97-F-36

Global Environmental Management: Incentives for Abatement Investment Anticipating an International Bargaining

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November 1997

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(this version: September 1997)

(previous versions: November 1995, August 1996)

Abstract

When future international agreement for global environmental control is anticipated, decisions for controlling current carbon gas emissions by improving the country's abatement capabilities are strongly affected by the likelihood of and the likely outcome of such agreements. We construct a two period two country model where the quality of the atmospheric environment is a global public capital, and countries invest in abatement investments in the first period and engage in production activities in the second period. Applying the incomplete contract approach to this model where (re)negotiation with or without side payment may take place in the second period, we examine the following questions. What are the characteristics of the country that make its bargaining position more advantageous, what are the cause of distortions in *ex ante* capital investments as well as in *ex post* incentives for environmental improvement, and what are the characteristics of countries which are prone to these distortions?

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*) Earlier version of this paper was presented at the JDB Symposium on the Environment and Sustainable Development, November 6-8, 1995 at Hakone, Japan. Authors benefited a great deal from helpful comments by Martin Weitzman at the Symposium. Financial support from Grants-in-Aid program from the Ministry of Education is gratefully acknowledged.

1. Introduction

The problem of global warming is a universal concern for the entire humankind. It will affect not only high-tech firms in industrialized world but also people living in an arid area of developing countries, and actions carried out by our generation will significantly affect the welfare of all future generations. Despite its universality of the consequence of our decisions about how to control global environment and, thereby, achieving a sustainable growth, there are heterogeneous, conflicting and often diametrically opposite views about how we should actually do for this global cause. For example, some people advocate for severe reduction of carbon gas emission, while others oppose to it. Even among advocates, some argue for uniform taxation which is enforced by tradable permits allocated to each country, while others argue for non-uniform taxation whose rates should positively related with the country's GDP[1]. The present paper is aimed at analyzing theoretically why these heterogeneous views appear and what accounts we should take into when a future international agreement for global environmental control is in sight, but not yet agreed because of such heterogeneity.

Compared with a decade ago, the problem of global environmental control has become much more exposed and the public's environmental consciousness has increased drastically. Despite such exposures and the public's concern, however, the effort for international agreement to contain global warming as well as individual country's attempts for reducing environmental destruction are slow to come. This seems to be quite a contrast compared with an increasing effort of individual companies. For example, the cost of carbon energy consumption is still very low in the US, and it has not changed drastically in the last few decades. The cost in Europe and Japan is relatively high, contributing somewhat to the reduction of the carbon gas. However, high cost in Japan is mainly the result of steep oil price increases in the 1970's, not reflecting a recent increase in public's

[1] Uzawa [1991] is an example of proposal for non-uniform taxation.

awareness of global environment. Why, then, is that an increase in public's concern as well as an increase in visibility of global environment does not induce spontaneous efforts to contain environmental destruction of major countries?

We view that one of the reasons for unwillingness of several major governments in actively pursuing the control of global environment lies in the very fact that a future international agreement comes into their view. When governments get together and a negotiation takes place in order to design an international agreement, an outcome will be significantly affected by the bargaining power of each country. Unfortunately, the magnitude of each country's bargaining power will depend negatively upon how much stakes the country will have in the bargaining outcome. Countries with larger stakes will become more desperate to sign a contract, sacrificing some of its possible gains. Similarly, those countries which can control pollution with relatively little cost cannot credibly argue for larger share, being forced to accept small bargaining gain. In contrast, those countries who must bear a larger cost in improving the global environment, but care little about the environment, will resist any agreement. Because such non-cooperation will be viewed credible by other negotiation partners, the negotiation is likely to be concluded with the countries with the latter characteristics benefiting more at the cost of those countries with the former characteristics.

This means that, anticipating a future international bargaining, countries may try to refrain from investments for controlling environmental destruction, because doing so only deteriorates the country's future bargaining position. Anticipating a future bargaining, countries may try to improve their strategic positions by investing less for energy saving and, in an extreme case, by further deteriorating its own environmental situation.

In this paper, we analyze such a possibility using a simple two-period two-country model. A country emits carbon gas as a by-product of economic activity in the second period. The amount of carbon gas per GDP is assumed to depend upon production function, reflecting the country's industrial structure, and upon efficiency of pollution abatement. Abatement efficiency, in turn, is assumed to depend upon the first period investment activity as well as its *ex ante* efficiency which it inherited from the past.

We compare several scenarios. In one scenario, two countries choose their actions in both periods non-cooperatively. That is, the solution concept we use will be the simple two-period subgame perfect Nash equilibrium. In the other scenario, we assume that two countries will sign a binding international agreement in period 2. For this scenario, we use two alternative solution concepts for the cooperative outcome, the Nash bargaining solution with side-payments and that without side-payments, with the assumption that the associated non-cooperative outcome will be realized if the negotiation breaks down. With the Nash bargaining solution concept, the agreement will provide exactly one half of the gains from an agreement (*i.e.*, the aggregate gains of achieving efficient outcome compared with the non-cooperative outcome) to each country, in addition to the payoff it would have obtained had the non-cooperative outcome prevailed. In period 1, non-cooperative game will be played anticipating this cooperative outcome to prevail in period 2.

Given such a setup, we shall show that bargaining power is stronger for those countries with higher marginal cost for carbon gas reduction in the second stage and for those who are concerned less with the global environment. Reflecting these bargaining powers, we shall illustrate that those countries characterized above will be the likely recipients of side payments if negotiation allows side payments, while they share less tax burden if not. We also show that, compared with the case of non-cooperative outcome, incentives for the first period investments for energy conservation is lower if a future international agreement is anticipated, at least if the negotiation permits side payments. This rather striking result stems primarily from the fact that a country's first period investment would improve other countries' second period bargaining position at the cost of its own bargaining power.

The rest of the paper is organized as follows. In section 2, we shall present our model and characterize the first best outcome. In section 3, we analyze non-cooperative equilibrium in the second period and analyze sub-game perfect equilibrium when there is no possibility of international agreement. Section 4 develops some basic tools for analyzing outcomes with international agreements. Section 5 analyzes and compares the outcomes when international negotiation is anticipated to take place in the second period. Section 6 concludes the paper. Some technical details are relegated to the Appendix.

2. Basic Model

2-1. Model Set-up

We consider a world consisting of two countries, 1 and 2. Country i (i = 1, and 2) produces a single final good, that can be used either for consumption or investment, with emitting carbon gas as its by-product. The final goods produced by the two countries are perfect substitutes. Thus if they are traded freely in the world market, then their prices should become equal.

The (reduced form) production function for the final good is denoted as:

(2- 1) $y_i = f(z_i, \alpha_i)$

where y_i is country i's level of final good production, z_i its level of carbon gas emission, and α_i a parameter representing its efficiency in environmental control. We assume that $f_z > 0$, $f_{zz} < 0$, $f_\alpha > 0$ and $f_{z\alpha} < 0$. Note that the marginal cost of reducing the emission, denoted by $MC_i(z_i, \alpha_i)$, is measured by the required output reduction in the final good, i.e., $f_z(z_i, \alpha_i)$[2]. It follows that an increase in α_i not only increases GDP with the same level of carbon gas emission but also increases the marginal cost of reducing the emission.

[2] Some readers may prefer to interpret it as the marginal productivity of allowing more pollution.

Each country's emission of pollutants aggravates the quality of global environment and damages the welfare of both countries. Welfare deterioration is assumed to depend upon the world total emission of pollutants;

(2- 2) $Z = \sum_{\ell} z_{\ell}$.

The gross welfare of each country, before subtracting the investment cost for abatement technology, is assumed as,

(2- 3) $\tilde{u}_i(y_i, Z) = y_i - \beta_i Z = f(z_i, \alpha_i) - \beta_i Z$

where β_i is the (constant) marginal value of global environment for the country *i*. That is, this parameter represents the country's valuation of global environment in terms of its GDP.

Each country can reduce pollutants emission either by reducing the final good output or by improving technology and increasing the efficiency of environmental control, α_i. Let

(2- 4) $c_i = C(\alpha_i, \overline{\alpha}_i, \gamma_i)$

be the investment cost for the technology improvement, where $\overline{\alpha}_i$ is the level of efficiency before the investment while α_i is the level after the investment, γ_i is a parameter expressing the country's marginal investment cost in terms of its final good.

The country's net welfare, after subtracting the investment cost, is then,

(2- 5) $u_i(y_i, c_i, Z) = y_i - \beta_i Z - c_i$.

In view of (2- 1), (2- 4) and (2- 5), the national welfare can be expressed as the function of z_i and Z, or

(2- 6) $u_i = f(z_i, \alpha_i) - \beta_i Z - C(\alpha_i, \overline{\alpha}_i, \gamma_i) = U(z_i, Z, \alpha_i, \overline{\alpha}_i, \gamma_i)$.

For the sake of simplicity, we assume the two countries have the same production technology, which is written as:

(2- 1)' $f(z_i, \alpha_i) = 1 - \dfrac{1}{\alpha_i}\exp(-\alpha_i z_i)$.

Note that, with this specific form of production function, marginal cost of reducing carbon gas pollution is;

(2- 7) $MC_i(z_i,\alpha_i) = f_z(z_i,\alpha_i) = \alpha_i \cdot (1-y_i) = \exp(-\alpha_i z_i) > 0$.

Note that this definition of marginal cost takes the level of carbon gas pollution fixed.

We also assume the following specific form for the cost of improving energy use,

(2- 4)' $C(\alpha_i,\overline{\alpha}_i,\gamma_i) = \gamma_i(\alpha_i - \overline{\alpha}_i)^{\varepsilon+1}$,

where we assume:

Assumption 1: $\overline{\alpha}_i \geq 1$ for i = 1 and 2.

Then since each country chooses $\alpha_i \geq \overline{\alpha}_i$, Assumption 1 ensures

(2-8) $f(0,\alpha_i) \geq 0$.

It is straightforward that(2- 3) and(2- 6) are rewritten as,

(2- 4)' $\tilde{u}_i = 1 - \frac{1}{\alpha_i}\exp(-\alpha_i z_i) - \beta_i Z$

(2- 6)' $u_i = 1 - \frac{1}{\alpha_i}\exp(-\alpha_i z_i) - \beta_i Z - \gamma_i(\alpha_i - \overline{\alpha}_i)^{\varepsilon+1}$

For the later references, we shall refer α_i ($\overline{\alpha}_i$, resp.) as the country *i*'s *ex post* (*ex ante*, resp.) *efficiency in emission control*, β_i the country's *marginal evaluation of global environment*, and γ_i its *marginal cost of abatement investment*.

2-2. Economic Interpretations of the Exogenous Parameters

Some intuition about these parameters may be helpful in interpreting our results. As for the *ex post* and *ex ante* measure of emission control, α_i and $\overline{\alpha}_i$, the following three observations are relevant for later discussion. First, α_i is larger as the country's industrial structure is less energy intensive, because it requires less energy, and hence less pollution emission, to produce a unit of output. It follows that more industrialized countries tend to have smaller α_i and $\overline{\alpha}_i$. Second, energy use tends to be inelastic in the short run because energy saving technology can be installed only over a long period. It follows that those countries with historically high energy costs tend to have lower $\overline{\alpha}_i$ as incentives to install energy saving technology have been less in the past. Countries like US are known to have lower $\overline{\alpha}_i$, while Japan is an example to have a relatively high $\overline{\alpha}_i$ because of the high energy cost following the oil shock. Third, the carbon gas tax will provide incentives to raise α_i. It follows that, given other parameters, each level of α_i may be associated with the appropriate level of the carbon gas tax.

The country's marginal evaluation of global environment, β_i, depends at least on the following two factors. First, poor countries tend to have lower marginal evaluation of global environment because its concern is the subsistence of its people as well as the physical growth of the economy. Second, geographical characteristics affects the value of this parameter. Countries with many neighbors, such as European nations, are apt to be more concerned with global environment because there is a higher probability of damage by neighbors. On the other hand, a country that is more isolated, such as US and Australia, can enjoy the luxury of not worried too much from the global pollution. alternatively, countries that are more prone to the change in global climate tend to have a higher value of β_i. An example is an island nation who must risk the danger of being submerged by the ocean.

The country's marginal cost of abatement investment, γ_i, is affected by at least the following two factors. First, the country's level of industrialization tends to make the value higher, because it makes the need of installing abatement equipment more extensive and the required equipment more complex. Second, on the other hand, the country's accumulated R&D stock may reduce the value, and the R&D poor country may suffer from high γ_i. This last point may, however, not matter very much if international cooperation, such as international joint implementation of abatement (*i.e.*, the rich country provides abatement investment for poor country), takes place.

In order to facilitate reading this paper, hereafter, we shall say that the country i is *more environment conscious* than j if $\beta_i > \beta_j$ for $i, j = 1,2$ and $i \neq j$. Similarly, we say that the country i is more energy conserving than j if $\overline{\alpha}_i > \overline{\alpha}_j$. We sometimes identify the two countries as Poor and Rich, with the presumption that the poor country has a relatively small values of $\overline{\alpha}$ and β (*i.e.*, the poor country is less energy conserving and less environment conscious than the rich country. We shall make remarks, however, when there is an important implication of the model that will escape if we take this specific presumption.

In the following, we analyze properties of various games played between two countries, with different institutional settings. Broadly, these games fall into two classes, separated by have timings of actions. One deals with the *ex post* games when the abatement investment is already sunk and, hence, α_i is fixed. Each country in such games, then, is completely characterized by the value of two parameter, (α_i, β_i). We consider two variants of the *ex post* games, one with decentralized decisions being made non-cooperatively, and another with centralized decisions being reached cooperatively. The former is meant to abstract the situation when there is no international agreement for carbon gas emission and the latter when such an agreement is possible using binding agreements. Relevant solution concepts are the Nash equilibrium for the former and the Nash bargaining solution for the latter.

