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How Effective and Efficient Can the Kyoto Protocol Be in Controlling Global Carbon Dioxide Emissions?

By A. Caplan, R. Cornes and E. Silva

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Abstract

We derive the circumstances under which the Kyoto Protocol leads to effective and efficient control of emissions of carbon dioxide. Carbon dioxide emissions are by-products of industrial production or deforestation. Since these emissions generate a positive private consumption benefit as well as a negative and global externality, we utilize the impure public good model to describe tastes. We find that the 'Kyoto Protocol Game' is Pareto efficient. We also show that both abatement trading and interregional transfers, implemented by an international authority, are necessary for the efficiency and effectiveness of the Kyoto Protocol.

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Non-Technical Summary

The Kyoto Protocol, completed in 1997, is intended to mitigate the global warming externalities associated with global greenhouse gas emissions. The benefits that accrue to an individual country when it curbs its own carbon dioxide emissions are typically greatly exceeded by the associated costs borne by that country the net global benefits from reducing the level of pollution accrue to other countries. Thus, to induce a country to curb its emissions, further net transfers of real resources to the emitting country are required. Viewed from this perspective, the Kyoto protocol has two interesting features. First, it envisages trading between countries in units of abatement along lines analogous to the marketable pollution permit programs that have recently proved effective as domestic policy instruments in the US. Second, redistributive transfers are effected by an international agency, the Global Environment Facility. These transfers are determined after the regions abatement provision and trading decisions have been observed.

This paper shows that both of these features the ability to trade pollution abatement and the existence of redistributive transfers are indeed required if the global warming externality resulting from carbon dioxide emissions is to be fully internalised and a Pareto efficient allocation achieved. We set up a simple two-region model and examine three possible games. In the first, called Autarky with International Transfers, the regions do not trade abatement units. In the second, Abatement Trading without International Transfers, abatement units are provided and traded, but there is no mechanism for effecting interregional transfers. The resulting noncooperative equilibria of these games are Pareto inefficient. However, the two-stage game that permits trading in abatement at the first stage, followed by interregional transfers, has equilibria that are Pareto efficient. Thus, abatement trading and redistributive transfers are crucial elements of the Kyoto Protocol, since both are necessary for it to generate an efficient outcome.

1. Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change, completed December 10, 1997, will probably be remembered most for its innovative use of emissions trading to control global greenhouse gas emissions.[1] However, it will also be remembered for the promulgation of two other incentives – clean development mechanisms and international transfers. The idea behind clean development mechanisms is articulated in Article 11 of the protocol, whereby (1) "[less developed] countries will benefit from project activities resulting in certified emissions reductions," and (2) "[developed countries] may use the certified emissions reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments."

The Kyoto Protocol's promotion of international transfers as a means to reduce global carbon dioxide emissions is apparently a step in the right direction. As Sandler (1997) points out, the control of global warming requires stronger effort to bring about collective action than that required to control other types of regional and global externalities, such as acid rain and CFC emissions. For example, both the Helsinki Protocol (1985) to control sulfur dioxide emissions and the Sofia Protocol (1988) to control nitrogen oxide emissions merely codified reductions that the parties had either already independently implemented or were soon to achieve (Murdoch, Sandler and Sargent, 1997). Similarly, the Montreal Protocol (1987) to control CFC emissions did not impose any new constraints on its signatories. Rather, the protocol served to legitimize the strategically chosen status quo (Murdoch and Sandler, 1997). Because a nation's benefits of curbing its carbon dioxide emissions are typically greatly outweighed by the associated costs, each nation, acting independently, has little incentive to abate. Transfers and abatement trading, however, may work together in promoting incentives for efficient control of global warming.

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[1] That emissions trading is a cost-effective means of controlling pollution is not much in debate. The theory behind its use is generally clear, simple, and favorable: compared to command-and-control policies, such as uniform quotas, emissions trading induces firms to obtain the same aggregate level of control at lower total cost (c.f. Tietenberg, 1992; Hanley, et al., 1997). Moreover, similar types of marketable permit programs in the U.S. used to control water, lead, and air pollution, have proven effective (Hahn, 1989; Stavins, 1998). All told, an impressive amount of research and experience underscores the benefits and costs associated with emissions trading programs (see Maloney and Yandle (1984), Coggins and Swinton (1996) and references therein).

In fact, the Conference of the Parties to the United Nations Framework Convention on Climate Change, which represents the supreme body of the Convention, has delegated the responsibility of operating the Convention's financial mechanism to the Global Environment Facility (GEF). The GEF was established in 1990 by the World Bank, the United Nations Development Program (UNDP) and the United Nations Environment Program (UNEP). The role of the convention's mechanism is to transfer funds and technology across nations. The GEF, however, lacks political and economical powers to design and enforce international mechanisms to control emissions of carbon dioxide. The GEF is incapable of punishing nations that do not comply with international standards. The international transfers implemented by the GEF are redistributive, namely, they are effected *after* the nations choose their environmental agendas.

