SIDE PAYMENTS OR EXEMPTIONS:

THE IMPLICATIONS FOR EQUITABLE AND EFFICIENT CLIMATE CONTROL

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INTRODUCTION

The predominant approach thus far to achieving equity in international climate control treaties has been to exempt developing countries from compulsory emissions reductions. Granting exemptions to developing countries, however, can compromise the efficiency of the treaty. Side payments in international treaties provide inducements for voluntary cooperation by countries for whom treaties would otherwise fail to yield welfare gains. This paper analyzes the conditions under which the side payments that are necessary to induce the participation of developing countries in an efficient climate control treaty can also satisfy prevailing notions of fairness in international climate control.

International agreements are necessary to overcome the free-rider problem and provide global public goods like climate control. Ideally, international treaties would be efficient as well as equitable. An efficient climate control treaty will satisfy two conditions. First, the treaty will produce the optimal level of global emissions abatement. At the optimal level of global emissions abatement, the global marginal benefit from the last unit of emissions reduction is equal to the global marginal cost[1]. Second, the treaty will minimize the total cost of global emissions abatement by allocating emissions abatement across countries in some way that equalizes countries' marginal abatement costs. A treaty that satisfies both of these conditions is efficient because it maximizes the potential net benefit from global emissions reduction. An inefficient treaty, therefore, is one that fails to satisfy one or both of these conditions.

Two problems immediately arise in designing an efficient treaty. First, not all countries may benefit equally from climate control. Second, equalizing marginal abatement costs will require countries with lower marginal abatement costs to abate more than countries with higher marginal abatement costs. This implies that an efficient climate control treaty may generate greater net benefits for some countries than for others and that some countries could potentially be worse off due to their participation in the treaty. In which case, side payments will be necessary to induce sovereign nations to join an efficient climate control treaty.

However, it is also true that countries do not equally share responsibility for the build-up of greenhouse gases in the atmosphere that is driving climate change. Nor do

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all countries exhibit equal ability to pay for the costs of reducing greenhouse gas emissions. The prevailing notion of equity in climate control recognizes that some countries should bear more of the burden for combating climate change than others. This notion of equity motivated the Kyoto Protocol's basic framework, which assigns countries differentiated responsibilities for reducing emissions according to their ability to pay and historic contribution to the problem of climate change. The Kyoto Protocol exempts developing countries from mandatory emissions reductions and assigns compulsory emissions reduction targets to the developed countries[2]. However, while the exemptions can be applauded on equity grounds, they have likely compromised the efficiency of the treaty. Because of the exemptions, the treaty provides little incentive to developing countries to limit their own emissions which are increasing at alarming rates[3]. The treaty, therefore, fails to produce the optimal level of global emissions abatement. Moreover, because the treaty does not require developing countries to reduce their emissions, abatement will take place mostly in the developed world where marginal abatement costs are higher[4]. Numerous analyses of the Kyoto Protocol have demonstrated that it neither minimizes the total cost of global abatement nor produces enough global abatement to minimize the risk of climate change[5].

As policy makers continue to debate the inefficiencies of the Kyoto Protocol and possible alternatives, the issue repeatedly raised is whether it is possible to improve efficiency by imposing mandatory emissions limits on developing countries without sacrificing equity. The current Kyoto framework enables developing countries to benefit from other countries' abatement efforts without paying for any of the cost. Admittedly, it is difficult to conceive of an alternative climate control framework that could treat the developing countries as favorably while avoiding the inefficiencies inherent to exemptions. One approach is to impose emissions limits on developing countries, but to transfer the cost to the developed countries. The willingness of developed countries to participate in such a treaty, however, will depend on whether the treaty also increases their own net benefits. If an international climate control agreement is to be self-enforcing, all sovereign countries must find it in their own self-interests to participate [Barrett, 1994].

By lowering global abatement costs and increasing the total level of global abatement, an alternative treaty framework that imposes limits on developing country emissions will generate a global efficiency gain that can potentially render all countries better off, depending upon how it is distributed. Side payments are a mechanism for distributing the global efficiency gain, enabling a distinction between where abatement takes place worldwide and who pays for it[6]. That side payments can be used to relax binding participation constraints and improve the efficiency of an international treaty is well known. However, because equity remains a priority in international climate control efforts, the key issue is whether the side payments that would be necessary to induce countries' voluntary cooperation with an efficient treaty can also achieve equity for developing countries. This will be the case if the countries that require side payments to participate in an efficient climate control treaty are developing countries. In which case, side payments could be viewed as a more efficient and direct approach to attaining fairness for developing countries than exemptions.

Articles by Barrett [1999], Maler and DeZeeuw [1998], Chen [1997], and Tahvonen [1993] demonstrate how differences in countries' benefits and costs from participating in various environmental agreements affect countries' incentives to participate. This paper analyzes which types of countries will require side payments to participate in an efficient climate control treaty when countries' abatement costs and benefits differ. The purpose is to determine whether the side payments that are necessary to induce an efficient treaty outcome can also satisfy the prevailing notion of fairness in climate control. Accordingly, this paper contributes to an emerging literature [Caplan, Cornes, and Silva, 2003; Chichilnisky, Heal, and Starrett, 2000; Chichilnisky and Heal, 1994] that rethinks the linkages between equity and efficiency in global climate control. The paper begins with a basic model of two countries with identical abatement costs and benefits to illustrate the efficiency gains produced by cooperation with an international climate control treaty. Subsequent models introduce key differences in the countries' abatement costs and benefits to illustrate more complicated relationships between equity and efficiency, some of which are counterintuitive.