Games with another timing are those *ex ante* games where countries choose the level of abatement investment anticipating an *ex post* game to follow in the next period. Each country is then characterized by three parameter values, $(\overline{\alpha}_i, \beta_i, \gamma_i)$. We shall consider a sequential game where decentralized decisions prevail in both periods in the next section. The relevant solution concept is a sub-game perfect equilibrium, anticipating the second period Nash equilibrium. Another sequential game we focus in this paper is the one when there is no agreement at the time of choosing the level of abatement investment, but they anticipate an agreement to be in force *ex post*. The relevant solution concept is the sub-game perfect equilibrium anticipating the Nash bargaining outcome *ex post*.

2-3. Governments

In each country i, government tries to maximize its total economic welfare by intervening its economy. There are two broad classes of such interventions; intervention to control *ex post* efficiency in emission control, α_i, by affecting the investment cost for technology improvement and intervention to directly control carbon gas emission, z_i. There are several alternative means for each intervention; *e.g.*, for the second class of intervention, direct quantity regulation and emission charge (price regulation) both work for the desired direction.

Obviously in our setup without uncertainty, two means of quantity control and price control are equivalent. For example, let the emission charge per unit of carbon gas emission in country i be τ_i in terms of its final product. Given this charge, firms maximize profit after tax payment:

(2-9) $$f(z_i, \alpha_i) - \tau_i z_i$$

It follows immediately that firms choose the optimal emission level, $z_i(\tau_i, \alpha_i)$, that solves:

(2-10) $$f_z(z_i(\tau_i, \alpha_i), \alpha_i) = \tau_i$$

or the marginal cost of emission reduction is equal to per unit charge. Thus, imposing emission charge of τ_i achieves the same result as the emission control with the ceiling of $z_i(\tau_i, \alpha_i)$.

Emission charge will generate revenue of $\tau_i z_i(\tau_i, \alpha_i)$ for the government, while the quantity control will not. However, we shall assume the revenue will be paid back to firms in the form of lump-sum subsidy and two forms of control are completely identical.

2-4. World First-Best Outcome

Before characterizing the decentralized outcome, we fist describe the world first-best outcome when $\overline{\alpha} = (\overline{\alpha}_1, \overline{\alpha}_2)$, $\beta = (\beta_1, \beta_2)$ and $\gamma = (\gamma_1, \gamma_2)$ are given. The world first-best outcome is defined as the state in which the world welfare given by:

(2- 11) $$u_w(z, \alpha; \overline{\alpha}, \beta, \gamma) = u_1(z, \alpha; \overline{\alpha}, \beta, \gamma) + u_2(z, \alpha; \overline{\alpha}, \beta, \gamma)$$
$$= \sum_i f(z_i, \alpha_i) - \left(\sum_i \beta_i\right)(z_1 + z_2) - \sum_i \gamma_i (\alpha_i - \overline{\alpha}_i)^{\varepsilon+1}$$

is maximized. The first order conditions (FOC's) are:

(2-12) $$\frac{\partial u_w}{\partial z_i} = f_z(z_i, \alpha_i) - \sum_\ell \beta_\ell = 0 \quad (\text{i} = 1 \text{ and } 2),$$

(2-13) $$\frac{\partial u_w}{\partial \alpha_i} = f_\alpha(z_i, \alpha_i) - \gamma_i(\varepsilon + 1)(\alpha_i - \overline{\alpha}_i)^\varepsilon = 0 \quad (\text{i} = 1 \text{ and } 2),$$

where we assume:

Assumption 2: $\sum_\ell \beta_\ell < 1$.

Assumption 2 assures that the world first-best outcome is given as an interior solution of (2-11). It is straightforward to see that the second order condition (SOC) is always satisfied. Let $\{z_i^{FB}(\overline{\alpha},\beta,\gamma), \alpha_i^{FB}(\overline{\alpha},\beta,\gamma)\}_{i=1,2}$ denote the solution. Let $Z^{FB}(\overline{\alpha},\beta,\gamma) = \sum_i z_i^{FB}(\overline{\alpha},\beta,\gamma)$ denote the associated optimal world pollution level. We now consider how the first-best outcome is affected by a change in the exogenous parameters $(\overline{\alpha},\beta,\gamma)$. For this purpose, there are two important remarks in order.

First, as is explicitly obtained in (A2-1) of Appendix, $z_i^{FB}(\overline{\alpha},\beta,\gamma)$ is shown to depend only on $\sum_\ell \beta_\ell$ and α_i, and is independent of z_j where $j \neq i$. That is, the first best pollution level of one country does not depend upon the other country's pollution level. This result is a direct consequence of our formulation where country *j*'s pollution level affects the country *i*'s welfare only additively. Put differently, externality exists and a change in *j*'s pollution affects *i*'s welfare, but it does not create any change in *i*'s behavioral incentives.

Second, as obtained in (A2-2), $\alpha_i^{FB}(\overline{\alpha},\beta,\gamma)$ is independent of $(\overline{\alpha}_j, \gamma_j)$ $(j \neq i)$ and depends only on $\sum_\ell \beta_\ell$, $\overline{\alpha}_i$, and γ_i. This follows because any change in $\overline{\alpha}_j$ and γ_j will affect the behavioral incentives of the country *j* but not those of the country *i*.

With these remarks in mind, one can immediately obtain the results of comparative statics shown in **Table 1**.

We briefly discuss the implications of the results. First, an increase in either country's environmental consciousness, β_i, decreases its emission of pollutants as well as the world pollution level. It also raises the world marginal benefit by improving the *ex post* efficiency in emission control. Second, improvement in either country's *ex ante* efficiency in emission control lowers the marginal cost of improving its *ex post* efficiency, which reduces its pollution level, without affecting the other country's pollution level and *ex post* efficiency in emission control. Lastly, either country's increase in the marginal cost of abatement investment lowers the *ex post* efficiency of emission control, thus increasing its pollution level.

Effect of an increase in \ Effect on		z_1^{FB}	z_2^{FB}	Z^{FB}	α_1^{FB}	α_2^{FB}
	$\sum_\ell \beta_\ell$	-	-	-	+	+
	$\overline{\alpha}_1$	-	0	-	+	0
	γ_1	+	0	+	-	0
	$\overline{\alpha}_2$	0	-	-	0	+
	γ_2	0	+	+	0	-

Table 1: Comparative Statics for the World First-Best Outcome

3. The Decentralized Outcome

In this section, we explore the properties of an equilibrium when there is no international agreement, lest it *ex post* or *ex ante*. Even without an international agreement, national government has an incentive to control pollution in order to maximize its welfare. As we already discussed in subsection 2-4, in our world of no uncertainty and complete information, price control and quantity control are equivalent for such purpose. In order to simplify our analysis, therefore, we shall represent such control measures in terms of emission charge in section 3. That is, we consider that the government of country *i* imposes an emission charge, τ_i, for each unit of pollution emitted from any producer of its territory. This charge is defined in terms of the final good.

To find a subgame perfect equilibrium, we first characterize the *ex post* non-cooperative equilibrium when $\alpha = (\alpha_1, \alpha_2)$ and $\beta = (\beta_1, \beta_2)$ are given.

3-1. *Ex Post* Non-Cooperative Equilibrium

Ex post, all investment costs for pollution abatement are sunk, and thus each country attempts to maximize the gross welfare (2-3)'. That is, the government sets the emission charge at the level that is equal to the marginal benefit of pollution reduction. The resulting first order condition for profit maximization is given by:

(3- 1) $\tau_i = MC_i(z_i, \alpha_i) \equiv f_z(z_i, \alpha_i) = \alpha_i[1 - y_i] = \beta_i$ for $i = 1,2$.

In view of (3-1) and (2-1)', the country *i*'s pollution, denoted by z_i^*, as well as the associated level of final good production, denoted as y_i^*, are conveniently expressed as:

(3-2) $$z_i^*(\alpha_i, \tau_i) = -\frac{\ln \tau_i}{\alpha_i} \geq 0,$$

with equality only when $\tau_i \doteq 1$, and

(3-3) $$y_i^*(\alpha_i, \tau_i) = 1 - \frac{\tau_i}{\alpha_i} \geq 0,$$

with equality only when $\alpha_i = \tau_i = 1$.

Note that the optimal charge the government *i* chooses, τ_i, is independent of the level of charge that the government *j* chooses, τ_j. This is so because country *j*'s pollution level does not create any change in behavioral incentives of the country *i*, and hence there is no strategic interaction. It follows that the best response of the *ex post* non-cooperative game is expressed as:

(3-4) $$\tau_i^{BR}(\tau_j) = \beta_i \text{ for all } \tau_j \text{ where } i, j = 1,2 \text{ and } i \neq j.$$

Reaction curves $(R_i R_i,\ \ i = 1,2)$ of this *ex post* game are as depicted in Figure 1. In the figure, we depicted representative indifference curves of the two countries. The curves, $\widetilde{u}_i$, $\widetilde{u}_i'$, $\widetilde{u}_i''$ are the indifference curves for the country *i* with $\widetilde{u}_i''$ representing higher level of utility than that of $\widetilde{u}_i'$, which in turn is higher than $\widetilde{u}_i$. By definition, these curves for country 1 (country 2, respectively) are horizontal (vertical, resp.) along the country 1's (country 2's, resp.) reaction curve. The intersection of two reaction curves, *N*, is the Nash equilibrium of this *ex post* game.

Of course, this property of no strategic interaction between the two countries is a direct consequence of our specific formulation of linear additivity of (2-3). In general, when each country's evaluation of world global environment is not linear in *Z*, the best response is no longer independent of other country's emission charge, and strategic interaction appears. However, when there is no international agreement in perspective, it is not unrealistic to assume that each country does not take into account of the other country's pollution level in making optimal decentralized decision.

As is shown in (A3-3) in the Appendix, when a country's *ex post* efficiency in emission control, α_i, increases, its equilibrium pollution level is reduced. Furthermore, the *ex post* non-cooperative equilibrium gross welfare of the country *i* increases (i) if its own *ex post* efficiency in emission control improves, (ii) if the other country's *ex post* efficiency improves, (iii) if its own marginal evaluation of global environment diminishes, or (iv) if the other country's marginal evaluation improves.

These results may be better understood with the help of Figure 2. Suppose there are two countries, *R* (Rich) and *P* (Poor), where *R* is more energy conserving and more energy conscious than *P*, that is, $\alpha_R > \alpha_P$ and $\beta_R > \beta_P$. Because an increase in α_i lowers its marginal cost, two countries' marginal cost curves are then positioned as in Figure 2. In view of (2-4)', the resulting pollution levels of z_R^N and z_P^N will satisfy $z_R^N < z_P^N$.

When α_R increases, MC_R shifts down and z_R^N is reduced to $z_R^{N\prime}$. Note that the marginal cost of pollution abatement may be interpreted as the marginal productivity of pollution emission. It follows that the change in α_R, holding z_R^N constant, improves the Rich country's GDP by the area of *a+f+g*. (Actually, there is an additional change in GDP because $f(0,\alpha_R)$ becomes larger when α_R increases.) On the other hand, the reduction of z_R^N to $z_R^{N}{}'$, holding α_R constant, deteriorates its GDP by the area *g+h+i+j*. The net GDP change (except for the associated change with zero pollution emission) is measured by the area *a+f-h-i-j*. However, the reduction of pollution will be evaluated as the welfare gain by the area of *g+h+i+j*. The total net welfare gain is, therefore, *a+f+g*, which coincides with (when including the associate change in $f(0,\alpha_R)$) the expression (A3-6). The effect of an increase in α_R on the country *P*'s welfare is straightforward and hence omitted.

When β_P, the marginal evaluation of the Poor country, increases, its pollution emission will diminish to $z_P{}'$. The associated welfare change consists of an increase in abatement cost (*i.e.*, a welfare loss) by the area *m+n*, a welfare gain due to pollution reduction by the area *n*, and a welfare loss due to the increased consciousness about pollution by the area $(d+i)+(d+i+k)$. The total effect is a welfare loss of $2(d+i)+k+m$.

The result of *ex post* non-cooperative equilibrium may be summarized in the following Proposition 1 and shown in Table 2.

Proposition 1: *Each country's pollution at the second-stage non-cooperative equilibrium $z_i^N(\alpha,\beta)$ is determined only by the own efficiency level of emission control α_i and its marginal environment evaluation β_i. Moreover,*

(1) Country *i*'s pollution level, z_i^N, and its GDP, y_i^N, decrease along with an increase in its marginal environment evaluation, β_i,

(2) Both z_i^N and y_i^N always increase with an increase in its *ex post* efficiency of emission control, α_i,

(3) Both countries' welfare increases with an increase in *i*'s *ex post* efficiency of emission control, α_i.

How do country's characteristics affect the outcome of this *ex post* non-cooperative game? In view of (A3-1) - (A3-3), the following corollary is immediate.

Corollary: *With other things being equal, environment conscious country produces less pollution at the cost of a smaller value of GDP, while energy conserving country (assuming $\alpha_i > \alpha_j$ if and only if $\overline{\alpha}_i > \overline{\alpha}_j$) produces less pollution and higher GDP.*

Effect of an increase in \ Effect on	z_i^N	$z_j^N(j \neq i)$	Z^N	y_i^N	$y_j^N(j \neq i)$	$\tilde{u}_i^N$	$\tilde{u}_j^N(j \neq i)$
α_i	-	0	-	+	0	+	+
β_i	-	0	-	-	0	-	+

Table 2: Comparative Statics for Ex-Post Non-Cooperative Equilibrium

As is evident from Figure 1, Nash equilibrium is not Pareto efficient and both countries will get better off by reducing the carbon gas emission simultaneously. If a binding international agreement is struck, then, such mutual reduction will take place. The agreed amount of reduction will depend upon many factors and we shall examine its details in later sections. In the rest of this section, however, we shall analyze the amount of abatement investment in the decentralized outcome in the *ex ante* non-cooperative equilibrium.