In this paper, we derive the circumstances under which the Kyoto Protocol lead to effective and efficient control of global carbon dioxide emissions. We focus our attention on abatement of carbon dioxide emissions produced as by-products of industrial production or deforestation. Carbon dioxide emissions generate a positive private consumption benefit as well as a negative and global externality. Thus, it seems natural to assume that the impure public good model provides an accurate description of tastes. In our framework, we assume that consumption preferences for each region -- for simplicity, there are only two -- can be represented by a single representative consumer and that both regions may participate in carbon dioxide abatement trading. There is an international agency, say the GEF, whose objective is to implement interregional income transfers in order to satisfy a politically determined distribution of utility levels between the regions.

We start the analysis by characterizing a Pareto efficient allocation. Then, we examine a Stackelberg game, called ‘Kyoto Protocol’, whereby both regions provide and trade abatement units prior to the GEF deciding on the level of interregional transfer to be made. The regions are Stackelberg leaders and the GEF is a common Stackelberg follower. As we mentioned above, the GEF effects interregional transfers after it observes the decisions of the regions. The equilibrium concept used for the Kyoto Protocol game is subgame perfection. We find that the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient. The intuition of our result is that, when combined with preexisting abatement trades, the GEF's redistributive transfers result in Lindahl prices for abatement decisions.

For comparison purposes, we investigate two other noncooperative games. In the game called 'Autarky With Interregional Transfers,' we examine a situation similar to the Kyoto Protocol except that the regions do not trade abatement units. In the game 'Abatement Trading Without Interregional Transfers,' we assume that both regions can provide and trade abatement units, but there is no mechanism in place for the implementation of interregional transfers. Since each one of these games deviates from the Kyoto Protocol game in only one 'dimension,' the comparisons between the equilibrium for each game equilibrium and the equilibrium for the Kyoto Protocol game are immediate and informative: *they reveal that both abatement trading and interregional transfers are necessary conditions for the efficiency of the Kyoto Protocol!* While the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient, the equilibria for the other two noncooperative games are generally Pareto inefficient.

2. The Model

Imagine an economy consisting of two politically autonomous regions, indexed by j, j = 1, 2, two regional governments and an international authority, the GEF. The GEF is created by both regions to implement interregional transfers. The regions decide ex-ante the allocation of minimum utility levels that must be satisfied by any global agreement. Formally, let $\bar{u}^j$ denote region j's reservation level of utility. Any interregional transfer scheme implemented by the GEF must give region j a level of utility at least as high as $\bar{\mathrm{u}}^{\mathrm{j}}$.

There are three commodities, a numeraire good, a regional good and a 'global' good. The representative individual of region j derives the following utility from consumption of x_j units of the numeraire good, a_j units of regional pollution abatement and $A = a_1 + a_2$ units of global pollution abatement:

$$u^j \equiv u^j\left(x_j, a_j, A\right).$$

This utility function is assumed to be strictly quasiconcave, increasing in the first and third elements and decreasing in the second element. Provision of pollution abatement in region j reduces the availability of a commodity (e.g., electricity) that is positively related to positive emissions of carbon dioxide. The cost of pollution abatement, in terms of the numeraire good, in region j is $c^j \equiv c^j\left(a_j\right)$. This cost function is assumed to be strictly convex and increasing. Finally, the representative individual's income level in region j is denoted m_j.

3. Pareto Efficiency

For a fixed θ, $\theta \in (0,1)$, a Pareto efficient allocation can be obtained as a solution to the following problem:

$$\underset{\{x_1, x_2, a_1, a_2\}}{Max}\, \theta\, u^1(x_1, a_1, a_1 + a_2) + (1-\theta)u^2(x_2, a_2, a_1 + a_2)$$

$$\text{s.t.:} \qquad x_1 + x_2 + c^1(a_1) + c^2(a_2) \leq m_1 + m_2. \qquad (\lambda \geq 0)$$

As the parameter θ is varied from 0 to 1, we can derive the entire Pareto frontier. The Lagrangian is

$$L = \theta u^1(x_1, a_1, a_1 + a_2) + (1-\theta)u^2(x_2, a_2, a_1 + a_2) - \lambda\left(x_1 + x_2 + c^1(a_1) + c^2(a_2) - m_1 - m_2\right).$$

