}$$

where $\Delta > 0$. Whether world pollution rises with permit trade now depends on the relative strength of bootstrapping and carbon leakage effects in the South. Since the world price has risen with permit trade, emissions should rise via carbon leakage. This is captured by the first positive bracketed term. But since our unconstrained country is an exporter of dirty goods, their income rises as well and this creates our bootstrapping term. Summarizing:

Proposition 10. In a three region world with East and West constrained by an emission treaty, and South unconstrained, then East-West permit trade can lower both Western and Eastern welfare. As well, if South is specialized in dirty good production, then if $\varepsilon^S_{MD,R} > 1$, West-East permit trade lowers world pollution; and if $\varepsilon^S_{MD,R} < 1$, then West-East permit trade raises world pollution.

Proof: See Appendix.

Terms-of-trade effects introduce an important channel through which countries are affected by permit trade. As Proposition 10 indicates, both the buyer and seller can lose, and moreover, permit trades between Northern countries can induce pollution increases in the South.

7. A Trade Theory View of the Kyoto Protocol

We are now in a position to combine our results from sections 4-6 and discuss their implications for the analysis of the Kyoto Protocol. Assume that Annex I countries (those agreeing to cut emissions) are composed of our East and West regions, both of which export clean goods by virtue of their relative abundance of human capital. Let our unconstrained country "South" represent the rest of the world and assume that these countries are relatively scarce in human capital and therefore export pollution-intensive goods.

Starting with the non-cooperative Nash equilibrium in emission levels, consider the impact of a credible and permanent reduction by the Annex I countries. This would most closely fit the "Kyoto forever" experiment adopted in the CGE literature. This will lead to an increase in the price of pollution-intensive goods, and our analysis suggests that since our unconstrained region is a dirty good exporter, its emissions will tend to rise via free rider effects and substitution effects in production, but will tend to fall via substitution and income effects in the demand for environmental quality (Proposition 2). Overall, the increase in emissions in the unconstrained region may be small or even non-existent (Proposition 3). This is in contrast to the standard analysis which predicts large increases in emissions from unconstrained countries.

In the constrained countries, the differential commitments imposed by the treaty will induce changes in trade flows. If the Eastern and Western countries comprising Annex I are not too different, this adjustment via trade flows will equalize marginal abatement costs (Propositions 5 and 6). The likelihood of this result is heightened if the incidence of cutbacks rises with a country's human capital level (that is, if the West's cuts are relatively greater than the East's).[33] Although countries will have very different emission allocations due to country size, and although trade in emission permits may take place either during the transition period or beyond, even countries with large emission allocations will have limited market power in the permit market (Proposition 7). Free trade in goods will limit market power in the permit market because goods and factor service trade are substitutes.

If adjustment via goods trade alone is not sufficient to equalize marginal abatement costs, then there are incentives for permit trade between Annex I countries. If world demand

[33] Since this moves h/z ratios closer together. See the plot of cutbacks/income levels in Frankel (1999).

for clean goods is sufficiently strong, then the West in Annex I will be specialized in Y and these countries will import permits from the East. Permit trade will then raise the relative price of dirty goods. This will generate terms of trade effects in the goods market which will dampen the benefits of permit trade and which may reduce welfare in those Annex I countries heavily dependent on imports of dirty goods. As well, the increase in the dirty goods price resulting from Annex I permit trades will raise Southern emission levels if substitution effects in production are stronger than income and substitution effects in the demand for environmental quality (Propositions 9 and 10).

Overall, the unilateral cutback alters the location of world production of dirty goods, raises their relative price, and may create complementary policy changes in the unconstrained countries especially over the long time horizons though relevant to the global warming debate. Compensating changes in trade flows dampen the adjustments and costs incurred in any one country as the world as a whole adjusts to its less carbon-intensive future.

A trade-theory approach therefore offers several unconventional answers to standard questions in international environmental economics. And although have couched our analysis in terms of issues raised by the Kyoto protocol, our results have implications for other international and inter-regional environment agreements as well

Why do our results differ so starkly from previous work? The answer depends of course on the point of departure. Our results showing that emissions may fall in unconstrained countries in response to an Annex I cutback stems from a serious consideration of policy linkages in a world with endogenous world prices. Previous research assumed either no world price effects (autarky analysis) or no policy linkages (much of the CGE literature). Combining the two leads to new results not present in either literature. This is a direct benefit of our general equilibrium methodology. And while our results indicate it is possible for emissions in the unconstrained world to fall, a dampening of leakage is perhaps more likely.

