

Markusen, James R.

**Working Paper**

## Per-Capital Income as a Determinant of International Trade and Environment Policies

CESifo Working Paper, No. 4618

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*Suggested Citation:* Markusen, James R. (2014) : Per-Capital Income as a Determinant of International Trade and Environment Policies, CESifo Working Paper, No. 4618, Center for Economic Studies and ifo Institute (CESifo), Munich

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## Per-Capita Income as a Determinant of International Trade and Environmental Policies

James R. Markusen

CESIFO WORKING PAPER NO. 4618

CATEGORY 8: TRADE POLICY

JANUARY 2014

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# Per-Capita Income as a Determinant of International Trade and Environmental Policies

## Abstract

International trade policy analysis has tended to focus on the production side of general equilibrium, with policies such as a tariff or carbon tax affecting international and internal income distributions through a Heckscher-Ohlin nexus of factor intensities and factor endowments. Here I move away from this structure to focus on demand, preferences, and endogenous policies set in a cooperative or non-cooperative manner. The specific context I choose is an international environmental externality such as carbon emissions, and I assume a high income elasticity of demand for environmental quality. I analyze how per-capita income levels of and differences between two countries affect their abatement efforts in a non-cooperative policy-setting game. This outcome can then be used as a disagreement point to analyze cooperative Nash bargaining. In both outcomes, the poor country makes a lower abatement effort in equilibrium; indeed, it may make none at all and cooperative bargaining with only abatement levels as an instrument may offer no gains. Other features include a novel terms-of-trade externality in which an abating country passes on a part of its abatement cost to its trading partner, in which case the non-cooperative and cooperative outcomes are identical under special symmetry assumptions. When per-capita income differences are large, the poor country may be worse off when the rich country abates. Finally, I examine “issue linking” in international bargaining, in which one country is both large and rich, and hence has both a high tariff and a high abatement effort in a non-cooperative equilibrium.

JEL-Code: F000, F180, F210, Q560.

Keywords: trade and environment, per-capita income, environmental policy.

*James R. Markusen*  
*University of Colorado, Boulder*  
*james.markusen@colorado.edu*

January 2014

I am primarily a trade economist and have been away from environment issues for a couple of decades. So I am currently seeking and reading related papers. I am especially interested in finding empirical work that estimates something like an income elasticity of demand for environmental quality. Please send references with attached notes explaining their relevance. Self-references are most welcome.

This paper originated following an invitation to present a paper at the conference *Environmental Protection and Sustainability Forum*, held at the University of Exeter April 13-15, 2011, which reignited a long-dormant interest in trade policy, more specifically trade and the environment. The first draft was finally written while a visitor at Hitotsubashi University, and I thank my colleagues there for a delightful and productive three months.

## 1. Introduction

Much of the literature on trade policy concentrates on the production side of general equilibrium. In the trade/environment literature for example, a typical model might involve the nexus among factor intensities in production, factor endowments of countries, and pollution intensities across goods. A common question might be how changes in trade or environmental policy of one country then change total world pollution and the distribution of pollution emissions across countries (e.g., the carbon leakage and pollution-haven literatures).

Considerations of the role and determinants of the demand for environmental quality across countries and hence endogenous policy are less featured, with the exception of a few papers on the environmental Kuznets curve. Per-capita income differences have, of course, played a prominent role in climate negotiations (most recently in Poland), with poor countries arguing again having to bear restrictions while high income countries want an even burden sharing. Many of the arguments strike me as playing at ethics, such as arguing whether or not the high-income countries' historic contribution to the stock of atmospheric CO<sub>2</sub> means that they should bear much of the burden. Economic analysis seems lacking.

The principal focus of the paper is on how the per-capita income levels of and differences between two countries affect their abatement efforts in a non-cooperative policy-setting game. This outcome can then be used as a disagreement point to analyze Nash bargaining to solve for a cooperative outcome. To attack this problem, I develop a model of non-homothetic preferences in which environmental quality has a high income elasticity of demand. At the same time, the usual production side factors just mentioned are neutralized via the use of a novel constant elasticity of substitution transformation function. Global, trans-boundary pollution depends only on both countries' total production and resources withdrawn from production are used in an abatement activity, financed by a non-distortionary tax. Comparative advantage in two consumption goods links the countries through trade, such that more abatement by either country shifts world commodity prices in that country's favor by withdrawing resources from production.

After developing the general two-country model, I present a simplified version which I call the "model of the model", with which we can derive analytical solutions for best responses by each country to the other country and how these best response functions and the non-cooperative Nash equilibrium relate to the levels of and differences between per-capita incomes in the two countries. Following this, I develop the a general simulation model using a relatively novel optimization solver in GAMS. I model the general-equilibrium policy problem as an MPEC (mathematical programming with equilibrium constraints). In a non-cooperative outcome, each country chooses an abatement tax, and a tariff in a later section, to maximizing its utility given the tariff and tax of the other country, with the two-country general-equilibrium model as a constraint set. Cooperative outcomes can be found using non-cooperation as a disagreement outcome, which I contrast to other reference solutions for world welfare.

A couple of basic results are apparent in the analytical model, illustrated again in the general-equilibrium model. One result is that optimal abatement policy produces a non-

monotonic Kuznet's curve. As per-capita income rises from a very low level, environmental quality falls, but later rises as an abatement policy is instituted, with the share of income devoted to abatement increasing in per-capita income. Second, non-cooperative policy is characterized by "policy leakage"; that is, a government will reduce its abatement effort in response to an increase by the other country. Third, an interesting result emerges when the two countries are identical and have a strong pattern of comparative advantage. Because an abating country passes on half the cost to the other country in a non-cooperative equilibrium, it turns out that the non-cooperative and cooperative outcomes are identical in a special case.

The main project is to examine non-cooperative and cooperative outcomes with respect to abatement efforts by two countries of equal total income. Allowing the per-capita income of the countries to differ holding total income constant (e.g., one country has fewer but more productive households), the Nash non-cooperative policy outcome has a higher abatement effort by the high-income country and a lower effort by the poor country relative to when both countries have identical per-capita incomes. The same is true for a cooperative Nash bargaining outcome using the non-cooperative outcome as the disagreement outcome.

Two further experiments are conducted on this question. In the first alternative to the base case, comparative advantage is eliminated so that there is no trade and no effect of one country's abatement on the terms of trade. This reduces the non-cooperative abatement effort of both countries, since a small increase in abatement no longer shifts the terms of trade in that country's favor. I note that it can now be the poor country that gains more at both the cooperative and non-cooperative outcome relative to zero abatement by both countries (it does not have a terms-of-trade loss).

In the second alternative case, the difference in the per-capita income of the two countries is widened considerably (returning to base-case comparative advantage). One interesting result is that the poor country may be made worse off by an optimal abatement effort by the rich country, since the term-of-trade deteriorating for the poor country may outweigh the smaller benefits of any spillover improvement to its environment. This case also illustrates an important policy point, which is that there may be no gains to cooperation if abatement efforts are the only instrument available to the two countries in their bargaining.

A natural extension of the analysis is to consider "issue linking" in international bargaining. Specifically, there is the standard motive for protection in that an import tariff improves a country's terms of trade. Is there a role for linking together bargaining on abatement efforts with trade liberalization? A clear possibility occurs when the rich country is also large, so that it will have a high tariff in a Nash equilibrium in tariff rates, as well as a high abatement tax. I present a case in which linking helps the small poor country without harming the large rich country, but bargaining theory suggests that robust results are unlikely.

Before turning to a brief literature review, two motivating data plots are given in Figures 1a and 1b. Figure 1a plots an environmental sustainability index from the Global Competitiveness Report against the log of country per-capita income. While there is variation in

the data, it is clear that richer countries have more sustainable policies despite having a lot more production and consumption. Because the policies behind this are unclear, Figure 1b show data on a specific policy. Although their focus is different from mine, Broner, Bustos and Carvalho (2012) have essentially shown a relationship between environmental standards and per-capita income, using the national standards on the maximum lead content of gasoline (petrol) across countries. I have gone to the source of this data (Lovei 1998) and show it in a plot against log per-capita income for the same year as the lead-content data (1996) from World Bank statistics in Figure 1b. Richer countries adopt tougher and more costly standards.

There is an immense amount of literature related to this paper, in part because it overlaps a little with three quite separate agendas. First there is the trade and environment literature. Second, there is a literature on income elasticities of demand generally and willingness to pay for environmental goods specifically. Third, there is a literature on bargaining and linked games. I have done a little work in all three areas but am an expert in none individually. I'll offer a short review, but will surely miss some things that are important. Please let me know.

The trade-and-environment literature is extensive, but few papers seem to include any theoretical consideration of per-capita income and non-homothetic preferences. Clearly, Copeland and Taylor's (2004) review article is a starting point, with other features in Copeland and Taylor (1994) and (2005). Papers embedding non-homothetic preferences in general-equilibrium trade models include Hunter (1991), Hunter and Markusen (1988), and Markusen (1986, 2013). There is a significant empirical literature on the environmental Kuznet Curve, relating environmental quality (or inversely pollution) to per-capita income or some other measure of development. Papers include Chiu (2012), Deacon and Norman (2006), Grossman and Krueger (1995), Selden and Song (1994) and Tang (2012). Evidence for a non-monotonic Kuznets Curve (environmental quality at first falls, then rises with per-capita income) seems mixed, but there are many separate factors at work other than simply preferences.

On the environmental economics side, there is a literature examining the income elasticity of demand for environmental quality and the income elasticity of willingness to pay. These are not the same as noted by Flores and Carson (1997) and it will be true in my model that the income elasticity of demand exceeds the income elasticity of willingness to pay.. Evidence that these income elasticities are clearly greater than one is mixed: evidence is presented in Hökby and Söderqvist (2003) and Kriström and Riera (1996) casts some doubt on this. Pearce (2006) summarizes evidence from a number of studies and, while there is a lot of variance, provides some support for environmental quality being an income-elastic good, a finding more strongly supported in Deacon and Norman (2006).

Finally, there is a general literature on cooperative and non-cooperative policy outcomes and issue linking in trade policy (in turn drawing on pure-theory literature which I will not discuss), generally or in a few cases explicitly on environmental negotiations. Literature includes Abrego, Perroni, Whalley and Wigle (2001), Bagwell and Staiger (2001), Conconi and Perroni (2002), Gori and Lambertini (2013), Harstad (2012a, 2012b), Horstmann, Markusen and Robles (2005), Markusen (1975), Markusen, Morey and Olewiler (1995), and Markusen and

Wigle (1989), and Spagnolo (2000). I find it hard to draw general conclusions here. It is certainly the case that issue linking can result in Pareto improvements for negotiating partners: there are more instruments to hit multiple targets (trade barriers, environmental protection). But it is also not hard to produce special cases where one country is worse off by linking.

## 2. Income and the Environment

In this section, I consider an international policy question that is of current interest: the relationship between trade policy and international environmental policy with a global pollutant such as CO<sub>2</sub>. Assume that we have two final consumption goods ( $X_1, X_2$ ), one environmental good ( $E$ ), and two countries ( $n, s$ ), where  $n$  (north) will be the higher per-capita income country.

Final goods are produced by a CET (constant elasticity of transformation) technology, with one input  $L$ , with  $L_x$  denoting the total efficiency units of labor allocation to production.

$$\left( \sum_i \alpha_i \left( \frac{X_i}{\alpha_i} \right)^\beta \right)^{\frac{1}{\beta}} = L_x \quad \infty \geq \beta \geq 1, \quad \sigma = \frac{1}{\beta - 1} \quad i = (1, 2) \quad (1)$$

$$\left( \sum_i \alpha_i \left( \frac{X_i}{\alpha_i} \right)^{\frac{\sigma+1}{\sigma}} \right)^{\frac{\sigma}{\sigma+1}} = L_x \quad \sum_i \alpha_i = 1$$

where  $\sigma$  is the elasticity of transformation along the production frontier. The alphas, normalized to sum to one, are parameters that indicate comparative advantage when they differ across countries. Use  $n$  and  $s$  superscripts to denote countries,  $\alpha_1^n > \alpha_1^s$  (and therefore,  $\alpha_2^n < \alpha_2^s$ ) indicates that the north has a comparative advantage in good  $X_1$  and the south has a comparative advantage in good  $X_2$ .