Assuming an interior solution, the first order conditions are:

$$\frac{\partial L}{\partial x_1} = \theta u_x^1 - \lambda = 0 \Rightarrow \theta u_x^1 = \lambda > 0. \tag{1}$$

$$\frac{\partial L}{\partial x_2} = (1-\theta)u_x^2 - \lambda = 0 \Rightarrow (1-\theta)u_x^2 = \lambda > 0. \tag{2}$$

$$\frac{\partial L}{\partial a_1} = \theta\left(u_a^1 + u_A^1\right) + (1-\theta)u_A^2 - \lambda c_a^1 = 0 \Rightarrow \frac{u_A^1}{u_x^1} + \frac{u_A^2}{u_x^2} = c_a^1 - \frac{u_a^1}{u_x^1}. \tag{3}$$

$$\frac{\partial L}{\partial a_2} = \theta u_A^1 + (1-\theta)\left(u_a^2 + u_A^2\right) - \lambda c_a^2 = 0 \Rightarrow \frac{u_A^1}{u_x^1} + \frac{u_A^2}{u_x^2} = c_a^2 - \frac{u_a^2}{u_x^2}. \tag{4}$$

$$\lambda > 0 \Rightarrow x_1 + x_2 + c^1(a_1) + c^2(a_2) = m_1 + m_2. \tag{5}$$

Equations (1) and (2) imply

$$\theta u_x^1 = (1-\theta)u_x^2. \tag{6}$$

Equations (3) and (4) are modified Samuelson conditions. The left hand side of each equation represents the marginal social benefit of abatement provision -- i.e., the sum of the marginal rates of substitution between the public good and the numeraire good. The right hand side of each equation represents the marginal regional cost of abatement provision -- i.e., the sum of marginal production and utility costs of abatement provision in terms of the numeraire good. For future reference, it is important to note that equations (3) and (4) imply the equalization of marginal regional costs of abatement provision:

$$c_a^1 - \frac{u_a^1}{u_x^1} = c_a^2 - \frac{u_a^2}{u_x^2}. \tag{7}$$

Equation (5) tells us that it is efficient to fully employ all resources available. Finally, equation (6) shows that an efficient allocation of the numeraire good between the regions should satisfy the equalization of weighted marginal utilities of income.

Equations (1) – (5) give us a solution to the Pareto efficiency problem. Since the utility functions are strictly quasiconcave and the cost functions are strictly convex, the first order conditions are necessary and sufficient, and the solution is a unique global maximum.

4. The "Kyoto Protocol" Game

We shall now analyze the allocation of resources under the "Kyoto Protocol" game. As we mentioned in the introduction, this game consists of two stages. In the first stage, each regional government decides how many units of abatement it wishes to provide and trade taking each other's decisions as given. Having observed the regional governments decisions concerning abatement provision and trade, the Global Environment Facility (GEF) decides in the second stage of the game the level of the interregional income transfer. The equilibrium concept used for the game is subgame perfection.

We need to introduce some notation prior to solving the game. Let $a_1 \equiv z_1^d + z_1^e - z_1^i$ and $a_2 \equiv z_2^d + z_2^e - z_2^i$ denote the quantities of abatement units available in regions 1 and 2, respectively, after the regional governments decide how much abatement to provide and how much abatement to trade. The quantities z_j^d represent the "domestic" units of pollution abatement available in region j prior to abatement trading. The quantities z_j^e and z_j^i denote the units of pollution abatement exported and imported by region j, respectively. Hence, $z_1^e = z_2^i$, $z_2^e = z_1^i$ and $A = a_1 + a_2 \equiv z_1^d + z_2^d$.

4.1 The Second Stage of the Game

As it is usually done, we start at the last stage of the game. We assume that the GEF's objective function is a weighted global welfare function as follows:

$$W\left(u^1,u^2\right)=\theta u^1+\left(1-\theta\right)u^2,$$

where $\theta \in (0,1)$; that is, the same objective function of the Pareto efficiency problem examined above. The GEF takes $\left\{z_1^d, z_2^d, z_1^i, z_2^i\right\}$ as given and solves:

$$\begin{aligned}
&\underset{\{x_1,x_2\}}{Max}\ \theta u^1\left(x_1, z_1^d+z_2^i-z_1^i, z_1^d+z_2^d\right)+\left(1-\theta\right)u^2\left(x_2, z_2^d+z_1^i-z_2^i, z_1^d+z_2^d\right)\\
&\text{s.t.:}\quad u^1\left(x_1, z_2^d+z_1^i-z_2^i, z_1^d+z_2^d\right)\geq \bar{u}^1,\\
&\qquad\quad u^2\left(x_2, z_2^d+z_1^i-z_2^i, z_1^d+z_2^d\right)\geq \bar{u}^2,\\
&\qquad\quad x_1+x_2+c^1\left(z_1^d+z_2^i-z_1^i\right)+c^2\left(z_2^d+z_1^i-z_2^i\right)\leq m_1+m_2.
\end{aligned}$$

The first two constraints are participation constraints. Voluntary participation is necessary for the effectiveness of the Protocol. Since there is potential for the Protocol to Pareto improve upon the status quo, both participation constraints may be satisfied nonbinding in the subgame perfect equilibrium for the Kyoto Protocol game. If the equilibrium allocation is Pareto efficient, there will be a range of θ values under which both regions will be strictly better off by participating in the agreement.