THE BASIC MODEL: IDENTICAL MARGINAL COSTS AND BENEFITS

In this basic model, there are two countries, C_1 and C_2, that generate carbon emissions. Carbon emissions are trans-boundary pollutants that can accumulate in the atmosphere and cause global warming. Reducing carbon emissions in either country generates a global public good, abatement. The magnitude of each country's benefit from the level of abatement produced globally is a function of its own damages from global warming. Abatement costs in each country are a function of the opportunity costs of its abatement activity. Thus, each country's benefits are a function of total world abatement while each country's costs are a function of only of its own abatement. Initially, it is assumed that both countries have the same abatement benefit and cost functions. This assumption is relaxed in subsequent models.

In line with standard assumptions, the total cost of abatement in each country is an increasing function of its own abatement. This is most easily expressed with a linear marginal cost function for each country in the form $MC_1 = x_1$ and $MC_2 = x_2$, where x_1 and x_2 represent abatement levels in C_1 and C_2 respectively[7]. Summing together each country's abatements yields total global abatement X, such that $X = x_1 + x_2$. The marginal cost function for the world is the horizontal summation of each country's marginal cost schedule and is given by $MC_w = X/2$.

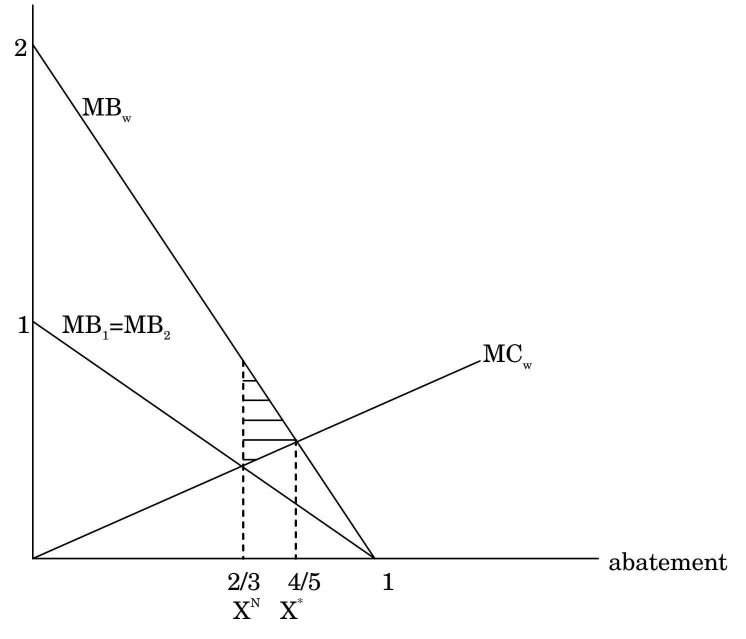
This basic model assumes diminishing marginal benefits from abatement. This is most easily expressed with a linear marginal benefit function in the form $MB_1 = MB_2 = 1\text{-}X$. Note that the intercept of this marginal benefit function, which is normalized to one for simplicity in this and subsequent models, determines the magnitude of marginal abatement benefits. Because abatement is a global public good, abatement in one country produces a positive external benefit for all other countries. Therefore, the marginal abatement benefit for any one country from a unit of abatement is less than the sum of the marginal abatement benefits for all countries combined. The marginal benefit function for the world is the vertical summation of each country's marginal benefit schedule and is given by $MB_w = MB_1 + MB_2 = 2\text{-}2X$.

X^* denotes the optimal level of global abatement where the global marginal benefit from the last unit of abatement is equal to the global marginal cost. This is the level of global abatement than an efficient climate control treaty would generate. Equating world marginal cost to world marginal benefit and solving for X^* yields condition 1:

$$MC_w = MB_w = \frac{X}{2} = 2 - 2X \tag{1}$$

Solving condition 1 for X^* finds the optimal level of global abatement equal to 4/5. In figure 1, X^* indicates the optimal level of global abatement.

FIGURE 1
Identical Marginal Benefits and Costs



Efficiency also requires that a climate control treaty minimize the cost of global abatement. This requires allocating abatement across countries such that all countries have the same marginal abatement cost. Equalizing marginal abatement costs for the optimal level of global abatement X^* yields condition 2:

$$\begin{aligned} x_1 + x_2 &= X^* = \frac{4}{5} \\ MC_1 = MC_2 &= x_1 = x_2 \end{aligned} \tag{2}$$

Solving condition 2 finds $x_1 = x_2 = 2/5$. Given equal and rising marginal abatement cost functions for the two countries in this model, minimizing global abatement costs requires each country to produce one-half of the total level of global abatement.

