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# FREE TRADE AND GLOBAL WARMING:
# A TRADE THEORY VIEW OF THE KYOTO PROTOCOL

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## ABSTRACT

This paper demonstrates how three 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 three 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.

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## I. Introduction

Although the debate over global warming has been very contentious, there is widespread agreement among economists on the basic principles underlying the effective design and implementation of a treaty once countries have agreed to greenhouse gas emission targets. 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. As well, because carbon emissions are a uniformly mixed pollutant, standard analysis suggests that free trade in emission permits will minimize global abatement costs and yield benefits to both buyers and sellers of permits. And unless all major polluters agree to cap emissions, 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 world of open trading nations. Since the results we highlight have framed much of the ongoing discussion and research on the Kyoto protocol 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 non-participating 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; and emission permit

[1] For a summary of the Kyoto protocol's main features 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 (Annex B countries by an average of 5%), the likely cost of the treaty to the U.S. (.1% of GDP), and the time frame for the cuts (2008-2012).

trading may make both participants to the trade worse off and increase global pollution.

We develop these results in a perfectly competitive general equilibrium trade model that incorporates a role for pollution emissions. 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. 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 obtain three main results. First, we provide 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 autarky. But we show that in an open economy, home and rest-of-world emissions may well be strategic complements. That is, leadership by one group of countries in lowering emissions may create an endogenous and self-interested emissions reduction in unconstrained countries.[2] International trade can therefore fundamentally alter the strategic interaction among countries over emission levels.

Second, we show how a wide range of rigid 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. The mechanism 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. With free trade in goods, countries assigned very tight emission quotas reduce their dirty good production, while countries with more generous quotas expand dirty good output. Because the (general equilibrium) marginal cost of cutting back on emissions is a function of the set of goods produced, this trade-induced substitution across dirty and clean goods shifts the marginal abatement cost curve in for some countries and out for others. This effect can be so complete that trade in goods alone can equalize marginal abatement costs across countries.

This result implies that with free trade in goods, there is an infinite number of ways to cutback 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 globally. In contrast, with little or no trade in goods, an attempt to use the initial allocation of permits to achieve distributional or participation goals always leads to inefficiencies.

Third, 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

[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.

also brings other unintended consequences. This is because international trade in pollution permits affects goods prices. Changes in goods prices must worsen at least one country's terms of trade and this can potentially lead to welfare losses. We show, for example, that a permit buyer can lose from permit trade via a terms of trade deterioration even if that buyer receives all of the direct benefits of permit trade by buying permits at the seller’s reservation price. As well, permit trade between two countries can lead to a terms of trade deterioration for both the buyer and seller, and raise emission levels in unconstrained countries, thereby raising global pollution and potentially 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. This result echoes 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).

The literature on global pollution abatement has proceeded in three distinct ways. First are 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 that environmental policy is fixed and exogenous to the model. This rules out an interaction between environmental policy and real income levels. 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 an income-environment link may provide a useful complement to these earlier analyses.[3]

In addition, CGE models in this literature typically offer a very detailed model of the energy sector, but a quite rudimentary model of trading interactions.[4] This approach is very useful in highlighting the importance of substitutability between fuel types in the adjustment process to emission reductions. But it has tended to make almost invisible the role of international trade in goods 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 domestic production by substituting towards goods with a lower energy intensity and importing energy intensive goods from countries with less binding emission constraints. It is exactly this margin of adjustment that generates a tendency towards equalizing marginal abatement costs worldwide via goods trade alone.[5]

Authors in the public economics and environmental economics literature [Hoel (1991), Chander and Tulkens (1992), Barrett (1994), Welsch (1995) and others] have also considered some of the issues we address but typically within models containing one private good, one public good, and no international trade. This literature highlights the strategic interaction among nations, the possibility of coalition formation, and the extent of free riding. However, given absence of goods trade in these models, there are no linkages via world

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[3] Recent empirical work by Grossman and Krueger (1993, 1995), Seldon and Song (1994), 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 implies a 0.1% greater emission reduction from business as usual.

[4] Early models had no international interactions at all. See for example Manne and Richels (1991). Even models with "trade" adopt a very simple trading environment. A typical set-up is given in Perroni and Rutherford (1993). They present a model where there is one final traded good and one traded intermediate, whereas the energy sector contains six alternative electric energy technologies, seven different methods to produce non-electric energy, and two supply functions for natural gas (high and low cost).

[5] Perroni and Rutherford (1993, p. 259) seem to come the closest to a definitive statement "When carbon rights are traded, there tend to be smaller changes in basic materials trade," but they don't make the connection to FPE or its determinants. Some of the simulations presented in Whalley and Wigle (1991a) appear to exhibit FPE but curiously they never remark on the fact that permit prices (carbon taxes) are virtually identical across countries even in the absence of permit trade.

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 focussed on the interaction between goods trade and international trade in emission permits. In our earlier work, Copeland and Taylor (1995), we did allow for income-induced policy responses, but in that paper focused on the strategic interaction between rich and poor countries in the move from autarky to free trade in goods.

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. A short conclusion 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 possibilities. 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.

Pollution emissions are modelled 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.[6] 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, and where f and g are increasing in both h and z. 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 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 both X and Y are essential in consumption, so that both goods are always consumed in equilibrium.

***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. The permits are auctioned off to firms, and all revenues are redistributed lump sum to

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6 For example if pollution is proportional to output, but factors can also be allocated to abating pollution, then (under certain regularity conditions) we can invert the abatement production function and write output as a function of the pollution emitted and total factor use in the industry. For a derivation see the appendix in Copeland and Taylor (1994).

consumers. Pollution permits have a market-clearing price we denote by $\tau$.

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:

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

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 $R \equiv I/\Phi(p)$ 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 separability and homotheticity are now apparent. The government's problem in choosing pollution is now drastically simplified to trading off increases in real income $R$ against a worsened environment $Z$.

## 3. Autarky

In this section we show that under mild assumptions, domestic and foreign emissions are always strategic substitutes when there is no trade in goods. This result is standard,[7] but it provides a benchmark to use when investigating the effects of international trade.

We abstract from all 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

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

where $m$ denotes net imports of the dirty good from country $k$. 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 function *MD*.

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7 For a demonstration of this within a partial equilibrium setting see Chapter 6 of Cornes and Sandler (1996).

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.[8] 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 which has real income on the vertical axis and world emissions on the horizontal axis. Indifference curves slope upward as illustrated since emissions are 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 Home does not pollute at all, then world emissions are $Z^o$, and at this point Home real income is zero, since we have assumed that emissions are an unavoidable aspect of production. As Home increases its emissions, real income begins to rise, yielding the concave function $R^o$ as illustrated (concavity of real income in emissions 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 are this point are $Z^A$, with domestic emissions given by the gap $z_k = Z^A - Z^o$.

We can now examine country k's response to changes in foreign emissions. Starting from an initial optimum at A, a fall in foreign 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]

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[8] Note that $u_I = u_R / \Phi$.

[9] If country k left its emission level unchanged world emissions would fall by the rest-of-world reduction and the equilibrium would move directly to the left of A. For this to be an optimum however, the indifference curves would need to be vertically parallel. But this implies that all income gains are captured by reductions in Z and our real income composite is not a normal good contrary to our assumption. A similar argument establishes that a movement directly vertical from A is also not possible. Consequently, emissions rise in country k but less than one-for-one with the fall in rest-of-world emissions.