We shall make it our working hypothesis that the participation constraints are satisfied slack in the equilibrium for the second stage and later show that this is indeed a possibility. Assuming slack participation constraints and an interior solution, the solution to the GEF’s problem is determined by the following two equations:

$$x_1+x_2+c^1\left(z_1^d+z_2^i-z_1^i\right)+c^2\left(z_2^d+z_1^i-z_2^i\right)=m_1+m_2, \tag{8}$$

$$\theta u_x^1\left(x_1, z_1^d+z_2^i-z_1^i, z_1^d+z_2^d\right)=\left(1-\theta\right)u_x^2\left(x_2, z_2^d+z_1^i-z_2^i, z_1^d+z_2^d\right). \tag{9}$$

Equations (8) and (9) are the rewriting of equations (5) and (6), respectively, but with the new notation. Equations (8) and (9) define x_1 and x_2 as implicit functions of the variables chosen in the first stage of the game, $\left\{z_1^d, z_2^d, z_1^i, z_2^i\right\}$. We shall denote the implicit functions by $x_j\left(z_1^d, z_2^d, z_1^i, z_2^i\right)$, $\mathrm{j}=1,2$. These functions tell us how the GEF respond to the choices of the regional governments. According to equations (8) and (9), the regional governments anticipate that the GEF's responses to their choices will always be directed towards satisfying both the global resource and equalization of the weighted marginal utilities of income.

The GEF, therefore, chooses the final allocation of the numeraire good between the two regions. The rationale for this is straightforward. The GEF is endowed with policy instruments to implement interregional income transfers. Such transfers take place after private and public goods are allocated. Income is measured in terms of the numeraire good, x. Then, departing from a particular economic environment, with a pre-established distribution of the numeraire good across regions, the GEF will transfer units of the numeraire good from one region to another in order to satisfy equations (8) and (9). This transfer will determine the final allocation of the numeraire good between the two regions.

4.2 The First Stage of the Game

Knowing how the GEF will respond to its choices, region 1 solves the following problem, taking the choices of region 2 as given:

$$\underset{\{z_1^d,\, z_1^i\}}{Max}\ u^1\left(x_1\left(z_1^d, z_2^d, z_1^i, z_2^i\right), z_1^d + z_2^i - z_1^i, z_1^d + z_2^d\right)$$

Region 2 also anticipates the GEF's responses and takes the choices of region 1 as given when it solves:

$$\underset{\{z_2^d,\, z_2^i\}}{Max}\ u^2\left(x_2\left(z_1^d, z_2^d, z_1^i, z_2^i\right), z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right)$$

As the proof of the proposition below demonstrates, the conditions that characterize the Nash equilibrium in this stage of the game are conditions (3) and (4). Therefore,

Proposition 1: Provided the solutions to the maximization problems are interior and the participation constraints are satisfied slack, the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient.

Proof. Differentiation of equations (8) and (9) yields the following partial derivatives:

$$\partial x_1 / \partial z_1^d = \left\{(1-\theta)\left(u_{Ax}^2 - u_{xx}^2 c_a^1\right) - \theta\left(u_{ax}^1 + u_{Ax}^1\right)\right\} / D,$$

$$\partial x_2 / \partial z_1^d = \left\{\theta\left(u_{ax}^1 + u_{Ax}^1 - u_{xx}^1 c_a^1\right) - (1-\theta) u_{Ax}^2\right\} / D,$$

$$\partial x_1/\partial z_2^d = \left\{(1-\theta)\left(u_{ax}^2 + u_{Ax}^2 - u_{xx}^2 c_a^2\right) - \theta u_{Ax}^1\right\}/D,$$

$$\partial x_2/\partial z_2^d = \left\{\theta\left(u_{Ax}^1 - u_{xx}^1 c_a^2\right) - (1-\theta)\left(u_{ax}^2 + u_{Ax}^2\right)\right\}/D,$$

$$\partial x_1/\partial z_1^i = -\partial x_1/\partial z_2^i = \left\{(1-\theta)\left(u_{ax}^2 + u_{xx}^2\left(c_a^1 - c_a^2\right)\right) + \theta u_{ax}^1\right\}/D,$$

$$\partial x_2/\partial z_2^i = -\partial x_2/\partial z_1^i = \left\{\theta\left(u_{xx}^1\left(c_a^2 - c_a^1\right) + u_{ax}^1\right) + (1-\theta)u_{ax}^2\right\}/D,$$

where

$$D \equiv \theta u_{xx}^1 + (1-\theta)u_{xx}^2.$$

For future reference, note that

$$\frac{\partial x_1}{\partial z_1^d} + \frac{\partial x_2}{\partial z_2^d} = -\frac{\partial x_1}{\partial z_1^i} - c_a^2 = -\frac{\partial x_2}{\partial z_2^i} - c_a^1. \tag{10}$$