This transformation function is presented in an appendix to the paper, which also shows two further results. First, the unit ( $L_x = 1$ ) revenue or national-product function is given by

$$r(p) = \left( \sum_i \alpha_i p_i^{\sigma+1} \right)^{\frac{1}{\sigma+1}} \quad (2)$$

Second, the optimal outputs of the  $X_i$  at  $L_x = 1$  are found by applying Shepard's lemma to (2):

$$X_i = \alpha_i p_i^\sigma \left( \sum_j \alpha_j p_j^{\sigma+1} \right)^{\frac{1}{\sigma+1} - 1} = \alpha_i p_i^\sigma \left( \sum_j \alpha_j p_j^{\sigma+1} \right)^{\frac{-\sigma}{\sigma+1}} = \alpha_i \left( \frac{p_i}{r(p)} \right)^\sigma \quad (3)$$

Relative production of  $X_1$  and  $X_2$  thus depend on prices and comparative advantage. The total output of  $X_i$  is given by (3) multiplied by the total labor allocated to production  $L_x$ .

$$X_i = \alpha_i (p_i/p_z)^{\sigma} L_x \quad (4)$$

It may help to interpret the  $\alpha$ 's to note from (2) and (3) that, if all prices equal one, then  $\alpha_i$  will give the value share of  $X_i$  in total output.

Let  $E^*$  be the level or “endowment” of world environmental quality at zero production. Pollution is modeled as a reduction in the endowment of good  $E$  and is proportional to the total aggregate input  $L_x$  in both countries. Input  $L$  can also be used for an abatement activity, such as planting trees which absorb  $\text{CO}_2$ . Aggregate labor in each country is then divided between production and abatement:  $\bar{L} = L_x + L_a$  where  $\bar{L}$  is effective labor supply (explained shortly).

$$\text{Pollution} = \text{Reduction in } E \text{ endowment} = L_x^n + L_x^s \quad (5)$$

$$\text{Abatement} = \text{Addition to the } E \text{ endowment} = L_a^n + L_a^s$$

For any allocation of labor between production and abatement in the two countries, world environmental quality is then given by:

$$E = E^* - (L_x^n + L_x^s) + (L_a^n + L_a^s) \quad (6)$$

Abatement is financed by consumption taxes in n and s:  $t^n, t^s$ . The government uses tax revenue to hire labor away from production and pays it to plant trees. Thus public policy, via the consumption tax, determines the allocation of the composite input  $L$  between production and abatement. Specifically, the equal taxes on both goods is equivalent to a tax  $t$  on the labor input to production. Budget balance then requires tax revenues  $t w L_x$  to equal abatement expenditures  $w L_a$  where  $w$  is the wage rate. Thus the tax rate (in either country) will equal the ratio of labor in abatement to labor in production.

$$t = \frac{L_a}{L_x} \quad \text{or} \quad \frac{t}{1+t} = \frac{L_a}{\bar{L}} = \text{share of labor in abatement} \quad (L_x = \bar{L} - L_a) \quad (7)$$

The advantage of this simple model is that it implies “neutrality” in several senses. By neutrality I mean:

- => no pollution-intensive sector
- => no comparative advantage in polluting sector
- => no factor-intensity, factor-endowment issues
- => no pollution-from-consumption-versus-production issue



The dominant model in the trade-and-environment literature has only one sector that pollutes, This leads to policy results that are very sensitive to:

- => which factor is intensive in which good
- => which good is the country's comparative advantage good
- => whether pollution is from consumption or production

Here we avoid these issues. However, at the same time, allowing the  $\alpha_i$ 's to differ across countries generates a comparative advantage motive for trade and gains from trade in the  $X$ 's. This will be important since world prices will change as one country withdraws labor from production in order to increase abatement. This terms-of-trade change in the relative prices of the two  $X$  goods will always favor the environmentally conscious country, a point I will return to shortly.

Preferences are Stone-Geary, lower case letters for per-capita or "household" quantities. Household utility in either country is given by

$$u = x_1^\epsilon x_2^\epsilon (E + e_0)^\gamma \quad 2\epsilon + \gamma = 1 \quad (8)$$

where  $e_0$  is a positive parameter for each household in each country which creates the non-homotheticity: up to a critical level of income, there will be no demand for (or not willingness to pay for) additional environmental quality. It can be useful to think of  $e_0$  as an endowment good given to each household which cannot be traded: every household can watch the sunset and that is a perfect substitute for a cleaner environment.  $E$  is the (world) environmental good supply given in (6) and is a pure (non-rival and non-excludable) public good. So each consumer in each country gets to consume the entire world supply.

Let  $E^i$  denotes the demand for environment in country  $i$ ,  
 $m^i$  is country  $i$ 's per-capita (household) income or labor productivity  
 $h^i$  is the number of households in country  $i$   
 $\bar{L}^i = m^i h^i$  is the total effective labor supply in  $i$ , equal to productivity per household time the number of households.  $L$  is used as numeraire, so country  $i$ 's total income is given by  $M^i = m^i h^i = \bar{L}^i$   
 $p_e^i$  is the price (willingness to pay) by a single household  $h$  for environment in  $i$ .

Consumer (household) optimization yields:

$$E^i = \max \left[ 0, (\gamma - 1) e_0^i + \frac{\gamma m^i}{p_e} \right] \quad (9)$$

$$E^i > 0 \quad \text{iff} \quad m^i > \frac{(1-\gamma)}{\gamma} p_e e_0 \equiv m^0 \quad (10)$$

The result is the one just noted: up to the threshold per-capita income given in (10), there is no demand for environmental quality. Once the threshold income is reached,

$$E^i = (\gamma - 1)e_0 + \gamma \frac{m^i}{p_e^i} \quad (\text{note that } (\gamma-1) < 0) \quad (11)$$

At a constant price, the income elasticity of demand for  $E$  is greater than one once the threshold is reached. In equilibrium,  $E$  must be the same for all consumers in all countries (perfect global public good). So for (11) to hold, it must be that the willingness to pay  $p_e$  differs across countries. This (private) willingness to pay can be found by inverting (11).<sup>1</sup>

$$p_e^i = \frac{\gamma m^i}{E + (1-\gamma)e_0} \quad (12)$$

Since the environment is a public good (non-rival and non-excludable), optimal policy depends on the aggregate benefits of the good across households. The “planner’s problem” is to maximize the aggregate equivalent of (8):  $U^i = (X_1^i)^\epsilon (X_2^i)^\epsilon (E + e_0 h^i)^\gamma$ , where  $X_j^i = x_j^i h^i$ . The social-welfare maximizing level of  $E$ , analogous to (11), is given by

$$E^i = (\gamma - 1)e_0 h^i + \gamma \frac{m^i}{q_e^i} h^i \quad \text{where} \quad m^i h^i = M^i \text{ is } i\text{'s total income} \quad (13)$$

When this is set equal to the (exogenous) quantity of  $E$ , the price that produces equality is denoted by  $q_e^i$ , which I’ll term the “social willingness to pay”. Invert (13).

$$q_e^i = \frac{\gamma m^i h^i}{E + (1-\gamma)e_0 h^i} = \frac{\gamma M^i}{E + (1-\gamma)e_0 h^i} \quad (14)$$

The income elasticity of social willingness to pay (for a fixed  $E$ ) with respect to  $m^i$ , holding  $h^i$  constant is one, while the income elasticity with respect to  $h^i$  holding  $m^i$  constant is less than one.

Holding total income  $M^i$  constant, an *increase* in per-capita income is a *reduction* in the number of households  $h^i$ , and so the social willingness to pay rises. Note that this passes one

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<sup>1</sup>Note from (11) and (12) that the income elasticity of demand for  $E$  (greater than one), is greater than the income elasticity of willingness to pay (equal to one in (12)). This difference is explored in Flores and Carson (1997).

simple check: if preferences are homothetic such that  $e_0 = 0$ , then the social willingness to pay depends only on total income and not per-capita income and the value of demand is a constant share of total income:  $q_e^i E = \gamma M^i$ . Note also that with or without homotheticity, the social price in (14) is greater than the private willingness to pay in (12) for  $h > 1$ .

From (14), the ratio of the social willingness to pay in  $n$  and  $s$  is given by

$$\frac{q_e^n}{q_e^s} = \left[ \frac{E + (1 - \gamma)e_0 h^s}{E + (1 - \gamma)e_0 h^n} \right] \frac{M^n}{M^s} \quad (15)$$

Since  $E$  is common to the two countries, we get the following results:

Result: country  $n$  will have the higher willingness to pay if:

- (a) both countries have the same total income but country  $n$  has a higher per-capita income ( $M^n = M^s$ ,  $h^n < h^s$ ).
- (b) both countries have the same number of households, but  $n$  has a higher per-capita income and therefore higher total income ( $M^n > M^s$ ,  $h^n = h^s$ ).
- (c) both countries have the same per-capita income, but country  $n$  has more households and therefore higher total income ( $h^n = \rho h^s$ ,  $M^n = \rho M^s$ ,  $\rho > 1$ ).

Willingness to pay does not easily translate into an optimal tax rate (abatement effort) in this model. The introduction of this tax by one country will lead to an increase in  $E$  for both countries, lowering the willingness to pay for environment by the passive country: the  $q$ 's are endogenous to the tax. Thus non-cooperative and cooperative tax rates will differ. Secondly, an optimal tax must take into account the effect of withdrawing resources from production to use in abatement on the terms of trade in goods. This terms-of-trade effect can partially compensate country  $n$  for the lower production of goods when it uses resources for abatement, but it creates a corresponding loss for country  $s$ .

In order to understand the terms-of-trade effect, consider some restrictive assumptions in order to derive a clear expression for the effect of abatement by one country on the terms of trade. First, assume that the elasticity on transformation is zero, so that goods are produced in fixed proportions in each country, with that proportion depending on the country's alpha parameters. Assume that there is free trade in goods, so that the world production ratio equals the (inverse) consumer price ratio in equilibrium (since the goods are Cobb-Douglas symmetric substitutes in consumption). We then have:

$$\frac{X_1^n + X_1^s}{X_2^n + X_2^s} = \frac{\alpha_1^n L_x^n + \alpha_1^s L_x^s}{\alpha_2^n L_x^n + \alpha_2^s L_x^s} = \frac{p_2}{p_1} \quad (16)$$

Let country  $n$  withdraw a unit of labor from production. Differentiating (16), we have:

$$\frac{(\alpha_2^n L_x^n + \alpha_2^s L_x^s) \alpha_1^n - (\alpha_1^n L_x^n + \alpha_1^s L_x^s) \alpha_2^n}{(\alpha_2^n L_x^n + \alpha_2^s L_x^s)^2} dL_x^n = d(p_2/p_1) \quad (17)$$

where we will assume that country  $n$  has the comparative advantage in good 1:

$$\alpha_1^n > \alpha_2^n = (1 - \alpha_1^n) \text{ and } \alpha_2^s > \alpha_1^s = (1 - \alpha_2^s).$$

Assume that the countries are identical initially and that there are no initial abatement taxes, so that  $L_x^n = L_x^s = L_x$  where  $L_x$  is the total endowment of each country. Second, assume symmetry in the comparative advantage parameters such that  $\alpha_1^n = \alpha_2^s = (1 - \alpha_2^n) = (1 - \alpha_1^s)$ . Because  $\alpha_1^n + \alpha_2^n = 1$  and  $p_1/p_2 = 1$  (symmetry in production and consumption), (17) simplifies to (shown in the appendix)

$$(\alpha_1^n - \alpha_2^n) \frac{dL_x^n}{L_x^n} = \frac{d(p_2/p_1)}{(p_2/p_1)} \quad \text{or} \quad -\frac{d(p_1/p_2)}{(p_1/p_2)} = \frac{d(p_2/p_1)}{(p_2/p_1)} = (\alpha_1^n - \alpha_2^n) \frac{dL_x^n}{L_x^n} \quad (18)$$

The effect of country  $n$  withdrawing a unit of labor from production ( $dL_x^n < 0$ ) is to reduce the relative price of country  $s$ 's export good  $X_2$  (country  $s$  has a deterioration in its terms of trade) with the size of this effect proportional to the comparative advantage spread  $(\alpha_1^i - \alpha_2^i)$ .

### 3. Analytical solutions for special cases

. Continue to assume that  $\bar{L} = m^i h^i$  is the same in both countries and the production ratio in each country is fixed as we have just done. But one country ( $n$ ) may have fewer numbers of more productive households. Two special cases are instructive.

$(\alpha_1^n - \alpha_2^n) = 0$ : no comparative advantage and hence no trade in goods. Country  $s$  has no adverse terms-of-trade effect and benefits from the reduction in admissions from country  $n$ .

This is shown in Figure 2a, where the (right angle) production frontiers are initially the same

and country  $n$ 's frontier moves in with labor transferred to abatement. All the reduction in commodity consumption is borne by country  $n$  while both countries benefit from an increase in  $E$ .