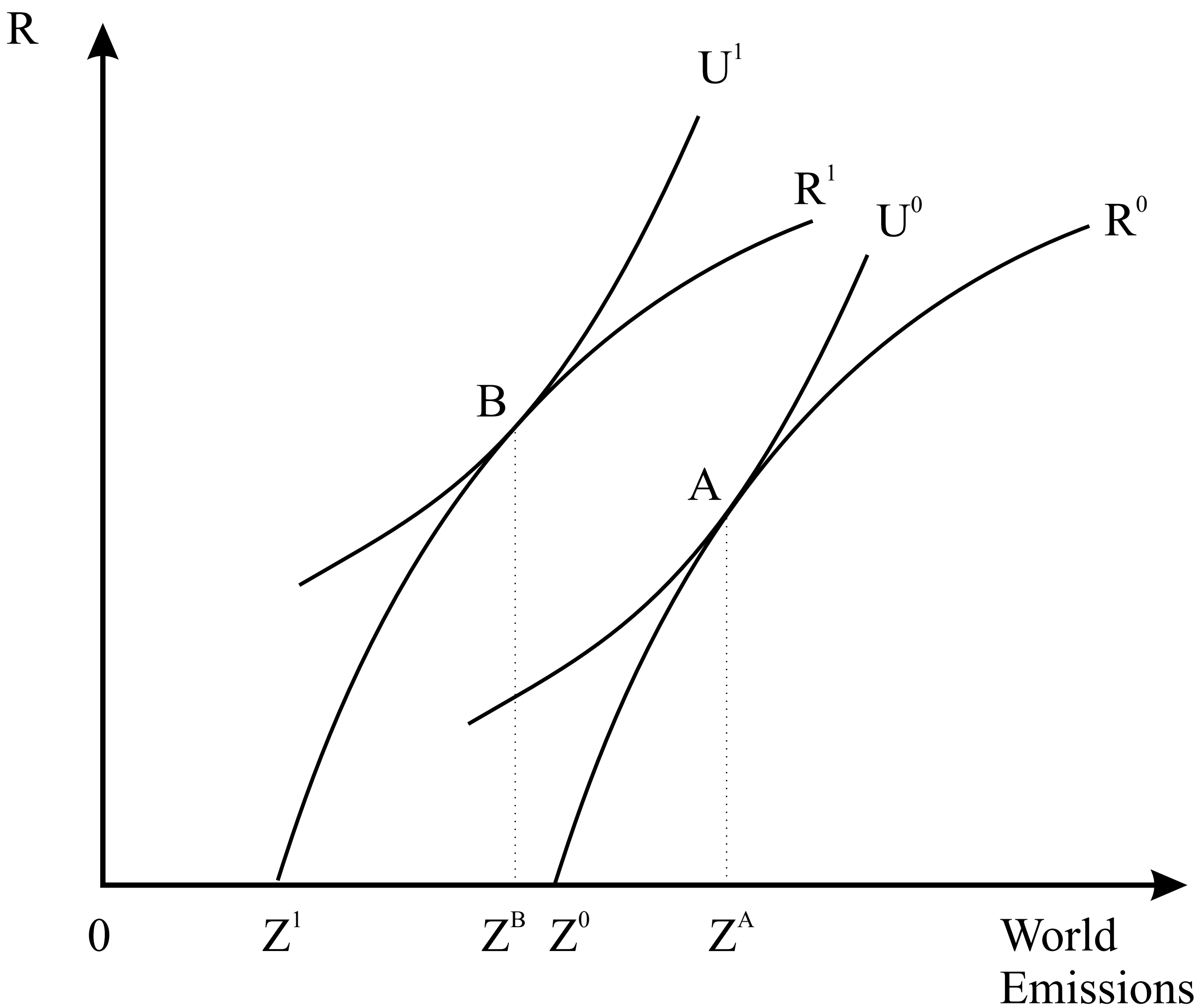


**Figure 1.**
**Domestic response to foreign emission reductions in autarky**

**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 leads to a fall in global pollution.

Proof: See appendix.

The intuition behind this result is straightforward. Foreign 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 present in Figure 1. Domestic and foreign emissions are therefore strategic substitutes in autarky.

## 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 Annex I 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. When combined with the free rider effect from the public economics literature, this suggests that unilateral emission cutbacks in an open economy setting must then be doubly deleterious – as both free-riding and carbon leakage would be present. 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.

Specifically, we show that, in contrast to the standard analysis (and in contrast to autarky), home and rest-of-world emissions may be strategic complements when there is free trade in goods. Therefore, when rest-of-world emissions fall unilaterally, optimal behavior by the non-participant country may well be to reduce and not increase emissions! This possibility arises because the same price change creating carbon leakage’s substitution effect will also create income and substitution effects that affect the demand for environmental quality. We refer to the income effect of the price change as "bootstrapping" since it calls forth an endogenous and self-motivated change in emissions.

To compare a typical country's best response function in trade and autarky, 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. This decomposition, although simple, is novel to the literature.

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). Although the conditions determining pollution in trade and autarky have the 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 effect of foreign emission changes ($\partial z_k/\partial Z_{-k}$) which we have already analyzed in autarky, there is also the effect of the change in world goods prices induced by the change in foreign emissions, captured by the second term above. Because countries are not linked via goods trade in autarky, this latter term is relevant only when there is free trade. 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.

The free rider effect is simply the direct strategic effect that arises when a change in rest-of-world emissions alters marginal damage. We can solve for it by differentiating (9) with respect to $Z_{-k}$, holding p constant, to obtain:

$$\frac{\partial z_k}{\partial Z_{-k}} = -\frac{MD_z}{\Delta} < 0, \tag{12}$$

where $\Delta \equiv MD_Z + MD_R R_Z - R_{ZZ} > 0$. A reduction in foreign emissions reduces marginal damage, and this in turn increases home emissions via the free rider effect. When there is no trade, only the free-rider effect is present: in Figure 1, the free-rider effect is responsible for the entire movement from A to B.

The carbon leakage and bootstrapping effects are both driven by the increase in the world price of dirty goods $p$ that ensues when rest-of-world emissions are reduced. Carbon leakage, captured by the second term in (11) is the pure substitution effect of the price change, holding utility constant. To solve for this effect, differentiate (9) with respect to $p$, using the constraint that utility $u(R^k + T,Z)$ is held constant:[10]

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

where $\varepsilon_{\tau p} = pG_{zp}/\tau$ is the elasticity of producer demand for emissions $\tau$ with respect to $p$ and $\theta_{x^c} = px^c/G < 1$ is the share of spending on good X. There are two terms in (13), reflecting substitution effects in both production and consumption.

The producer substitution effect reflects the shift of producers' derived demand for emissions when the price of the dirty good rises. As long as X is produced, the derived demand shifts out, and we have $\varepsilon_{\tau p} \geq 1$, so that the marginal benefit of polluting for producers increases more than in proportion to the price increase.[11] If instead the economy is specialized in the clean good (Y), then the economy is not polluting and there is no substitution effect in production ($\varepsilon_{\tau p} = 0$).

On the consumption side, an increase in the price of the dirty good increases the price of consumption goods relative to environmental quality. Consumers would like to substitute towards the cheaper good (environmental quality), which shifts in the supply of emissions. The strength of this substitution effect depends on the share of the dirty good in consumption spending ($\theta_{x^c} < 1$).

The producer and consumer substitution effects work against each other, but as long as the dirty good is produced, the producer effect dominates ($\varepsilon_{\tau p} > \theta_{x^c}$) and the net marginal benefit of polluting rises. This leads the domestic country to substitute towards more

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[10] That is, we allow for a hypothetical change in income T to ensure that consumers stay on the same indifference curve.

[11] 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 $\varepsilon_{\tau p} = 1$.

emissions. Carbon leakage is positive in this case.

If instead the economy is specialized in the clean good, then since there is no substitution effect on the producer side, the consumption effect dominates and the net marginal benefit of polluting falls via the substitution effect. In this case, carbon leakage is negative, tending to reduce emissions.[12]

The final term in (11), the bootstrapping effect, is the income effect of the price change. Since environmental quality is a normal good, $\partial z_k/\partial T < 0$, and so emissions fall if real income rises. If the domestic country exports the dirty good ($m<0$), then an increase in $p$ corresponds to an improvement in its terms of trade. This increases real income and hence the bootstrapping effect tends to reduce pollution. That is,

$$-\frac{\partial z_k}{\partial T}\, m/\Phi(p) \;=\; \frac{MD_R}{\Delta} m/\Phi(p) \;<\; 0 \qquad \text{if } m < 0. \tag{14}$$

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 cutback 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 (carbon leakage) also creates an income effect (bootstrapping). These substitution and income effects always move in opposite directions for a dirty good exporter, and sometimes move in opposite directions for a dirty good importer.[13] As a result it is possible in trade – but not in autarky – that South may lower emissions in the face of unilateral Northern cuts.

We illustrate each of these effects with the aid of Figure 2, which assumes that the

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[12] The strength of the producer substitution effect is dependent on the Hecksher-Ohlin production structure of the economy. If instead we had a specific factors model, with emissions playing the role of the intersectorally mobile factor, then the producer substitution effect would be weaker, and it would be possible for the consumption effect to dominate the producer effect even when there is some dirty good production in the economy.

[13] For a dirty good importer, bootstrapping tends to increase emissions since real income falls via the terms of trade loss. Carbon leakage is negative and tends to reduce emissions if the country is specialized in production of the clean good; but carbon leakage is positive if both goods are produced.