Assuming interior solutions, the first order conditions in the first stage of the game yield:

$$\frac{u_A^1}{u_x^1} + \frac{u_a^1}{u_x^1} = -\frac{\partial x_1}{\partial z_1^d}, \tag{11a}$$

$$\frac{u_a^1}{u_x^1} = \frac{\partial x_1}{\partial z_1^i}, \tag{11b}$$

$$\frac{u_A^2}{u_x^2} + \frac{u_a^2}{u_x^2} = -\frac{\partial x_2}{\partial z_2^d}, \tag{11c}$$

$$\frac{u_a^2}{u_x^2} = \frac{\partial x_2}{\partial z_2^i}. \tag{11d}$$

Substituting (11b) and (11d) into the second equation in (10), we obtain

$$c_a^1 - \frac{u_a^1}{u_x^1} = c_a^2 - \frac{u_a^2}{u_x^2}. \tag{12}$$

Substituting (11a), (11b) and (11c) into the first equation in (10) yields

$$\frac{u_A^1}{u_x^1} + \frac{u_A^2}{u_x^2} = c_a^2 - \frac{u_a^2}{u_x^2}. \tag{13}$$

Equation (13) is identical to equation (4). Furthermore, equations (12) and (13) imply equation (3) and equations (8) and (9) correspond to equations (5) and (6), respectively. Hence, the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient. ◎

Proposition 1 tells us that the redistributive transfers implemented by the GEF are powerful enough to nullify each nation's incentive to ignore the negative externality caused by its own carbon dioxide emission. Since the modified Samuelson conditions are satisfied in the equilibrium of the game, equations (11a) and (11c) clearly demonstrate that both regions face their Lindahl prices when they choose how much pollution abatement to produce. In other words, the negative of the GEF's marginal responses to pollution abatement provision, $-\partial x_1 / \partial z_1^d$ and $-\partial x_2 / \partial z_2^d$, correspond to the regions’ Lindahl prices of pollution abatement -- see the right sides of equations (11a) and (11c). This implies that each region has no unilateral incentive to deviate from fully internalizing the externality.

It is important to point out that Proposition 1 holds if the participation constraints are satisfied slack in the equilibrium. Since the status quo allocation is inefficient and the equilibrium allocation for the Kyoto Protocol game is efficient when the participation constraints are ignored, there exists a range of q values under which both regions can be made better off by participating in the Kyoto Protocol scheme. We shall assume henceforth that the designers of the Kyoto Protocol scheme -- that is, the regional governments themselves -- agree before ratification on a q value that will make both regions better off upon implementation of the Protocol. Such an agreement may emerge, for example, from a Nash bargaining game played by the regions prior to the commencement of the Kyoto Protocol game.

In a closely related study, Caplan and Silva (2000) examine three noncooperative "global warming games" where carbon dioxide emissions and international transfers are determined. As in this paper, they assume that there is an international agency in charge of implementing redistributive transfers across nations. Their analysis is mostly concerned with examining the efficiency and implementability properties of international transfer mechanisms that obey predetermined equity principles, horizontal, proportional and green equity. They find that horizontal and proportional equity schemes are Pareto efficient. Unlike this paper, however, their model is autarkic and ignores the fact that reductions in carbon dioxide emissions may bring about national as well as global effects.

5. Abatement Trading and Interregional Transfers are Necessary for Pareto Efficiency

We shall now demonstrate that each one the two key elements of the Kyoto Protocol -- abatement trading and interregional transfers -- is necessary for Pareto efficiency. We first analyze a game with interregional transfers but no abatement trading and show that its subgame perfect equilibrium is generally inefficient. Then, we consider a game with abatement trading but no interregional transfers. The Nash equilibrium for this game is also generally inefficient. Since each one of these games deviates from the Kyoto Protocol in only one 'dimension,' and both dimensions, if put together, comprise the Kyoto Protocol game analyzed above, we will be able to conclude that both abatement trading and interregional transfers are necessary for Pareto efficiency.