The cooperative outcome in these models is full participation by all countries in an efficient climate control treaty. Countries can only be expected to voluntarily participate in an efficient climate control treaty if the treaty increases their net benefits as compared to the no treaty or non-cooperative outcome[8]. The non-cooperative outcome finds each country abating at its Nash equilibrium. Each country will choose its own level of abatement to maximize its net benefit from abatement given the abatement level of the other country. The Nash equilibrium level of abatement for C_1 solves the maximization problem:

(3) $$\underset{x_1}{Max}\, TB_1(x_1, x_2) - TC_1(x_1) = NB_1(x_1, x_2)$$

where x_1 and x_2 represent abatement levels in C_1 and C_2 respectively, TB_1 represents total benefits to C_1, TC_1 represents total costs to C_1, and NB_1 represents net benefits to C_1.

$$TB_1 = \int_0^X (1 - X)dx = X - \frac{X^2}{2}$$

$$TC_1 = \int_0^{x_1} x_1 dx = \frac{x_1^2}{2}$$

Condition 3 reduces to

$$\underset{x_1}{Max}(x_1 + x_2) - \frac{(x_1 + x_2)^2}{2} - \frac{x_1^2}{2}$$

This yields the first order condition:

$$FOC_1 = \frac{\partial NB}{\partial x_1} = 1 - (x_1 + x_2) - x_1 = 0$$

which is equivalent to

(4) $$MC_1(x_1) = MB_1(x_1 + x_2)$$

In this model where C_1 and C_2 have identical abatement cost and benefit functions, the first order condition for C_2 similarly reduces to

(5) $$MC_2(x_2) = MB_2(x_1 + x_2)$$

Solving equations (4) and (4.1) for x_1 and x_2 finds that each country's Nash equilibrium level of abatement is equal to 1/3. This generates total global abatement at the Nash equilibrium equal to 2/3, which is less than the optimal level of global abatement. In figure 1, X^N represents the total level of global abatement at the Nash equilibrium.

Comparing the Nash equilibrium level of global abatement to the optimal level of global abatement demonstrates why an international climate control treaty is necessary. When each country considers only its own costs and benefits from abatement, it abates less than what is optimal from the perspective of global efficiency. This is the essence of the free rider problem. No country has an incentive to abate more than its Nash equilibrium level unless the other country commits to the same.

An efficient treaty which induces the full participation of all countries in this model will increase global abatement from X^N to X^* and generate a global efficiency gain equal to the shaded triangle area in figure 1. The total global benefit from abatement is given by

$$TB_w = \int_0^X (2 - 2X)dx = 2X - X^2$$

The total global cost of abatement is given by

$$TC_w = \int_0^X \frac{X}{2} dx = \frac{X^2}{4}$$

Therefore, the global net benefit from abatement is given by

(6) $$NB_w = TB_w - TC_w = 2X - X^2 - \frac{X^2}{4}$$

Evaluating equation (6) at abatement levels X^* and X^N finds the world net benefit from optimal abatement (i.e., the treaty level of abatement) and the world net benefit at the Nash equilibrium level of abatement (i.e., the no treaty level of abatement) equal to 36/45 and 35/45 respectively. Therefore, full participation in an efficient climate control treaty generates an efficiency gain equal to 1/45. In this first model where the two countries have identical marginal abatement cost and benefit functions, the efficiency gain is divided equally between them. Each country's share of the efficiency gain is 1/90.

Since the efficient treaty produces a welfare gain for both countries, both countries have the incentive to sign the treaty.

Although this model predicts that both countries will find it in their self interests to cooperate and sign the efficient treaty, the cooperative outcome is not necessarily a stable outcome, i.e., one from which countries have no incentive to defect. There is a difference between the incentive countries have to sign a particular treaty assuming full cooperation by other countries, and the incentive countries may have to defect from that treaty once other countries have signed. Barrett [1994] argues that international environmental treaties can only be self-enforcing if individual countries have no incentive to defect. Using a model in which the terms of the agreement, the number of signatories, and the actions of non-signatories are determined endogenously, Barrett [1994] finds that when the efficiency gain produced by the treaty is large, a self-enforcing treaty will involve only a small number of signatory countries. Barrett assumed, as this first model does, that countries' have identical linear marginal abatement cost and benefit functions. However, when this assumption is relaxed, it is no longer necessarily the case that full cooperation yields welfare gains for all countries. In other words, when marginal abatement costs and benefits differ, some countries may lack the incentive to sign the treaty, even if full cooperation by all other countries could be ensured. In which case, side payments will be necessary to induce treaty signing.

IDENTICAL MARGINAL BENEFITS, DIFFERENT MARGINAL COSTS

When two countries have identical abatement cost and benefit functions, participating in an efficient climate control treaty is a Pareto improvement. The remainder of this paper explores how differences in countries' abatement benefits and costs give rise to the need for side payments to induce countries' participation. The first case considered is one where countries have identical abatement benefits but different abatement costs. As in the first basic model, each country's marginal abatement benefit function is given by $MB_1 = MB_2 = 1\text{-}X$. Accordingly, the marginal benefit function for the world is given by $MB_w = MB_1 + MB_2 = 2 - 2X$.

As in the first basic model, the marginal abatement cost function for C_1 is given by $MC_1 = x_1$. However, C_2 now has lower marginal abatement costs than C_1. The marginal cost function for C_2 is given by $MC_2 = x_2 / \beta$ where $\beta > 1$. The greater β is, the greater is the difference in marginal abatement costs between the two countries. Horizontal summation of the two marginal cost functions yields the marginal cost function for the world $MC_w = X / \beta + 1$. Equating the global marginal abatement cost and benefit functions yields the optimal level of global abatement X^*:

$$MC_w = MB_w = \frac{X}{\beta + 1} = 2 - 2X$$

(7)
$$X^* = \frac{(\beta + 1)}{(\beta + 3/2)}$$

from which it is clear that as β increases and abatement costs in C_2 decline, the optimal level of global abatement rises.