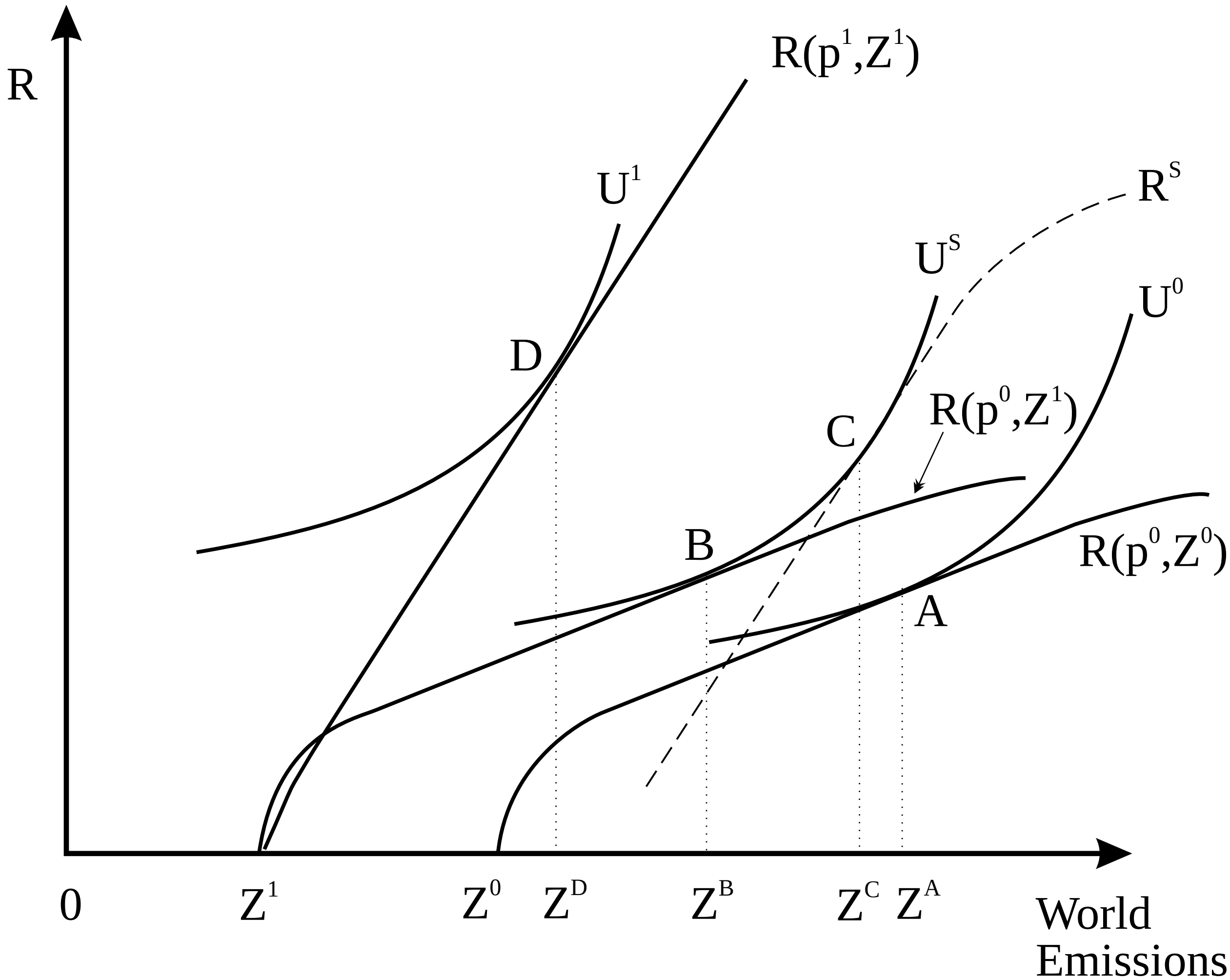


**Figure 2.**
**Domestic response to foreign**
**emission reductions in an open economy**

domestic country is a dirty good exporter. Initially world emissions are $Z^o$. The corresponding real income frontier is $R(p^o,Z^o)$ which yields the initial domestic optimum at point A. Notice that 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 $(w,\tau)$ are completely determined by the zero profit conditions:

$$c^x(w,\tau) = p, \tag{15}$$

$$c^y(w,\tau) = 1, \tag{16}$$

where $c^x$ and $c^y$ are the unit cost functions in industry X and Y respectively. Since the country is a price taker, $p$, and hence $\tau$ and $w$, do not vary with emission levels. Since $\tau$ is independent of $z$ when both goods are produced, the slope of the real income frontier is constant in this region. When emissions z are either very high or very low the economy specializes in either X or Y, and the real income frontier is strictly concave.[14]

A reduction in foreign emissions to $Z^1$ in free trade will both shift the real income frontier to the left and also change its slope (as we will explain below), so that the new real income frontier is $R(p^1,Z^1)$ and the new domestic optimum is at point D. Notice that in this example, the domestic country's emissions have fallen in response to the foreign cutback since domestic emissions $z_k^D = Z^D - Z^1 < Z^A - Z^o = z_k^A$. We now wish to decompose this total change into the three effects discussed above.

Let us first isolate the free rider effect. This is pure strategic effect of the foreign emission cutback, 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 $R(p^o,Z^1)$. The slope of

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[14] This follows from diminishing returns as more emissions are added while labour is held constant.

the frontier is unchanged. Along this frontier, home chooses point B, which corresponds to an increase in its emissions (since $z_k^B = Z^B - Z^1 > Z^A - Z^o = z_k^A$).

Next, consider the price change induced by the foreign emission reduction. From our discussion after (13) above, an increase in the price of the dirty good makes the real income frontier steeper for a dirty good exporter,[15] yielding the new frontier $R(p^1,Z^1)$. As well, 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 $z_k$). Since our country is a dirty good exporter, its real income has risen, as reflected in the new domestic optimum at point D.

Carbon leakage is the pure substitution effect of this price change and represents the emission level country k would choose if it faced the relative prices reflected in the new income frontier, but was held to its current level of utility. To find this point, we take the new frontier, and eliminate the real income gain due to the price change by shifting the frontier vertically downward[16] until we obtain the (thin dashed-line) frontier[17] $R^s$ which is tangent to the indifference curve $U^s$ at point C. The movement along the indifference curve from B to C is the pure substitution effect of the price change: this is carbon leakage. As shown by (13) and confirmed here in the diagram, carbon leakage increases emissions in a country that produces the dirty good. In Fig. 2, carbon leakage yields $Z^C - Z^B$ additional units of emissions.

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. Note that because environmental quality is a normal good, country k emissions must fall via the income effect (from $Z^C$ to $Z^D$ in the diagram). And in

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[15] From (13), $R_{zp} > 0$ as long as x is produced (which must be the case for a dirty good exporter).

[16] That is, we introduce a hypothetical negative transfer T to shift the real income frontier down.

[17] We have only drawn the upper part of this frontier to avoid clutter.

the example we have illustrated, bootstrapping outweighs both carbon leakage and free riding, so that country k's emissions fall in response to rest-of world cutbacks.

***Conditions for Strategic Complements***

Putting the three effects together – free-riding, carbon leakage and bootstrapping – leads to the conclusion that domestic and foreign emissions are strategic complements in the case illustrated above: reductions in foreign emissions lead to reductions in domestic emissions.[18] To determine when this can occur, we compare the strength of the three effects:

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

Proof: Follows from (11).

The left hand side of (C1) is the net increase in demand for environmental quality arising from the price change (reflecting both substitution and income effects in consumption), while the right hand side is the increase in demand for emissions from producers and the free rider effect. Domestic and foreign emissions are strategic complements if the increase in the demand for environmental quality arising from the terms

[18] 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 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.

of trade change is sufficiently strong.

For a dirty good exporter, the demand for environmental quality unambiguously rises via both income and substitution effects. Domestic and foreign emissions are strategic complements if this increase in demand is sufficiently strong. A strong income (bootstrapping) effect will ensure this.

However, strong income effects are not the only way that strategic complements can arises. For a dirty good importer, $\theta_X < 0$, and so the income effect tends to reduce the demand for environmental quality. But the demand for environmental quality will still rise if the substitution effect in consumption is stronger than the income effect.[19]

To gain insight into the strength of income effects needed to generate strategic complements, it is useful to consider an example where country k is specialized in production and where marginal damage is insensitive to changes in aggregate emissions (i.e., $MD_Z = 0$):

**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

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19 If the domestic country is diversified in production and a dirty good importer, then (C1) cannot be satisfied. That is, domestic and foreign emissions must be strategic substitutes for a diversified dirty good importer. However if the domestic country specializes in clean good production, then $\varepsilon_{\tau p} = 0$, and carbon leakage tends to reduce emissions. In this case, domestic and foreign emissions may be strategic complements if the income and free riding effects are sufficiently *weak*.