3-2. Ex Ante Non-Cooperative Equilibrium

Because there is no strategic interaction in the *ex post* non-cooperative game, even *ex ante*, governments of both countries choose the level of abatement investment independent of other country's action. More precisely, each country i chooses α_i and z_i to maximize (2-6). The associated first order condition is:

(3-5) $$\frac{\partial u_i}{\partial \alpha_i} = \frac{\partial \tilde{u}_i^N}{\partial \alpha_i} - \frac{\partial c_i}{\partial \alpha_i} = \frac{\beta_i}{(\alpha_i)^2}(1+\alpha_i z_i^N) - (1+\varepsilon)\gamma_i(\alpha_i - \overline{\alpha}_i)^\varepsilon = 0 .$$

We shall denote by $\alpha_i^N(\overline{\alpha},\beta,\gamma)$ the optimal solution which is characterized by (3-5)[1]. Comparing it with the first best *ex post* efficiency, $\alpha_i^{FB}(\overline{\alpha},\beta,\gamma)$, which internalizes externality, it readily follows that the non-cooperative level of *ex post* efficiency level is lower than the first best level, *i.e.,* $\alpha_i^{FB}(\overline{\alpha},\beta,\gamma) > \alpha_i^N(\overline{\alpha},\beta,\gamma)$. It also follows that $\alpha_i^N(\overline{\alpha},\beta,\gamma)$ increases (i) if its *ex ante* efficiency, $\overline{\alpha}_i$, increases by lowering marginal investment cost, (ii) if its marginal evaluation, β_i, increases by increasing the marginal benefit of higher *ex post* efficiency, and (iii) if its marginal cost of abatement investment, γ_i decreases. Similarly, combining these results with the result in Proposition 1, comparative statics about the country i's *ex ante* welfare is immediate. That is, *ex ante* welfare $u_i^N(\overline{\alpha},\beta,\gamma) = \tilde{u}_i^N(\alpha_i^N(\overline{\alpha},\beta,\gamma),\beta_i) - \gamma_i(\alpha_i^N(\overline{\alpha},\beta,\gamma) - \overline{\alpha}_i)$, increases (i) if its *ex ante* efficiency improves, (ii) if its marginal evaluation diminishes, (iii) if its own marginal cost of abatement investment diminishes, (iv) if the other country's *ex ante* efficiency improves, (v) if the other country's marginal evaluation improves, and (vi) if the other country's marginal cost of abatement investment diminishes.

These results of the *ex ante* non-cooperative equilibrium are summarized in the following proposition.

Proposition 2: *Each country's ex post efficiency level of emission control,* α_i^N *, is determined only by its own ex ante efficiency,* $\overline{\alpha}_i$*, its marginal environmental evaluation,* β_i*, and its marginal cost of abatement investment,* γ_i*. Moreover,*

(1) Country *i*'s *ex post* emission control efficiency, α_i^N , (and hence its welfare) increases along with an increase in its own *ex ante* emission control efficiency, $\overline{\alpha}_i$, and along with its marginal environment evaluation, β_i,

(2) Country *i*'s *ex post* emission control efficiency, α_i^N , (and hence its welfare) increases along with a decrease in its own marginal cost of abatement investment, γ_i,

(3) When the other country's *ex ante* emission control efficiency, $\overline{\alpha}_j$, increases, or marginal environment evaluation, β_j, increases, or marginal cost of abatement investment, γ_j, decreases, country *i*'s welfare improves.

Effect of an increase in \ Effect on	a_i^N	$a_j^N(j \neq i)$	u_i^N	$u_j^N(j \neq i)$
$\overline{a}_i$	+	0	+	+
β_i	+	0	-	+
γ_i	-	0	-	-

Table 3: Comparative Statics for the Ex-Ante Non-Cooperative Equilibrium

It follows straightforwardly from Proposition 1 and Proposition 2 that:

Corollary: *With other things being equal, environment conscious country achieves a higher ex post efficiency in emission control in the ex ante non-cooperative game, energy conserving country*

[1] Note that $\alpha_i^N(\overline{\alpha},\beta,\gamma)$ does not actually depend upon $\overline{\alpha}_j,\beta_j$ and γ_j $(j \neq i)$.

achieves a higher ex post efficiency, and country with a higher marginal abatement cost achieves a lower ex post efficiency.

4. Coordinated Outcomes: Preliminary Results

4-1. Bargaining Solutions with and without Side Payments

We have now fully characterized both *ex ante* and *ex post* non-cooperative equilibria. In this and the next sections, using the Nash bargaining solution, we shall analyze the outcome of *ex post* cooperation when an enforceable international agreement in the second period is possible. With that in mind, in this subsection we define the Nash bargaining solution for the case when side payments are allowed and the case when they are not. We also sketch our analyses to be employed in the rest of our paper, in order to facilitate our readers.

There are two distinctly different possibilities for international agreements. For one, two countries may negotiate over their respective domestic regulations without any international income transfer. Agreement reached through such a negotiation may be described by the Nash bargaining solution for the game *without side payments*. Alternatively, two countries may negotiate over domestic regulations with transfer of incomes as an additional term in negotiation. For example, the negotiation may be carried out over total amount of and its initial distribution of tradable permits. In this case, side payment will be realized in the form of either receipts from the sales of or expenditures for the purchase of permits. Corresponding solution concept will be the Nash bargaining solution for the game *with side payments*.

The outcomes for these solution concepts are summarized in Figure 3. Given (α,β), the set of all payoff allocations, U^{NSP}, that would be achieved by an international coordination without side payments is identified by its frontier, $U_P B_P C_0 C_T B_P' U_P'$. We shall call this efficient portion of U^{NSP} as the *before-transfer Utility Possibility Frontier* (*UPF*). The second period bargaining game is then characterized as $(U^{NSP},\widetilde{u}^N)$. $B=\widetilde{u}^N=(\widetilde{u}_1^N,\widetilde{u}_2^N)$ represents the threat point or the (individually rational) payoff outcome that two countries would anticipate when the negotiation broke down, and it is precisely the non-cooperative equilibrium payoff outcome. The associated Nash bargaining solution generates the payoff outcome C_0 where the Nash product is maximized among all payoff pairs on *UPF*.

When side payments are available, two countries can transfer payoffs and the set of feasible payoff allocations becomes U^{SP} with its frontier becoming $PS_T C_T P'$, a line with slope -1 which is tangent to the *UPF* at C_T in the Figure. The second period bargaining game becomes $(U^{SP},\widetilde{u}^N)$ and the associated Nash bargaining solution is the payoff allocation S_T, which maximizes the Nash product with respect to the non-cooperative payoff outcome, $B = \left(\tilde{u}_i^N(\alpha,\beta)\right)_{i=1,2}$, among all the feasible payoff pairs U^{SP}. Put differently, two countries coordinate to achieve the *coordinated outcome*, C_T, as an intermediate outcome. Then they make side payments to realize the true *cooperative outcome with side payment*, S_T.

It is clear that we must identify the properties of the before-transfer utility frontier in order to analyze these two bargaining solutions. This is precisely the question we now turn in the next sub-sections.

4-2. Before Transfer Utility Frontier

As is shown in Figure 3, the before-transfer UPF is readily shown to be strictly convex towards the origin[1]. In order to simplify our analysis, we introduce country *i*'s bargaining surplus defined by:

(4-1) $\tilde{w}_i = f(z_i,\alpha_i) - \beta_i(z_1+z_2) - \tilde{u}_i^N(\alpha,\beta)$ (i = 1 and 2).

At the bargaining table, two countries bargain over the surplus combinations in the set of *ex post* barraging surpluses, which will be referred to as the before-transfer bargaining possibility frontier (BPF). Graphically, the before-transfer BPF is the portion of the UPF with the origin replaced by the disagreement payoff, $B = \left(u_1^N(\alpha,\beta), u_2^N(\alpha,\beta)\right)$.

To characterize the BPF, a shadow price for each country's welfare plays a crucial role. Let q_i denote the shadow price of country *i*'s welfare (*i* = 1 and 2) and define the *Nash bargaining Surplus* as:

(4-2) $\tilde{S}(q;\alpha,\beta) = \max_{\{z\}} \sum_i q_i\left[f(z_i,\alpha_i) - \beta_i(z_1+z_2) - \tilde{u}_i^N(\alpha,\beta)\right]$.

Let $z_i^C(q;\alpha,\beta)$ (i=1 and 2) denote this *coordinated* solution. It must satisfy the first order condition:

(4-3) $q_i f_z(z_i^C,\alpha_i) = \sum_\ell q_\ell \beta_\ell$ or $\mathrm{MC}_i(z_i^C,\alpha_i) \equiv f_z(z_i^C,\alpha_i) = \beta_i + \frac{q_j}{q_i}\beta_j$.

In view of (3-1), it readily follows that:

[1] The proof is given in the Appendix.

Proposition 3: *At the cordinated outcome, both countries choose the pollution level that is smaller than the one associated with the decentralized outcome, i.e.,* $z_i^N(\alpha,\beta) < z_i^C(q;\alpha,\beta)$ *for all i, q with* $\frac{q_i}{q_j} > 0$, *and* (α,β) *with* $\beta_j > 0$.

We denote the payoff at the coordinated outcome as:

(4-4) $\tilde{u}_i^C(q;\alpha,\beta) = f\left(z_i^C(q;\alpha,\beta),\alpha_i\right) - \beta_i \sum_{\ell=i,j} z_\ell^C(q;\alpha,\beta)$.

Any efficient bargaining surplus, such as the point $C_T = \left(\tilde{w}_1^C(q;\alpha,\beta), \tilde{w}_2^C(q;\alpha,\beta)\right)$ of Figure 3 with the slope $q = \frac{q_2}{q_1}$, is given by:

(4-4) $\tilde{w}_i^C(\boldsymbol{q};\alpha,\beta) = \frac{\partial \tilde{S}(\boldsymbol{q};\alpha,\beta)}{\partial q_i}$ for $i = 1$ and 2

where use was made of the envelope theorem. We call $\tilde{w}_i^C(q;\alpha,\beta)$ the *before-transfer bargaining gain* (BBG) of country *i* with the relative welfare weights *q*. Clearly,

(4-5) $\tilde{w}_i^C(q;\alpha,\beta) = \tilde{u}_i^C(q;\alpha,\beta) - \tilde{u}_i^N(\alpha,\beta)$.

4-3. Comparative Statics of Before-Transfer Bargaining Gains

In this subsection, we analyze how a change in parameters (such as a country's *ex post* efficiency in emission control and/or marginal evaluation of global environment) affects the size of before-transfer bargaining gain. We shall leave an intuitive explanation later and first present formal results. A straightforward but a tedious computation will yield the following outcome[2]:

Proposition 4: *With the given welfare weight, q, a country may suffer a gain or a loss from international cooperation, the size of which depends upon different parameters.*

(1) *A country's welfare gain from international cooperation,* $\tilde{w}_i^C(q;\alpha,\beta)$, *increases with an increase in its efficiency of ex post emission control,* α_i.

(2) *A country's welfare gain,* $\tilde{w}_i^C(q;\alpha,\beta)$, *diminishes as the other country's efficiency of ex post emission control,* α_j, *increases.*

[2] The derivation is in the Appendix.

(3) *A ocuntry's welfare gain,* $\widetilde{w}_i^C(q;\alpha,\beta)$*, may increase or decrease with an increase in its own marginal evaluation,* β_i*, depending upon the relative size of the ratio of two countries' ex post emission efficiency and the ratio of two countries' marginal valuation.*

(4) *A country's welfare gain,* $\widetilde{w}_i^C(q;\alpha,\beta)$*, diminishes with an increase in the other country's marginal evaluation of environment,* β_j*,*

(5) *The Nash bargaining surplus,* $\widetilde{S}(q;\alpha,\beta)$*, diminishes with an increase of a country's ex post emission control,* α_i*,*

(6) *The Nash bargaining surplus,* $\widetilde{S}(q;\alpha,\beta)$*, may increase or decrease with an increase in a country's marginal evaluation,* β_i*.*

At the table of an international bargaining with side payments, a country may end up making a transfer payment to the other country. Type of the country that will make such a transfer is easily identified with the help of this proposition. Such an agreement will dictate the before-transfer welfare allocation such as C_T of Figure 3 where the slope of the before-transfer UPF equals -1. Question is then reduced to the following one: what type of the country will have a larger before-transfer bargaining gain at C_T or, equivalently, what type of the country will have a larger value of $\widetilde{w}_i^C(1;\alpha,\beta)$. The country with larger value of $\widetilde{w}_i^C(1;\alpha,\beta)$ will make a transfer to the other country as a result of international agreement. The answer is then straightforward and summarized in the following corollary.

Corollary: *By an international agreement that permits side payment, the country with a higher ex post efficiency in emission control will make a transfer to the country with a lower efficiency. The country with a larger value of marginal evaluation will make a transfer to the country with a smaller evaluation. In terms of Poor vs. Rich interpretation, it is the rich country that provides a transfer to the poor country.*

Intuitive interpretations for these results are now provided with the help of Figure 4, which is depicted for the case of $q_i/q_j = 1$. (Needless to say, the following interpretations can be extended to general case of $q_i/q_j \neq 1$.) We suppose two countries are the Poor and the Rich with the parameter combinations satisfying $\alpha_R > \alpha_P$ and $\beta_R > \beta_P$. At the non-cooperative outcome of $(\widetilde{u}_1^N, \widetilde{u}_2^N)$ two countries emit pollution of the amounts, z_P^N and z_R^N, while at the coordinated outcome of $(\widetilde{u}_1^C, \widetilde{u}_2^C)$ they emit the amounts, z_P^C and z_R^C. Compared with the non-cooperative outcome, the Rich gains from the reduction of its own pollution by $f+e$ at the cost of $d+e+f$, but it also gains from the reduction of the Poor's pollution by $b+c+g$. The net gain for the Rich is $b+c+g-d$. The Poor gains *c* from its own reduction at the cost of $a+b+c$, but it also gains from Rich's reduction by *f*. The net welfare gain is $f-(a+b)$. It is then clear that the Poor may require an income transfer in order to offset such a loss at the international agreement, while the net total gain (summed over two countries) must be always positive.