$(\alpha_1^n - \alpha_2^n) = 1$ , that is,  $\alpha_2^n = \alpha_1^s = 0$ : each country is fully specialized. Country  $s$  has the maximum possible adverse terms-of-trade effect but does benefit from the reduction in emissions from country  $n$ .

This is shown in Figure 2b: because of Cobb-Douglas preferences between  $X_1$  and  $X_2$ , the world price ratio changes so that both countries share the same reduction in commodity consumption. Fully half the burden of withdrawing resources from production by country  $n$  is shifted to country  $s$ . With Cobb-Douglas demand, each country will have the same income  $M$ :

$$M^n = p_1 X_1^n = p_1 L_x^n = M^s = p_2 X_2^s = p_2 L_x^s \quad \text{since} \quad \frac{X_1^n}{X_2^s} = \frac{p_2}{p_1} \quad (19)$$

which follows from (8), and the symmetry of the alphas ( $\alpha_1^n = \alpha_2^s = 1$ ).

With identical Cobb-Douglas sub-utility functions over  $X_1$  and  $X_2$ , the countries will have identical  $(X_1, X_2)$  consumption bundles regardless of the level of country  $n$ 's abatement effort. In other words, the change in the terms-of-trade change fully compensates country  $n$  (relative to country  $s$ ) for its unilateral abatement effort. Both countries have an identical consumption loss and the same aggregate improvement in the environment. We would expect that the full-specialization case should lead to higher non-cooperative abatement efforts as each country passes part of the burden of its tax to its partner.

Consider first the case of no comparative advantage. From our earlier assumptions, utility of country  $n$  is given by

$$U = U(L_x^n/2, L_a^n/2, E^* - L_x^n + L_a^n - L_x^s + L_a^s + e_0 h^n) \quad (20)$$

where  $-L_x^n + L_a^n = -(\bar{L} - 2L_a^n)$ . Using the explicit function form in (8) and exploiting the symmetry between the two consumption goods, this becomes

$$U = \left( \frac{\bar{L} - L_a^n}{2} \right)^{2\epsilon} \left( E^* - (\bar{L} - 2L_a^n) - (\bar{L} - 2L_a^s) + e_0 h^n \right)^\gamma \quad (21)$$

The non-cooperative (Nash) solution is found by taking the derivative of (21) with respect to  $L_a^n$  holding  $L_a^s$  constant. This derivative rearranges to:

$$\frac{\epsilon}{2\gamma} \geq \frac{(\bar{L} - L_a^n)/2}{E^* - 2\bar{L} + 2L_a^n + 2L_a^s + e_0 h^n} \quad \text{complementary } (\perp) \text{ to } L_a^n \geq 0 \quad (22)$$

If the first-order condition holds with strict equality, then the complementary variable is strictly positive and vice versa.

Give equal weights to all three goods, such that  $\epsilon = \gamma = 1/3$ . (22) simplifies to

$$L_a^n \geq \bar{L} - E^*/3 - (2/3)L_a^s - (1/3)e_0 h^n \quad \perp \quad L_a^n \geq 0 \quad (23)$$

Let  $E^* = 0$  to make things even simpler. Then divide through (23) by  $\bar{L}$ .

$$\frac{L_a^n}{\bar{L}} \geq 1 - \frac{e_0}{3m^n} - \frac{2}{3} \frac{L_a^s}{\bar{L}} \quad \perp \quad L_a^n \geq 0 \quad \text{since } \frac{h^i}{\bar{L}} = \frac{1}{m^i} \quad (24)$$

Although I will use a consumption tax in the general-equilibrium model, a very simple tax is just one on all labor. With  $L$  as numeraire, the budget-balance condition that tax revenues equal payments to labor in abatement is given by  $t^i \bar{L} = L_a^i$  or  $t^i = L_a^i / \bar{L}$ . (24) and the corresponding equation for country s become

$$t^n \geq 1 - \frac{e_0}{3m^n} - \frac{2}{3} t^s \quad \perp \quad t^n \geq 0 \quad t^s \geq 1 - \frac{e_0}{3m^s} - \frac{2}{3} t^n \quad \perp \quad t^s \geq 0 \quad (25)$$

These are Nash best-response functions giving each country's "optimal" (non-cooperative) tax as a function of its rival's tax. Clearly, the taxes are strategic substitutes. An increase in the North's tax improves the environment, therefore reducing the South's marginal willingness to pay, and therefore reducing the South's tax. Each country's best response tax is increasing in its per-capita income.

Assuming that the two equations have an interior solution (both taxes positive), the solution is:

$$t^n = \frac{3}{5} - \frac{3}{5} \frac{e_0}{m^n} + \frac{2}{5} \frac{e_0}{m^s} \quad t^s = \frac{3}{5} - \frac{3}{5} \frac{e_0}{m^s} + \frac{2}{5} \frac{e_0}{m^n} \quad (26)$$

Each country's tax is increasing in its per-capita income and decreasing in the other country's per-capita income, the two country's total incomes constant by assumption. The difference between the two countries' taxes is given by:

$$t^n - t^s = \frac{e_0}{m^n m^s} (m^n - m^s) \quad (27)$$

The symmetric solution when both countries have the same per-capita incomes is

$$t^n = t^s = \frac{3}{5} - \frac{e_0}{5m} \quad \text{at} \quad m = m^n = m^s \quad \text{critical } m: m = \frac{e_0}{3} \quad (28)$$

where the critical  $m$  is the common value of  $m$  at which (28) holds with equality at  $t = 0$ . Taxes will be zero at any lower level of  $m$ . Once the tax kicks in at  $m = e_0/3$ , further increases in  $m$ , raise the tax rate, and so the share of resources devoted to abatement.

Now consider the case of full specialization, with country  $n$  producing  $X_1$  and  $s$  producing  $X_2$ , continuing to assume a common value of  $\bar{L}$ . The situation follows from equation (19) and Figure 1b. Each country's consumption will be half the world output of each good, so the identical consumption bundles are:  $X_1^i = L_x^n/2$  and  $X_1^i = L_x^s/2$ . Utility in the North is:

$$U^n = U(L_x^n/2, L_x^s/2, E^* - L_x^n + L_a^n - L_x^s + L_a^s + e_0 h^n) \quad (29)$$

where  $-L_x^n + L_a^n = -(\bar{L} - 2L_a^n)$ . Notice in (29) that  $n$ 's consumption of  $X_2$  is now not reduced by its own abatement effort. As we did above, (29) can be written as

$$U = \left( \frac{\bar{L} - L_a^n}{2} \right)^\epsilon \left( \frac{\bar{L} - L_a^s}{2} \right)^\epsilon \left( E^* - (\bar{L} - 2L_a^n) - (\bar{L} - 2L_a^s) + e_0 n^n \right)^\gamma \quad (30)$$

With the first-order condition given by

$$\frac{\epsilon/2}{2\gamma} \geq \frac{(\bar{L} - L_a^n)/2}{E^* - 2\bar{L} + 2L_a^n + 2L_a^s + e_0 h^n} \quad \perp \quad L_a^n \geq 0 \quad (31)$$

Assuming again equally consumption weights such that that  $\epsilon = \gamma = 1/3$ , we have

$$L_e^n \geq \bar{L} - E^*/2 - (1/2)L_a^s - (1/4)e_0 h^n \quad \perp \quad L_a^n \geq 0 \quad (32)$$

Divide through by  $\bar{L}$  as before and use  $h^i/\bar{L} = 1/m^i$  and  $t^i = L_a^i/\bar{L}$ . (32) yields the best-response functions

$$t^n \geq 1 - \frac{e_0}{4m^n} - \frac{1}{2}t^s \quad \perp \quad t^s \geq 0 \quad t^s \geq 1 - \frac{e_0}{4m^s} - \frac{1}{2}t^n \quad \perp \quad t^s \geq 0 \quad (33)$$

Assuming an interior solution, we have

$$t^n = \frac{2}{3} - \frac{1}{3} \frac{e_0}{m^n} + \frac{1}{6} \frac{e_0}{m^s} \quad t^s = \frac{2}{3} - \frac{1}{3} \frac{e_0}{m^s} + \frac{1}{6} \frac{e_0}{m^n} \quad (34)$$

The difference between the tax rates in this solution is

$$t^n - t^s = \frac{e_0}{2m^n m^s} (m^n - m^s) \quad (35)$$

The symmetric solution when both countries have the same per-capita incomes is

$$t^n = t^s = \frac{2}{3} - \frac{e_0}{6m} \quad \text{at} \quad m = m^n = m^s \quad \text{critical } m: \quad m = \frac{e_0}{4} \quad (36)$$

Comparing (36) to (28), we see that non-cooperative taxes are higher under full specialization, where each country can pass on part of the burden of its tax to the other country. The critical  $m$ , the level of income at which a tax is first introduced, is lower in the case of full specialization (36).

The weak inequalities in (25) and in (33) each constitute two linear complementarity problems in the non-negative tax variables. Figure 3 shows a numerical example of these two cases, in which  $e_0 = 2$ . Moving to the right on the horizontal axis, per-capita income increases for the North, with the South's income being the reciprocal of the North's. The taxes diverge under growing income inequality and the taxes under full specialization are greater than under no comparative advantage.

Now let's consider a cooperative outcome or a Nash bargaining outcome using the non-cooperative outcome as a disagreement point. Impose the assumptions that both countries are the same size ( $\bar{L}$  is the same) and have the same per-capita income ( $m^n = m^s$ ,  $h^n = h^s$ ). Since everything is symmetric in this special case (including equal taxes in the non-cooperative outcome), the cooperative outcome will involve a common abatement effort  $L_a = L_a^n = L_a^s$ , and the solution can be represented by maximizing the utility of either country under the assumption of equal abatement efforts. Second, the solution will be the same in either the no-comparative-



advantage case or the full-specialization case. In the latter case, each country produces  $(\bar{L} - L_a)$  of its specialization good and trades half of that for the other country's good, consuming  $(\bar{L} - L_a)/2$  of each good. In the no-comparative-advantage case, each country both produces and consumes  $(\bar{L} - L_a)/2$  of each good. So both cases will yield the same cooperative outcome given the symmetry assumptions. Dropping the country superscript on  $L_a$  and  $h$  in (21), utility for each country is maximized with respect to a common value of  $L_a$ . Equation (21) becomes

$$U = \left( \frac{\bar{L} - L_a}{2} \right)^{2\epsilon} \left( E^* - 2\bar{L} + 4L_a + e_0 h \right)^\gamma \quad (37)$$

The cooperative and Nash-bargaining solution is found by taking the derivative of (37) with respect to  $L_a$ . This derivative rearranges to:

$$\frac{\epsilon}{4\gamma} \geq \frac{(\bar{L} - L_a)/2}{E^* - 2\bar{L} + 4L_a + e_0 h} \quad \text{complementary } (\perp) \text{ to } L_a \geq 0 \quad (38)$$

Give equal weights to all three goods, such that  $\epsilon = \gamma = 1/3$ . (38) simplifies to

$$L_a \geq (2/3)\bar{L} - E^*/6 - (1/6)e_0 h \quad \perp \quad L_a \geq 0 \quad (39)$$

Let  $E^* = 0$  to make things even simpler. Then divide through (39) by  $\bar{L}$  and use  $h/\bar{L} = 1/m$  and  $L_a/\bar{L} = t$  as before.

$$t^n = t^s = \frac{2}{3} - \frac{e_0}{6m} \quad \text{at} \quad m = m^n = m^s \quad (40)$$

Here we have an interesting result that the cooperative outcome is the same as the non-cooperative outcome under the full-specialization assumption (equation (36)). Under the latter, each country raises its tax non-cooperatively because it can pass on half the burden to the other country. Under all our special symmetry assumptions, this substitutes perfectly for a country raising its tax in order to cooperatively internalize its externality on the other country.

Two final comments before moving on to general equilibrium. First, it is probably clear that an economy can exhibit a non-monotonic Kuznets' curve. Starting from a very low  $m$ , the optimal taxes are zero as income increases, meaning that there is an unambiguous fall in  $E$ . Eventually taxes kick in, and after that the tax rates rise with  $m$ , and so the share of labor devoted to abatement rises. At some point, environmental quality may exceed the initial quality, an

outcome we will see in the next section. Second, note from the best-response functions (26) and (33) that we can have something I dub “policy leakage”. As one country increases its abatement tax and effort, the environment improves and so the optimal response of the other country is to lower its tax. This is reinforced to the extent that the increase in the first country’s tax makes the second country poorer through the terms-of-trade effect and hence lowers its willingness to pay.