Skeptics will note that the strength of this dampening depends on the magnitude of the income and substitution effects in the demand for environmental quality. But there is evidence that suggests these effects may be important. Carbon leakage reflects, in essence, a pollution haven effect, but the evidence for pollution havens is actually quite weak, with the evidence linking environmental protection to real income levels far stronger. For example, Antweiler, et al (1998) find strong evidence of income effects on environmental quality in a study of international trade and SO2 pollution, and very little evidence for pollution havens. Similarly, Dasgupta et al. (1985) find a strong relationship between income gains and environmental protection starting at even the lowest level of development. And Levinson (1995), in a review of the literature, finds little evidence of dirty industry migration. At a more general level, the results of Grossman and Krueger (1993, 1995) cast doubt on the assumption of unchanged environmental protection as growth proceeds.

Our results demonstrating the role trade may play in equalizing marginal abatement costs and maintaining production efficiency follow from our assumption that goods trade and factor service flows are substitutes, and from an assumption that there exists enough integration in the world economy to link factor prices across the Annex I countries. It is important to note that while we have adopted a homogenous good model, goods trade and factor service trade are substitutes in a much larger class of models than ours. For example, the analysis of Section 5 would carry through if either or both industries were monopolistically competitive and countries produced distinct and differentiated products. In contrast, the Armington assumption almost universally adopted in the CGE literature rules out by assumption the extent of factor and goods trade substitutability that we have exploited. Differentiated goods are not the issue, the Armington assumption is.[34] Unless we believe that there is something inherently different about the production technology for manufacturing goods produced in one developed country

[34] It is interesting to note that the one CGE study we have found without the Armington assumption, Whalley and Wigle (1991a), gives results very similar to ours. The Armington assumption places another constraint on set of factor endowments consistent with factor price equalization. In effect, it requires that in order to replicate the integrated economy each country needs to have available factors sufficient to produce its own Armington goods in a free trading world with no factor mobility. This restriction is very much like that added by the introduction of non-traded goods.

versus another, goods trade and factor service flows may well be as substitutable as we assume. And while adding additional domestic factors and/or intermediate production processes or goods to our model can remove the sharpness of our results, the subsequent adding of international markets for goods or factors can just as easily return them. Therefore, the role trade can play in the adjustment to carbon cutbacks is an empirical matter.

Finally our results on permit trade differ considerably from autarky analysis of permit trade because of the absence of terms of trade effects in autarky. And while our results showing world price effects of permit trade are present in the CGE literature, their normative effects and the possibility of affecting policy elsewhere appear to be currently absent.

One major benefit of general equilibrium analysis is the discipline it imposes on researchers.[35] And hence it is important to note not only what our view from trade implies, but also what it rules out. For example, the belief that carbon leakage will be significant relies on an absence of strong income effects in unconstrained dirty good exporters – if they are specialized it requires $\varepsilon^{S}_{MD,R} < 1$ (Corollary 3.1). A belief that marginal abatement costs will differ considerably in the absence of permit trade implies that terms of trade effects will arise from East to West permit trade. But taken together this implies permit-trade induced carbon leakage from the unconstrained South (since $\varepsilon^{S}_{MD,R} < 1$ was assumed above) and possible losses from permit trade for all trading countries (Proposition 10). The only set of assumptions consistent with our analysis and the view that Kyoto will create large changes in emissions by unconstrained countries, very different marginal abatement costs from differential cutbacks, and Pareto-improving permit trade - is one with no international trade at all!

8. Conclusion

This paper has shown how the presence of international trade can radically alter several standard results in environmental economics. We have highlighted the difference between

---

[35] This is a lesson most recently learned in the Double-Dividend literature. See for example, Fullerton and Metcalf (1997) and Goulder (1995).

autarky and open economy analysis using the current discussion of the Kyoto Protocol as a useful springboard. Our results, however, apply with equal force to the analysis of any international environmental agreement where the changes in environmental policy are large, the environmental problem is international in scope, and the actors involved are nation states.