More intuitively, this result stems from the following properties. Compared with the Rich, the Poor is required to reduce a larger amount of pollution in order to achieve the Pareto efficient allocation. Not only this creates a heavier burden for the Poor but the fact that the Rich will reduce only a small amount of pollution also provides a smaller benefit to the Poor. Hence, the Poor country may not be allured to join an international agreement unless either a compensation is assured by the Rich if the game is with side payments, or a preferential treatment such as lower pollution tax is allowed if the game is without side.

More interesting may be the case of two industrialized countries bargaining over pollution. As we briefly discussed in section 2-2, some advanced countries (say, US) are known for their inefficiency in conserving energy and in controlling emission compared with other countries (say, Europe). That is, countries like US tend to have a lower value of *ex ante* (and, hence, a lower value of *ex post*) efficiency in emission control compared with other industrialized countries such as the Europe. The corollary above shows that, even if two countries have the same value of β_i, the country with higher value of efficiency α_i will end up paying transfer to the country with lower α_i. This may seem counterintuitive, because it is the Europe which has been more environmental conscious than US. However, the economic logic implies that the very fact the Europe has been environmental conscious made its bargaining power small and, thereby, brings about the agreement where Europe makes a transfer to US.

It also implies that the net gain for each country is larger, (1) as the country's *ex post* efficiency is higher, (2) as the other country's efficiency is lower, (4) as the other country's marginal evaluation is higher, but the effect is ambiguous when (3) when the own marginal evaluation becomes higher. Consider (1) in Figure 4. The rich country's α_R increases and its *MC* shifts down from MC_R to MC_R'. The net gain from the reduction of its own pollution changes from the area $b+c+g-d$ to $b+c+g-d'$. This change improves the country's welfare because, reflecting the higher efficiency of pollution control, the reduction of pollution from the non-cooperative level to the cooperative level is now smaller ($z_R^N - z_R^C > z_R^{N\prime} - z_R^C$).

This also assures the result (2). When the country *j*'s *ex post* efficiency becomes higher, that country's reduction of pollution will become smaller and the country *i's* benefit will become smaller. (4) is now straightforward because such a change will reduce the rival country's pollution smaller and improves the home country's welfare. Finally, the effect of (3) is ambiguous because it will reduce its cost d because the function MC_R is convex in z, but the country now evaluates the rival country's pollution reduction more highly. The net effect is then ambiguous, but this conclusion is dependent on the property that MC_R is convex in z, the property critically hinges upon the choice of our specific form of production function.

Perhaps the most counter-intuitive and most important result of Proposition 4 is its (5), *i.e.*, when a country's *ex post* efficiency improves, the bargaining surplus at the international bargaining diminishes. Put differently, the result (2) above dominates the result (1). To understand this result, the following explanation is probably more illustrative.

Figure 5 depicts the before-transfer utility possibility frontier (UPF) as well as the bargaining possibility frontier (BPF). With the original parameter values, (α,β), the non-cooperative equilibrium payoff outcomes are at $TP=\left(\tilde{u}_R^N,\tilde{u}_P^N\right)$, the associated UPF is $U_0B_0c_0^{NSP}B_0'U_0'$ while the associated BPF is $B_0c_0^{NSP}B_0'$ with the new origin at TP'. Given the welfare weights, q, the payoff pair of the coordinated outcome is c_0^{NSP} and the associated welfare gain, $\tilde{w}^{C0}=\left(\tilde{w}_R^{C0},\tilde{w}_P^{C0}\right)$, is the vector $\overrightarrow{Bc_0^{NSP}}$.

Now consider the Rich's *ex post* efficiency, α_R, improves. It will shifts the UPF outwards so that the new UPF will become $U_1B_1c_1^{NSP}B_1'U_1'$ and the new coordinated outcome at c_1^{NSP}. However, it will not necessarily shifts the BPF outwards because the non-cooperative equilibrium changes as well. Indeed, from Proposition 1(3), we know that not only the Rich's welfare but also the Poor's welfare at the non-cooperative equilibrium improves, because the Poor free-rides on the Rich's pollution reduction. Because this increase in $\tilde{u}_P^N$ dominates the gain in payoff at the coordinated outcome, not only $\tilde{w}_P^{C0}>\tilde{w}_P^{C1}$ and the Poor's welfare gain deteriorates by an increase in α_P, but also the Nash bargaining surplus after an increase in α_P, $\tilde{S}_1=q_R\tilde{w}_R^{C1}+q_P\tilde{w}_P^{C1}$ is smaller than $\tilde{S}_0=q_R\tilde{w}_R^{C0}+q_P\tilde{w}_P^{C0}$. It follows that, as is depicted in Figure 6, the BPF shifts inwards from $B_0c_0^{NSP}B_0'$ to $B_1c_1^{NSP}B_1'$ and associated Nash bargaining surplus becomes smaller from $\tilde{S}_0$ to $\tilde{S}_1$.

Finally, one of the major factors that affect each country's incentive in abatement investment is to improve its share from the bargaining, which equals one-half of the Nash bargaining surplus, $\tilde{S}(q;\alpha,\beta)$. This incentive, $\frac{1}{2}\frac{\partial\tilde{S}}{\partial\alpha_i}$, itself depends upon various parameters. We now summarize the comparative statics properties of this incentive in the following proposition.

Proposition 5: *When a country i increases its abatement investment, the marginal gain from Nash bargaining surplus:*

(1) *decreases as its abatement investment and, hence, its ex post efficiency,* α_i, *increases,*

(2) *does not change the value when the other country's ex post efficiency,* α_j, *changes,*

(3) *increases as the country's marginal evaluation,* β_i, *increases,*

(4) *decreases as the other country's marginal evaluation,* β_j, *increases.*

5. *Ex Ante* Investment Incentives Anticipating Future International Bargaining

5-1. International Bargaining with Side Payments

We are now ready to discuss how *ex ante* investment incentives are affected by the anticipation of a future international agreement. In this subsection, we analyze such incentives with the assumption that side payments will be allowed in the future international bargaining.

Note first that, given (α,β), the eventual payoff outcome for the country i at the international bargaining with side payment is expressed as:

(5-1) $\tilde{u}_i^{SP}(\alpha,\beta)=\tilde{u}_i^{N}(\alpha,\beta)+\frac{1}{2}\tilde{S}(1;\alpha,\beta)$.

That is, each country will share the Nash bargaining surplus (with the welfare weights being unity) equally, in addition to the corresponding non-cooperative equilibrium payoff. Anticipating this payoff, countries will engage in the *ex ante* game with the corresponding payoff of:

(5-2) $u_i=\tilde{u}_i^{N}(\alpha,\beta)+\frac{1}{2}\tilde{S}(1;\alpha,\beta)-C(\alpha_i,\overline{\alpha}_i,\gamma_i)$.

Let $\alpha_i^{SP}(\overline{\alpha},\beta,\gamma)$ be the *ex post* efficiency in emission control that maximizes (5-2). Note that this value could be potentially dependent upon $\alpha_j\ (j\neq i)$, representing the strategic interaction in *ex ante* actions between two countries, both of whom anticipate the future international bargaining. However, as is shown in the Appendix, there is no such effect if the bargaining permits side payments. We shall denote the equilibrium payoff as:

(5-3) $u_i^{SP}(\overline{\alpha},\beta,\gamma)=\tilde{u}_i^{N}(\alpha,\beta)+\frac{1}{2}\tilde{S}(1;\alpha,\beta)-C(\alpha_i,\overline{\alpha}_i,\gamma_i)\equiv u_i^{N}(\overline{\alpha},\beta,\gamma)+\frac{1}{2}\tilde{S}(1;\alpha,\beta)$

with $\alpha_i^{SP}(\overline{\alpha},\beta,\gamma)$ substituting α_i.

The following proposition is then immediate in view of our previous results.

Proposition 6: *Each country's ex post efficiency,* α_i^{SP}, *is determined only by its own ex ante efficiency,* $\overline{\alpha}_i$, *its own marginal evaluation,* β_i, *and the rival country's evaluation,* β_j *(as well as* γ_i*), and it is not affected by the other country's ex ante efficiency,* $\overline{\alpha}_j$. *Put differently;*

(1) *there is no strategic interaction between two countries in this game of abatement investment. Moreover,*

(2) *when a bargaining with side payment is anticipated, the ex post efficiency is lower than the level when no bargaining is anticipated, i.e.,* $\alpha_i^{SP}(\overline{\alpha},\beta,\gamma) < \alpha_i^N(\overline{\alpha},\beta,\gamma)$,

(3) *the ex post efficiency,* α_i^{SP}, *is higher when the country's ex ante efficiency,* $\overline{\alpha}_i$, *is higher,*

(4) *the ex post efficiency,* α_i^{SP}, *is independent of the other country's ex ante efficiency,* $\overline{\alpha}_j$,

(5) *the ex post efficiency,* α_i^{SP}, *is higher as the country's marginal evaluation,* β_i, *is higher,*

(6) *the ex post efficiency,* α_i^{SP}, *is lower as the other country's marginal evaluation,* β_j, *is lower.*

Perhaps, the most important and counter-intuitive among six results of Proposition 6 is (b). To see why it is true, note first that the relevant payoff is the sum of the non-cooperative payoff, u_i^N, and the share of the Nash bargaining gain, $\frac{1}{2}\widetilde{S}$, as depicted in (5-2). Because there is no strategic interaction, it is the fact that $\frac{\partial\widetilde{S}}{\partial\alpha_i}$ is negative which provides lower abatement investment incentive (and, hence, lower *ex post* efficiency level) when a bargaining is anticipated compared with when it is not. As we have seen in Proposition 4 (5) and the discussion that follows it, this term is negative because an increase in α_i increases its own bargaining surplus, $\widetilde{w}_i^C$, but deteriorates the other country's surplus, $\widetilde{w}_j^C$, with the latter always dominating the former. Repeating our exposition in the previous section, the main reason why $\widetilde{w}_j^C = \widetilde{u}_j^C - \widetilde{u}_j^N$ deteriorates lies in the fact that an increase in α_i improves the country *j*'s non-cooperative payoff, $\widetilde{u}_j^N$, because *j* can free ride on *i*'s now improved emission control.

It is then clear why we have a rather counter-intuitive result of Proposition 6(b). When α_i increases, the country *j* enjoys better bargaining position in the international bargaining, reflecting a higher individually rational payoff, $\widetilde{u}_j^N$, which *j* could achieve even if the negotiation breaks down. Anticipating that, if *i* increased in its own abatement investment, *j* would end up having a better bargaining position in future because its investment gain would spill over to *j*, *i*'s investment incentive is suppressed.

5-2. International Bargaining without Side Payments

When the bargaining does allow side payments, how are our results in sub-section 5-1 altered? Unfortunately, the. analysis of this case is much more involved than the case with side payments. Therefore, we shall only sketch how our result in Proposition is altered when the bargaining does not allow side payments.

We first note that the effect of a change in α_i on the ultimate payoff outcome will be broken down into (a) a change in the non-cooperative outcome, $\tilde{u}_i^N$, and (b) a change in the bargaining surplus, $\tilde{w}_i^C = \tilde{u}_i^C - \tilde{u}_i^N$. Different from the case of bargaining with side payments discussed in sub-section 5-1, the latter is no longer $\frac{1}{2}\tilde{S}(1;\alpha,\beta)$. It is not because the bargaining frontier is no longer the line segment *PP'* but it is the frontier $B_P C_0 C_T B_P'$ in Figure 3, and the Nash bargaining solution chooses the payoff pair such as C_T where the Nash product is maximized on $B_P C_0 C_T B_P'$.

The situation is illustrated in Figure 7. With the original values of (α,β), the bargaining possibility frontier (BPF) is the locus $B_0 C_0^{NSP} B_0'$ and the bargaining dictates the payoff outcome of C_0^{NSP} where the Nash indifference curve, $N_0 N_0'$, is tangent to the BPF. We assume the two countries are rich (R) and poor (P) so that C_0^{NSP} lies below the 45 degree line. Let the slope of the BPF at C_0^{NSP} be $-q_R/q_P$ where $q=(q_R,q_P)$ is the relative welfare weights of the two countries associated with the bargaining equilibrium. The line that is tangent to the BPF at C_0^{NSP} intersects with the horizontal axis at $\tilde{S}_0/q_R$, whose distance from the origin is $\tilde{S}(q;\alpha,\beta)/q_R$. Note that the ultimate payoff that the country *i* receives in the bargaining without side payment is:

$$\text{(5-4)}\quad \tilde{u}_i^{NSP}(\alpha,\beta) = \tilde{u}_i^N(\alpha,\beta) + \frac{1}{2q_i}\tilde{S}(q;\alpha,\beta),$$

and, for the rich country, the net gain (in addition to the non-cooperative outcome) it can realize through bargaining is $\frac{1}{2}\tilde{S}_0/q_R$. We shall denote the solution of (5-4) by $\alpha_i^{NSP}(q;\alpha,\beta)$.

Now suppose α_R increases and the parameters change to (α',β). This effect can be conveniently divided into two parts, the *total surplus* effect and the *shadow price* effect. We first explain the former effect. From (5) of Proposition 4, we know that the new BPF lies strictly inside of the old BPF, like $B_1 C_1^{NSP} C_2^{NSP} B_1'$ in Figure 5. Moreover, from (1) and (2) of Proposition 4, the point on the new BPF whose slope equals the ratio of the original welfare weights $-q_R/q_P$, *i.e.*, C_2^{NSP}, lies southeast of C_0^{NSP}. The Nash bargaining surplus evaluated at C_0^{NSP} is represented by the distance between the origin and the point where the tangent line intersects with the horizontal axis, $\tilde{S}_2/q_R$. The distance between $\tilde{S}_0/q_R$ and $\tilde{S}_2/q_R$, therefore, represents twice the change of its net gain, had the bargaining kept the relative welfare weights of two countries constant when α_R is increased. Thus, the change from c_0^{NSP} to C_2^{NSP} represents the change of payoffs caused by a change in α_R with the shadow price, q, constant. Put differently, this effect reflects the change in total surplus caused by a change in α_R but with the constant shadow price.