#### 4. The general-equilibrium simulation model

The model developed above seems simple, but there is a lot more simultaneity if relative commodity outputs are endogenous and countries may differ in size ( $L$ ) as well as per-capita incomes. Optimal policy depends on income, for example, and income depends on the policy chosen, both by determining the domestic resources available for production of goods and through the international general-equilibrium terms-of-trade effect. Note, for example, that the simple result in (18) requires severe assumptions and even then it is only locally valid in the neighborhood of zero abatement. So let’s turn to a numerical general-equilibrium model to see how per-capita income matters for cooperative and non-cooperative outcomes.

The model belongs to a class of problems loosely known as MPEC: mathematical programming with equilibrium constraints. In our case, the set of equilibrium constraints is the two-country general-equilibrium model. The latter, in turn, is known as an MCP: mixed complementarity problem. This is a set of weak inequalities with associated non-negative variables such as quantities and prices. When a weak inequality holds as an equality, the complementary variable is positive, zero if the inequality is strict in equilibrium.

The MPEC consists of maximizing some function such as a Nash bargaining function (cooperative) with respect to instrument variables such as tax rates (pollution taxes and/or tariffs) subject to the economic equilibrium constraint set. A non-cooperative Nash equilibrium is found by iteration: maximize the welfare of  $i$  holding  $j$ ’s taxes constant, then hold  $i$ ’s taxes constant at the solution values and maximize  $j$ ’s welfare, repeat. This converges to a best-response, non-cooperative outcome in about eight iterations. There is one small difference from the model above that has no effect on any results.<sup>2</sup> Here is a description of the model.

##### (A) Alternative objective functions

welfare of country  $n$   
welfare of country  $s$   
joint welfare (or Nash bargaining function)

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<sup>2</sup>I define a composite output quantity  $Z$  in each country equal to the left-hand side of (1), analogous to a Dixit-Stiglitz composite differentiated good in monopolistic-competition models. This carries a price  $p_z$  which can be useful in comparing the relative price of consumption to the environment.

(B) The mxm economic equilibrium problem (constraint set): 28 inequalities and unknowns

Inequalities	Complementary Variables	Number
marginal cost $\geq$ price	quantities	
production of $Z$ by $n, s$	quantities of $Z$	2
trade in $X_1, X_2$ by $n, s$	quantities traded	4
welfare in $n$ and $s$	welfare in $n$ and $s$	2
abatement activities in $n$ and $s$	quantity of abatement	2
market clearing: supply $\geq$ demand	prices	
supply / demand for $Z^n, Z^s$	prices of $Z$ in $n, s$	2
supply / demand for $X_i$ in $n, s$	prices of $X_i$ in $n, s$	4
supply / demand for $L$ in $n$ and $s$	prices of $L$ in $n, s$	2
supply / demand for welfare	price index in $n, s$	2
supply / demand for abatement in $n, s$	price of abatement in $n, s$	2
supply / demand for environment good	willingness to pay in $n, s$	2
income balance: income $\geq$ expenditure		
income balance for $n, s$	income in $n, s$	2
auxiliary equations		
pollution reduction = abatement	pollution abatement	1
pollution = emissions	pollution	1

(C) Additional unmatched instrument variables chosen to optimize welfare:

pollution abatement effort (abatement tax) in countries $n, s$	2
tariffs imposed by countries $n, s$	2

(D) The MPEC (mathematical programming with equilibrium constraints)

Maximize objective function, subject to:	
instruments: pollution abatement taxes and tariffs in $n, s$	4
mxm economic equilibrium problem constraint set	28

A sample program, written and solved in GAMS, is provided in appendix two to the paper.

## 5. Policy experiments<sup>3</sup>

The first policy experiment is shown in Figure 4. This considers environmental quality as a function of per-capita income, where I make the countries identical (in total and in per-capita incomes) for simplicity. Productivity or “effective” labor units per household are increased holding the number of households constant. The MPEC solves for the optimal taxes or abatement effort at each level of income (productivity).

This produces a non-monotonic Kuznets curve in Figure 4 as we expect. At very low levels of per-capita income, there is no demand for abatement or additional environmental quality and the latter falls with increases in productivity. At a critical level around 0.9 in this experiment, there is a positive demand for additional environmental quality and the tax kicks in. The tax *rate* rises steadily thereafter due to the non-homotheticity, and is equal to 0.25 on the right-hand boundary where environmental quality is now higher than in the very poor county.

What is perhaps not so obvious is that there is still some non-monotonicity in the Kuznets curve with homothetic demand. This is due to the fact that the initial fixed endowment of  $E = E^*$  is too high or rather the demand price too low to justify abatement at low income levels. Intuitively, a really poor country would want to sell off some of the environmental good if it could under either homothetic or non-homothetic demand. Adding the non-homotheticity assumption shifts the minimum point to the right in Figure 4 (not shown). If there was no initial endowment of  $E$ ,  $E^* = 0$ , then the homothetic case would produce a constant tax rate at all levels of income such that environmental quality is a linear function of income passing through the origin, while the non-homothetic case continues to look like Figure 4,  $E$  can go negative provided that  $-E < e_0$ . This possibly expected result occurs only when  $E^* = 0$ .

The next exercise is to examine how cooperative and non-cooperative policy outcomes depend on per-capita income. Some results are shown in Figure 5. In all cases, the total incomes ( $\bar{L}$ ) of the countries are equal. There is a strong pattern of comparative advantage in the case considered,  $\alpha_1^n = \alpha_2^s = 0.9$ , and  $\sigma = 1$ . Thus when per-capita incomes and taxes are unequal, there will be a fairly strong terms-of-trade effect that favors country  $n$ .

The solid boxes in Figure 5 show an outcome when the two countries have equal per-capita incomes (or same number of equally productive households). Each country's (unilateral) optimal tax is shown when the other country's tax is zero as are the non-cooperative Nash equilibrium rates. There is no difference in the values of the taxes across countries in this latter equilibrium as we expect to be the case. The (equal) cooperative tax rates are Nash bargaining

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<sup>3</sup>Somewhat different parameterizations are used here than in simplified analytical model. Here environmental quality is:  $E = E^* - (L_x^n + L_x^s)/2 + 4(L_a^n + L_a^s)$  with  $E^* = (\bar{L}^n + \bar{L}^s)/2$ . A consumption tax is used instead of a labor tax, though there is a simple relationship between them as can be seen from (10): the equivalent labor tax is equal to  $t/(1+t)$  where  $t$  is the consumption tax. These are simply for expositional purposes and do not affect the qualitative results in any way.

outcomes where the disagreement outcome is the non-cooperative Nash equilibrium. The cooperative rates are considerably higher than the non-cooperative ones as shown in Figure 5. The terms-of-trade in both outcomes is one and there is no trade in goods.

The second set of outcomes, shown with a slash through the boxes in Figure 5, assumes that country  $n$  has a per-capita income 1.5 times that of country  $s$ . Total incomes are the same as in the first case (solid boxes), so country  $n$  now has fewer, more productive households while  $s$  has more, less productive households. Figure 5 shows that the non-cooperative equilibrium shifts to a higher tax for country  $n$  and to a lower tax for country  $s$  (as we would expect). The cooperative Nash bargaining outcome using the non-cooperative outcomes as the disagreement point shifts from the equal-per-capita-income scenario in about the same way.

As suggested earlier, country  $n$  will be partially, perhaps significantly, compensated for its higher abatement effort by an improvement in its terms of trade. Specifically, the relative price of good  $X_1$ , country  $n$ 's export good, is 1.12 at the non-cooperative Nash outcome and 1.14 at the cooperative outcome (these are equal to one at the solution with equal  $m$ 's).

Table 1 presents numerical values for these results and compares them to several alternative scenarios. The first three columns of number are the case where country  $n$ 's per-capita income is 1.5 times that of country  $s$  as in Figure 5. The first row gives the welfare values when there is no intervention by either country, where these welfare values are normalized at one. The second and third row of Table 1 give the welfare values for the non-cooperative and cooperative outcomes, and the lower panel the corresponding tax rates ( $PTAXN$ ,  $PTAXS$ ), which are those in Figure 5. Note that the non-cooperative outcome results in a substantial welfare gain over non-intervention: unlike a non-cooperative tariff "war" for example, here the non-cooperation is a failure to internalize a positive rather than a negative externality.

The tax rates that maximize the Cobb-Douglas world welfare function and a Rawlsian welfare function are also shown (world welfare is the minimum of the two countries' welfare levels. In the fourth and fifth rows of Table 1 (and tax rates below).. The Cobb-Douglas is equivalent to a Nash bargaining outcome when the disagreement outcome for both countries is zero

An interesting feature of these results is that country  $n$  is actually the relative gainer over the no-intervention outcomes (except the Rawlsian one). How much of this is simply due to the fact that country  $n$  places a much higher value on the environment at the no-intervention point, and how much might be due to the this terms-of-trade effect? In order to examine this question, I compute an alternative scenario in which there is no comparative advantage:  $\alpha_1^n = \alpha_2^s = 0.5$ .

Results are shown in columns 3 and 4 of Table 1. Here we see some significant differences. First, the relative gainer is reversed in the cooperative and non-cooperative Nash outcomes. Now country  $s$  is the relative gainer. This verifies the conjecture that the terms-of-trade effect that favors the higher-tax country  $n$  in columns 1 and 2 is indeed important in determining the relatively larger gains for country  $n$  in those columns. Second, note in the lower

part of the Table that the non-cooperative rates for both countries are lower when there is no comparative advantage. This is clearly due to the fact that raising your tax rate has no compensating beneficial effect on the terms of trade with no comparative advantage. Third, the cooperative Nash is almost unchanged from the comparative-advantage case, which seems to follow from section 3: cooperative internalizes the terms-of-trade externality to the extent there is one.

The CD maximum rates are also unchanged in alternative scenario 1, because there is no terms-of-trade effect when the countries have the same rates. Fourth, the Rawlsian maximum rate is now lower for country  $n$  and higher for country  $s$ . I think that the intuition here is that, starting from the Rawlsian taxes with comparative advantage, removing comparative advantage reduces the welfare of high-tax country  $n$  and raises it for country  $s$ . The Rawlsian outcome then adjusts  $n$ 's tax down and  $s$ 's tax up in alternative scenario 1.

A second alternative case is presented in columns 5 and 6 of Table 1. Comparative advantage is reinstated, but country  $n$  now has ten times the per-capita income of country  $s$ . Results are now that country  $s$  has a zero tax rate at both the cooperative and non-cooperative Nash outcomes. The non-cooperative outcome is in fact a Pareto optimum: there are no gains from cooperative. Second, note that country  $s$  is indifferent between the no-intervention outcome and the cooperative or non-cooperative equilibrium (in fact, I search until I found the per-capita income difference, a factor of ten, that gave this borderline result). If I push the size difference a little higher, then country  $s$  is actually worse off than with no intervention. Country  $s$  places little value on improved environmental quality and suffers a negative terms-of-trade effect when country  $n$  imposes its abatement tax. The relative price of country  $n$ 's export good is 1.22 at the cooperative and non-cooperative tax rate of 0.41 in alternative scenario 2.

Alternative case 2 also gives large difference between CD world welfare maximum tax rates and the Rawlsian rates. The CD rates are again equal to one another, while country  $n$  bears all the abatement effort in the Rawlsian equilibrium, which is equal to the non-cooperative Nash equilibrium in all respects.

The model is then used to consider an experiment in which countries agree to a common tax rule  $t^n = t^s$ , and then bargain over the level of this shared tax rate. The countries are initially identical in total and per-capita incomes, and then the per-capita income of country  $s$  is reduced holding its total income constant (more but less productive households). Results are shown in Figure 6, where the common tax rate is on the horizontal axis. Both countries' welfare levels are shown by the curve "country  $n$ 's welfare" when they have the same per-capita income. Now lower country  $s$ 's per-capita income to one-fifth and then one-tenth of country  $n$ 's per-capita income. The curve for country  $n$  does not change, while that for country  $s$  is flatter and has its maximum at a lower level of per-capita income. When the difference between the countries' per-capita incomes is a factor of ten, country  $s$  cannot gain at any common tax rate. Thus having agreed on an "equal sharing rule" and then bargaining on the rate, the outcome is a zero rate when the per-capita-income difference is large. This has some clear applications to situations such as the Kyoto protocol, where there was considerable controversy over whether or not the

poor and rich countries should suffer the same proportional cuts in carbon emissions. The result was that the poor countries did not participate at all, which is consist with the model here.

Now I turn to issue linking and introduce two additional policy instruments: import tariffs for countries  $n$  and  $s$ . We will assume that country  $n$  has five times both the total income and the per-capita income of country  $s$ . Comparative advantage is the same as we used earlier:  $\alpha_1^n = \alpha_2^s = 0.9$  and  $\sigma = 1$ . A shorted version of the GAMS program (it doesn't solve for all scenarios) is attached at the end of the paper. The no-intervention case shown in the first row of Table 2 fixes the four policy instruments at zero.