Throughout our analysis we have adopted a model that is purposely stark and devoid of many complications - including all of the energy market impacts that are often the centerpieces of research in this area. We have done so to bring into sharp relief the largely unappreciated and often quite surprising role that international markets can play in the process of adjustment to a less carbon-intensive world. Although the results we obtain are in many cases radically different from standard results, our methods are not. In fact, the results follow from the serious application of just three core lessons drawn from international economics: changes in world prices – or terms of trade effects – matter to production, consumption and real income levels; trade in internationally mobile goods is implicit trade in internationally immobile factor services; and access to international markets creates policy linkages across countries.

Whether our specific results hold up to empirical scrutiny is, at present, unknown. Any one paper – let alone a theory paper – cannot resolve the debate over global warming or resolve the debate over the cost of a potential cure. But we can add to the toolkit of environmental economics some of the lessons learned in the sphere of international economics. International markets can play a major role in determining the response in unconstrained countries to emission reductions, the benefits of emission permit trade, and the efficiency of various emission reduction trajectories. Without a complete understanding of the role that international markets can play in this process, we have little hope of measuring the role they may actually play. A serious consideration of international economics may therefore be a necessary condition for future empirical and theoretical work examining the costs of international environmental agreements.

Appendix

Proof of concavity of real income in z

Define $$R(h,z) = \max_{\{x,y\}}\{q(x,y) \ \ s.t. \ (x,y) \in \Theta(h,z)\}. \qquad \text{(A1)}$$

This is equivalent to our definition of real income in (5) when the economy is closed and p is endogenous since the competitive equilibrium solves the above optimization problem. Let $(h^\lambda,z^\lambda) = \lambda(h^o,z^o) + (1-\lambda)(h^1,z^1)$; and let (x^o,y^o) solve (A1) when the endowment is (h^o,z^o), Similarly let (x^1,y^1) solve (A1) for (h^1,z^1), and let (x^λ,y^λ) solve (A1) for (h^λ,z^λ). Then: $R(h^\lambda,z^\lambda) = q(x^\lambda,y^\lambda) \geq q[\lambda(x^o,y^o) + (1-\lambda)(x^1,y^1)] \geq \lambda q(x^o,y^o) + (1-\lambda)q(x^1,y^1) = \lambda R(h^o,z^o) + (1-\lambda)R(h^1,z^1)$. The first inequality follows since by the convexity of Θ, $\lambda(x^o,y^o) + (1-\lambda)(x^1,y^1)$ is feasible but not optimal for (h^λ,z^λ). The second inequality follows since q is concave.

Proof of Proposition 1

Differentiating (9) with respect to Z_{-k} yields, after some rearrangement, an expression for the effect of an increase in rest-of world emissions:

$$1 > -\frac{dz^k}{dZ_{-k}} = \frac{MD_z}{MD_z + MD_R R_z - R_{zz} - R_{zp}dp/dz^k} > 0.$$

But $MD_R R_z > 0$ from the text, and $-R_{zz} - R_{zp}(dp/dz^k) > 0$ by the concavity of R in z (taking into account the endogenous price response) as shown above. This yields the result.

Proof of Proposition 2

Define $T(Z_{-k},p,u)$ as the minimum transfer T needed to implement utility level u:

$$T(Z_{-k},p,u) = \min_{z,T}\{T: \ \ u(R(p,h,z)+T, z+Z_{-k}) = u\}$$

Let $z^c(Z_{-k},p,u)$ be the compensated emissions supply that solves this problem. Then:

$$z(Z_{-k},p,T(Z_{-k},p,u)) = z^c(Z_{-k},p,u) \qquad \text{(A2)}$$

where $z(Z_{-k},p,T)$ is defined in the text above eq. (10). Differentiating (A2) with respect to p and rearranging yields $z_p = z_p^c - z_T T_p$ But $T_p = -R_p = m/\Phi(p)$ from (8) in the text. Hence

$z_p = z_p^c - z_T m / \Phi(p)$. Substituting this into (10) yields (11).

Proof of Corollary 3.1

First suppose the country is specialized in X. Then $\varepsilon_{\tau p}$ = 1. And since MD_Z = 0, then $\varepsilon_{MD,z}$ = 0. Plugging these into (C1) and noting that $\theta_X = 1 - \theta_{Xc}$ if the country is specialized in X, reduces (C1) to $\varepsilon_{MD,R} > 1$. If instead the country is specialized in the clean good, then $\varepsilon_{\tau p}$ = 0 and $\theta_X = - \theta_{Xc}$. Again, plug into (C1) to obtain $\varepsilon_{MD,R} < 1$. Noting that $m < 0$ if the country is specialized in X and $m > 0$ when specialized in Y yields the result.