However, C_2^{NSP} does not maximize the Nash product among the new BPF. In view of the fact that the BPF is strictly convex from the origin, the new Nash bargaining solution must lie to the left of C_2^{NSP}, say at C_1^{NSP}, with a flatter slope $-q_R'/q_P'$ where $q' = (q_R', q_P')$ is the new welfare weights (shadow price). It follows straightforwardly that $\widetilde{S}_1/q_R'$, the Nash bargaining surplus associated with C_1^{NSP}, is strictly larger than $\widetilde{S}_2/q_R$, the surplus associated with C_2^{NSP}, but it may or may not be larger than $\widetilde{S}_0/q_R$, the surplus associated with C_0^{NSP}. We shall label the first half of this change, from c_0^{NSP} to C_2^{NSP}, as the *total surplus effect*, while the second half, from C_2^{NSP} to C_1^{NSP}, as the *shadow price effect*.

There are two important observations regarding these two effects. First, as we have seen in the previous section, there are no strategic interaction in the *ex ante* game of choosing the investment level as long as the total surplus effect is concerned. However in such a game, players must consider the shadow price effect which makes $\alpha_i^{NSP}(q;\alpha,\beta)$ dependent upon α_j. It follows that, different from the case of negotiation with side payments, strategic interaction becomes an important aspect of the *ex ante* game if bargaining does not allow side payments.

Second, as we have seen in the previous sub-section, the total surplus effect makes the share from the bargaining smaller if a country improves its *ex post* efficiency. However, the shadow price effect works toward the opposite direction. That is, $\left(\widetilde{S}_0/q_R - \widetilde{S}_2/q_R\right) > \left(\widetilde{S}_0/q_R - \widetilde{S}_1/q_R'\right)$ always holds but $\widetilde{S}_0/q_R - \widetilde{S}_1/q_R'$ may be positive or negative. Note that the right hand side of this inequality represents the total change (*i.e.*, sum of two effects) in the country's net gain of increasing α_R when international bargaining does not allow side payments. When $q_R/q_P = 1$ is the associated relative welfare weights at the original equilibrium with (α,β), the left hand side of the inequality represents the same change when the bargaining allows side payments. It follows that the incentive for abatement investment in order to achieve a higher *ex post* efficiency is larger when the bargaining does not permit side payments, but it is ambiguous whether or not this incentive (when bargaining does not allow side payment) is larger or smaller compared with the non-cooperative outcome.

We should provide a caution at this moment. The left-hand side of the above inequality represents the net welfare gain when international bargaining allows side payments only when the relative welfare weights are the same or $q_R/q_P = 1$. There are several important cases when $q_R/q_P = 1$ holds at the equilibrium bargaining solution without side payments. Among them is the case when the two countries have the same characteristics and, hence, the resulting equilibrium is symmetric. Thus, the following proposition is immediate:

Proposition 7: *When the ex post bargaining does not permit side payments, a strategic interaction is likely to exist in the ex ante non-cooperative game for abatement investments. Moreover, when two countries have the same ex ante characteristics and hence* $(\overline{\alpha}_1, \beta_1, \gamma_1) = (\overline{\alpha}_2, \beta_2, \gamma_2)$, *each country's equilibrium abatement investment is larger compared with the case when the anticipated bargaining permits side payments, i.e.,* $\alpha_i^{NSP}(\overline{\alpha}, \beta, \gamma) > \alpha_i^{SP}(\overline{\alpha}, \beta, \gamma)$ *for all* $(\overline{\alpha}, \beta, \gamma)$. *However, the sign of* $\alpha_i^{NSP}(\overline{\alpha}, \beta, \gamma) - \alpha_i^{N}(\overline{\alpha}, \beta, \gamma)$ *is ambiguous.*

6. Concluding Remarks

In this paper, we analyzed a two-period two-country model with or without anticipating a future international agreement on environmental control. Several remarks may be in order before we conclude the paper.

In order to simplify our analysis and in order to enable us to track down the likely outcomes, we employed several crucial assumptions. One of the most important is that an international agreement being binding. Any foreseeable international agreement on global environment will lack enforcing power other than self-enforcing property, because there is no world government that can enforce the agreement. Ideally, we should analyze a two period model with second period agreement being designed only to satisfy the self-enforcing property, or even better the renegotiation-proof self-enforcing property. Unfortunately, little is known about renegotiation-proof equilibrium of this nature[2] and restricting feasible outcomes to be either self-enforcing or renegotiation-proof would make our analyses more complicated than necessary. Therefore, instead of using these equilibrium concepts to be satisfied for all feasible negotiation outcomes, we simply assumed that a binding contract is possible and any feasible outcome is potentially agreeable.

The specific mathematical formulations we employed for production function (2-1)' and national welfare (2-5) are also restrictive. In particular, most of our results that strategic interactions fail to exist in various forms of competition are clearly the result of the linearity of (2-5). Nonetheless, most important message of the paper is that the incentives for *ex ante* investment is smaller when an international negotiation is anticipated *even if strategic interaction does not exist.*

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2 See, for example, Farrell and Maskin [1989] and Barrett [1994]. However, their concept of renegotiation proof equilibrium is not well-established in economics.

When such interaction exist, because national welfare becomes non-linear, our conclusion is likely to be strengthened.

Among our various results, we should comment on two results. First we have shown that, among those industrialized countries with high values of β, those countries with low *ex ante* or *ex post* efficiency in emission control, $\overline{\alpha}_i$ or α_i, will receive transfer (and, hence, will receive larger initial distribution of tradable permits) from those industrialized countries with low values of $\overline{\alpha}_i$ or α_i. This prediction may be considered as unfair, because such countries are precisely the countries who have failed to make global contribution historically and should be held responsible for a heavier burden in future. Unfortunately, however, the reality of international negotiations is likely to reflect the relative bargaining position of the countries as we have assumed in this paper, and unlikely to reflect ethical judgements even if we all think that should be the case. If one is concerned with fairness of this kind, perhaps he should consider the possibility of changing the subjects of negotiation, for example, from tax rates and/or amount and distribution of tradable permits to the proportion of carbon gas reduction from the base year.

Probably the most controversial result of this paper is that the countries will have less incentive for *ex ante* abatement investment if they anticipate an international agreement in future. As we have repeatedly suggested, this result seems fairly robust. However, we have not made any simulation study to assess the magnitude of this effect and, therefore, we do not know how serious we should take this effect into consideration. Nonetheless, we should emphasize the following. In the model, we treated the two periods, *ex ante* and *ex post*, without paying any attention to their lengths. However, the *ex ante* investment is a flow variable, and its impact on the *ex post* becomes larger as the length of the first period (*ex ante* period) becomes longer. An obvious implication of this observation is that, once the possibility of a future international agreement becomes non-negligible, the sooner an agreement get struck, the less impact this negative incentive affects the *ex ante* investment for improving emission efficiency.

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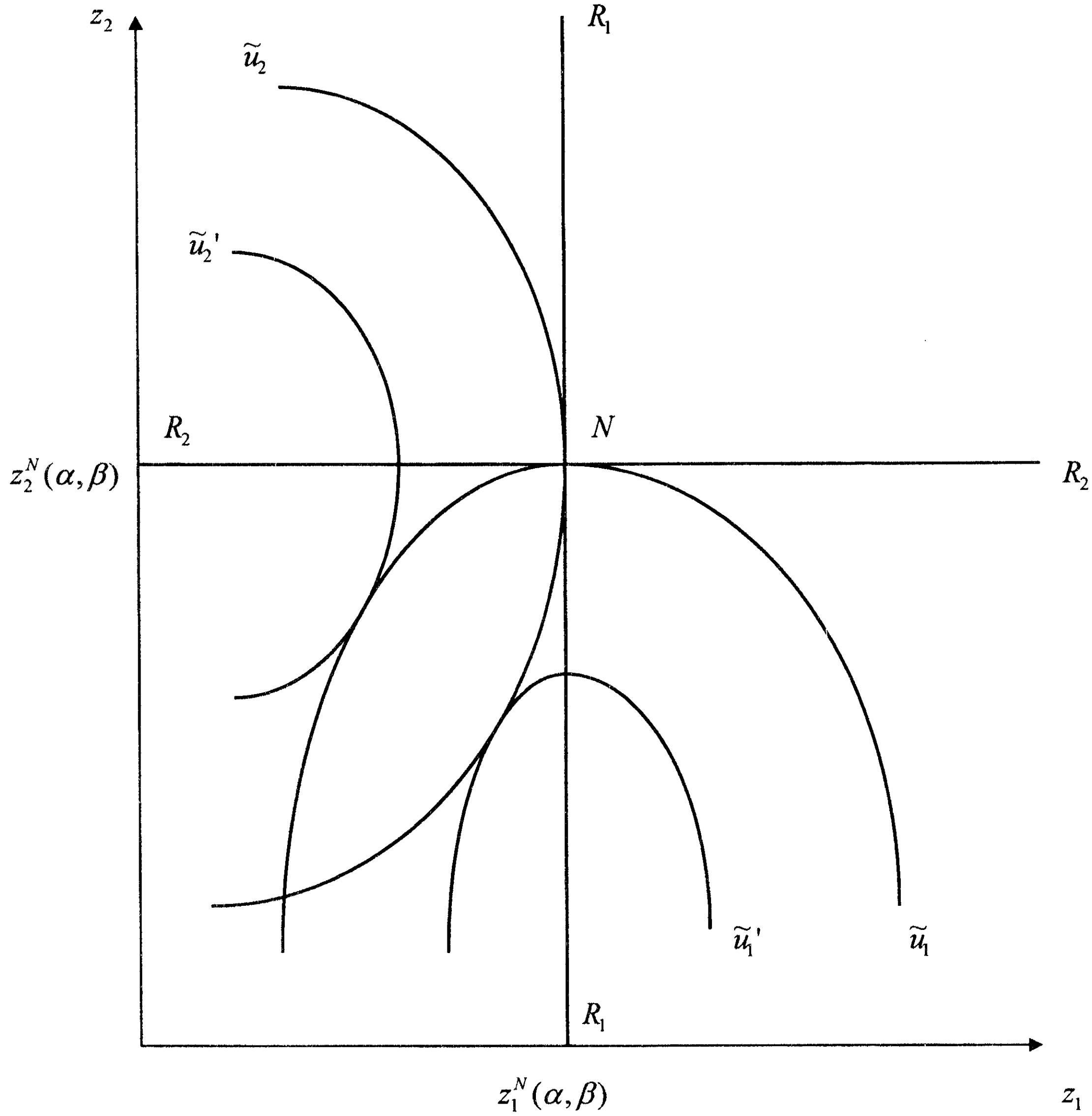


z_2
R_1
$\widetilde{u}_2$
$\widetilde{u}_2'$
R_2
N
$z_2^N(\alpha,\beta)$
R_2
$\widetilde{u}_1'$
$\widetilde{u}_1$
R_1
$z_1^N(\alpha,\beta)$
z_1