Efficiency also requires that the treaty equalize marginal abatement costs. For the optimal level of abatement X^* this yields condition 7:

$$x_1 + x_2 = X^* = \frac{(\beta + 1)}{(\beta + 3/2)}$$

(8)
$$MC_1 = MC_2 = x_1 = \frac{x_2}{\beta}$$

Solving for x_1 and x_2 that satisfy condition 7 finds

$$x_1 = \frac{1}{(\beta + 3/2)} \ and \ x_2 = \frac{\beta}{(\beta + 3/2)}$$

Because the cost of abatement is higher in C_1 than C_2, C_2 abates β times more than C_1 under an efficient treaty.

Because abatement is a global public good, each country's total benefit is a function of global abatement, while each country's total cost is a function of its share of global abatement. Subtracting total abatement costs from total abatement benefits yields net benefit functions for C_1 and C_2 equal to

(9)
$$NB_1 = X - \frac{X^2}{2} - \frac{x_1^2}{2}$$

(10)
$$NB_2 = X - \frac{X^2}{2} - \frac{x_2^2}{2\beta}$$

Unlike in the basic model, the two countries no longer have the same net benefit functions. Total costs are higher in C_2 because an efficient treaty requires C_2 to do a greater share of global abatement. As in the basic model, an efficient treaty will generate a global increase in net benefits as compared to the no treaty Nash equilibrium outcome. However, given that C_2 derives the same benefit from optimal global abatement as C_1 but must pay for a larger share of the total cost, the question is whether or not C_2 finds the efficient treaty in its own best interests to sign. This will depend on whether the efficient treaty increases C_2's net benefits as compared to the Nash equilibrium.

Each country's Nash equilibrium level of abatement is given by:

(11)
$$MC_1(x_1) = MB_1(x_1 + x_2) = x_1 = \frac{1 - x_2}{2}$$

$$MC_2(x_2) = MB_2(x_1 + x_2) = x_2 = \frac{\beta(1-x_1)}{(1+\beta)}. \tag{12}$$

Solving for x_1 and x_2 yields

$$x_1 = \frac{1}{(\beta+2)} \;\; and \;\; x_2 = \frac{\beta}{(\beta+2)}.$$

This produces total global abatement in a Nash equilibrium $X^N = (\beta + 1)/(\beta + 2)$. This is less than total global abatement would be under an efficient treaty. Since benefits are the same in both countries and the cost of abatement is β times more costly in C_1, C_2 again does β times more abatement than C_1.

Plugging $X^N = (\beta + 1)/(\beta + 2)$ and $x_2 = (\beta)/(\beta + 2)$ into equation (10) and solving for net benefits for C_2 under the Nash equilibrium β finds

$$NB_2(Nash) = \frac{\beta^2 + 3\beta + 3}{2\left(\beta^2 + 4\beta + 4\right)}.$$

Similarly, substituting $X^* = (\beta + 1)/(\beta + 3/2)$ and $x_2 = (\beta)/(\beta + 3/2)$ into equation (10) finds the net benefits to C_2 under an efficient treaty equal to

$$NB_2(Treaty) = \frac{2\beta^2 + 4\beta + 4}{\left(4\beta^2 + 12\beta + 9\right)}.$$

C_2 should be willing to sign an efficient treaty if the treaty raises its net benefits as compared to the Nash equilibrium. Therefore, the necessary condition for cooperation by C_2 is given by

$$NB(Treaty)_2 \geq NB(Nash)_2$$

$$\frac{2\beta^2 + 6\beta + 4}{\left(4\beta^2 + 12\beta + 9\right)} \geq \frac{\beta^2 + 3\beta + 3}{\left(2\beta^2 + 8\beta + 8\right)}, \tag{13}$$

from which it is clear the value of β determines whether or not C_2 has an incentive to sign the treaty. Solving condition 13 numerically finds $\beta = 2.8$ as the value of β that equates net benefits for C_2 under the treaty and Nash outcomes.

The critical β value that equates net benefits under an efficient treaty and the no treaty Nash outcome for a low abatement cost country like C_2 depends on the specifications of the marginal abatement cost and benefit functions. In this particular case where abatement benefits are the same for both countries, a difference in abatement costs of 2.8 times or more is sufficient to prevent treaty participation by the lower abatement cost country. This is because an efficient treaty will require this country to do more of the abatement, thereby decreasing global abatement costs. As global abatement costs fall, the optimal level of abatement rises. Although the lower abatement cost country also benefits from the increase in global abatement, it pays for a larger share of the cost. Therefore, there must be some critical value for the difference in marginal abatement costs between countries such that the lower abatement cost country prefers the Nash outcome and will not voluntarily participate in an efficient treaty unless side payments are made.