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, then as discussed above, carbon leakage tends to reduce emissions. And if the income effect is weak, then carbon leakage dominates bootstrapping, and we get a net fall in emissions 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 we have focused in our analysis in Figure 2 on 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. These asymmetries arise because countries differ in their trade pattern, and they can be strong enough to produce surprising changes in the strategic interaction among countries.

The possibility that international trade can change the qualitative aspects of strategic interaction in emissions between countries introduces 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 actually fall. In contrast 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 across North and South suggests the North can play an important leadership role in emission reductions.

## 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 equally rigid rules for emission cutbacks 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 would almost never be efficient under 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***

To set the stage, we start by demonstrating the inefficiency of such rules in autarky. Suppose there is a binding global treaty fixing total global emissions. Our main result in this section is that if there is no free 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. Since the number of countries makes little difference to the analysis in this section, we simplify by adopting a two-region model.[20] North and South are each composed of any number of identical countries, with regions

[20] The case with K heterogeneous countries is algebraically intensive and leads to no new insights.

differing in only their levels of human capital. North has greater human capital than South and we indicate Southern variables with an asterisk (*) when necessary.

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 Northern utility, the planner solves:

$$\max_{z,T}\left\{\lambda u\left(\frac{I}{\Phi(p)},Z\right)+(1-\lambda)u^*\left(\frac{I^*}{\Phi(p^*)},Z\right)\right. \\ \left. s.t.\ Z=z+z^*,\ \ I=G(p,h,z)-T,\ I^*=G^*(p^*,h^*,z^*)+T\right\} \tag{17}$$

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

$$\lambda\frac{\partial u}{\partial I}=(1-\lambda)\frac{\partial u^*}{\partial I^*} \tag{18}$$

$$\frac{\partial G(p,h,z)}{\partial z}=\frac{\partial G(p^*,h^*,z^*)}{\partial z^*} \tag{19}$$

The first condition, (18), 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[21] be equalized across regions.[22]

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 (19); these are labelled $MAC^A$ and $MAC^{*A}$. The intersection of these curves at B determines the efficient shares of emissions allocated to North $S^B$, and South $1\text{-}S^B$.

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 (19) as

$$\frac{\partial G(p,h/z,1)}{\partial z}=\frac{\partial G(p^*,h^*/z^*,1)}{\partial z^*} \tag{20}$$

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[21] Recall that ∂G/∂z is the general equilibrium demand for emissions – or in the parlance of environmental economics, the marginal abatement cost.

[22] These first order conditions are sufficient given the concavity of the objective function and also render unique solutions under standard conditions.

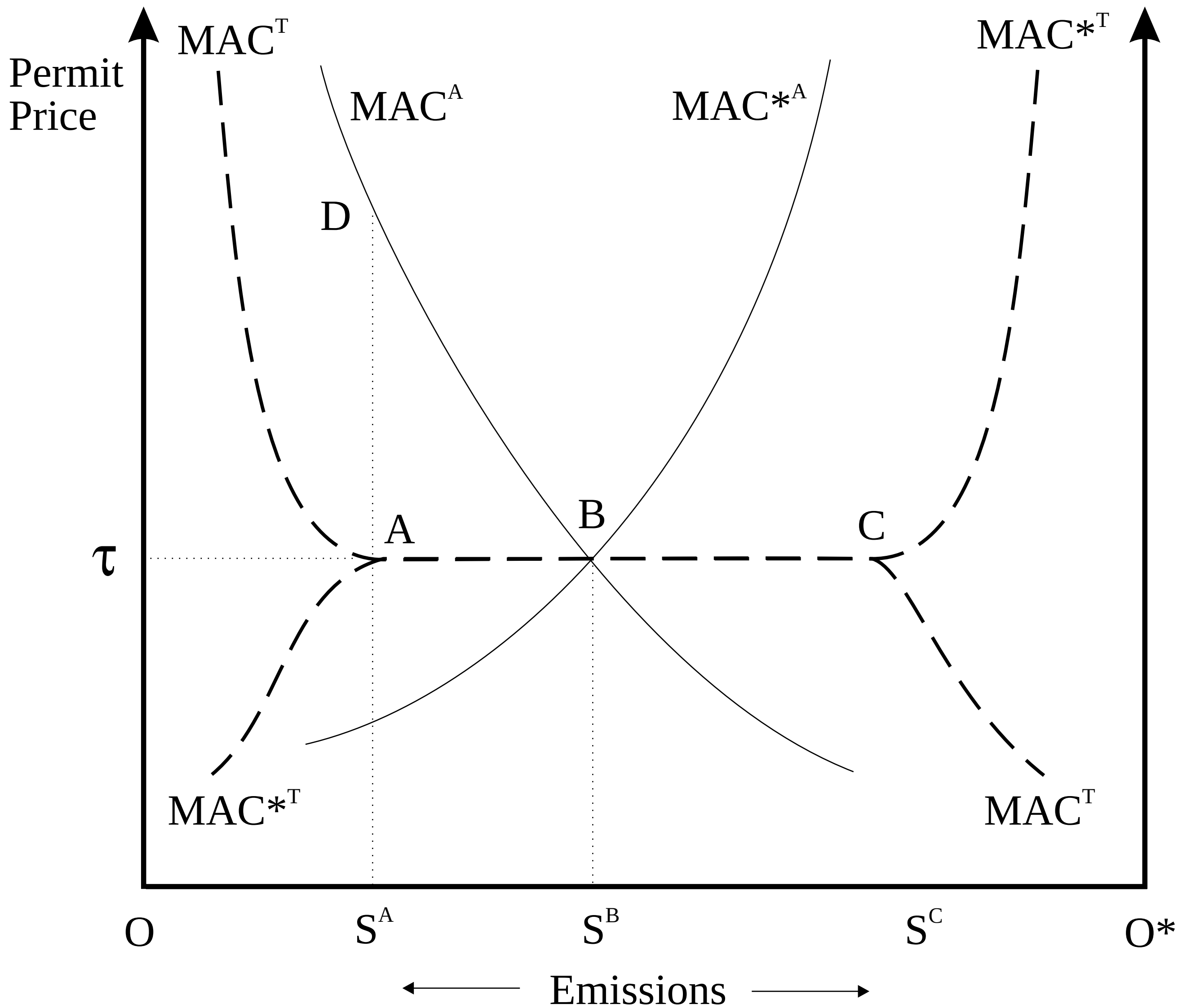


**Figure 3.**
**Marginal abatement cost curves and efficiency**

The solution to (20) 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 (20). Thus we conclude that for efficiency, North's share of permits $S(Z)$must be equal to its share of human capital:

$$S(Z) = \frac{h}{h + h^*} \tag{21}$$

What is striking about this rule is that for any level of world emissions $Z$, there is only one allocation of emissions across countries that is efficient, regardless of the weight $\lambda$ placed on North in the solution to the planner's problem (17). 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 – movements away from B in Fig. 3 lead to differences in marginal abatement costs. 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. That is, there is only one path $S(Z)$ that is efficient. If lump sum transfers and international permit trading are ruled out, North and South 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.[23] 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 North. In autarky, this was not efficient because we moved down South's marginal abatement cost curve and up North'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 $\tau$ and $w$ in both North and South are fully determined by the zero profit conditions (15) and (16). These conditions are independent of the supply of permits in each country. 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 North and South and not in the price of emissions. North absorbs the extra permits by increasing clean good production and reducing dirty good production, and thereby begins to export the clean good. South does the reverse. But since both countries employ the same techniques of production, North’s production expansion in Y (and contraction in X), must exactly mirror changes in the South. Consequently, world supply of both goods is unaffected by the reallocation of emission rights.

On the demand side, a reallocation of permits from North to South raises income in

[23] Recall from the discussion after (20) that autarky goods prices are equalized across countries when $h/z = h^*/z^*$. Since $p = p^*$, there is no incentive to trade at point B.

the North and reduces it in the South. But because preferences are identical and homothetic,[24] 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.[25]

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 countries as long as each country continues to produce both goods. For very skewed allocations of permits, at least one country will specialize in production and permit prices are no longer tied down by goods prices. Once this occurs, then permit prices will differ across countries and marginal abatement cost curves are no longer flat and diverge, as illustrated.

We conclude that there is a continuum of allocations of permits between countries that is efficient. 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.

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24 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.

25 Another way to see that the marginal abatement cost curves have flat segments in free trade is to refer to Figure 2, and note that the slope of the real income frontier is $G_z/\Phi(p)$ which, for given p, is proportional to the marginal abatement cost $G_z$. The flat segment on the marginal abatement cost curve corresponds to the linear segment on the real income frontier.