Figure 1

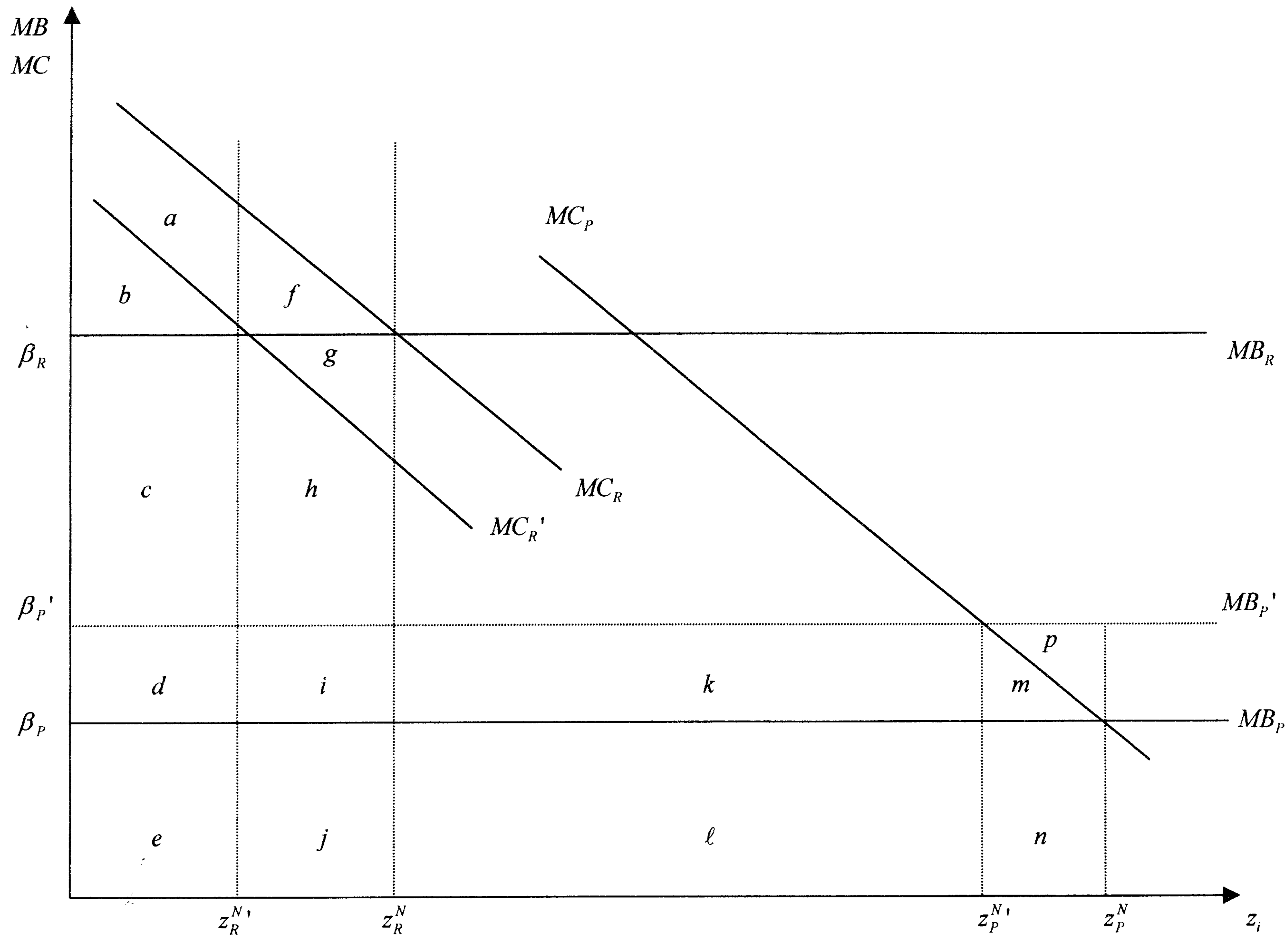
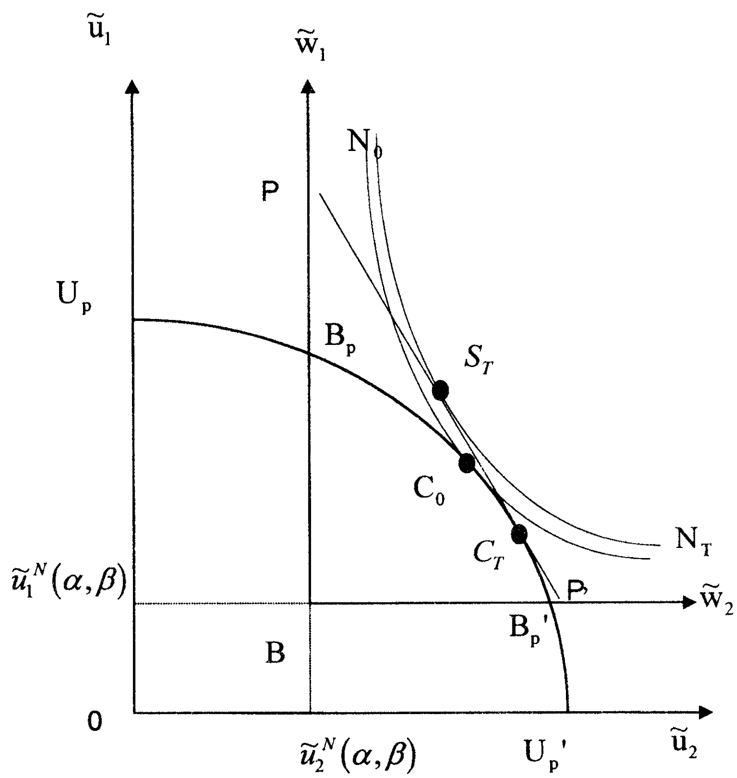
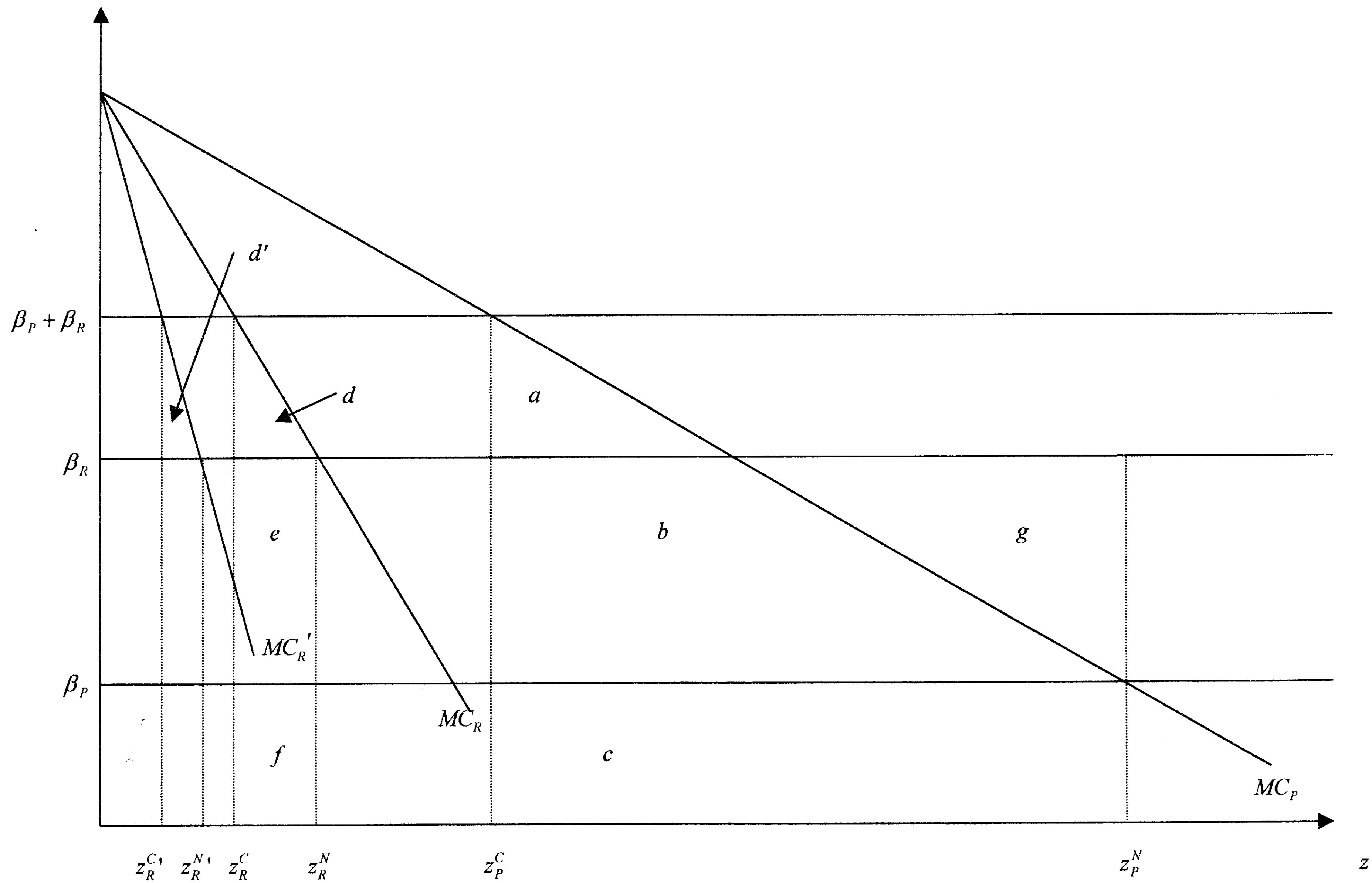

MB
MC
a
b
f
g
c
h
d
i
k
m
p
e
j
ℓ
n
MC_P
MC_R
MC_R'
MB_R
MB_P'
MB_P
β_R
β_P'
β_P
z_R^N'
z_R^N
z_P^N'
z_P^N
z_i

Figure 2



$\tilde{u}_1$
$\tilde{w}_1$
N_0
P
U_p
B_p
S_T
C_0
N_T
C_T
$\tilde{u}_1^N(\alpha,\beta)$
P
$\tilde{w}_2$
B_p'
B
0
$\tilde{u}_2^N(\alpha,\beta)$
U_p'
$\tilde{u}_2$

Figure 3



d'
d
a
$\beta_P + \beta_R$
β_R
β_P
e
b
g
MC_R'
MC_R
f
c
MC_P
z_R^{C}'
z_R^{N}'
z_R^C
z_R^N
z_P^C
z_P^N
z

Figure 4

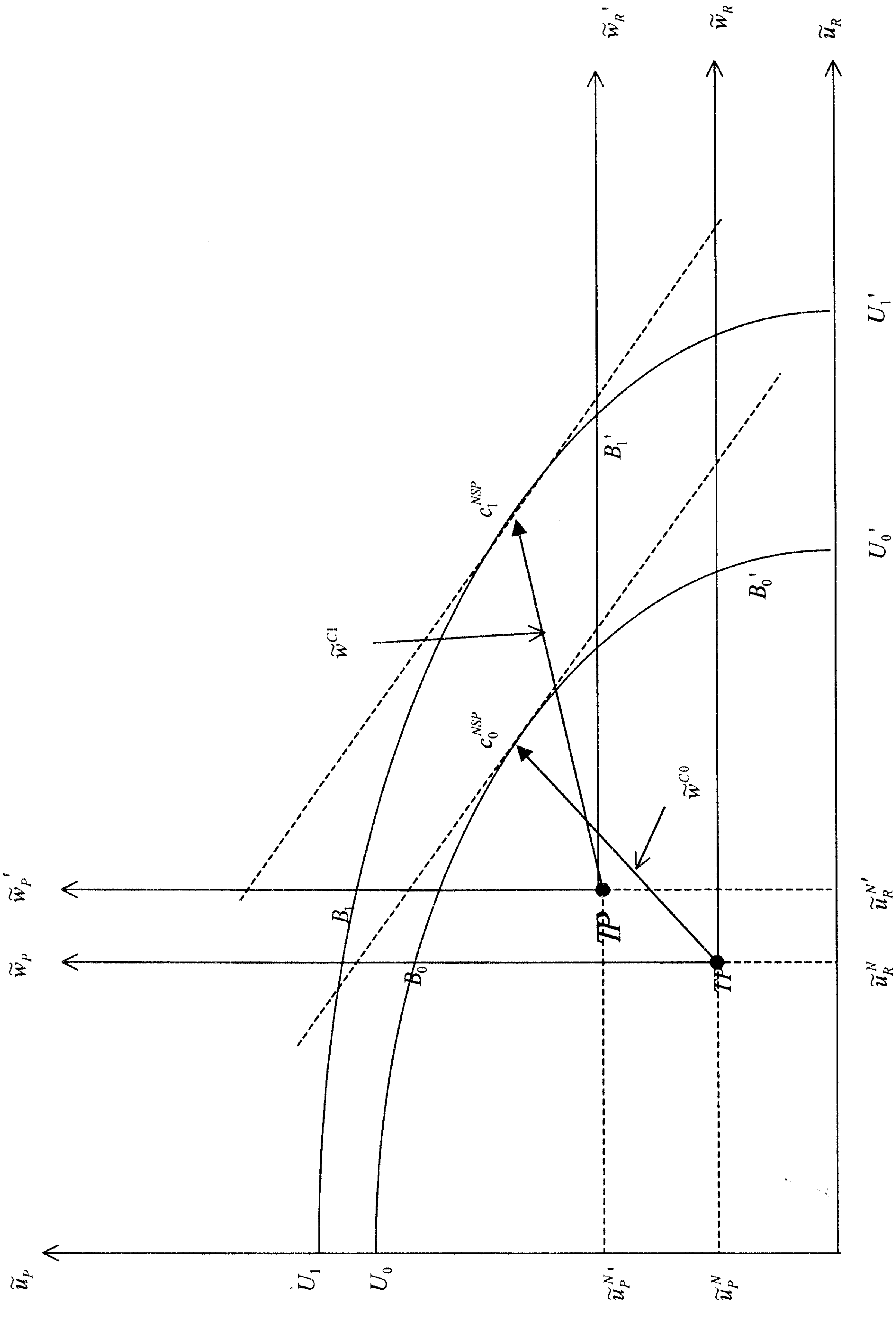
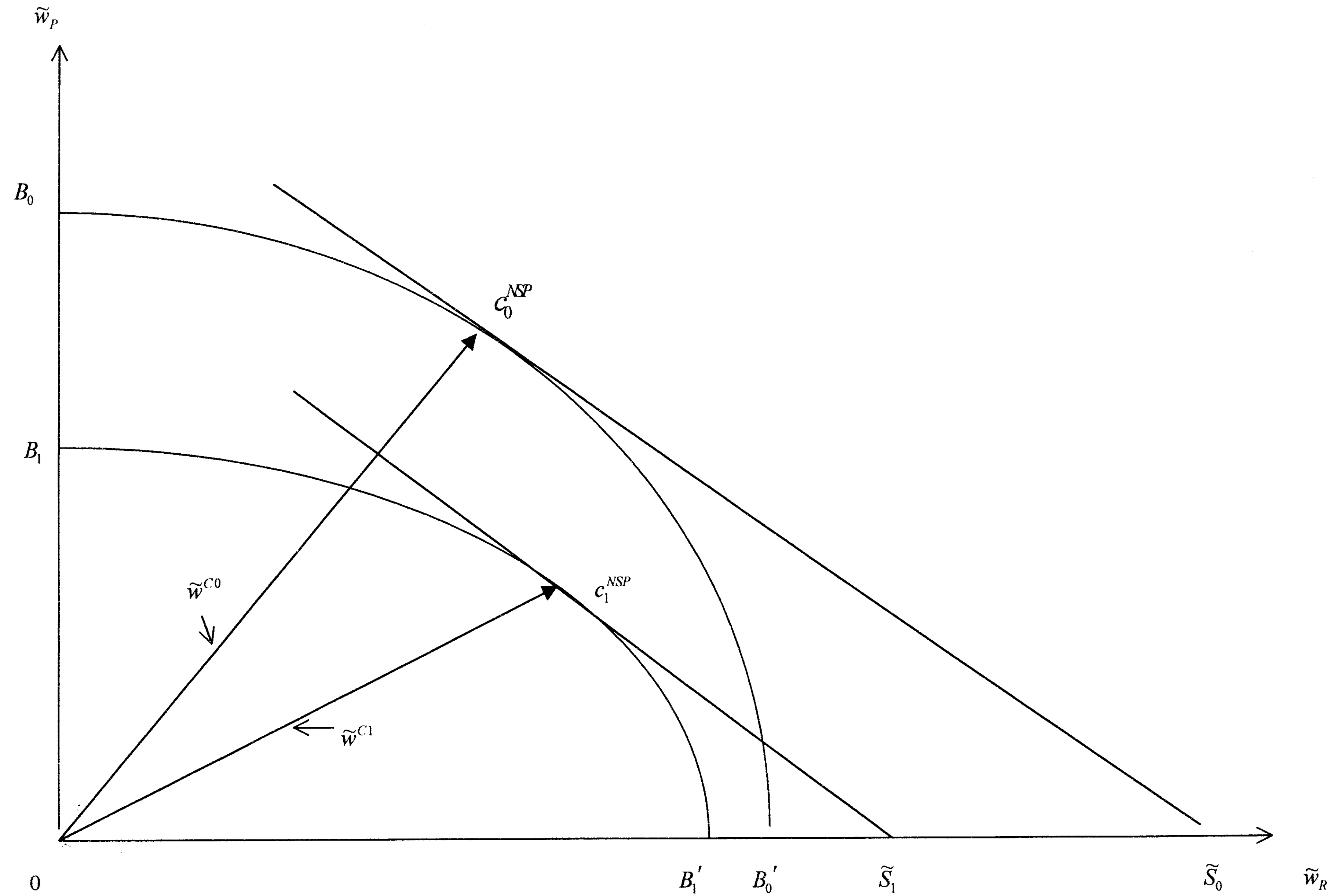
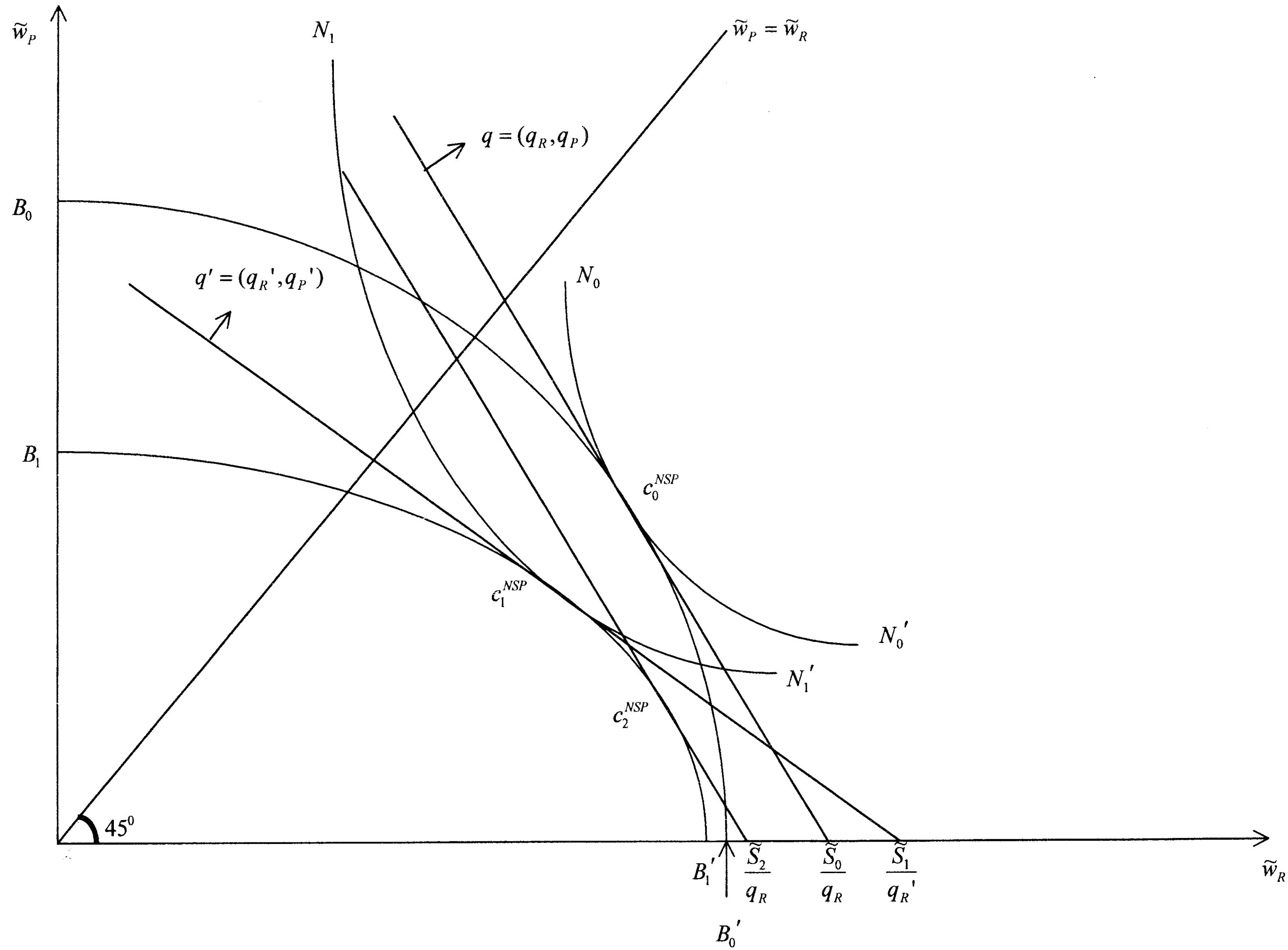