IDENTICAL MARGINAL COSTS, DIFFERENT MARGINAL BENEFITS

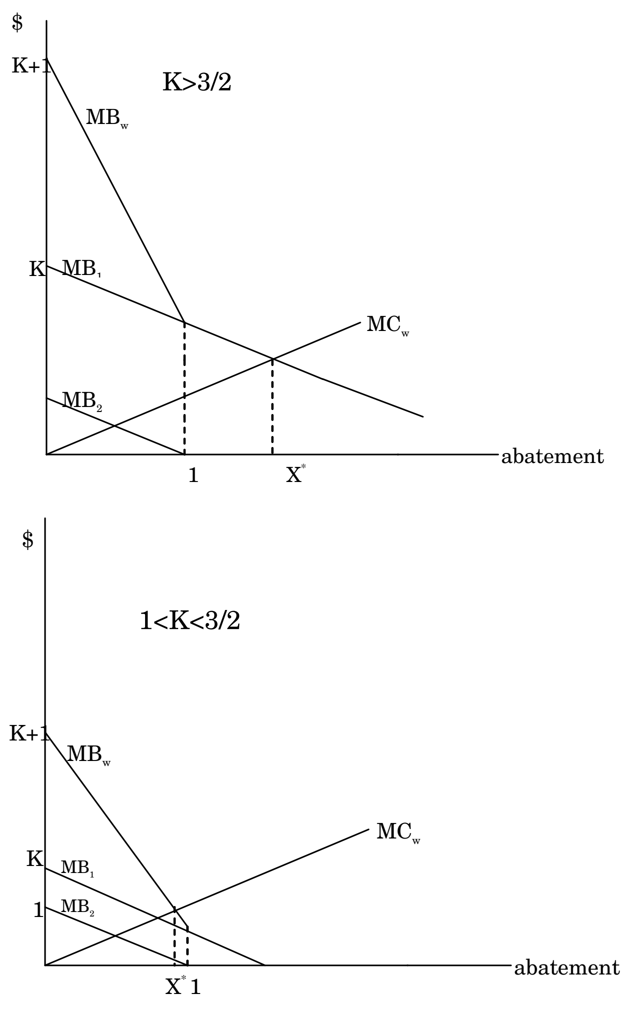
This model explores the influence of real or perceived differences in benefits on the incentives of individual countries to cooperate with an efficient climate control treaty. As in the original model, the marginal abatement cost functions are the same for both countries and are given by $MC_1 = x_1$ and $MC_2 = x_2$. This implies a world marginal cost function given by $MC_w = X/2$. The marginal benefit function for C_2 will be the same as in the original model, $MB_2 = 1\text{-}X$. However, now C_1 benefits more from emissions abatement than C_2. The marginal benefit function for C_1 is given by $MB_1 = K\text{-}X$, where $K>1$ indicates that C_1 benefits K more per each additional unit of abatement than C_2. The greater K is, the greater is the difference in benefits between the two countries.

This way of expressing differences in abatement benefits between countries presumes that marginal benefits diminish at the same rate in both countries, but that one country's marginal benefits are K times higher than the other's for every level of abatement. This also implies that marginal benefits will cease at a lower abatement level for the low benefiting country than the high benefiting country[9]. As illustrated in figure 2, for abatement levels $0<X<1$, marginal abatement benefits are positive for both countries. In that range, the world marginal benefit function is equal to the horizontal summation of the two countries' marginal benefit functions and is given by $MB_w = (K+1)\text{-}2X$. However, for all $X \geq 1$, the only country that continues to benefit from global abatement is the high benefiting country, C_1. This means that the world marginal benefit function is equivalent to C_1's marginal benefit function for all $X \geq 1$. This explains the "kink" in the world marginal benefit function at X=1.

At the optimal global level of abatement, $MC_w = MB_w$. Given that the $MB_w = (K+1)\text{-}2X$ for all $X<1$ and $MB_w = K\text{-}X$ for all $X \geq 1$, there are two possible solutions for X^*. The value of K determines whether the world marginal cost function intersects the world marginal benefit function at X<1 or $X \geq 1$. Simulation finds that for all K<3/2, X^*<1 and equation (14) denotes the optimal level of global abatement. For all $K \geq 3/2$, $X^* \geq 1$ and equation (15) denotes the optimal level of global abatement.

In figure 2, it is evident that for $K \geq 3/2$, an efficient treaty produces a level of abatement beyond the capacity of the low benefiting country, C_2, to benefit. However, an efficient treaty will also equalize marginal abatement costs across countries. Since both countries have identical marginal abatement costs in this model, an efficient treaty will allocate one-half of total global abatement to each country. When K=3/2, optimal global abatement is equal to 1. C_2's net benefit from an efficient treaty (.38) is less than its net benefit under the Nash equilibrium (.48) and it has no incentive to sign an efficient treaty. When K increases beyond 3/2, optimal global abatement exceeds 1. For all units of abatement beyond 1, C_2's marginal abatement benefits are negative, though its marginal abatement costs are positive. This means that when K exceeds 3/2, C_2 derives an even greater net benefit from the Nash outcome than the efficient treaty outcome. Therefore, whenever $K \geq 3/2$, C_2 will have no incentive to sign an efficient climate control treaty.

FIGURE 2
Different Marginal Benefits, Identical Marginal Costs



(14) $$X^* = \frac{X}{2} = (K+1) - 2X \quad for\ X^* < 1$$

(15) $$X^* = \frac{X}{2} = (K - X) \quad for\ X^* \geq 1$$

For all $K< 3/2$, $X^*<1$ and C_2's marginal benefit from the last unit of abatement is positive. However, it still benefits less from abatement than C_1 and is required by an efficient treaty to do one-half of the total abatement. Whether C_2 is willing to sign the efficient treaty depends on whether the treaty raises its net benefits as compared to the Nash equilibrium. Solving equation (14) finds optimal global abatement $X^* = 2(K+1)/5$. Each country will abate one-half of X^* such that $x_1 = x_2 = (K+1)/5$.