6. Autarky With Interregional Transfers

As in the Kyoto Protocol game, let us assume that the participation constraints are satisfied slack in the solution to the GEF's problem. After characterizing the subgame perfect equilibrium for the current game, we will comment on the reasonableness of this assumption. Assuming further that the solution to the GEF’s problem is interior, the second d stage of this game is characterized by the GEF allocating the numeraire commodity in order to satisfy:

$$x_1 + x_2 + c^1\left(z_1^d\right) + c^2\left(z_2^d\right) = m_1 + m_2, \tag{14}$$

$$q u_x^1\left(x_1, z_1^d, z_1^d + z_2^d\right) = \left(1 - q\right) u_x^2\left(x_2, z_2^d, z_1^d + z_2^d\right). \tag{15}$$

Observe that because there is no trade of pollution abatement the final quantity of pollution abatement available in each region corresponds to each government’s choice of domestic provision of pollution abatement. In the Kyoto Protocol game, each region chose its own *domestic availability* of pollution abatement prior to abatement trading, but the final quantities of pollution abatement available in each region were only determined after abatement trading took place.

Equations (14) and (15) implicitly define the functions $x_j\left(z_1^d, z_2^d\right)$, $\mathrm{j} = 1, 2.$ Differentiation of equations (14) and (15) enable the following partial derivatives:

$$\partial x_1 / \partial z_1^d = \left\{\left(1 - q\right)\left(u_{Ax}^2 - u_{xx}^2 c_a^1\right) - q\left(u_{ax}^1 + u_{Ax}^1\right)\right\} / D, \tag{16a}$$

$$\partial x_2 / \partial z_1^d = \left\{q\left(u_{ax}^1 + u_{Ax}^1 - u_{xx}^1 c_a^1\right) - \left(1 - q\right) u_{Ax}^2\right\} / D, \tag{16b}$$

$$\partial x_1 / \partial z_2^d = \left\{(1-q)\left(u_{ax}^2 + u_{Ax}^2 - u_{xx}^2 c_a^2\right) - q u_{Ax}^1\right\} / D, \tag{16c}$$

$$\partial x_2 / \partial z_2^d = \left\{q\left(u_{Ax}^1 - u_{xx}^1 c_a^2\right) - (1-q)\left(u_{ax}^2 + u_{Ax}^2\right)\right\} / D, \tag{16d}$$

where

$$D \equiv q u_{xx}^1 + (1-q) u_{xx}^2 .$$

Equations (16a) through (16d) indicate that the GEF’s responses to the regional governments’ choices of domestic provision of pollution abatement in the current game are identical to its responses in the Kyoto Protocol game. The crucial difference between this arrangement and the Kyoto Protocol can be formally explained by the absence in this arrangement of the GEF's responses to quantities of pollution abatement traded between the regions.

6.1 The First Stage of the Game

Knowing how the GEF will respond to its choice of pollution abatement quantity, region 1 solves the following problem, taking the choice of region 2 as given:

$$\underset{\left\{z_1^d\right\}}{Max} \; u^1\left(x_1\left(z_1^d, z_2^d\right), z_1^d, z_1^d + z_2^d\right)$$

Assuming an interior solution, the first order condition is

$$u_x^1 \frac{\partial x_1}{\partial z_1^d} + u_a^1 + u_A^1 = 0 \Rightarrow \frac{u_A^1}{u_x^1} + \frac{u_a^1}{u_x^1} = -\frac{\partial x_1}{\partial z_1^d}. \tag{17a}$$

Similarly, region 2 takes the choice of region 1 as given and solves:

$$\underset{\left\{z_2^d\right\}}{Max} \; u^2\left(x_2\left(z_1^d, z_2^d\right), z_2^d, z_1^d + z_2^d\right)$$

Assuming an interior solution, the first order condition can be written as follows:

$$\frac{u_A^2}{u_x^2} + \frac{u_a^2}{u_x^2} = -\frac{\partial x_2}{\partial z_2^d}. \tag{17b}$$

Equations (17a) and (17b) are identical to equations (11a) and (11c). However, as we now show, the right sides of these equations do not correspond to regions’ Lindahl prices because the subgame perfect equilibrium for the current game does not satisfy the modified Samuelson conditions. Substituting (16a) and (16d) into (17a) and (17b), respectively, and adding up the implied equations lead to:

$$\frac{u_A^1}{u_x^1}+\frac{u_A^2}{u_x^2}=\frac{q\left(u_{ax}^1+u_{xx}^1c_a^2\right)+(1-q)\left(u_{ax}^2+u_{xx}^2c_a^1\right)}{D}-\frac{u_a^1}{u_x^1}-\frac{u_a^2}{u_x^2}. \tag{18}$$

Adding and subtracting the term $(1-q)u_{xx}^2c_a^2/D$ in the right side of (18), we obtain a more illuminating expression:

$$\frac{u_A^1}{u_x^1}+\frac{u_A^2}{u_x^2}=c_a^2-\frac{u_a^2}{u_x^2}+\left\{\frac{qu_{ax}^1+(1-q)\left(u_{ax}^2+u_{xx}^2\left(c_a^1-c_a^2\right)\right)}{D}-\frac{u_a^1}{u_x^1}\right\}. \tag{19}$$

Equation (19) deviates from the modified Samuelson condition for region 2 by the bracketed term in the right side. The first term inside of the brackets should be familiar to the reader -- it corresponds to $\partial x_1/\partial z_1^i$ in the Kyoto Protocol game!