Figure 5



$\tilde{w}_P$
B_0
B_1
c_0^{NSP}
c_1^{NSP}
$\tilde{w}^{C0}$
$\tilde{w}^{C1}$
0
B_1'
B_0'
$\tilde{S}_1$
$\tilde{S}_0$
$\tilde{w}_R$

Figure 6



$\tilde{w}_P$
N_1
$\tilde{w}_P = \tilde{w}_R$
$q = (q_R, q_P)$
B_0
$q' = (q_R', q_P')$
N_0
B_1
c_0^{NSP}
c_1^{NSP}
N_0'
N_1'
c_2^{NSP}
45^0
B_1'
$\frac{\tilde{S}_2}{q_R}$
$\frac{\tilde{S}_0}{q_R}$
$\frac{\tilde{S}_1}{q_R'}$
$\tilde{w}_R$
B_0'

Figure 7

APPENDICES

Appendix to Section 2:

Substituting (2-1)' and (2-7) into (2-12),

$$\text{(A2-1)} \quad z_i^{FB}(\overline{\alpha},\beta,\gamma) = -\frac{\ln\sum_\ell \beta_\ell}{\alpha_i^w(\overline{\alpha},\beta,\gamma)}.$$

Substituting (A2-1) into (2-13),

$$\text{(A2-2)} \quad \frac{\left(1-\ln\sum_\ell \beta_\ell\right)\sum_\ell \beta_\ell}{\left\{\alpha_i^{FB}(\overline{\alpha},\beta,\gamma)\right\}^2} - \gamma_i(\varepsilon+1)\left\{\alpha_i^{FB}(\overline{\alpha},\beta,\gamma)-\overline{\alpha}_i\right\}^\varepsilon = 0.$$

Appendix to Section 3:

In view of (3-1) and (2-1)', the country *i*'s equilibrium level of pollution in the *ex post* game, denoted by z_i^N, is conveniently expressed as:

$$\text{(A3-1)} \quad z_i^N(\alpha,\beta) = -\frac{\ln\beta_i}{\alpha_i},$$

which is larger than the first best level because (A3-1) does not take into account of the other country's evaluation of pollution. The associated level of the final good production, denoted by y_i^N, is:

$$\text{(A3-2)} \quad y_i^N(\alpha,\beta) = 1-\frac{\beta_i}{\alpha_i},$$

which is non-negative by virtue of Assumption 1 and Assumption 2. In view of (A3-1), it readily follows that:

$$\text{(A3-3)} \quad \frac{\partial z_i^N}{\partial \alpha_i} = -\frac{z_i^N}{\alpha_i} < 0.$$

Consider the world total pollution at the *ex post* non-cooperative equilibrium, denoted by $Z^N(\alpha,\beta)$. By virtue of (A3-1), (A3-4) $$Z^N(\alpha,\beta) = -\sum_i \frac{\ln \beta_i}{\alpha_i}.$$

Next, denote the *ex post* non-cooperative equilibrium gross welfare of country i by:

(A3-5) $$\tilde{u}_i^N(\alpha,\beta) = y_i^N(\alpha,\beta) - \beta_i Z^N(\alpha,\beta).$$

It follows directly from (A3-5),

(A3-6) $$\frac{\partial \tilde{u}_i^N}{\partial \alpha_i} = \frac{\beta_i}{(\alpha_i)^2}\left(1 + \alpha_i z_i^N(\alpha,\beta)\right) > 0,$$

(A3-7) $$\frac{\partial \tilde{u}_j^N}{\partial \alpha_i} = \frac{\beta_j}{\alpha_i} z_i^N > 0.$$

(A3-8) $$\frac{\partial \tilde{u}_j^N}{\partial \beta_i} = -Z_i^N(\alpha,\beta) < 0,$$

(A3-9) $$\frac{\partial \tilde{u}_j^N}{\partial \beta_j} = \frac{\beta_j}{\alpha_i \beta_i} > 0.$$

Note that the first order condition for the *ex ante* optimization, (3-5), can be rewritten as:

(A3-10) $$\frac{\beta_i(1-\ln\beta_i)}{\left(\alpha_i^N(\overline{\alpha},\beta,\gamma)\right)^2} = (1+\varepsilon)\gamma_i\left(\alpha_i^N(\overline{\alpha},\beta,\gamma) - \overline{\alpha}_i\right)^{\varepsilon}.$$

Comparing (A3-10) with (A2-2), the following property is immediate:

(A3-11) $\alpha_i^{FB}(\overline{\alpha},\beta,\gamma) > \alpha_i^N(\overline{\alpha},\beta,\gamma)$ for all $i = 1,2$ and all $(\overline{\alpha},\beta,\gamma)$,

in view of Assumption 1 and the property that $f(x) = (1-\ln x)x > 0$ for all x with $0 < x \le 1$.

The comparative statics of *ex post* non-cooperative equilibrium, $\alpha_i^N(\overline{\alpha},\beta,\gamma)$[1], can be found by straight derivation as:

(A3-12) $$\frac{\partial \alpha_i^N}{\partial \overline{\alpha}_i} = -\varepsilon(1+\varepsilon)\gamma_i(\alpha_i^N - \overline{\alpha}_i)^{\varepsilon-1}/\Delta > 0,$$

(A3-13) $$\frac{\partial \alpha_i^N}{\partial \beta_i} = -z_i^N/\alpha_i^N\Delta > 0, \text{ and}$$

(A3-14) $$\frac{\partial \alpha_i^N}{\partial \gamma_i} = (1+\varepsilon)\left(\alpha_i^N - \overline{\alpha}_i\right)^{\varepsilon}/\Delta < 0,$$

where $\Delta \equiv \dfrac{\partial^2 u_i}{\partial \alpha_i^2} = -2\beta_i\left(1+\alpha_i^N z_i^N\right)/\left(\alpha_i^N\right)^3 - \varepsilon(1+\varepsilon)\gamma_i\left(\alpha_i^N - \overline{\alpha}_i\right)^{\varepsilon-1} < 0.$

Denote the country *i*'s *ex ante* non-cooperative equilibrium welfare by:

(A3-15) $$u_i^N(\overline{\alpha}_i,\beta_i,\gamma_i) = \widetilde{u}_i^N\left(\alpha_i^N(\overline{\alpha},\beta,\gamma),\beta_i\right) - \gamma_i\left(\alpha_i^N(\overline{\alpha},\beta,\gamma) - \overline{\alpha}_i\right)^{\varepsilon+1}.$$

Using the envelope theorem, the following results are also immediate.

(A3-16) $$\frac{\partial u_i^N}{\partial \overline{\alpha}_i} = (1+\varepsilon)\gamma_i(\alpha_i^N - \overline{\alpha}_i)^{\varepsilon} > 0,$$

(A3-17) $$\frac{\partial u_i^N}{\partial \beta_i} = -Z^N\left(\alpha^N,\beta\right) < 0,$$

(A3-18) $$\frac{\partial u_i^N}{\partial \gamma_i} = -\left(\alpha_i^N - \overline{\alpha}_i\right)^{1+\varepsilon} < 0,$$

(A3-19) $$\frac{\partial u_i^N}{\partial \overline{\alpha}_j} = -\beta_i\frac{\partial z_j^N}{\partial \alpha_j}\cdot\frac{\partial \alpha_j^N}{\partial \overline{\alpha}_j} > 0,$$

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[1] We have already noted that $\alpha_i^N(\overline{\alpha},\beta,\gamma)$ is actually independet of $\overline{\alpha}_j$, β_j and γ_j.