Tables 2 then gives the non-cooperative Nash equilibrium in the second row, where each country jointly chooses its abatement tax and tariff for fixed values of the other country's instruments.<sup>4</sup> This is solved as an iterative MPEC. Country  $n$ 's welfare is maximized with respect to  $PTAXN$  and  $TARN$  holding  $PTAXS$  and  $TARS$  constant. Then the solution values of  $PATXN$  and  $TARN$  are held constant and the welfare of country  $s$  is maximized with respect to  $PTAXS$  and  $TARS$ . The iteration converges to the non-cooperative Nash equilibrium in about six to eight iterations.

Table 2 shows that, not surprisingly, country  $n$  has a high abatement tax and tariff. Country  $s$  has a small tariff and a zero abatement tax. The tariff difference would be expected by any trade economist from simple non-cooperative tariff theory given the size difference. Table 2 notes a substantial welfare improvement over no intervention for both countries: country  $s$  benefits more from  $n$ 's abatement effort than  $s$  is hurt by  $n$ 's tariff. However, I imagine a case can easily be produced in which country  $s$  is worse off than in the no-intervention equilibrium.

Four cooperative bargaining outcomes are then computed using the Nash equilibrium as a disagreement point in Table 2. The first computes an isolated environmental tax bargain, tariffs held at their Nash values. The second computes an isolated tariff bargain, abatement taxes held at their Nash values. One interesting result here is that there are no gains to an isolated environment negotiation. No Pareto improving changes in taxes can help and nothing will come of such a negotiation (sound familiar?). The isolated tariff negotiation does produce a positive result, as country  $n$  lowers its tariff significantly in exchange for country  $s$  eliminating its tariff.

In the third case using the non-cooperative outcome as a disagreement point (row 5 of Table 2), country  $n$  offers a lower tariff in exchange for a positive abatement effort by country  $s$ . In my view, this is what some writers and politicians in high-income countries want to do: offer trade liberalization in exchange for environmental and labor standards to poor countries. Results in Table 2 indicate a Pareto improvement with the north trading trade liberalization for

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<sup>4</sup>The welfare numbers are normalized at 1.0 in the non-cooperative outcome in the second row, but I should note that the difference in the welfare levels is nowhere near a factor of five:  $n$ 's welfare is about twice that of country  $s$ . This is due to a large relative price advantage for country  $s$ : the relative price ratio is 0.472 or inverting, the relative price of country  $s$ 's export good  $X_2$  is 2.121.

abatement by the south.

Row 6 of Table 2 takes the non-cooperative Nash outcome as a disagreement outcome and computes a cooperative bargaining solution treating all four instruments as endogenous variables. Here the outcome is a zero abatement tax and a zero tariff for country  $s$ . Country  $n$  bears the burden of abatement and, in exchange, retain a high tariff but substantially less than the non-cooperative tariff.

Row 6 emphasizes the fact that free trade may not be achievable even in the four-instrument case using the Nash equilibrium as the disagreement outcome. Row 7, the final one in Table 2, therefore adds a final instrument which is a transfer payment to the other four instruments. In this case, the outcome does involve free trade as intuition probably suggests. It requires a large transfer payment from  $s$  to  $n$ : in effect,  $s$  bribes  $n$  into free trade (this transfer result is driven by the trade distortion, not the environment distortion). Row 7 also indicates that the north should bear all of the abatement effort. This is being driven by country size: with  $s$  a lot smaller, the world is scarce in good  $X_2$ , south's comparative-advantage good, and abundant in  $X_1$ , north's comparative-advantage good. Thus efficiency dictates that the real cost of the abatement should fall on  $X_1$ , meaning the north does the abatement.

It is interesting to see, in both Table 1 and Table 2, that cooperative bargaining does not extract much in the way of additional gains. The non-cooperative outcomes do a "good job" of extracting gains, since the non-internalized pollution externality is a positive spillover between countries. I have no reason to believe that this specific result has great generality beyond this specific case: results are suggestive and illustrative.

Finally, I'll just note in passing (without showing another simulation) a point alluded to in the analytical section. The model is characterized by "policy leakage", a term I will use to indicate one country reducing its abatement effort in response to an increase in its trading partner's abatement effort. There is no particular role for differences in per-capita income here, but I thought a couple of brief comments are worthwhile having developed the model. Most literature that I am aware deals with leakage through changes in market prices when one country imposes a carbon tax, for example, and the other country is (countries are) passive. Action by the first country lowers world fossil fuel prices and so firms and consumers in the passive country will use more. This traditional mechanism doesn't work here by virtue of the fact that there is no carbon-intensive sector and hence no relative price change lowering fossil fuel prices in response to one country's tax. Instead, leakage occurs in non-cooperative outcomes insofar as the abatement efforts of countries are "strategic substitutes". A higher tax in  $n$  improves the environment and lowers the willingness to pay in country  $s$ . This is nothing other than a free-rider problem in environmental policy.



## 6. Summary and Conclusions

The purpose of the paper is to make the case that per-capita income has an interesting role to play in cooperative and non-cooperative international trade policy. The setting is a world with a global environmental externality such as CO<sub>2</sub> pollution and consumers who have a high income-elasticity of demand for environmental quality. While some of the results are not surprising, there are a number of interesting subtleties than may have gone unnoticed.

A couple of basic results are that (a) environmental quality will exhibit a u-shape with respect to per-capita income, an example of an environmental Kuznets curve. (b) non-cooperative outcomes will involve “policy leakage”: an increase in one country’s abatement effort improves the world environment and hence leads the other country to reduce its effort. But the bulk of the paper focuses on countries with different per-capita incomes. I show that a poorer country will have a lower abatement effort in both a non-cooperative outcome and in a Nash bargaining outcome using the non-cooperative equilibrium as a disagreement outcome. It may be that the poor country makes no abatement effort in a non-cooperative outcome and, beginning from that equilibrium, it may be that there are no gains to bargaining when abatement taxes are the only instrument available to the countries.

I believe that the terms-of-trade externality is rather novel: when a country withdraws resources from production to abate, it effectively shrinks its economy, and this will move the world terms of trade in its favor. Thus it passes on part of the cost of abatement to the non-abating country. I show a case using the simple analytical model where fully half the cost is passed on, and so it turns out that the non-cooperative and cooperative outcomes are the same.

The final section of the paper allows countries to set tariffs as well as abatement taxes, and focuses on the case where the rich country is large, and so has both a high tariff and a high abatement tax. Part of the advantage of the numerical model, using the relatively new MPEC solver in GAMS, is that we can compute a Nash equilibrium in four instruments. Then using this as a disagreement outcome, we can compute bargaining outcomes for linked or unlinked negotiations. Results are interesting, but my (superficial) knowledge of bargaining theory suggests that general results (e.g., is it better to link) are unlikely to be found.

In the area of understanding how we got to where we are, the results here may help explain why the high-income countries often seem to give up more than they get in international negotiations (some will surely dispute this assertion), such as the Kyoto Protocol. While this may indeed be all or in part due to simple altruism, some of our results here suggest that this is also predicted by standard economic theories of cooperative and non-cooperative behavior. Specifically, with environmental quality a high-income-elasticity good, standard theory predicts a high abatement effort by high income countries, no need to appeal to altruism.

## APPENDIX

First, the algebra on the CET transformation function, the national product function and the supply functions. I derive the unit national product function: the revenue derived from one unit of labor input into production.

$$\underset{x}{Max} \quad \sum p_i x_i + \lambda \left[ \left( \sum_i \alpha_i \left( \frac{x_i}{\alpha_i} \right)^\beta \right)^{\frac{1}{\beta}} - 1 \right] \quad (A1)$$

$$\frac{\partial L}{\partial X_i} = p_i - \lambda \frac{1}{\beta} \left( \sum_i \alpha_i \left( \frac{x_i}{\alpha_i} \right)^\beta \right)^{\frac{1}{\beta} - 1} \alpha_i \beta \left( \frac{x_i}{\alpha_i} \right)^{\beta - 1} \frac{1}{\alpha_i} = 0 \quad (A2)$$

$$\frac{p_j}{p_i} = \left( \frac{x_i/\alpha_i}{x_j/\alpha_j} \right)^{\beta - 1} \quad \frac{x_j}{\alpha_j} = \left( \frac{p_j}{p_i} \right)^{\frac{1}{\beta - 1}} \frac{x_i}{\alpha_i} = \left( \frac{p_j}{p_i} \right)^\sigma \frac{x_i}{\alpha_i} \quad (A3)$$

$$p_j x_j = \alpha_j p_j^{\sigma + 1} p_i^{-\sigma} x_i / \alpha_i \quad (A4)$$

$$r(p) = \sum p_j x_j = \left( \sum \alpha_j p_j^{\sigma + 1} \right) p_i^{-\sigma} \frac{x_i}{\alpha_i} \quad (A5)$$

Inverting this gives unit supply functions: the optimal output of each good for one unit of labor input into production.

$$x_i = \alpha_i p_i^\sigma \left( \sum \alpha_j p_j^{\sigma + 1} \right)^{-1} r(p) \quad (A6)$$

$$\alpha_i \left( \frac{x_i}{\alpha_i} \right)^{\frac{\sigma + 1}{\sigma}} = \alpha_i p_i^{\sigma + 1} \left( \sum \alpha_j p_j^{\sigma + 1} \right)^{-\frac{\sigma + 1}{\sigma}} r(p)^{\frac{\sigma + 1}{\sigma}} \quad (A7)$$

$$\sum \alpha_i \left( \frac{x_i}{\alpha_i} \right)^{\frac{\sigma + 1}{\sigma}} = \sum \left( \alpha_i p_i^{\sigma + 1} \right) \left( \sum \alpha_j p_j^{\sigma + 1} \right)^{-\frac{\sigma + 1}{\sigma}} r(p)^{\frac{\sigma + 1}{\sigma}} = \left( \sum \alpha_i p_i^{\sigma + 1} \right)^{-\frac{1}{\sigma}} r(p)^{\frac{\sigma + 1}{\sigma}} \quad (A8)$$

$$\left( \sum \alpha_i \left( \frac{x_i}{\alpha_i} \right)^{\frac{\sigma+1}{\sigma}} \right)^{\frac{\sigma}{\sigma+1}} = 1 = \left( \sum \alpha_i p_i^{\sigma+1} \right)^{-\frac{1}{\sigma+1}} r(p) \quad (\text{A9})$$

This gives us the unit national product function, which could also be termed the producer price index in an analogy to the CES consumer price index so widely used in monopolistic competition and economic geography.

$$r(p) = \left( \sum \alpha_i p_i^{\sigma+1} \right)^{\frac{1}{\sigma+1}} = p_z \quad (\text{A10})$$

The unit national product function or producer price index is also CET, a self-dual property familiar from the CES demand literature. Substitute this into the supply functions above.

$$x_i = \alpha_i p_i^{\sigma} \left( \sum \alpha_j p_j^{\sigma+1} \right)^{-1} \left( \sum \alpha_i p_i^{\sigma+1} \right)^{\frac{1}{\sigma+1}} = \alpha_i p_i^{\sigma} \left( \sum \alpha_j p_j^{\sigma+1} \right)^{-\frac{\sigma}{\sigma+1}} \quad (\text{A11})$$

This gives us more compact unit and total supply functions.

$$x_i = \alpha_i p_i^{\sigma} r(p)^{-\sigma} \quad X_i = \alpha_i p_i^{\sigma} r(p)^{-\sigma} L_z \quad (\text{A12})$$

Second, the algebra for the terms-of-trade effect under the special assumptions noted in the text.

$$\frac{X_1^n + X_1^s}{X_2^n + X_2^s} = \frac{\alpha_1^n L_z^n + \alpha_1^s L_z^s}{\alpha_2^n L_z^n + \alpha_2^s L_z^s} = \frac{p_2}{p_1} \quad (\text{A13})$$

$$\frac{(\alpha_2^n L_z^n + \alpha_2^s L_z^s) \alpha_1^n - (\alpha_1^n L_z^n + \alpha_1^s L_z^s) \alpha_2^n}{(\alpha_2^n L_z^n + \alpha_2^s L_z^s)^2} dL_z^n = d(p_2/p_1) \quad (\text{A14})$$

Assume that the countries are identical initially and that there are no initial abatement taxes, so that  $L_z^n = L_z^s = L_z$  where  $L_z$  is the total endowment of each country. Second, assume symmetry in the comparative advantage parameters such that  $\alpha_1^n = \alpha_2^s = (1 - \alpha_2^n) = (1 - \alpha_1^s)$ . Then (A14) can be simplified to

$$\frac{(\alpha_1^{n^2} - \alpha_2^{n^2}) L_z^n L_z^s}{(\alpha_1^n + \alpha_2^n)^2 L_z^{s^2}} \frac{dL_z^n}{L_z^n} = d(p_2/p_1) \quad (\text{A15})$$

Because  $\alpha_1^n + \alpha_2^n = 1$  and  $p_1/p_2 = 1$  initially, this further simplifies to

$$(\alpha_1^n - \alpha_2^n) \frac{dL_z^n}{L_z^n} = \frac{d(p_2/p_1)}{(p_2/p_1)} \quad \text{or} \quad \frac{d(p_2/p_1)}{(p_2/p_1)} = (\alpha_1^n - \alpha_2^n) \frac{dL_z^n}{L_z^n} \quad (\text{A16})$$

The effect of country n withdrawing a unit of labor from production ( $dL_z^n < 0$ ) is to reduce the relative price of country s's export good (country s has a deterioration in its terms of trade) with the size of this effect being proportional to the size of comparative advantage spread.