A similar manipulation of the equations that determine the subgame perfect equilibrium for the current game enables us to write:

$$\frac{u_A^1}{u_x^1}+\frac{u_A^2}{u_x^2}=c_a^1-\frac{u_a^1}{u_x^1}+\left\{\frac{q\left(u_{ax}^1+u_{xx}^2\left(c_a^2-c_a^1\right)\right)+(1-q)u_{ax}^2}{D}-\frac{u_a^2}{u_x^2}\right\}. \tag{20}$$

Equation (20) also deviates from the modified Samuelson condition for region 1 by the bracketed term in the right side. This term corresponds to $\partial x_2/\partial z_2^i$ in the Kyoto Protocol game. Had the regions been allowed to trade abatement units, their choices of how many units to trade with each other would satisfy conditions similar to equations (11b) and (11d). Hence, the inability of the regions to trade abatement units with each other is the reason why the modified Samuelson conditions are not satisfied in the subgame perfect equilibrium for the current game. In sum,

Proposition 2: Provided the solutions to the maximization problems are interior and the participation constraints are satisfied slack, the subgame perfect equilibrium for the 'Autarky with Interregional Transfers' game is characterized by equations (14), (15), (19) and (20). Since the equilibrium allocation does not satisfy the modified Samuelson conditions for pollution abatement provision, it is Pareto inefficient.

The result above makes it clear to us that the interregional income transfer mechanism implemented by the GEF falls short of providing the regions with incentives to behave efficiently. Had the GEF an additional policy instrument to implement interregional transfers of pollution abatement levels, it would do so in order to equalize the marginal regional costs of abatement provision. This is obviously the case because the problem the GEF would solve, if endowed with this additional instrument, would exactly correspond to the Pareto efficiency problem. In principle, one can envision the GEF being endowed with an instrument that enables it to match the quantities of pollution abatement provided by the regional governments. Such "matching grants" would be perfect substitutes for abatement trading in that they would have the same impact on the allocation of resources.

Although the equilibrium allocation for the 'Autarky with Interregional Transfers' game is not efficient, it may represent a strict Pareto improvement relative to the status quo allocation. The equilibrium allocation satisfies two efficiency conditions, namely, the overall resource constraint and the equalization of the weighted marginal utilities of income. Hence, for some q values, it is possible that both participation constraints are satisfied slack in equilibrium.

7. Trade Without Interregional Transfers

Suppose that there is no effective international authority and thus there is no mechanism to implement interregional income transfers. In the absence of income transfers, the game played by the regions simplifies to a simultaneous Nash noncooperative game, whereby each region decides how much abatement to provide and trade taking the other region's decisions as given.

We assume that both regions take the price of pollution abatement as given. We denote by $p > 0$ the per unit price of abatement. Region 1’s expenditure with imports net of exports is thus $p\left(z_1^i - z_2^i\right)$. Region 1 takes the choices of region 2 as given and solves:

$$\underset{\{z_1^d,\, z_1^i\}}{Max}\; u^1\left(m_1 - c^1\left(z_1^d + z_2^i - z_1^i\right) - p\left(z_1^i - z_2^i\right), z_1^d + z_2^i - z_1^i, z_1^d + z_2^d\right)$$

The first order conditions can be written as follows:

$$\frac{u_A^1}{u_x^1} = c_a^1 - \frac{u_a^1}{u_x^1}, \tag{21a}$$

$$c_a^1 - \frac{u_a^1}{u_x^1} = p. \tag{21b}$$

Equation (21a) informs us that region 1 ignores the positive effects that its provision of abatement confers on region 2 -- it provides abatement at a level that satisfies the equalization of the region's marginal benefit to the region's marginal cost. Equation (21b) shows that the volume of abatement units traded by region 1 satisfies the equalization of marginal regional cost of abatement provision and the marginal revenue originating with the sale of abatement.