(A3-20) $$\frac{\partial u_i^N}{\partial \beta_j} = -\beta_i\left(\frac{\partial z_j^N}{\partial \beta_j} + \frac{\partial z_j^N}{\partial \alpha_j}\cdot\frac{\partial \alpha_j^N}{\partial \beta_j}\right) > 0, \text{ and}$$

(A3-21) $$\frac{\partial u_i^N}{\partial \gamma_j} = -\beta_j\frac{\partial z_j^N}{\partial \alpha_j}\cdot\frac{\partial \alpha_j^N}{\partial \gamma_j} < 0.$$

Appendix to Section 4:

Given β and q, define $\hat{\beta}_i(t;q) = \beta_i + t\frac{q_j}{q_i}\beta_j = \beta_i\left(1 + tQ_i^j\right)$ for $t \in [0,1]$ where $Q_i^j = \frac{q_j\beta_j}{q_i\beta_i}$. Let

(A4-1) $$\hat{z}_i(\alpha,\beta,q;t) = \arg\max_z\left\{f(z_i,\alpha_i) - \hat{\beta}_i(t;q)z_i\right\},$$

and $\hat{y}_i(\alpha,\beta,q,t) = f\left(\hat{z}_i(\alpha,\beta,q,t),\alpha_i\right)$. In view of the definition of $\hat{\beta}_i(t;q)$, (3-1) and (4-3), for all (α,β,q);

(A4-2) $$\hat{z}_i(\alpha,\beta,q,t) = -\frac{1}{\alpha_i}\ln\hat{\beta}_i(t;q), \text{ and}$$

(A4-3) $$\hat{y}_i(\alpha,\beta,q,t) = 1 - \frac{\hat{\beta}_i(t;q)}{\alpha_i}.$$

By the definition, clearly, the following equations should hold.

(A4-4) $$z_i^N(\alpha,\beta) = \hat{z}_i(\alpha,\beta,q;0) \text{ and}$$

(A4-5) $$z_i^C(q;\alpha,\beta) = \hat{z}_i(\alpha,\beta,q,1).$$

The difference between these two pollution levels will generate the difference in the bargaining surplus for country i, $\widetilde{w}_i^C(q;\alpha,\beta) = \widetilde{u}_i^C(q;\alpha,\beta) - \widetilde{u}_i^N(\alpha,\beta)$. In order to analyze its property, we define the following auxiliary function for $t \in [0,1]$,

(A4-6) $$\hat{u}_i(\alpha,\beta,q,t) = \hat{y}_i\left(\alpha,\beta,q,t\right) - \beta_i\hat{Z}(\alpha,\beta,q,t),$$

where $\hat{Z}(\alpha,\beta,q,t)=\sum_i \hat{z}_i(\alpha,\beta,q,t)$. That is, $\hat{u}_i(\alpha,\beta,q,t)$ is the level of utility country i will enjoy at the non-cooperative equilibrium if both countries choose actions so as to take $\beta_i(t;q)$ as its marginal valuation for the global environment, but evaluate the outcome according to its true marginal valuation, β_i. Given (A4-6), we readily obtain:

(A4-7) $\hat{w}_i(\alpha,\beta,q,t)=\hat{u}_i(\alpha,\beta,q,t)-\tilde{u}_i^N(\alpha,\beta)$.

Clearly, $\hat{w}_i(\alpha,\beta,q,1)=\tilde{w}_i^C(q;\alpha,\beta)$ and $\hat{w}_i(\alpha,\beta,q,0)=0$. In view of (A4-2)-(A4-3), it then follows that:

(A4-8)
$$\begin{aligned}\tilde{w}_i^C(q;\alpha,\beta) &= \int_0^1 \frac{\partial \hat{w}_i(\alpha,\beta,q,t)}{\partial t}dt = \hat{u}_i(\alpha,\beta,q,1)-\hat{u}_i(\alpha,\beta,q,0)\\ &= -\frac{\beta_i}{\alpha_i}Q_i^j+\frac{\beta_i}{\alpha_i}\ln\left(1+Q_i^j\right)+\frac{\beta_i}{\alpha_j}\ln\left(1+Q_j^i\right).\end{aligned}$$

That is, the welfare change induced by a change in t consists of three effects. Output change, change in value of global environment caused by the own change in pollution, the similar change caused by the other country's pollution. The first two would offset had the country evaluate the environment by the marginal valuation of $\hat{\beta}_i(t;q)=\beta_i\left(1+Q_i^j\right)$, because the pollution is controlled optimally for this valuation. However, the country values it smaller at β_i, and the difference appears negatively in the first term of the RHS of (A4-8). Second term of the RHS of (A4-8) is the benefit accrued from the improved pollution from the other country. Because sum of two countries' welfare must always improve as t increases, (A4-8) is positive for at least one country. However, it is possible that one country may become worse off by an increase of t.

A straightforward computation then yields;

(A4-9) $$\frac{\partial \tilde{w}_i^C(q;\alpha,\beta)}{\partial q_i}>0 \text{ and } \frac{\partial \tilde{w}_i^C(q;\alpha,\beta)}{\partial q_j}<0.$$

It follows immediately that the before-bargaining UPF and BPF are both convex towards the origin, as stated in the text. Further, (A4-10) $$\frac{\partial \widetilde{w}_i^C(q;\alpha,\beta)}{\partial \alpha_i} = \frac{\beta_i}{(\alpha_i)^2}\left[Q_i^j - \ln\left(1+Q_i^j\right)\right] > 0,$$

(A4-11) $$\frac{\partial \widetilde{w}_i^C(q;\alpha,\beta)}{\partial \alpha_j} = -\frac{\beta_i}{(\alpha_j)^2}\ln\left(1+Q_j^i\right) < 0,$$

(A4-12) $$\frac{\partial \widetilde{w}_i^C(q;\alpha,\beta)}{\partial \beta_i} = \frac{1}{\alpha_i}\left[\ln\left(1+Q_i^j\right) - \frac{Q_i^j}{1+Q_i^j}\right] + \frac{1}{\alpha_j}\left[\ln\left(1+Q_j^i\right) + \frac{Q_j^i}{1+Q_j^i}\right] \gtrless 0,$$

(A4-13) $$\frac{\partial \widetilde{w}_i^C(q;\alpha,\beta)}{\partial \beta_j} = -\frac{\beta_i}{\alpha_i\beta_j}\frac{(Q_i^j)^2}{1+Q_i^j} - \frac{\beta_i}{\alpha_j\beta_j}\frac{Q_j^i}{1+Q_j^i} < 0,$$

where (A4-10) is positive because $x > \ln(1+x)$ for any $x > 0$. Noting $\widetilde{S}(\cdot) = q_i\widetilde{w}_i^S + q_j\widetilde{w}_j^S$, it follows that:

(A4-14) $$\frac{\partial \widetilde{S}(q;\alpha,\beta)}{\partial \alpha_i} = \frac{q_i\beta_i}{(\alpha_i)^2}\left[Q_i^j - \left(1+Q_i^j\right)\ln\left(1+Q_i^j\right)\right] < 0,$$

(A4-15) $$\frac{\partial \widetilde{S}(q;\alpha,\beta)}{\partial \beta_i} = \frac{q_i}{\alpha_i}\left[\ln\left((1+Q_i^j\right)-1\right] + \frac{q_i}{\alpha_j}\ln\left(1+Q_j^i\right) \gtrless 0.$$

Negativity of (A4-14) is shown by letting $f(x) = x - (1+x)\ln(1+x)$. Defining $y = 1+x$ and $g(y) = y\left(1 - \ln y - \frac{1}{y}\right) = f(x)$, it readily follows that $g(1) = 0$ and $g'(y) = -\ln y < 0$ for all $y > 1$. It then follows that $g(y) < 0$ for all $y > 1$ or, equivalently, $f(x) < 0$ for all $x > 0$.

The effect of a country's *ex post* efficiency in pollution control on the Nash bargaining surplus can now be shown as follows:

(A4-16) $$\frac{\partial^2 \widetilde{S}(q;\alpha,\beta)}{\partial(\alpha_i)^2} = -\frac{2q_i\beta_i}{(\alpha_i)^3}\left[Q_i^j - \ln\left(1+Q_i^j\right)\right] < 0,$$

(A4-17) $$\frac{\partial^2 \widetilde{S}(q;\alpha,\beta)}{\partial\alpha_i \partial\alpha_j} = 0,$$

(A4-18) $$\frac{\partial^2 \widetilde{S}(q;\alpha,\beta)}{\partial\alpha_i \partial\beta_i} = \frac{q_i}{(\alpha_i)^2}\left[Q_i^j - \ln\left(1+Q_i^j\right)\right] > 0,$$

(A4-19) $$\frac{\partial^2 \widetilde{S}(q;\alpha,\beta)}{\partial\alpha_i \partial\beta_j} = -\frac{q_j}{(\alpha_i)^2}\ln\left(1+Q_i^j\right) < 0.$$

Appendix to Section 5:

Let

(A5-1) $$\alpha_i^{SP}(\overline{\alpha},\beta,\gamma) = \arg\max_{\alpha_i}\left\{\widetilde{u}_i^N(\alpha,\beta) + \tfrac{1}{2}\widetilde{S}(1;\alpha,\beta) - C(\alpha_i,\overline{\alpha}_i,\gamma_i)\right\}.$$

The first order condition for this maximization problem is:

(A5-1) $$\begin{aligned}\frac{\partial u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial\alpha_i} &= \frac{\partial\widetilde{u}_i^N(\alpha,\beta)}{\partial\alpha_i} + \tfrac{1}{2}\frac{\partial\widetilde{S}(1;\alpha,\beta)}{\partial\alpha_i} - \frac{\partial C(\alpha_i,\overline{\alpha}_i,\gamma_i)}{\partial\alpha_i} \\ &= \frac{\partial u_i^N}{\partial\alpha_i} + \tfrac{1}{2}\frac{\partial\widetilde{S}(1;\alpha,\beta)}{\partial\alpha_i} = 0.\end{aligned}$$

In view of (A3-2), (A3-6) and (A4-17), (A5-1) is independent of α_j $(j \neq i)$, and α_i^{SP} is shown to be independent of α_j $(j \neq i)$ as is claimed in Proposition 6(a). In view of (3-5), (A4-14), and concavity of u_i^{SP} in α_i,

(A5-2) $\alpha_i^{SP}(\overline{\alpha},\beta,\gamma) < \alpha_i^N(\overline{\alpha},\beta,\gamma)$ for all $(\overline{\alpha},\beta,\gamma)$,

as is claimed in Proposition 6(b).

The following relationship are also immediate in view of (A3-2), (A3-6) and (A4-16)-(A4-19).

(A5-3) $$\frac{\partial^2 u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial(\alpha_i)^2} < 0,$$

(A5-4) $$\frac{\partial^2 u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial \alpha_i \partial \overline{\alpha}_i} = -\frac{\partial^2 C(\alpha_i,\overline{\alpha}_i,\gamma_i)}{\partial \alpha_i \partial \overline{\alpha}_i} > 0$$

(A5-5) $$\frac{\partial^2 u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial \alpha_i \partial \overline{\alpha}_j} = 0,$$

(A5-6) $$\frac{\partial^2 u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial \alpha_i \partial \beta_i} = \frac{\partial^2 \widetilde{u}_i^N(\alpha,\beta)}{\partial \alpha_i \partial \beta_i} + \tfrac{1}{2}\frac{\partial^2 \widetilde{S}(1;\alpha,\beta)}{\partial \alpha_i \partial \beta_i} > 0,$$

because $\frac{\partial^2 \widetilde{u}_i^N(\alpha,\beta)}{\partial \alpha_i \partial \beta_i} = \frac{\alpha_i z_i^N}{(\alpha_i)^2} > 0$, and

(A5-7) $$\frac{\partial^2 u_i^{SP}(\alpha,\beta;\overline{\alpha})}{\partial \alpha_i \partial \beta_j} = \tfrac{1}{2}\frac{\partial^2 \widetilde{S}(1;\alpha,\beta)}{\partial \alpha_i \partial \beta_j} < 0.$$

It then follows immediately that:

(A5-8) $$\frac{\partial \alpha_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \overline{\alpha}_i} = -\frac{\partial^2 u_i^{SP} / \partial \alpha_i \partial \overline{\alpha}_i}{\partial^2 u_i^{SP} / \partial (\alpha_i)^2} > 0,$$

(A5-9) $$\frac{\partial \alpha_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \overline{\alpha}_j} = 0,$$

(A5-10) $$\frac{\partial \alpha_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \beta_i} = -\frac{\partial^2 u_i^{SP} / \partial \alpha_i \partial \beta_i}{\partial^2 u_i^{SP} / \partial (\alpha_i)^2} > 0,$$

(A5-11) $$\frac{\partial \alpha_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \beta_j} = -\frac{\partial^2 u_i^{SP} / \partial \alpha_i \partial \beta_j}{\partial^2 u_i^{SP} / \partial (\alpha_i)^2} < 0.$$

Combining (A3-14)-(A3-19), (A4-14)-(A4-15), and (A5-8)-(A5-11) with (A5-1), we readily obtain the following results:

(A5-12) $$\frac{\partial u_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \overline{\alpha}_i} = \frac{\partial u_i^N}{\partial \overline{\alpha}_i} + \tfrac{1}{2}\sum_{\ell=1,2}\frac{\partial \widetilde{S}}{\partial \alpha_\ell}\frac{\partial \alpha_\ell^{SP}}{\partial \overline{\alpha}_i} \gtrless 0,$$

(A5-13) $$\frac{\partial u_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \overline{\alpha}_j} = \frac{\partial u_i^N}{\partial \overline{\alpha}_j} + \tfrac{1}{2}\sum_{\ell=1,2}\frac{\partial \widetilde{S}}{\partial \alpha_\ell}\frac{\partial \alpha_\ell^{SP}}{\partial \overline{\alpha}_j} \gtrless 0,$$

(A5-14) $$\frac{\partial u_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \beta_i} = \frac{\partial u_i^N}{\partial \beta_i} + \tfrac{1}{2}\sum\nolimits_{\ell=1,2} \frac{\partial \widetilde{S}}{\partial \alpha_\ell} \frac{\partial \alpha_\ell^{SP}}{\partial \beta_i} \gtrless 0,$$

(A5-15) $$\frac{\partial u_i^{SP}(\overline{\alpha},\beta,\gamma)}{\partial \beta_j} = \frac{\partial u_i^N}{\partial \beta_j} + \tfrac{1}{2}\sum\nolimits_{\ell=1,2} \frac{\partial \widetilde{S}}{\partial \alpha_\ell} \frac{\partial \alpha_\ell^{SP}}{\partial \beta_j} \gtrless 0.$$