A simple example that highlights the difference between free trade and autarky is the case where elasticities of substitution are unity in both production and consumption. In autarky, uniform reductions in emissions are never efficient except in the unlikely case where pre-treaty levels of emissions are such that 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, any point on the Pareto frontier can be implemented in infinitely many different ways when there is free trade in goods. For example, suppose North 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 North and $U^*$ in the South. This same distribution of utilities can be implemented by giving North any share of permits in the range ($S^B S^C$) to the right of point $S^B$ and requiring a lump sum transfer from North to South. Or North could be given a smaller share of permits and in return for a transfer from the South. As long as the allocation of permits is consistent with diversified production in both countries, production efficiency is assured.

Third, as is apparent from the discussion above, reallocations of permits and lump sum transfers can be perfect substitutes along the range $S^A S^C$ in Fig. 3. This gives countries a great deal of flexibility in implementing emission reduction agreements. If the political process focusses on choosing emission allocation rules that seem "fair", then they also have a good chance of being efficient as well.

Fourth, our results indicate that the projected costs of cutting emissions cannot be measured with reference to any one country’s marginal abatement cost curve in isolation (derived perhaps from engineering estimates, historical experience, or CGE estimates that fail to account for international trade). The costs of cutbacks depend critically on the role that international trade in goods can play in diffusing the costs of abatement across countries. We highlight this point with the following proposition:

**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 (15) and (16).

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 in this area 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.[26]

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[26] 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. Hanson and Slaughter (1999) also find evidence that states do not respond to changes in factor supplies via changes in factor supplies. Gandal, Hanson, and Slaughter (1999) find similar results for Israel. And Card and Dinardo (2000) conclude that the labour markets absorb immigrants primarily via output changes and not by wage changes.

In our context, failing to take into account the role of trade in affecting marginal abatement costs can lead to overestimates of the cost of adjusting to emission reductions. As an example, referring to Figure 3, suppose North 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, North's emission reduction would cost the much smaller area $BAS^AS^B$ under the perfectly elastic free trade marginal abatement cost curve.

Finally, our results in this section can be useful in interpreting the CGE literature. What is missing from that literature is an appreciation for how large a difference assumptions regarding the tradable goods sector 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.

## 6. The Gains and Losses from Permit Trade

We now turn to the case where free trade in goods alone is not enough to equalize marginal abatement costs across countries. This happens in our model if the allocation of permits across countries is outside the range AC in Fig. 3. Firms in different countries will then have an incentive to trade emission permits to reduce their abatement costs.

It is tempting to infer from standard gains from trade results that the resulting permit trade must benefit both buying and selling countries. This point is often made explicitly in discussions of the Kyoto Protocol. 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).

However, while permit trade does indeed benefit all countries in autarky, it can be welfare-reducing if countries are already trading goods.[27] This is because trade in pollution permits can change world goods prices, which must necessarily worsen at least one country's terms of trade. As well, even though total pollution generated by permit-trading regions is the same before and after the trade, world emissions may rise because of the responses of unconstrained countries to changed goods prices. Permit trade may therefore both reduce real income in some countries and raise global pollution.

***Welfare effects of permit trade***

To focus on the differences between permit trade in open and closed economies, we divide the world into two regions: North and South. We initially assume that countries in each region are identical, with Northern countries being abundant in human capital relative to the South ($h/z > h/z^*$). Let $\tau$ be the permit price in the North and $\tau^*$ be the permit price in the South. Suppose $\tau > \tau^*$, so that Northern firms want to import permits from the South. This occurs in our model if the allocation of permits is to the left of point $S^A$ in Fig. 3.

We consider a small amount of trade in permits. This is the case most relevant to the Kyoto agreement, since there is resistance to the idea of complete free trade in permits, with many countries suggesting that each country be required to meet a significant amount of its reduction target through abatement rather than by buying permits.[28]

We start by obtaining a general expression for the welfare effects of permit trade, and

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[27] Standard gains-from-trade theorems compare welfare in trade with complete autarky (no trade in any goods or factors). With pre-existing trade in goods, we cannot simply apply the theorems.

[28] See for example Zhang's (1998) discussion of international trade "supplemental to domestic actions".

then use this to contrast the closed and open economy cases. North's budget constraint is:

$$I = G(p, h, z + z^I) - \tau^I z^I \tag{22}$$

where $z^I$ denotes net imports of pollution permits, and $\tau^I$ is the price at which permits are traded internationally.[29] To find the welfare effect on the North of a small amount of permit trade, totally differentiate (4) and use (22) to obtain:

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

The first term in brackets in (23), $\tau - \tau^I$, represents the standard gains from trade in permits for given goods prices. Since a buyer must willingly agree to a trade, we must have $\tau \geq \tau^I$, so that the direct gains from trade must always be non-negative. The second term is the terms of trade effect, which is relevant only when there is international goods trade (i.e., when $m \neq 0$), and the final term is the effect of permit trade on global pollution. We discuss each of these terms in more detail below as they become relevant.

***Autarky***

If there is no trade in goods, then permit trade cannot be harmful. The terms of trade effect drops out of (23) when there is no goods trade ($m = 0$). And there is no effect on global pollution ($dZ/dz^I = 0$) even if some countries are unconstrained by emissions treaties. 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. This leaves only the direct gains from trade term in (23) and so permit trade must be beneficial:

**Proposition 7.** Suppose all countries are initially in autarky (with no trade in any goods or factors), and that there are no distortions (except possibly that the aggregate level of allowable

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[29] Since we are considering only small trades, the price at which permits are traded will be determined by bargaining between buyer and seller (which we do not model here). Individual rationality puts bounds on the price: $\tau^* \leq \tau^I \leq \tau$.

pollution may be too high or low). Then trade in emission permits between countries constrained by emission limits cannot harm any country.

Proof: see appendix

Proposition 7 captures the standard argument for mutually beneficial trade in permits. If abatement costs are lower in the South than the North, then the extra output that North can generate by increasing its pollution is more than enough to compensate the South for reducing its pollution. Trade in permits allows global consumption to rise without any increase in pollution, and each country shares in these gains.

***Permit Trade in an Open Economy with all countries constrained by an emissions treaty***

Now suppose there is free trade in goods. First consider the case where all countries are constrained by an emissions treaty. Permit trade does not affect global pollution in this case, and so (23) reduces to:

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[(\tau - \tau^I) - m\frac{dp}{dz^I}\right] \tag{24}$$

The direct gains from trade must now be weighed against a terms of trade effect. Since North imports X ($m > 0$), its terms of trade deteriorate if $p$ rises and improve otherwise. Permit trade can either increase or decrease $p$, as we shall see below. But with any price change, at least one country's terms of trade must worsen. Losses from permit trade occur when a terms of trade deterioration more than offsets the direct gains from trade. This possibility can arise for either North and South, depending on relative *h/z* ratios.

If North produces only clean goods (Y),[30] then a permit flow from South to North must increase world Y output and reduce world X output. Hence $p$ rises and North's terms of trade deteriorate. If North buys permits at their domestic opportunity cost ($\tau = \tau^I$), then all of the direct gains from trade go to the South, and it is clear from (24) that the North will lose

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[30] This case arises if North's h/z ratio is sufficiently large.

from this trade since it is left with only a terms of trade deterioration.

But if North produces *both* X and Y, while South produces only X,[31] then a permit inflow in the North will stimulate the supply of X at the expense of Y in the North. The expansion in Northern X output will be larger than the Southern contraction because the marginal product of permits in X is higher in the North than the South (since $\tau > \tau^*$).[32] Hence $p$ falls in this case. If South does not receive any of the direct gains from permit trade, then from the Southern analog to (24), South will lose since its terms of trade deteriorate.

Figure 4 illustrates the possibility of losses from permit trade for the first case discussed above, where North specializes in the production of Y. The left panel depicts North's domestic permit market. North's demand for permits is $G_z$, and prior to permit trade, its permit supply is $z_o$, yielding a Northern permit price of $\tau_o$. If North imports $z^I$ permits at price $\tau^I$, there will be direct permit trade gains given by the shaded area abc. The middle panel (Fig. 4b) illustrates the effect of this trade on the world goods market. The world demand for X relative to Y is denoted RD, the initial world relative supply is $RS_o$, and the initial relative price of x is $p_o$. A sale of permits from South to North reduces the supply of X in the South and increases Northern output of Y. Hence the RS curve shifts left to $RS_1$, pushing up the price of x to $p_1$. The effect of this price increase on the North is illustrated in right panel (Fig. 4c). North's compensated import demand for X is labelled M. The welfare cost of the increase in p is measured by the area defg. If the direct permit gains (abc) are less than the terms of trade loss (defg) as illustrated, then North loses from permit trade.