Proof of Proposition 4

Given Z, the allocation defined by (20) is unique if G_Z is strictly decreasing in z; that is, if

$$G_{Zp}(dp/dz) + G_{ZZ} < 0. \qquad \text{(A4)}$$

But $G_{ZZ} \leq 0$ since G is concave in z; and $G_{Zp} = \partial\tau/\partial p > 0$ by the Stolper-Samuelson Theorem (both goods are produced in autarky since both are essential). By homotheticity we can let $RD(p)$ denote relative demand (X/Y), and by constant returns to scale we can let $RS(p,z)$ denote relative supply (X/Y). Then in autarky, $RD(p) = RS(p,z)$, and

$$\frac{dp}{dz} = -\frac{RS_z}{RS_p - RD_p} < 0.$$

The inequality follows because (i) by the Rybczinski Theorem, $RS_Z > 0$ since X is pollution intensive, (ii) $RS_p < \infty$ since technology is strictly concave and since X is always strictly more pollution intensive than Y; and (iii) $RD_p < \infty$ since preferences over goods are strictly quasiconcave. Plugging dp/dz into (A4) yields the desired inequality. The second part of Prop. 4 refers to (21) which was derived in the text.

Proof of Proposition 5

For any Z, follow Dixit and Norman (1980) and consider the hypothetical equilibrium that would obtain if there were an integrated world economy with free factor mobility across countries and with endowment H=h+h* and Z. Let (w^o,τ^o) and (x^o,y^o) be the equilibrium factor price and world output vectors in this integrated equilibrium, and let a_x and a_y be the corresponding unit input vectors for x and y ($a_x \equiv (h_x,z_x)$ etc.). Now consider the set

$$V = \{(h,z) \mid \exists\, (x,y) \text{ s.t. } 0 \le x \le x^o,\ 0 \le y \le y^o, \text{ and } xa_x + ya_y = (h,z)\}.$$

This is the set of allocations of endowments to the West for which it is possible to solve West's full employment conditions at factor prices (w^o,τ^o) with outputs no larger than produced in the integrated equilibrium. If this can be done, then East's full employment conditions are also automatically satisfied (let $z^* = Z - z$, $x^* = x^o - x$, and $y^* = y^o - y$). And because preferences over goods are identical and homothetic, relative demand is unaffected. These allocations therefore yield free trade equilibria which replicate the integrated equilibrium, and hence in which permit prices are the same in West and East.

The set V defines a non-degenerate parallelogram since the vectors a_x and a_y are linearly independent (since x is strictly more pollution intensive than y). Now consider West's h. This yields a slice through the parallelogram V; that is, for any h, there is a continuum of z in V. Hence for any global pollution level Z, there are infinitely many allocations z and z* which replicate the integrated equilibrium and which are therefore efficient.

Proof of Proposition 6

Since both countries are initially diversified, each country's endowment ratio must lie between the equilibrium industry input ratios. Hence $z_y/h_y < z/h < z_x/h_x$ in the West and $z_y/h_y < z^*/h^* < z_x/h_x$ in the East. With equiproportionate reductions, we have $\hat{z} = \hat{z}^* = \hat{Z}$. Since h and h* are given, factor price equalization will continue to hold if $(z_x \hat{/} h_x) = (z_y \hat{/} h_y) = \hat{Z}$ and similarly for the East. But with standard manipulations (see Jones (1965)), we have:

$$(z_i \hat{/} h_i) = \frac{\sigma_i \hat{Z}}{|\theta||\lambda|(\sigma_s + \sigma_D)}$$

for i = x,y, where σ_i is the elasticity of substitution in industry i, σ_S is the elasticity of substitution between X and Y along the production frontier, σ_D is the elasticity of substitution in demand, $|\theta| = \theta_{xz} - \theta_{yz} > 0$, $|\lambda| = \lambda_{xz} - \lambda_{xL} > 0$, θ_{ij} is the share of input j in the cost of good i, and λ_{ij} is the fraction of input j employed in sector i. If $\sigma_X = \sigma_Y = \sigma_D = 1$, the above simplifies to $(\hat{z}_x / \hat{h}_x) = (\hat{z}_y / \hat{h}_y) = \hat{Z}$, as required for the result.