The Nash equilibrium levels of abatement for each country are given by

(16) $$MC_1(x_1) = MB_1(x_1 + x_2) = x_1 = \frac{K - x_2}{2}$$

(17) $$MC_2(x_2) = MB_2(x_1 + x_2) = x_2 = \frac{1 - x_1}{2}.$$

Solving for x_1 and x_2 under the Nash equilibrium finds:

$$x_1 = \frac{2K-1}{3} \; and \; x_2 = \frac{2-K}{3}.$$

This yields total abatement under a Nash equilibrium $X^N = (K+1)/3$.

Net benefits for C_2 are given by

(18) $$NB_2 = X - \frac{X^2}{2} - \frac{x^2}{2}.$$

Plugging $X^* = 2(K+1)/5$ and $x_2 = (K+1)/5$ into equation (18) finds net benefits to C_2 from the treaty equal to

$$NB_2(Treaty) = \frac{-K^2 + 2K + 3}{10}.$$

Plugging $X^N = (K+1)/3$ and $x_2=(2-K)/3$ into equation (18) finds net benefits to C_2 from the Nash outcome equal to

$$NB_2(Nash) = \frac{-2K^2 + 8K + 1}{18}.$$

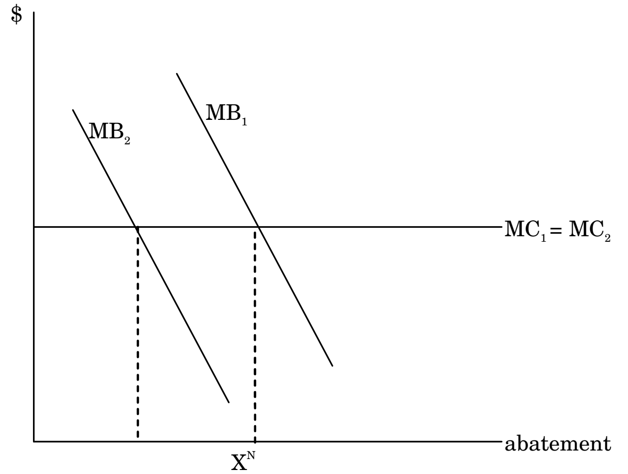
Therefore, the following condition must hold for C_2 to be willing to sign an efficient treaty

(19) $$\frac{-K^2 + 2K + 3}{10} \geq \frac{-2K^2 + 8K + 1}{18}$$

Condition 19 is satisfied for all $K \leq 1.05$. For all $K>1.05$, side payments are required to induce C_2's cooperation.

The critical value for K that precludes treaty signing by the low benefiting country is particular to this model. Nevertheless, this model reveals that if abatement benefits differ sufficiently between countries, side payments will be necessary to induce a low benefiting country to participate in an efficient treaty. Even though it benefits less, the low benefiting country will be required to abate at the same level as the high benefiting country and that level will rise due to its participation in the treaty. This is because including the low benefiting country in the efficient treaty increases global abatement benefits, thereby increasing the optimal level of global abatement. This implies that there must be some critical value for the difference in countries' marginal abatement benefits such that a low benefiting country will be worse off under an efficient treaty than it would have been otherwise.

FIGURE 3
Constant Marginal Costs, Different Marginal Benefits



In this model where marginal abatement benefits differ, the significance of rising marginal abatement costs is apparent. Figure 3 presents the case of different marginal abatement benefits and constant marginal abatement costs. With constant marginal abatement costs, only the high benefiting country abates in the Nash equilibrium. The high benefiting country, $C_{1,}$ will abate at X^N, where $MB_1 = MC_{1.}$ At X^N, the marginal cost to C_2 exceeds its marginal benefit, so it has no incentive to abate at all. If, however, marginal costs are rising, C_2 will abate some in the Nash equilibrium because the marginal costs of its initial abatements are less than its marginal benefits. In general, the "flatter" the marginal cost function, the more C_1 abates than C_2 at a Nash equilibrium. If the low benefiting country is abating less under the Nash, it has even less of an incentive to abate more under an efficient treaty. Therefore, the flatter the marginal abatement cost function, the less likely it is that the low benefiting country will voluntarily cooperate with an efficient climate control treaty.

DIFFERENT MARGINAL BENEFITS, DIFFERENT MARGINAL COSTS

This model explores the incentives for treaty signing when both abatement costs and benefits differ across countries. In this model, marginal abatement costs are rising and marginal abatement costs are β times lower in C_2 than C_1. This yields marginal abatement cost functions, $MC_1 = x_1$ and $MC_2 = x_2 / \beta$ where $\beta > 1$ and a world marginal cost function, $MC_w = X/(\beta + 1)$. One country, C_1, benefits K more than C_2 from each additional unit of abatement. But in this model, constant marginal benefits are assumed[10]. This yields marginal abatement functions, $MB_1 = K$ where $K>1$ and $MB_2 = 1$. Vertical summation yields a world marginal benefit function, $MB_w = (K+1)$.