Region 2 takes the choices of region 1 as given and solves:

$$\underset{\{z_2^d, z_2^i\}}{Max}\; u^2\left(m_2 - c^2\left(z_2^d + z_1^i - z_2^i\right) - p\left(z_2^i - z_1^i\right), z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right)$$

The first order conditions can be written as follows:

$$\frac{u_A^2}{u_x^2} = c_a^2 - \frac{u_a^2}{u_x^2}, \tag{22a}$$

$$c_a^2 - \frac{u_a^2}{u_x^2} = p. \tag{22b}$$

Similarly to the behavior displayed by region 1, region 2 chooses to provide abatement at a level that equates its marginal regional benefit from abatement provision to its marginal regional cost and to trade abatement units at a level where the marginal regional cost equates the marginal revenue from selling abatement.

Note that we observe the following conditions in the Nash equilibrium for this game:

$$c_a^1 - \frac{u_a^1}{u_x^1} = c_a^2 - \frac{u_a^2}{u_x^2} = p, \tag{23a}$$

$$\frac{u_A^1}{u_x^1} = \frac{u_A^2}{u_x^2} = p. \tag{23b}$$

Equations (23a) reveal that equations (21b) and (22b) imply equation (7); that is, due to abatement trading, marginal regional costs of abatement provision are equalized. But, equations (23b) tell us that the allocation is characterized by equalization of the marginal regional benefits from abatement provision to marginal regional costs of abatement provision rather than the equalization of the sum of the marginal regional benefits from abatement provision to marginal regional costs of abatement provision. Hence, we obtain the following result:

Proposition 3: Provided the solutions to the maximization problems are interior, the Nash equilibrium for the simultaneous game with abatement trading and no interregional income transfers is characterized by equations (23a) and (23b). Since the equilibrium allocation does not satisfy the modified Samuelson conditions, it is Pareto inefficient.

This result is not very surprising. It is well known from the literature on voluntary contributions to (pure and impure) public goods that in the simultaneous noncooperative Nash game each contributor fails to acknowledge the positive effects that his contribution bestows on the other contributors. However, the result of Proposition 3, when considered together with the result of Proposition 1, leads to a very important insight about the key role played by the interregional transfer mechanism studied in this paper. The sole difference between the arrangement without interregional income transfers and the Kyoto Protocol setting is the absence of a player, the GEF, which is in charge of implementing *redistributive* interregional income transfers -- that is, the second stage of the Kyoto Protocol game is missing in the game examined in this section. Hence, redistributive interregional income transfers are of fundamental importance for the result of Proposition 1, that the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient. They force the regions to face their own Lindahl prices!

What would happen if the interregional income transfers did not take place after the regions decide how much pollution abatement to provide and trade? It is straightforward to show that if we changed the timing of the game, so that the GEF moved first, the subgame perfect equilibrium for the implied game would generally be Pareto inefficient![2] The game played by

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[2] For a two-stage game played by a benevolent central government and two self-interested regional governments, whereby the central government makes interregional transfers in order to maximize social welfare in the first stage and two regional governments choose how much to contribute to a pure public good in the second stage, Caplan, Cornes and Silva (2000) show that its subgame perfect equilibrium is isomorphic to the equilibrium of the simultaneous Nash game played by both regional governments in absence of interregional transfers. In other words, they obtain a policy neutrality result. However, when the timing of the game is changed, so that the regional governments move first and the central government implements interregional transfers in the second stage, the subgame perfect equilibrium for the game is Pareto efficient. Therefore, the question of leadership is crucial for

the two regions in the second stage would essentially be the game examined in this section except that the composition of the regional income endowments would be such that region 2 would have at the beginning of the second stage just enough income to enable it to reach its own reservation utility level. Taking the interregional distribution of income as given, as well as each other's pollution abatement provision, each region would have an incentive to ignore the positive effect that its own pollution abatement provision confers on the other region. Each region, however, would have an incentive to engage in efficient abatement trading and hence regional marginal costs of pollution abatement would be equalized.

8. The Main Result

We are now ready to describe our main result:

Theorem: The two key elements of the Kyoto Protocol, namely, free trading of pollution abatement and interregional income transfers, are both necessary conditions for the Pareto efficiency of the agreement.

Proof. Compare the subgame perfect equilibrium for the Kyoto Protocol game with the equilibria for the other two games examined above. While the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient, the other equilibria are generally inefficient. ◎

9. Conclusion

The Kyoto Protocol calls for the creation of a system of pollution abatement trading and for the implementation of interregional income transfers. Our analysis demonstrates that these two elements are necessary for the efficiency of the Protocol. It appears that an international agreement to control global warming can be effective provided that there is an international authority in charge of making appropriate transfers after the nations decide how much abatement to provide and trade. Such a redistributive income transfer mechanism may induce the nations to face their Lindahl prices when they decide on their contributions to the impure global good.

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the allocation of resources. See also Arce (2000) for various implications of leadership to allocation of resources in economies with public goods.

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