Proof of Proposition 7

Suppose there is free trade in emission permits but no goods trade. West's income is:

$$I = G(p,h,z+z^I) - \tau^* z^I$$

where z^I denotes Western net imports of pollution permits and τ^* is the world price of permits. Suppose that West decides to change z^I. Differentiating (4), with world Z fixed, and starting from the point where there is free trade in the permit market, yields:

$$\left.\frac{du}{dz^I}\right|_{\tau=\tau^*} = -\frac{u_R}{\Phi} z^I \frac{d\tau^*}{dz^I}. \qquad \text{(A5)}$$

Since Eastern permit demand is downward sloping, we can show $d\tau^*/dz^I > 0$. If West is a permit importer ($z^I > 0$), then (A5) is negative and West can increase its welfare by restricting permit imports. If West is a permit seller ($z^I < 0$), then (A5) is positive and West has an incentive to reduce its permit exports.

Now suppose there is free trade in goods and the permit allocation is in the interior of $S^A S^C$ in Fig. 3. Equilibrium can be achieved via either permit trade, goods trade, or some combination of both. Suppose West attempts to manipulate the permit market with a small change in z^I. Since the East's permit supply curve is perfectly elastic in this range, any small change in z^I has no effect on τ^*. And moreover, since permit prices do not change, goods prices will not change either. Hence starting in $S^A S^C$, we have $du/dz^I = 0$.

Proof of Proposition 8

This is a standard gains-from-trade proof (see Grossman, 1984). Let p be the goods price vector after free permit trade, let τ be the equilibrium permit price and let z^I be net imports of permits. Also u is utility after permit trade, u^a is utility prior to permit trade, and x^a and y^a are outputs prior to permit trade. Let E(p,Z,u) be the expenditure function. Then:

$$E(p,Z,u) = G(p,z+z^I) - \tau z^I \geq px^a + y^a \geq E(p,Z,u^a)$$

The first inequality follows since the private sector maximizes national income: pre-permit trade outputs (x^a,y^a) are feasible but not optimal after permit trade. The next inequality follows since (x^a,y^a) yields utility u^a (because there is no goods trade), but this utility could be attained at lower cost given the new prices p. Finally, $u \geq u^a$ since E is increasing in u.

Proof of Proposition 9

The proof is by example. Suppose u = xy – D(Z). Assume endowments are mirror images (z* = h, h* = z); and East is abundant in permits (z*/h* > z/h). Let technology be $x = z^{\beta}h^{1-\beta}$ and $y = z^{1-\beta}h^{\beta}$, with β > 1/2 so that x is pollution intensive. By symmetry, p = 1 in free trade. The boundaries of the cone of diversification are $z_x/h_x = \beta/(1-\beta)$ and $z_y/h_y = (1-\beta)/\beta$. Suppose z*/h* > β/(1-β) and z/h < (1-β)/β, so that both countries specialize in production. Because permits are scarce in the West, we have τ > τ*.

Suppose West imports a permit at the Eastern price τ*; that is, West receives all of the direct gains from trade. The effect on West's welfare is

$$E_u du = (\tau - \tau^*)dz^I - mdp. \qquad \text{(A6)}$$

Imports m are just West's demand for X, and hence m = Y/2p (West's income is just Y). To find dp, equate relative demand and supply to obtain p = Y/X*. Differentiating and using the condition that the value of the marginal product of emissions is the permit price, we obtain dp = $(p\tau/Y + \tau^*/X)dz^I$. Substituting for dp into (A6) and simplifying yields

$$E_u du = (\tau - 3\tau^*)/2. \qquad \text{(A7)}$$

But from cost minimization, τz/Y = (1-β) and τ*z*/X* = β. By symmetry, Y=X*, and so τ/τ* = βz*/(1-β)z. Using this in (A7) shows that if

$$\frac{\beta}{1-\beta} < \frac{z^*}{z} < \frac{3(1-\beta)}{\beta}.$$

then we have both τ > τ* and $E_u du/dz^I < 0$. Finally note that for this to be possible and consistent with X being pollution intensive, we require β∈(1/2,3/4).