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TABLE 1: Welfare and abatement taxes under alternative scenarios

	Base case: h's per-capita income 1.5 that of country f			Alternative case 1: no comparative advantage		Alternative case 2: h's per-capita income 10 times that of f	
	Welfare h	Welfare f	CD welfare index*	Welfare h	Welfare f	Welfare h	Welfare f
PTAX = 0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Non-cooperative NE	1.207	1.196	1.201	1.136	1.120	1.161	1.000
Coop Nash NE outside option	1.237	1.217	1.227	1.197	1.255	1.161	1.000
CD world welfare index max*	1.290	1.173	1.231	1.290	1.173	1.261	0.936
Rawlsian world welfare max**	1.225	1.225	1.225	1.237	1.228	1.161	1.000
TAX RATES	PTAXH	PTAXF		PTAXH	PTAXF	PTAXH	PTAXF
Non-cooperative NE	0.32	0.08		0.24	0.03	0.41	0
Coop Nash NE outside option	0.51	0.21		0.51	0.22	0.41	0
CD world welfare index max*	0.35	0.35		0.35	0.35	0.20	0.20
Rawlsian world welfare max**	0.57	0.20		0.48	0.28	0.41	0

\*Cobb-Douglas index used is  $(WELH)^{0.5} \cdot (WELF)^{0.5}$ ; welfare h,f normalized to 1 at zero taxes

\*\*Rawlsian welfare index is  $\min(WELH, WELF)$ ; welfare h,f normalized to 1 at zero taxes

TABLE 2 Welfare and abatement taxes under alternative linking scenarios  
Country n has five times the total income and per-capita income of country s

	Welfare n	Welfare s	PTAXN	PTAXS	TARN	TARS
No intervention	0.731	0.788	0	0	0	0
Non-cooperative Nash each county coordinates their tax and tariff	1.000	1.000	0.386	0	1.567	0.196
Cooperative Nash using non-cooperative outcome as disagreement outcome						
Isolated environment negotiation	1.001	1.008	0.451	0.036	1.567	0.196
Isolated tariff negotiation	1.008	1.048	0.386	0	1.015	0
Bargain over TARN and PTAXS	1.005	1.025	0.386	0.150	0.692	0.196
Bargain over all four instruments	1.009	1.059	0.452	0.034	1.015	0
Bargain over all four instruments with transfer s to n (= 22.0% of s's income)	1.024	1.075	0.541	0	0	0



Figure 1a: Environmental sustainability index and per-capita income  
(World Economic Forum, Global Competitiveness Report 2012-2013)

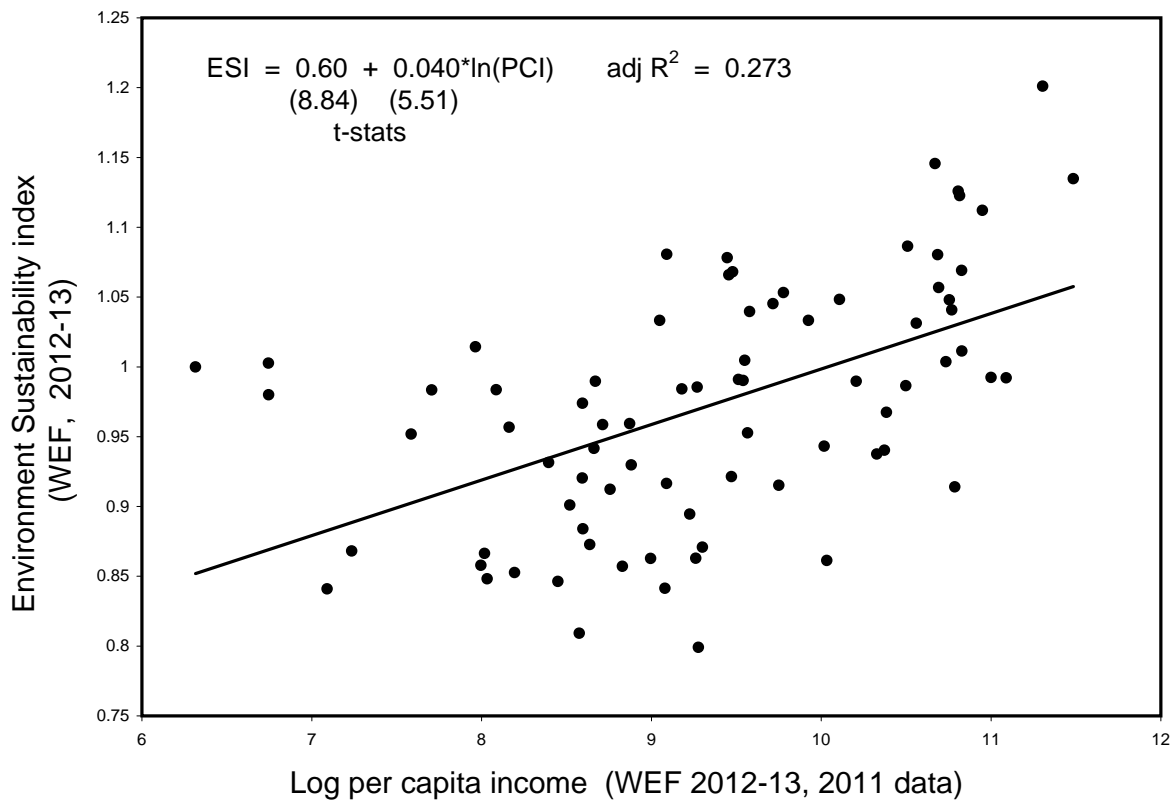


Figure 1b: Maximum lead content of gasoline (petrol) in relation to log GDP per-capita at PPP

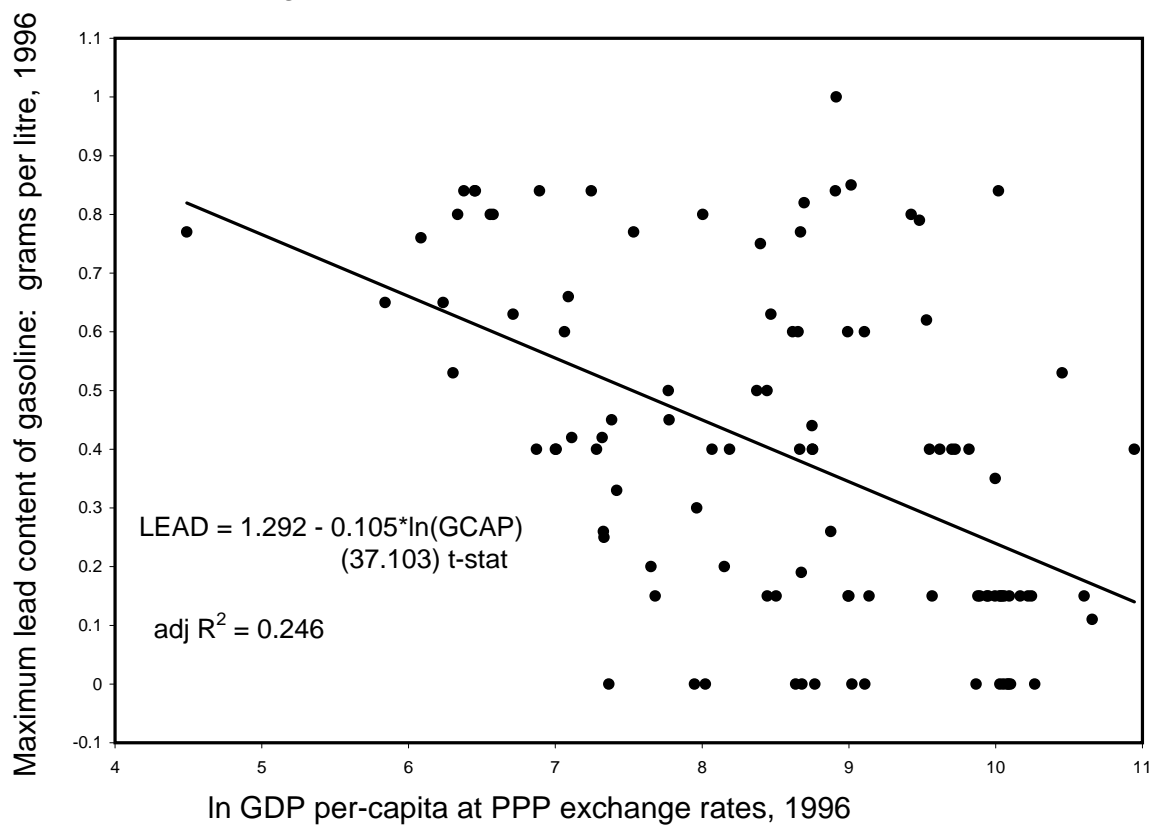


Figure 2a: Effect of abatement by country n on the commodity consumption of both countries: no comparative advantage

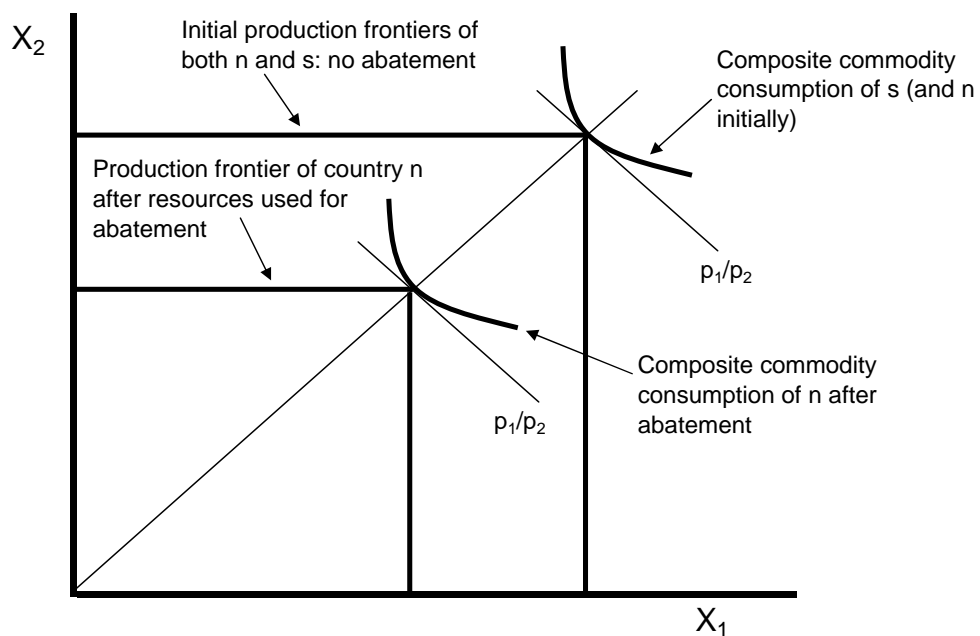


Figure 2b: Effect of abatement by country n on the commodity consumption of both countries: complete specialization