Solving for the optimal level of global abatement X^* by equating the world marginal benefit and cost functions finds $X^* = (K+1)(\beta+1)$. As the benefits from emissions abatement increases (i.e., K increases) and the costs of emissions abatement decline (i.e., β rises), the optimal level of global abatement rises. An efficient treaty will allocate emissions abatement across countries such that $MC_1 = MC_2$ and $x_1 + x_2 = X^*$. Solving for the values of x_1 and x_2 that satisfy these conditions finds $x_1 = (K+1)$ and $x_2 = \beta(K+1)$.

As in previous models, each country's marginal abatement costs are a function of only its own level of abatement. However, because constant marginal benefits have been assumed in this model, marginal abatement benefits are no longer a function of either country's abatement level. This means that, in the absence of a treaty, each country chooses an abatement level that is optimal for that country regardless of what the other country does[11]. In a Nash equilibrium, each country produces abatement until its marginal cost from the last unit of abatement is equivalent to its constant marginal benefit. Therefore, in a Nash equilibrium, $x_1 = K$ and $x_2 = \beta$, for total global abatement in a Nash equilibrium $X^N = K + \beta$.

As in previous models, an efficient treaty generates an increase in global net benefits as compared to the Nash equilibrium. Previous models demonstrated the disincentives to treaty signing for the country with lower marginal abatement costs and benefits. Comparing net benefits from the Nash equilibrium and efficient treaty outcome to the low benefiting and low abatement cost country in this model determines whether or not it has an incentive to participate. Net benefits for C_2 are given by:

(20) $$NB_2 = X - \frac{x_2^2}{2\beta}.$$

Plugging $X^* = (K+1)(\beta+1)$ and $x_2 = \beta(K+1)$ into equation (20) finds C_2's net benefits from the treaty equal to

$$NB_2(Treaty) = \frac{-K^2 + 2K + 3}{2\beta}.$$

Plugging $X^N = K + \beta$ and $x_2 = \beta$ into equation (20) finds C_2's net benefits from the Nash equilibrium equal to

$$NB_2(Nash) = \frac{2K+1}{2\beta}.$$

C_2 will voluntarily cooperate in an efficient treaty as long as $NB_2(Treaty) \geq NB_2(Nash)$. Therefore, C_2 will cooperate as long as

(21) $$\frac{-K^2+2K+3}{2\beta} \geq \frac{2K+1}{2\beta} \quad or \quad \frac{2}{\beta} \geq K.$$

Condition 21 demonstrates that there is a critical combination of differential marginal abatement benefits and costs that will yield voluntary cooperation. An increase in β implies an increase in global abatement under an efficient treaty and an increased share of abatement for C_2, even though it benefits less. If K is also large, an efficient treaty will require more global abatement and C_2's share of the net benefits from the treaty predictably will be small. C_2 will prefer the Nash outcome. The more that countries differ in terms of their marginal abatement costs, the less they can differ in terms of their marginal abatement benefits and still be expected to voluntarily cooperate. This model predicts that side payments will be necessary to induce cooperation from countries that are both low benefitters and low cost abaters.

DISCUSSION OF RESULTS AND CONCLUSIONS

The previous models demonstrate that an efficient treaty raises global net benefits as compared to the no-treaty Nash equilibrium outcome. The source of the global welfare gain is two-fold. First, the treaty requires each country that participates to internalize the external benefits of its own emissions reduction, thereby securing the optimal level of global emissions abatement. Second, the treaty minimizes the total cost of global abatement by equalizing countries' marginal abatement costs. However, even though an efficient treaty can make every country better off as compared to the Nash equilibrium, whether or not it will make every country better off depends on how the global efficiency gain is distributed. What these models have demonstrated is that an efficient treaty fails to yield an increase in net benefits for low abatement cost and (or) low abatement benefit countries when countries' abatement costs and benefits differ substantially. The participation of these countries, however, is critical to achieving an efficient treaty outcome. Side payments, therefore, are necessary to induce voluntary cooperation by countries that have lower abatement costs and (or) benefit less from global emissions abatement.

When abatement costs and benefits differ substantially, efficiency will require the use of side payments. The direction of side payments, however, also has implications for global equity. Since the prevailing notion of equity as reflected in the Kyoto Protocol recognizes that developing countries should not pay for the cost of mitigating global climate change, a convenient link between equity and efficiency emerges if developing countries are the recipients of side payments under an efficient treaty. As these models demonstrate, developing countries will be the recipients of an efficient treaty if their abatement costs are lower than developed countries and (or) they benefit less from emissions abatement.