Proof of Proposition 10

To show that both West and East can lose from permit trade in a three-region world, it is sufficient to consider the case where $\varepsilon^S_{MD,R}$ = 1, so that Southern pollution does not change. Totally differentiating the market clearing condition for X yields

$$\frac{dp}{dz^I} = \frac{x_I(\tau^W - \tau^E) - (\frac{\partial x^W}{\partial z^W} - \frac{\partial x^W}{\partial z^W})}{D} , \qquad \text{(A8)}$$

where $x_I = \partial x^c/\partial I$ (where x^c is the demand for X in the North) and I is Northern income), D = $H + x_I m + x_I m^S$, with $H = G^W_{pp} + G^E_{pp} + G^S_{pp} - E_{pp} - E^S_{pp} > 0$, and where m denotes Northern (aggregate East and West) imports of X and m^S Southern net X imports. Stability requires D > 0. Using (A8) in (23) (but with $dz^S/dp = 0$) yields

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[\frac{(\tau^W - \tau^E)(H + x^S_I m^S) - m\,\frac{\partial x^E}{\partial z^E}}{D}\right],$$

where $m^S < 0$ since South exports X and $\partial x^E/\partial z^E > 0$ since X is intensive in emissions. There are two ways that utility may fall from the permit trade. First, if pure substitution effects (embodied in H) are locally small, and the Southern income effect ($x_I^S m^S < 0$) is large, then utility may fall. This corresponds to the case of an inelastic foreign offer curve, since if the foreign income effect dominates the substitution effect, an increase in the price of X leads to a fall in foreign exports. Second, even if this condition is not satisfied, a strong fall in X production in East can be enough to cause a price increase big enough to lower Western utility. This shows that it is possible for the terms of trade loss from permit trade to be larger than the direct permit trade gains in three country context. Hence West and East can be collectively worse off, and there will exist some division of the permit trade gains such that both can lose from the trade. Finally, the result that West-East trades can affect Southern pollution follows from (24).

References

Antweiler, Werner; Copeland, Brian R. and Taylor, Scott M. "Is Free Trade Good for the Environment?" *American Economic Review*, forthcoming.

A.L. Bovenberg, and L.H.Goulder. "Introducing intertemporal and open economy features in applied general equilibrium models", De Economist 139, Nr. 2, (1991): 186-203.

Barrett, Scott. "Self-Enforcing International Environmental Agreements." *Oxford Economic Papers*, 46 (1994): 878-894.

Barrett, Scott, "Economic incentives and enforcement are crucial to a climate treaty," Resources for the Future, Weathervane: Perspectives on policy, (December 1997).

Brecher, R.A. and E.U.Choudri, "Immiserizing Investment from Abroad: The Singer-Prebisch Thesis Reconsidered," *Quarterly Journal of Economics* 97(1982): 181-90.

Card, David, "The Impact of the Mariel Boatlift on the Miami Labor Market," *Industrial and Labor Relations Review*, 43 (1990): 245-57.

Card, David, and John E. DiNardo, "Do Immigrant Inflows Lead to Native Outflows?" NBER Working Paper No. 7578, March 2000.

Carraro, C. and D. Siniscalco. "International environmental agreements: Incentives and political economy", *European Economic Review*, 42 (1998): 561-572.

Copeland, Brian R. and Taylor, Scott M. "North-South Trade and the Environment." *Quarterly Journal of Economics*, 109 (1994): 755-787.

Copeland, Brian R. and Taylor, Scott M. "Trade and Transboundary Pollution." *American Economic Review*, 85 (1995): 716-737.

Cornes, Richard and Sandler, Todd, *The Theory of Externalities*, *Public Goods And Club Goods*, 2nd edition, Cambridge University Press,1996.

Dasgupta, S., A. Mody, S. Roy, and D. Wheeler. "Environmental Regulation and Development: A Cross-Country Empirical Analysis", World Bank discussion paper, April (1995).

Dixit, Avinash and Norman, Victor, *Theory of International Trade*. Cambridge: Cambridge University Press, 1980.

Edmonds, J.A.E., Michael J. Scott, Joseph M. Roop, and Christopher McCracken, "International emissions trading and global climate change: impacts on the costs of greenhouse gas mitigation," Pew Center on Global Climate Change, 1999.