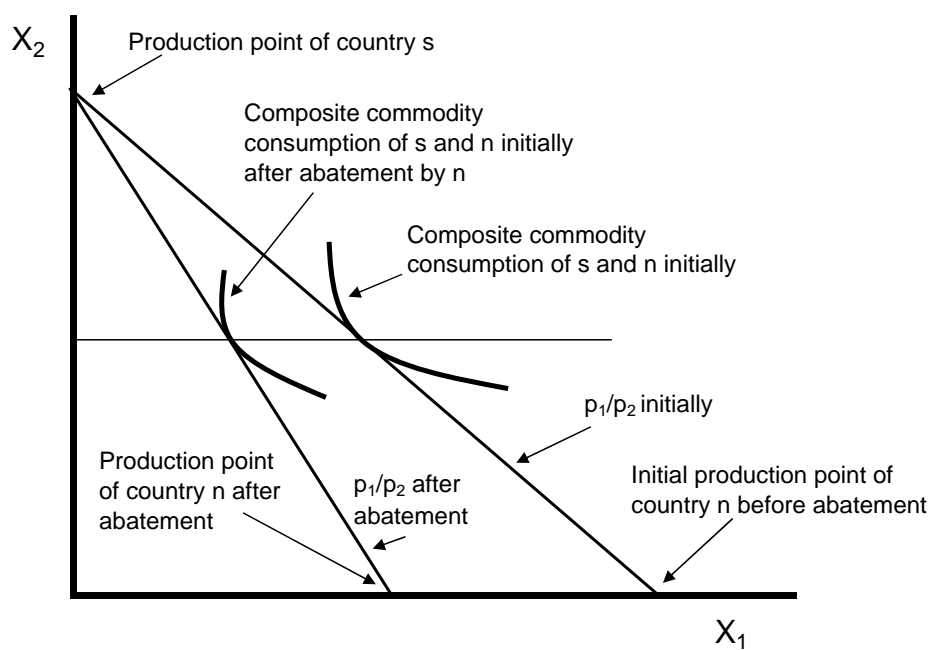


Figure 3: Abatement taxes and per-capita income  
(model of the model)

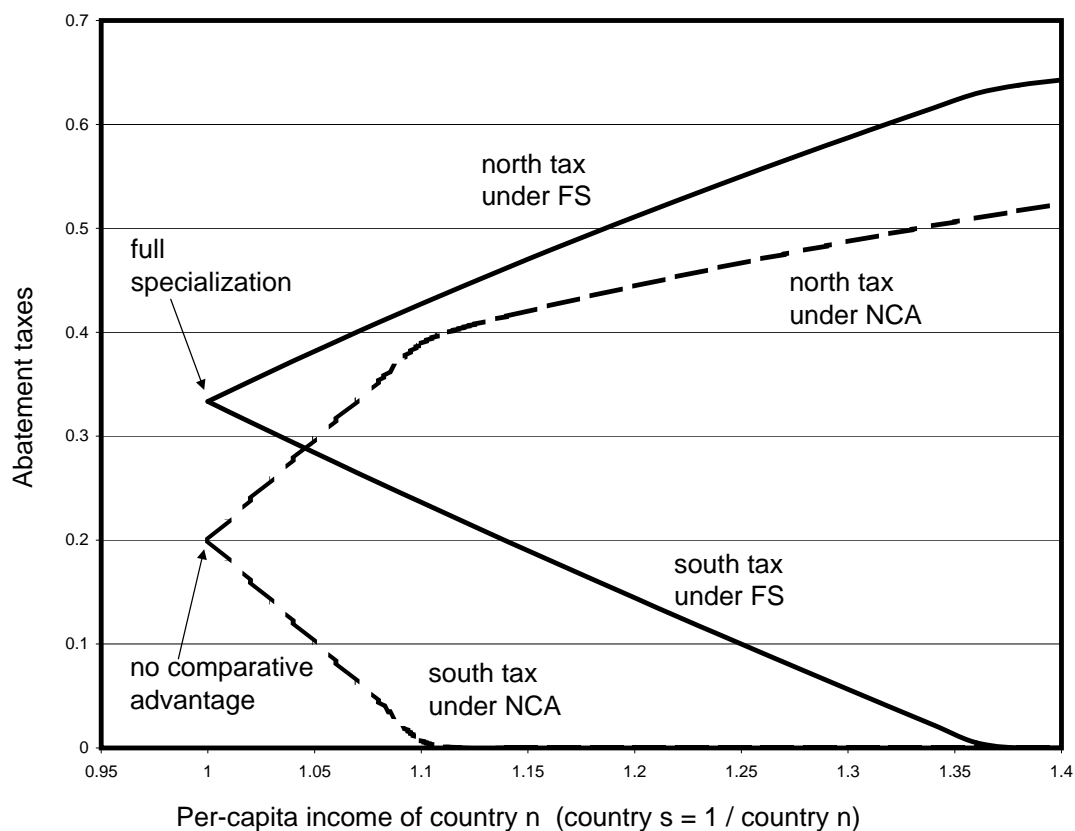


Figure 4: Welfare, environmental quality

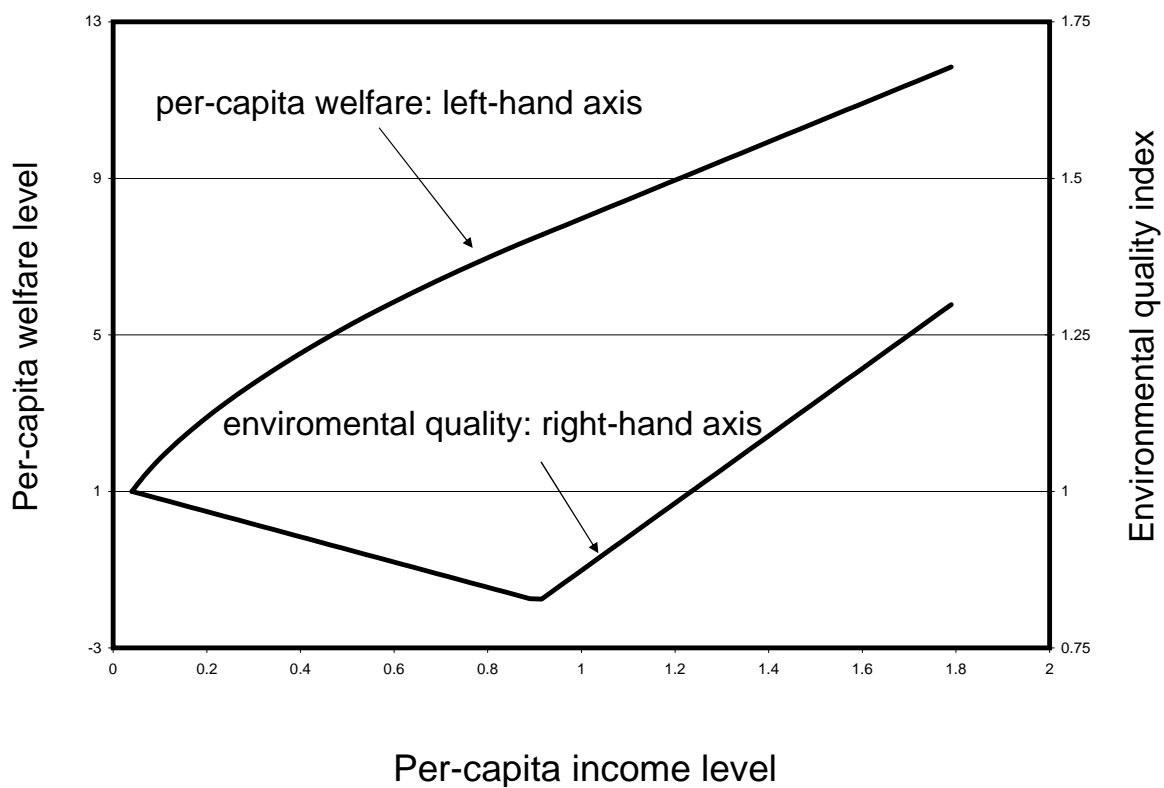


Figure 5: Effect of differing per capita income on equilibria

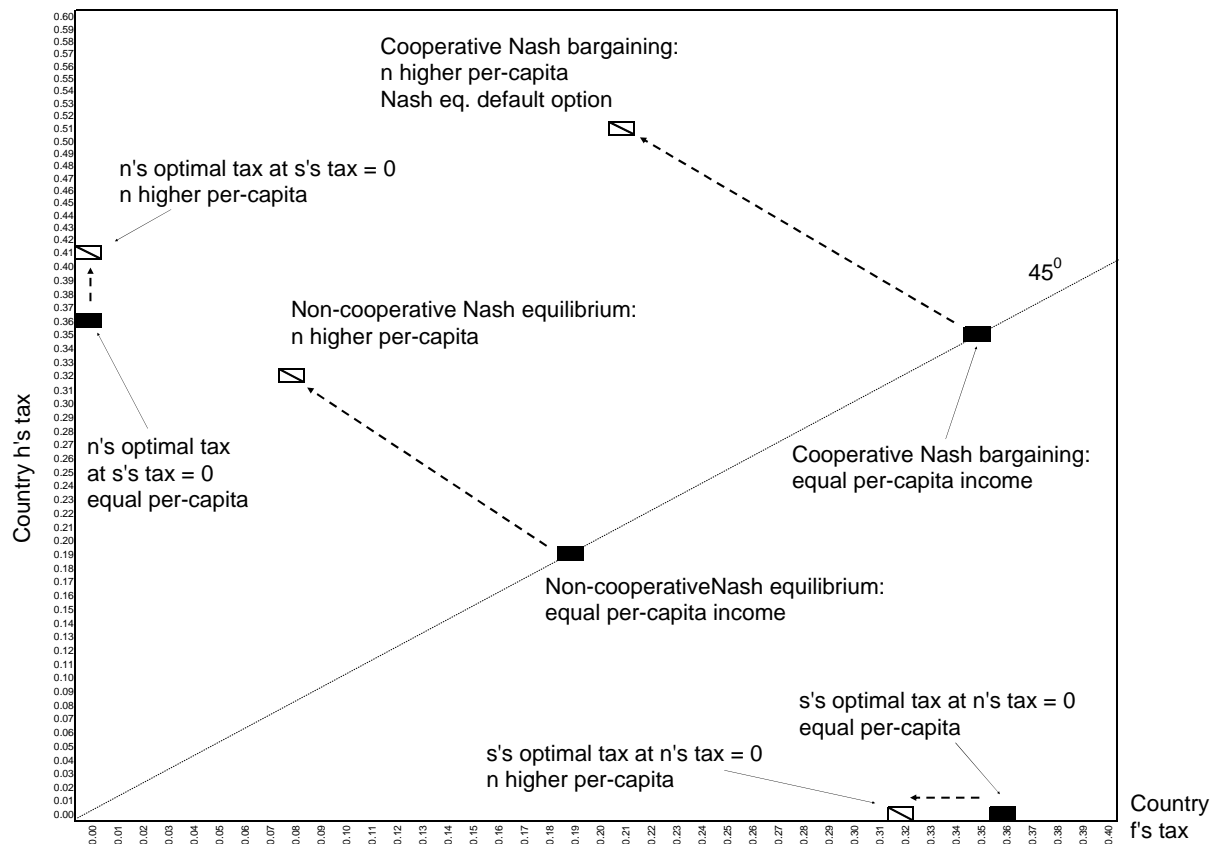
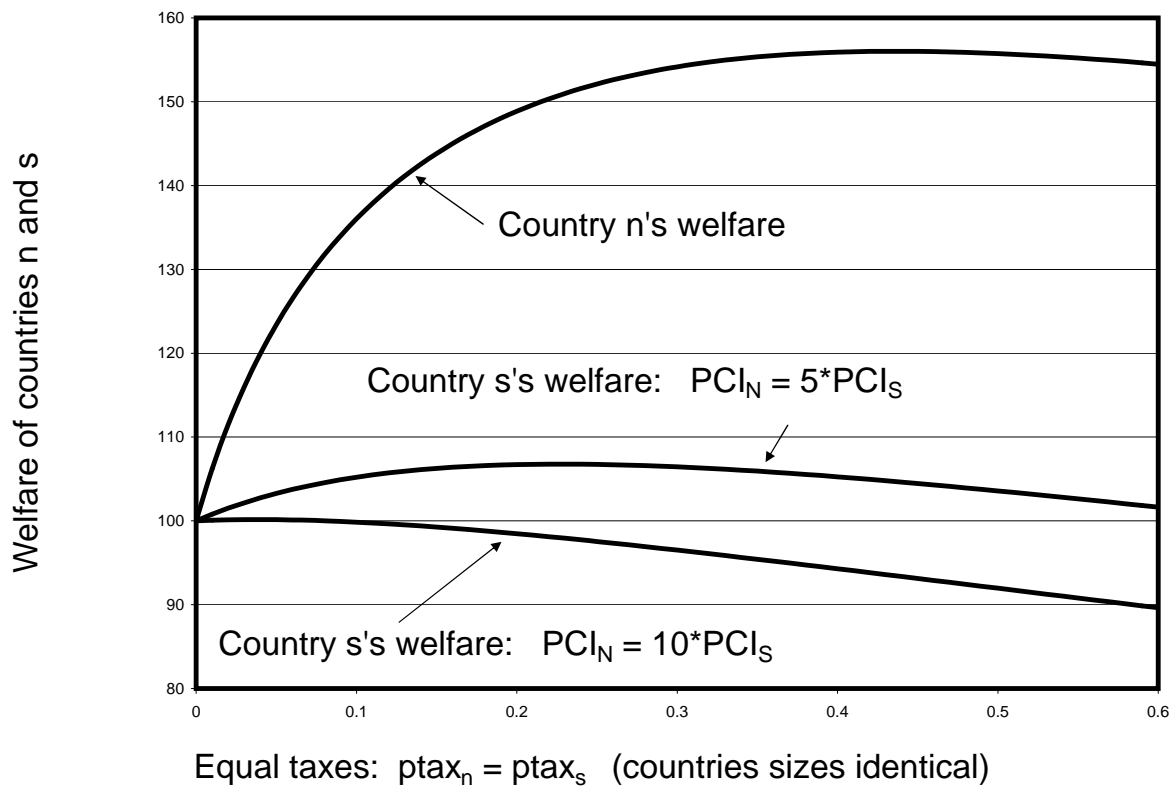