It is generally assumed that developing countries have lower marginal abatement costs than developed countries. This is based on the presumption of rising marginal abatement costs and the observation that developing countries, as a group, have engaged in less emissions abatement activity than developed countries thus far. Many low cost options for reducing emissions still exist in the developing world, such as fuel-switching, implementing basic energy efficiency measures, and sequestering carbon emissions through forestry. The availability of such low cost abatement options in the developing world prompted the inclusion of the Clean Development Mechanism (CDM) in the Kyoto Protocol. The CDM allows developed countries to obtain credit toward their own emissions targets for abatement activity that takes place in the developing world[12]

Whether or not developing countries will benefit less than developed countries from reducing the risk of climate change is a more complicated issue. Predicting which countries will endure greater damage from climate change is difficult, as scientists remain uncertain about the exact scale and timing of climate change. It is likely that developing countries in Africa and the tropics will suffer declines in agricultural productivity, losses to the resource intensive sectors of their economies, and the spread of climate related diseases. Moreover, low-lying developing countries and developing countries with extensive coastlines may suffer the effects of rising sea-levels. Nordhaus and Boyer [2000] estimate sectoral damages from global warming for different regions in the world. Their model predicts that the U.S. and China will suffer the lowest aggregate damages from climate change, .45 percent and .20 percent of GDP respectively. Nordhaus and Boyer predict the highest aggregate damages for India at 4.9 percent of GDP. Damages for the U.S., Russia, Japan, and China will be modest, while Europe, India, Africa, and many middle income, lower middle income, and lower income countries may be significantly impacted.

A country's potential damages from climate change are largely a function of its geographic location and climate. The location of so many developing countries in tropical and sub-tropical regions suggests than developing countries may, on average, suffer more damage from climate change that many developed countries. However, comparing countries' damages from climate change as a means for identifying which countries will benefit more from global emissions reduction presumes that developed and developing countries value income the same at the margin. This is highly unlikely given the vast income disparities that characterize the divide between developed and developing countries. Since the value of what is damaged on the margin is greater in developed countries than developing countries, developed countries benefit more from each unit of abatement. This could explain the reticence of so many developing countries to partake in current climate control efforts. Reducing emissions to prevent future climate change means forgoing income today, a luxury many developing countries simply do not have.

If indeed developing countries benefit less than developed countries from emissions reduction and can reduce emissions at relatively lower cost, side payments to developing countries may be necessary to induce their participation in an efficient climate control treaty. At a minimum, side payments will render the developing countries no worse off than they were prior to their involvement with the efficient treaty. This should allay the fears of many that involving developing countries in a climate control treaty necessarily means mitigating climate change at developing countries' expense. Side payments, in fact, could be used in an efficient treaty to make even further concessions to equity. As long as an efficient treaty generates a global welfare gain, developed countries could allocate the entire global efficiency gain to the developing countries and still be no worse off themselves than they were beforehand.

What these models reveal is that side payments to developing countries are justified on efficiency as well as equity grounds. Contrary to prevailing beliefs, a climate control treaty that involves the participation of developing countries need not sacrifice equity to achieve efficiency. Side payments avoid the inefficiencies inherent to exemptions and provide a more direct mechanism for addressing equity in international climate control. Policy makers should remain mindful of the efficiency and equity implications of side payments as they contemplate revisions and alternatives to the Kyoto Protocol

NOTES

1. Because emissions abatement is a global public good, abatement in one country produces a positive external benefit for all other countries. The global marginal benefit from a unit of abatement is equal to the sum of each country's marginal benefit from abatement. The optimal level of global abatement internalizes the positive externality associated with each individual country's own emission abatement.
2. On average, the developed countries must reduce their emissions by 5.2 percent below their 1990 baseline emissions levels during the commitment period, 2008-2012.
3. The Kyoto Protocol's Clean Development Mechanism (CDM) does allow the developed countries to pay for some emissions abatement in the developing world and apply the resulting "emissions credits" toward their own quotas. However, the Kyoto Protocol restricts the scale and scope of abatement activity that can take place under the CDM due to concerns for the permanence, verifiability, and additionality of emissions reductions in developing countries.
4. This presumes rising marginal abatement costs and low cost options for reducing emissions in the developing world that have not yet been exhausted.
5. A special issue of *The Energy Journal*, "The Costs of the Kyoto Protocol: A Multi-model Evaluation"[1999] compiles the results of thirteen different analyses of the costs of the Kyoto Protocol under different implementation regimes. Cline [2001] and Weyent and Hill [1999] provide overviews of the analyses and the results.
6. The manner in which side payments could be made could vary depending upon how the treaty is structured. For example, if the treaty allocated non-tradable emissions targets to countries, side payments could take the form of lump sum income transfers between countries. If the treaty instead allocated tradable emissions permits to countries, the distribution of initial permits could serve as side payments.
7. Non-linear marginal abatement benefit and cost functions were tried, but analytical solutions could not be derived. Linear marginal abatement benefit and cost functions are used in the literature for the same reason. See Barrett [1994].
8. This and all subsequent models assume zero transactions costs associated with treaty negotiation and implementation.

9. An alternative way to express differences in benefits would have been to give both marginal benefit functions the same horizontal intercept but different slopes. However, there is no reason to suspect that one country's marginal benefits diminish faster than another's. There is evidence to suggest that some countries benefit more from abatement than others.
10. Constant marginal benefits is a necessary assumption in order to derive an analytical solution for this model, but it is not without precedent in the literature. For example, Nordhaus [1991] and Nordhaus and Boyer [2000] assume constant marginal benefits, arguing that marginal changes in the flow of carbon emissions will have a negligible impact upon the stock of carbon dioxide in the atmosphere and the marginal benefit from emissions reduction is more or less invariant to the current level of abatement. Diminishing returns to abatement are still expected over a wider range of abatement levels.
11. Unlike in the previous models, the Nash equilibrium is a dominant strategy equilibrium.
12. The amount of credits each developed country can receive are limited. Therefore, the CDM cannot equalize marginal abatement costs between countries.

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