Ellerman, A. Denny, Henry D. Jacoby, and Anneline Decaux, "The effects on developing countries of the Kyoto protocol and CO2 emissions trading," MIT joint program on the science and policy of global change, 1999.

Frankel, J., "Greenhouse Gas Emissions," Brookings Institution, Policy Brief No. 52, June 1999.

Fullerton, D. and G. E. Metcalf. "Environmental Taxes and the Double-Dividend hypothesis: did you really expect something for nothing", NBER working paper 6199, (1997).

Goulder, L. "Environmental Taxation and the Double Dividend: A Reader's Guide", *International Tax and Public Finance* 157 (1995).

Grossman, G.M., "The Gains from International Factor Movements," *Journal of International Economics* 17(1984): 73-83.

Grossman, Gene M, and Alan B. Krueger. 1995. "Economic Growth and the Environment, *Quarterly Journal of Economics*, 353-377, 1995.

Hahn, R.W. "Market Power and Transferable Property Rights", *Quarterly Journal of Economics*, Vol. 99, No. 4, Nov. (1984), 753-765.

Hoel, Michael. "Global Environmental Problems: The effects of Unilateral Actions taken by one country," *Journal of Environmental Economics and Management*, 20(1991): 55-70.

Hoel, Michael, "Efficient International Agreements for Reducing Emissions of CO2," *The Energy Journal*, 12 (1991): 93-107.

Hill, J. and J.P. Weyant,, "Introduction and Overview of the Costs of Kyoto, a special issue: A Multi-model Evaluation," J.P. Weyant, guest editor, *Energy Journal* (2000).

Jones, R., "The simple analytics of general equilibrium," *Journal of Political Economy* 1965.

Jorgenson, Dale W. and Wilcoxen, Peter J. "Reducing US Carbon Emissions: An Econometric General Equilibrium Assessment." *Resource and Energy Economics* 15 (1993): 7-25.

Levinson, A, "Environmental Regulations and Industry Location: International and Domestic Evidence" in *Fair Trade and Harmonization: Prerequisite for Free Trade?* J. Bhagwati and R. Hudec, eds. MIT Press 1995.

The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis, July 1998

Manne, Alan S. and Richels, R.G, "Global CO_2 emission reductions: the impacts of rising energy costs," *The Energy Journal*, 12 (1991): 87-107.

Markusen, J.R. and J.R. Melvin, "Tariffs, Capital Mobility, and Foreign Ownership," *Journal of International Economics* 9 (1979): 395-409.

McKibbin, Warwick, J., Robert Shackleton, and Peter J. Wilcoxen, "What to expect from an international system of tradable permits for carbon emissions," *Resource and Energy Economics* 21 (1999): 319-346.

Mundell, Robert, A, "International Trade and Factor Mobility", *American Economic Review*, 47 (1957): 321-335.

Nordhaus, W. and J. Boyer, "Requiem for Kyoto: An Economic Analysis," *The Energy Journal*, Special issue: *The Costs of the Kyoto Protocol: A multimodel Evaluation* (2000): 93-124.

Perroni, C. and R. M. Wigle. "International Trade and Environmental quality: how important are the linkages", *Canadian Journal of Economics* August (1994): 551-567.

Perroni, C. and T.F.Rutherford. "International Trade in Carbon Emission Rights and Basic Materials: General Equilibrium Calculations for 2000," *Scandinavian Journal of Economics* 95 (1993): 257-278.

Samuelson, Paul A. "International Factor-Price Equalization Once Again," *Economic Journal*, 59 (1949): 181-197.

Welsch, Heinz. “Incentives for Forty-five Countries to Join Various Forms of Carbon Reduction Agreements.” *Resource and Energy Economics*, 17 (1995): 213-237.

Whalley, John and Wigle, Randall. “The International Incidence of Carbon Taxes, ” in *Global Warming: Economic Policy Responses*, edited by R.Dornbusch and J.M. Poterba, MIT Press, Cambridge, 1991a, pp. 233-263.

Whalley, John and Wigle, Randall. “Cutting CO_2 Emissions: The Effects of Alternative Policy Approaches.” *The Energy Journal*, 12 (1991b): 1109-24

Woodland, A.D. *International Trade and Resource Allocation*, North-Holland:Amsterdam (1982).