Figure 6: Infeasibility of an equal tax bargaining rule ( $ptax_n = ptax_s$ ) when countries differ greatly in per-capita income:  $PCI_N = 10 * PCI_S$



\$TITLE:LINK-MPEC.GMS cooperation over all four policy instruments

\$ONTEXT INITIAL CALIBRATION (countries h = n in paper, f = s in paper)  
*calibrated to initial abatement taxes constrained to equal zero*  
 Rows = markets; row sums zero: zero profits  
 Columns = sectors; column sums zero: market clearing, income balance

	ZH	ZF	XHF	XFF	YFF	YFH	WH	WF	CONSH	CONSF
PXH	180		-80				-100			
PYH	20					80	-100			
PXF		20	80					-100		
PYF		180				-80		-100		
PWH							300		-300	
PWF								300		-300
PLH	-200								200	
PLF		-200								200
PENVH							-100		100(a)	
PENVF								-100		100(b)

(a):100 = 100 units of initial E endowment plus e\_0 = 100 equals 200  
 minus 100 units of pollution generated by production = 100 for WH

(b):100 = 100 units of initial E endowment plus e\_0 = 100 equals 200  
 minus 100 units of pollution generated by production = 100 for WF

\$OFFTEXT

#### PARAMETERS

VALH per-capita income paramater for the S-G preferences - h  
 VALF per-capita income paramater for the S-G preferences - f  
 SIGMA elasticity of transformation between X and Y  
 ENDOWLH factor endowment of country h  
 ENDOWLF factor endowment of country f  
 WELHN disagreement outcome for country h in bargaining  
 WELFN disagreement outcome for country f in bargaining;

VALH = 1;  
 VALF = 1;  
 SIGMA = 1;  
 ENDOWLH = 200; ENDOWLF = 200;  
 WELHN = 1;  
 WELFN = 1;

#### VARIABLES

WELH welfare of country h  
 WELF welfare of country f  
 WELG value of Nash bargaining objective function;

#### POSITIVE VARIABLES

ZH activity for composite X-Y commodity output in h  
 ZF activity for composite X-Y commodity output in f  
 XHF export activity: X from h to f  
 YHF export activity: Y from h to f  
 XFH export activity: X from f to h  
 YFH export activity: Y from f to h  
 WH welfare index for h (activity for "production" of WH)  
 WF welfare index for h (activity for "production" of WF)  
 ABH abatement activity for h  
 ABF abatement activity for f

PZH price of Z (composite X-Y) in h  
 PZF price of Z (composite X-Y) in f  
 PXH price of X in h  
 PXF price of X in f  
 PYH price of Y in h  
 PYF price of Y in f  
 PLH price of composite factor L in h  
 PLF price of composite factor L in f  
 PWH price of welfare in h (real consumer price index)  
 PWF price of welfare in f (real consumer price index)  
  
 PABH price (cost) of the abatement activity in h  
 PABF price (cost) of the abatement activity in f  
 PENVH consumer valuation of environmental quality in h  
 PENVF consumer valuation of environmental quality in f  
  
 CONSH consumer income in h  
 CONSF consumer income in f  
  
 POLRED pollution reduction due to combined abatement in h and f  
 POL pollution generated by production of ZH and ZF  
  
 PTAXH pollution tax in h - receipts allocated to abatement in h  
 PTAXF pollution tax in f - receipts allocated to abatement in f  
 TARH tariff in country h  
 TARF tariff in country f;

#### EQUATIONS

WELFAREH welfare of country h  
 WELFAREF welfare of country f  
 WELFAREG Nash bargaining objective function  
  
 COSTZH pricing equation for ZH (cost =G= price) - comp var ZH  
 COSTZF pricing equation for ZF (cost =G= price) - comp var ZF  
 COSTXHF pricing equation for XHF (cost =G= price) - comp var XHF  
 COSTYHF pricing equation for YHF (cost =G= price) - comp var YHF  
 COSTXFH pricing equation for XFH (cost =G= price) - comp var XFH  
 COSTYFH pricing equation for YFH (cost =G= price) - comp var YFH  
  
 COSTWH pricing equation for WH (cost =G= price) - comp var WH  
 COSTWF pricing equation for WH (cost =G= price) - comp var WF  
  
 COSTABH pricing equation for ABH (cost =G= price) - comp var ABH  
 COSTABF pricing equation for ABF (cost =G= price) - comp var ABF  
  
 MKTPZH market clearing equation for ZH - complementary variable PZH  
 MKTPZF market clearing equation for ZF - complementary variable PZF  
 MKTPXH market clearing equation for XH - complementary variable PXH  
 MKTPYH market clearing equation for YH - complementary variable PYH  
 MKTPXF market clearing equation for XF - complementary variable PXF  
 MKTPYF market clearing equation for YF - complementary variable PYF  
  
 MKTPLH market clearing equation for LH - complementary variable PLH  
 MKTPLF market clearing equation for LF - complementary variable PLF  
 MKTPWH market clearing equation for WH - complementary variable PWH  
 MKTPWF market clearing equation for WF - complementary variable PWF

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MKT PABH  mkt clear for abatement in h: taxes = expenditure - comp PABH
MKT PABF  mkt clear for abatement in f: taxes = expenditure - comp PABF
MKT ENVH  mkt clear environment in h: supply = demand          - comp PENVH
MKT ENVF  mkt clear environment in f: supply = demand          - comp PENVF

```

```

ICONSH    income balance equation in h - complementary variable ICONSH
ICONSF    income balance equation in f - complementary variable ICONSF

```

```

APOLRED    pollution reduction = abatement by h and f - comp var POLRED
APOL       pollution generated by production by h and f - comp var POL;

```

*\*specify equations and inequalities*

```

WELFAREH.. WELH =E= WH;
WELFAREF.. WELF =E= WF;
WELFAREG.. WELG =E= ((WH - WELHN)*(WF - WELFN));

COSTZH.. 200*PLH =G= 200*PZH;
COSTZF.. 200*PLF =G= 200*PZF;
COSTXHF.. 80*PXH*(1+TARF) =G= 80*PXF;
COSTYHF.. 80*PYH =G= (80*0.999)*PYF;
COSTXFH.. 80*PXF =G= (80*0.999)*PXH;
COSTYFH.. 80*PYF*(1+TARH) =G= 80*PYH;

COSTWH.. 300*((PXH*(1+PTAXH))**(1/3) * (PYH*(1+PTAXH))**(1/3)
           * PENVH**(1/3)) =G= 300*PWH;
COSTWF.. 300*((PXF*(1+PTAXF))**(1/3) * (PYF*(1+PTAXF))**(1/3)
           * PENVF**(1/3)) =G= 300*PWF;

COSTABH.. 100*PLH =G= 100*PABH;
COSTABF.. 100*PLF =G= 100*PABF;

MKT PZH.. 200*PZH =E= 200*(0.9*PXH**(1+SIGMA)
           + 0.1*PYH**(1+SIGMA))**(1/(1+SIGMA));
MKT PZF.. 200*PZF =E= 200*(0.1*PXF**(1+SIGMA)
           + 0.9*PYF**(1+SIGMA))**(1/(1+SIGMA));
MKT PXH.. 0.9*200*ZH*(PXH/PZH)**SIGMA - 80*XHF + 80*XFH
           =G= 100*WH*PWH/(PXH*(1+PTAXH));
MKT PYH.. 0.1*200*ZH*(PYH/PZH)**SIGMA - 80*YHF + 80*YFH
           =G= 100*WH*PWH/(PYH*(1+PTAXH));
MKT PXF.. 0.1*200*ZF*(PXF/PZF)**SIGMA - 80*XFH + 80*XHF
           =G= 100*WF*PWF/(PXF*(1+PTAXF));
MKT PYF.. 0.9*200*ZF*(PYF/PZF)**SIGMA - 80*YFH + 80*YHF
           =G= 100*WF*PWF/(PYF*(1+PTAXF));

MKT PLH.. ENDOWLH =G= 200*ABH + 200*ZH;
MKT PLF.. ENDOWLF =G= 200*ABF + 200*ZF;
MKT PWH.. 300*WH =G= CONSH/PWH;
MKT PWF.. 300*WF =G= CONSF/PWF;

MKT PABH.. 200*PABH*ABH =G= PTAXH*200*WH*PWH/(1+PTAXH);
MKT PABF.. 200*PABF*ABF =G= PTAXF*200*WF*PWF/(1+PTAXF);
MKT ENVH.. (100+100*VALH) + 100*POLRED - 100*POL =G= 100*WH*(PWH/PENVH);
MKT ENVF.. (100+100*VALF) + 100*POLRED - 100*POL =G= 100*WF*(PWF/PENVF);

```

```

ICONSH..  CONSH =E= ENDOWLH*PLH + ((100+100*VALH)+100*POLRED-100*POL)*PEN VH
          + 80*YFH*PYF*TARH;
ICONSF..  CONSF =E= ENDOWLF*PLF + ((100+100*VALF)+100*POLRED-100*POL)*PEN VF
          + 80*XHF*PXH*TARF;

```

```

APOLRED.. POLRED =G= 4*(ABH + ABF);
APOL..    POL =G= (ZH + ZF)/2;

```

*\*declare model definition, including matching equations and variables*  
*\*in the economics equilibrium constraint set (general-equilibrium model)*

**MODEL** NHD /

```

WELFAREG
WELFAREH
WELFAREF
COSTZH.ZH
COSTZF.ZF
COSTXHF.XHF
COSTYHF.YHF
COSTXFH.XFH
COSTYFH.YFH
COSTWH.WH
COSTWF.WF
COSTABH.ABH
COSTABF.ABF

```

```

MKTPZH.PZH
MKTPZF.PZF
MKTPXH.PXH
MKTPYH.PYH
MKTPXF.PXF
MKTPYF.PYF
MKTPLH.PLH
MKTPLF.PLF
MKTPWH.PWH
MKTPWF.PWF

```

```

MKTPABH.PABH
MKTPABF.PABF
MKTENVH.PENVH
MKTENVF.PENVF

```

```

ICONSH.CONSH
ICONSF.CONSF

```

```

APOLRED.POLRED
APOL.POL /;

```

*\*set starting values*

```

ZH.L = 1;  ZF.L = 1;  XHF.L = 1;  YHF.L = 0;  XFH.L = 0;  YFH.L = 1;
WH.L = 1;  WF.L = 1;  ABH.L = 1;  ABF.L = 1;

```

```

PZH.L = 1; PZF.L = 1; PXH.L = 1; PXF.L = 1; PYH.L = 1; PYF.L = 1;
PLH.L = 1; PLF.L = 1; PWH.L = 1; PWF.L = 1;

```

```

PABH.L = 1; PABF.L = 1; PEN VH.L = 1; PEN VF.L = 1;
CONSH.L = 300; CONSF.L = 300; POLRED.L = 0; POL.L = 1;

```



*\*choose numeraire*

PXH.FX = 1;

VALH = 1;

VALF = 1;

ENDOWLH = 200;

ENDOWLF = 200;

*\* simplist scenario: outside options are zero*

*\* equivalenet to maximzing Cobb-Douglas world welfare function*

WELHN = 0;

WELFN = 0;

**OPTION** MPEC = NLPEC;

*\* benchmark replication with ptax constrained to = 0*

PTAXH.FX = 0;

PTAXF.FX = 0;

*\* solve command specifying maximand*

**SOLVE** NHD USING MPEC MAXIMIZING WELG;

*\* allow taxes to be set endogenously*

PTAXH.LO = 0; PTAXH.UP = +**INF**;

PTAXF.LO = 0; PTAXF.UP = +**INF**;

*\* solve for joint max*

**SOLVE** NHD USING MPEC MAXIMIZING WELG;