Why does North agree to a permit trade that ultimately ends up being harmful? The key is that "North" doesn't agree to these trades, but rather small Northern firms do. Individual firms (or individual Northern countries) 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

31 This case arises if South's h*/z* ratio is sufficiently small.
32 See appendix for proof.

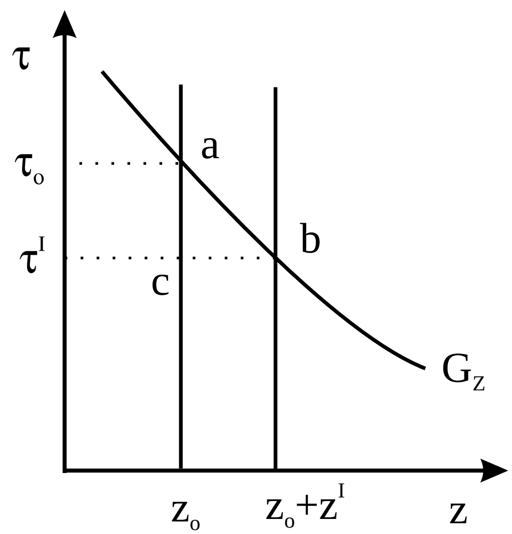


**Figure 4a.**
**North's permit market**

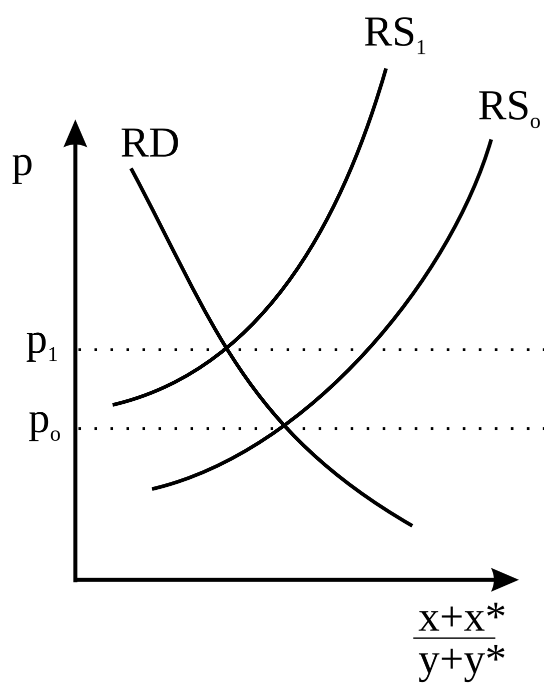


**Figure 4b.**
**World goods market**

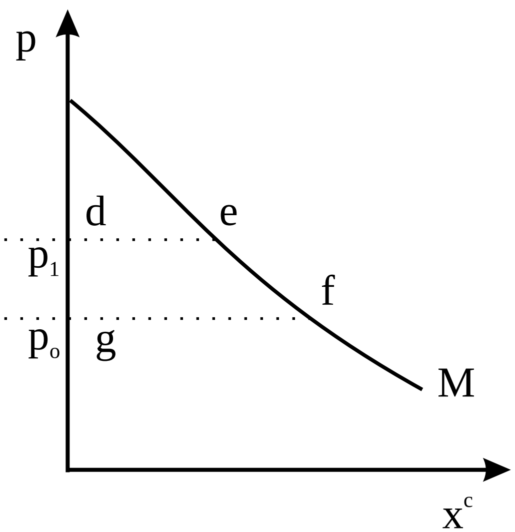


**Figure 4c.**
**North's import demand**

that the governments of Northern countries could anticipate the terms of trade deterioration and perhaps join with other Northern countries to block such trades, but that is precisely our point: free trade in emission permits may not be beneficial to all countries.[33]

Although our discussion above focuses on the case where the losing country enjoys either none or only a small portion of the direct gains from permit trade, this is not necessary for the result. It is possible for either region to receive *all* of the direct benefits from permit trade and still lose. Moreover, nothing perverse is required for this to happen – it can occur in a simple Cobb-Douglas economy. We give an example in the appendix, and hence can show that:

**Proposition 8.** There exist economies in which North loses from permit trade even when it receives all of the direct gains from permit trade with South by buying the permits at the current Southern market price: $\tau^I = \tau^*$.

Proof. See Appendix.

Proposition 8 merely points out that terms of trade effects can be significant. We cannot simply assert that the direct gains will swamp terms of trade effects.[34]

Of course permit trades of the type discussed in this section always improve global production efficiency. Our point here is that the distributional effects of such trades need not benefit both parties to the trade.

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33 Results from CGE models illustrate the sometime large distributional consequences of trade in emission permits that we are highlighting here. For example, in McKibbin et al. (1999), Japan loses about $16 billion when free trade in emission permits is introduced.

34 This shouldn't be surprising. Take for example a situation where South produces X and North produces only Y. The direct gains from permit trade are proportional to the difference between permit prices across countries ($\tau - \tau^*$). But the terms of trade effect depends on a weighted sum of permit prices since it reflects the fall in the supply of X in the South (proportional to $\tau^*$) and the increase in the supply of Y in the North (proportional to $\tau$). Therefore, there exist situations where the terms of trade effect of a permit trade can be large even if the direct gains from trade are relatively small.

***Permit trade can harm both the buyer and seller***

A more striking result is that in a world with at least three countries, *both* the permit buyer and seller can lose from permit trade. The buyer and seller of permits may suffer a terms of trade loss if they both export the same good to the rest of the world. If this terms of trade loss is large enough, both may lose from the trade. To see that this is possible, consider the following example.

Suppose there are two Northern countries, A and B, both of which export good Y to the South. Suppose South is specialized in X, Northern country B is diversified, and Northern country A is specialized in Y.[35] With this pattern of production, we consider the effects of a permit sale from B to A. To do so, it is useful to consider the fiction of a representative consumer straddling countries A and B. Factor endowments and technologies cannot move across boundaries for production, but the consumer has access to the final goods of both. If we show that this fictional representative consumer is made worse off by the trade, then for some division of the permit trade gains, both countries must lose.

The income of the representative Northern consumer is

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

A permit trade sale from B to A reduces X production in B and increases Y production in A. Both effects push up the price of X. The effect on Northern utility is

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[(\tau^A - \tau^B) - m\frac{dp}{dz^I}\right], \qquad (25)$$

where $m$ is net imports of the two Northern countries from the South. Since $p$ rises and $m>0$, the terms of trade effect works against the direct gains from trade effect. Both Northern countries can lose from the permit trade if the terms of trade effect is sufficiently strong. We confirm that this can happen in the appendix, and hence can show:

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[35] This will arise with $z^A/h^A < z^B/h^B < z^*/h^*$, and with differences sufficiently large that A specializes in Y. Note also that in this case, we have $\tau^A > \tau^B$.

**Proposition 9.** In a world with at least three countries, all of which are constrained by an emissions treaty, it is possible for both the permit buyer and seller to lose from a permit trade that is freely entered into by price-taking firms.

Proof: See appendix.

Permit trade here leads to an outcome which is similar to immiserizing growth.[36] By trading permits, the two Northern countries increase their production efficiency. Moreover because of the pattern of specialization, this increase in production efficiency increases the joint supply of their export good. Hence permit trade in this case is not unlike the effects of "growth" in the combined output potential of the two Northern countries. As Bhagwati (1958) showed, growth in one's export sector may be harmful if the terms of trade deterioration offset the direct benefit of growth.

***Permit-trade-induced Carbon leakage***

In the above analysis all countries were constrained in their permit choice, and so permit trade did not affect world pollution. More realistically, some countries may choose their emissions unilaterally. This is relevant to the Kyoto protocol where much of the developing world is unconstrained in its choice of emission levels.

Permit trade will affect emissions in unconstrained countries via its effect on world goods prices. This is different than the standard "leakage" argument. Standard carbon leakage occurs when dirty good production expands in the South in response to a higher dirty good price created by the North’s unilateral cutback in emissions. Permit-trade-induced carbon leakage arises when permit trade alters world prices but the North is holding its aggregate emission level constant.

We can illustrate this possibility with the same pattern of production laid out in the

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[36] If Northern A and B have different preferences then the conditions under which both can lose from permit trade expand, since payment for permits acts like a transfer of income across countries. If the benefits of permit trade go to the country with the largest marginal propensity to consume their importable, then the terms of trade deterioration is greater than that in the current proposition.

previous section – two Northern countries A and B exporting the clean good to the South. The only difference is that we assume that South is free to choose its emissions unilaterally, while A and B are constrained by a treaty. As we found in the previous section, a sale of permits from B to A leads to an increase in the price of X.

South's response can be found by combining the substitution and income effects we previously derived in (13) and (14) and simplifying to take into account South being specialized in X. This yields:

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

where recall that $\Delta > 0$. If marginal damage is relatively unresponsive to income ($\varepsilon^*_{MD,R} < 1$), then carbon leakage dominates and emissions in the South rise as a result of Northern permit trade. However when $\varepsilon^*_{MD,R} > 1$, the bootstrapping effect dominates and emissions will fall in the South. Summarizing:

**Proposition 10.** Suppose the North is constrained by binding pollution quotas while the South is unconstrained. Suppose also that the South is specialized in the dirty good, Northern country A is specialized in the clean good, Northern country B is diversified, and both Northern countries export the clean good. Then if $\varepsilon^*_{MD,R} < 1$, then trade in permits between the two Northern countries will increase world pollution. If instead $\varepsilon^*_{MD,R} > 1$, Northern permit trade will reduce world pollution.

The conditions for Prop. 10 to hold are much weaker than those needed in Prop. 9 for permit trading to be immiserizing. All that is required for Northern permit trade to increase world pollution is that the price of the dirty good rise, and income effects in the South be relatively weak. If in addition the terms of trade effect is very strong, then permit trade can both increase global pollution and reduce real income in the trading countries.

## 7. Conclusion

This paper has shown how the presence of international trade can significantly alter some standard results in environmental economics. International trade introduces two important adjustment channels not present in autarky: terms of trade effects, and the possibility of substituting trade in goods for trade in factors. These channels can have a major impact on how economies respond to emission cutbacks.

In the standard literature, domestic and foreign emissions are strategic substitutes: emission cutbacks in one country lead to increases in emissions by unconstrained countries because of the free rider problem. This is also true in our model in autarky. But with international trade, emission cutbacks affect the world price of dirty goods, and the ensuing terms of trade effects lead to a much richer strategic interaction between countries. The CGE literature has focussed on carbon leakage, which tends to reinforce the free rider effect and suggests that unilateral emission reductions may be even more harmful in free trade than in autarky. Our contribution has been to show that once we examine the full implication of both endogenous policy (which is necessary for free riding) and endogenous world prices (which is necessary for carbon leakage), there are both substitution and income effects affecting the demand for environmental quality that may more than offset carbon leakage. With these extra adjustment channels, it is possible for domestic and foreign emissions to be strategic complements.

Our results on permit trade also follow from terms of trade effects. In partial equilibrium or closed economy models, emission permit trade must benefit buyers and sellers of permits. But in an open economy, trade in emission permits will affect the terms of trade in the goods market. These terms of trade effects will in turn create income gains and losses for regions party to the original permit trade, and for all other excluded countries. One consequence of this is that permit trades voluntarily entered into by a region’s private agents can produce welfare losses for this same region. Another consequence is that when a group of countries in the world are unconstrained in their pollution choice, world pollution may rise when these excluded countries raise their emission levels in response to changed world prices. Permit trade between two constrained regions can also be immizerizing. We do not wish to argue against permit trade, since in many cases it can increase global production efficiency. But a more realistic assessment of its potential adverse distributional and environmental consequences may speed the way to a more widespread agreement on permit trade.

Finally, international trade also has a major impact on the efficiency of emission reduction rules. In standard autarky or partial equilibrium models, rigid emission reduction rules are inefficient because marginal abatement costs differ across sources. The intuition from the standard analysis suggests that politically-inspired rigid reduction rules across countries will be inefficient unless an international emission permit trading regime is introduced. But as Mundell (1957) pointed out, international trade in goods can be a substitute for international trade in factors; and in our context, we find that international trade in goods can substitute for international trade in emission permits. This suggests that there are a great many emission reduction rules that will lead to efficient allocations, and that the costs of not introducing an emission permit regime may be drastically overestimated if we use models which give only a limited role to international trade.

Throughout our analysis we have adopted a model that is purposefully 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. In a more general model, some of our results will lose their sharpness. However, the two key mechanisms we have highlighted – terms of trade effects and the substitution of trade in goods for trade in factors – will continue to be important and should play a more prominent role in open economy environmental economics.

# Appendix

**Proof of concavity of real income in z**

Assume T(h,z) is convex and the subutility function q(x,y) is homogeneous of degree 1 and concave (this yields an indirect subutility function of the form I/Φ(p)). Define

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

Note this is the same as our definition of real income in equation (1.5) 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 $(x^\lambda,y^\lambda)$ solve (A1) for $(h^\lambda,z^\lambda)$. Then:

$$\begin{aligned} R(h^\lambda,z^\lambda) = q(x^\lambda,y^\lambda) &\geq q[\lambda(x^o,y^o) + (1-\lambda)(x^1,y^1)] \\ &\geq \lambda q(x^o,y^o) + (1-\lambda)q(x^1,y^1) \quad \text{since q is concave} \\ &= \lambda R(h^o,z^o) + (1-\lambda)R(h^1,z^1) \end{aligned}$$

The first inequality above follows since by the convexity of Θ, $\lambda(x^o,y^o) + (1-\lambda)(x^1,y^1)$ is feasible but not optimal for $(h^\lambda,z^\lambda)$.

**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 $u$ in the country under consideration:

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

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

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

where $z(Z_{-k}, p, T)$ is the uncompensated supply of emissions we 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

$$z_p = z_p^c - z_T m / \Phi(p). \tag{A3}$$

Substituting (A3) into (10) yields (11).

**Proof of Corollary 3.1**

First suppose the country is specialized in the dirty good. Since $MD_Z = 0$, then $\varepsilon_{MD,z} = 0$. As well, if the country is producing only X, then $\varepsilon_{\tau p} = 1$. Plugging these into (C1) and noting that $\theta_X = 1 - \theta_{Xc}$ if the country is specialized in x production reduces (C1) to that $\varepsilon_{MD,R} > 1$. If instead the country is specialized in the clean good, then $\varepsilon_{\tau p} = 0$ and $\theta_X = -\theta_{Xc}$. Again, plug into (C1) and then (C1) reduces to the condition $\varepsilon_{MD,R} < 1$. Noting that imports $m < 0$ if the country is specialized in the dirty good and $m>0$ if the country is specialized in the clean good gives us the result.

**Proof of Proposition 4**

Given $Z$, the efficient allocation defined by (20) is unique if the marginal abatement cost curves $G_Z$ are strictly decreasing in z in both regions; that is, if

$$G_Z = G_{Zp}(dp/dz) + G_{ZZ} < 0. \tag{A4}$$

But $G_{ZZ} \leq 0$ from the properties of the GNP function; and $G_{Zp} = \partial\tau/\partial p > 0$ by the Stolper-Samuelson Theorem from international trade (note that both goods will be produced in autarky by our assumption that both goods are essential in consumption). By homotheticity we can let $RD(p)$ denote demand for X relative to Y, and by constant returns to scale we can let $RS(p,z)$ denote the supply of X relative to Y. Then in autarky, $p$ is determined by $RD(p) = RS(p,z)$, and

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

The inequality follows because (i) by the Rybczinski Theorem of international trade, we have $RS_z > 0$ since X is pollution intensive and output is increasing in $z$, (ii) we have $RS_p < \infty$ since technology is strictly concave and since X is always strictly more pollution intensive than Y; and (iii) we have $RD_p < \infty$ 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 integrated equilibrium which is the hypothetical equilibrium that would obtain if there were one integrated world economy with free factor mobility across countries and with endowment H=h+h* and Z. Let $(w^o,\tau^o)$ be the equilibrium factor price vector in this equilibrium, let $(x^o,y^o)$ be the world output vector in the integrated equilibrium, and let $a_x$ and $a_y$ be the unit input vectors for x and y in this equilibrium ($a_x \equiv (h_x,z_x)$ etc.). Now consider the set

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

That is, this is the set of allocations of endowments to the North (h,z) for which it is possible to solve North's full employment conditions at factor prices $(w^o,\tau^o)$ with outputs no larger than produced in the integrated equilibrium. If this can be done, then South'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. This allocation therefore yields a free trade equilibrium which replicates the integrated equilibrium, and hence in which factor prices are the same in North and South, which in turn implies marginal abatement costs are equalized so that production efficiency is obtained.

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) and hence span a two dimensional space. Now fix h < H to be North's endowment of human capital. This yields a slice through the parallelogram V; that is, for any h, there will be 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. Hence as Z falls, there are infinitely many allocations of permits across countries that are efficient.

**Proof of Proposition 6**

Suppose the allocation of emissions across countries is consistent with diversified production by both regions. Then for this level of global pollution, there is an equilibrium goods price p, and via the zero profit conditions, this implies a common τ/w ratio and equal marginal abatement costs. For this given ratio of factor prices we then determine the equilibrium emissions to human capital ratio in each industry ($z_x/h_x$ and $z_y/h_y$). Since factor prices are identical across regions, these ratios are the same in both regions. To be consistent with factor market clearing in each country, each country's endowment ratio ($z/h$) must lie between the industry input ratios. That is, we have $z_y/h_y < z/h < z_x/h_x$ in the North and $z_y/h_y < z^*/h^* < z_x/h_x$ in the South.

Note that equiproportionate reductions require $\hat{z} = \hat{Z} = \hat{z}^*$. Since human capital levels are given, an original allocation within the factor price equalization set would remain in the set in this case if $\hat{z}_x = \hat{z}_y = \hat{z}$ and similarly for the South. We prove this below. Note that from the cost minimizing conditions, we can obtain $(z_x / h_x)^{\wedge} = -\sigma_x(\hat{\tau} - \hat{w})$ where $\sigma_x > 0$ is the elasticity of substitution in X with respect to input prices. A similar expression holds in industry Y. Using standard manipulations (see Jones (1965)), we can solve for the change in factor prices when global emissions $Z$ change, taking into account the induced goods price change. This yields

$$\hat{(z_x / h_x)} = \frac{\sigma_x \hat{Z}}{|\theta||\lambda|(\sigma_s + \sigma_D)}$$

where $\sigma_S$ is the elasticity of substitution between X and Y along the production frontier, $\sigma_D$ is the elasticity of substitution in demand, $|\theta| = \theta_{XZ} - \theta_{YZ} > 0$, and $|\lambda| = \lambda_{XZ} - \lambda_{XL} > 0$ given our factor intensity assumptions. $\theta_{ij}$ is the share of input j in the cost of good i, and $\lambda_{ij}$ is the fraction of input j employed in sector i. Similarly,

$$\hat{(z_y / h_y)} = \frac{\sigma_y \hat{Z}}{|\theta||\lambda|(\sigma_s + \sigma_D)}$$

Hence as world pollution rises, the z/h ratio must rise in both industries. In the special case with $\sigma = \sigma_X = \sigma_Y = \sigma_D = 1$, the above simplifies and we have: $\hat{(z_x / h_x)} = \hat{(z_y / h_y)} = \hat{Z}$. Therefore, any allocation with equal marginal abatement costs retains this property as cutbacks occur.

**Proof of Proposition 7**

This is a standard gains-from-trade proof (see for example, Grossman, 1984). Let p denote the goods price vector after free permit trade, let $\tau$ denote the equilibrium permit price and let $z^I$ denote net imports of permits (if permits are exported, then $z^I < 0$). Also u is the 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 corresponding to u. Then we have:

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

The first equality is the budget constraint of the economy in permit trade. The next step (the first inequality) follows since the private sector maximizes national income: the 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, we conclude u must be at least as great as $u^a$ since the expenditure function is increasing in utility.

**Proof for footnote 32:**

We need to show that when the South is specialized in X and North is diversified, then $dp/dz^I < 0$ (that is, a sale of permits from South to North reduces the price of the dirty good). To show this define $\lambda$ so that $\tau - \tau^I = \lambda(\tau - \tau^*)$. (note: $0 \le \lambda \le 1$). Then $\tau^I - \tau^* = (1-\lambda)(\tau - \tau^*)$. Then using the equilibrium conditions for the market for x we can find the terms of trade effect as

$$\left.\frac{dp}{dz^I}\right|_{z^I=0} = \frac{x_I(\tau - \tau^I) + x_I^*(\tau^I - \tau) - \left(G_{pz} - G_{pz}^*\right)}{D}$$

where $x_I$ and $x_I^*$ are the income derivatives of the demand for X in North and South, respectively (these are positive since both goods are normal), and $D > 0$ under the Marshall-Lerner stability condition. Then we have:

$$D\frac{dp}{dz^I} = \lambda x_I(\tau - \tau^*) + (1-\lambda)x_I^*(\tau - \tau^*) - (G_{pz} - G^*_{pz^*})$$

$$< \lambda x_I(\tau - \tau^*) + (1-\lambda)x_I^*(\tau - \tau^*) - (\tau/p - \tau^*/p)$$

$$= \frac{(\tau - \tau^*)[\lambda p x_I + (1-\lambda)p x_I^* - 1]}{p} < 0,$$

where the final inequality follows since $px_I < 1$ and $px_I^* < 1$. (recall $x_I = \partial x^c/\partial I$, where $x^c$ is demand for x). Note $G_{pz} = \partial x/\partial z > \tau/p$ because of the Rybczinski theorem, while $G^*_{pz^*} = \tau^*/p$ since South is specialized. Hence provided the Marshall - Lerner condition holds (i.e., $D > 0$), the above implies that $dp/dz^I < 0$ as required.

**Proof of Proposition 8**

Since emissions are constant throughout we suppress the effect on Z on utility and assume $u = xy$; as well assume endowments are mirror images ($z^* = h$, $h^* = z$); and South is abundant in permits ($z^*/h^* > z/h$). Technology is given by $x = z^{\beta}h^{1-\beta}$ and $y = z^{1-\beta}h^{\beta}$, with $\beta > 1/2$ so that x is pollution intensive. By construction $p = 1$. If both countries are diversified in production, we also have $\tau/w = 1$, and using this, the boundaries of the cone of diversification are $z_x/h_x = \beta/(1-\beta)$ and $z_y/h_y = (1-\beta)/\beta$. Hence if $z^*/h^* > \beta/(1-\beta)$ and $z/h < (1-\beta)/\beta$, both countries specialize in production. Because permits are scarce in the North and the two countries face a common goods price (because of free trade in goods), we have $\tau > \tau^*$. Suppose the South sells a permit to the North. This will reduce the supply of X and increase the supply of Y (and given preferences are identical and homothetic), the price of X will rise. Hence South's terms of trade improve and it must gain. Suppose we assume all of the direct gains from permit trade are given to the North. That is, North's buys the permit at the Southern price $\tau^*$. The effect on North's welfare is

$$E_u du = (\tau - \tau^*)dz^I - m dp.$$

Imports m are just North's demand for X, and hence m = Y/2p (recall that North's income is just Y). And equating relative demand and supply yields

$$p = Y/X^*.$$

Differentiating the equation above and using the condition that the value of the marginal product of emissions is the permit price, we obtain the change in p from the permit trade:

$$dp = (p\tau/Y + \tau^*/X)dz^I.$$

Substituting for dp into our first statement and simplifying yields

$$E_u du = (\tau - 3\tau^*)/2.$$

But from the Cobb-Douglas technology we have $\tau z/Y = (1-\beta)$ and $\tau^* z^*/X^* = \beta$. Since also Y =X* by construction, we have

$$\tau/\tau^* = \beta z^*/(1-\beta)z$$

Using this in the above shows that we have both $\tau > \tau^*$ and $E_u du/dz^I < 0$ if

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

Finally note that for this to be possible and consistent with X being pollution intensive, we require $\beta \in (1/2,3/4)$.

**Proof of Proposition 9.**

Totally differentiating the market clearing condition for X yields

$$\frac{dp}{dz^I} = \frac{x_I(\tau^A - \tau^B) - (\frac{\partial x^A}{\partial z^A} - \frac{\partial x^B}{\partial z^B})}{D^{AB}} , \qquad \text{(A5)}$$

where $D^{AB} = S + x_I m + x_I m^*$, with $S = G^A{}_{pp} + G^B{}_{pp} + G^*{}_{pp} - E_{pp} - E^*{}_{pp} > 0$. (Southern terms are denoted with an asterisk (*) as usual.) Stability requires $D^{AB} > 0$.

Using (A5) in (25) yields

$$\left.\frac{du}{dz^I}\right|_{z^I=0} = \frac{u_R}{\Phi(p)}\left[\frac{(\tau^A - \tau^B)(S + x_I^* m^*) - m\,\frac{\partial x^B}{\partial z^B}}{D^{AB}}\right], \qquad \text{(A6)}$$

where $m^* < 0$ since south exports X and $\partial x^B/\partial z^B > 0$ since X is intensive in emissions. Note that there are two ways that utility may fall from the permit trade. First, if pure substitution effects (embodied in S) are locally small, and the foreign income effect ($x_I^* m^* < 0$) 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 B can be enough to cause a price increase big enough to lower Northern utility. This result 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 North and South can be collectively worse off, and there will exist some division of the permit trade gains such that both can lose from the trade.

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