Optimal Control of Acid Rain in Japan and China: A Game-Theoretic Analysis

Yoko Nagase
Department of Economics, Colgate University
Emilson C. D. Silva
Department of Economics, Tulane University

The International Centre for the Study of East Asian Development, Kitakyushu

Optimal Control of Acid Rain in Japan and China: A Game-Theoretic Analysis

By

Yoko Nagase

Department of Economics, Colgate University, Hamilton, NY 13346-1389 USA.
Tel: (315) 228-7541; Fax: (315) 228-7033; E-mail: ynagase@mail.colgate.edu

And

Emilson C. D. Silva

Department of Economics, Tulane University, New Orleans, LA 70118-5698 USA.
Tel: (504) 862-8354; Fax: (504) 865-5869; E-mail: emilson@tulane.edu

March 29, 2001

Abstract: Chinese sulfur dioxide emissions cause acid rain in China and in Japan. The China-Japan acid rain problem is an interesting case of unidirectional transboundary pollution which has received little attention in the economics literature. We construct a simple model to highlight the key incentives underlying environmental policy making in each country. We examine simultaneous and sequential noncooperative games to illustrate the shortcomings of decentralized policy making. Sequentiality seems to be important, since one may interpret China's disposition against limiting its sulfur dioxide emissions as a sign of policy leadership vis-à-vis Japan. Motivated by the inefficiency of decentralized behavior, we design international schemes under which an international agency (IA) is in charge of implementing income transfers from Japan to China. Participation in each scheme is voluntary. We show that the proposed international schemes are Pareto efficient and implementable. We also show that policy leadership play no role in the allocation of resources when the IA is a common follower.

1. Introduction

In both China and Japan, acid rain is a serious and growing problem. Acid rain occurs when acidic pollutants, sulfur dioxide (SO_2) and nitrogen oxide (NO_x), precipitate in the form of rain, snow, hail or fog and the pH level of the precipitation is below 5.6 – the average acidity of "pure" rain. Acid rain affects human life in a variety of ways. Acidification of ground water and soil hampers the growth of forests and agricultural crops and it is life threatening to several animal species. At a pH level of 6.0 or below, freshwater shrimp cannot survive. At a pH level of 5.5, bottom-dwelling bacterial decomposers begin to die, causing non-decomposed leaf litter and other organic debris to lay on the bottom and depriving plankton of food supply. At a pH level of 4.5 or below, all fish and most frogs and insects die. Acid rain also damages buildings and historical monuments, leads to the release of harmful chemicals, such as aluminum, from rocks and soils into drinking water sources, and corrodes lead and copper piping.

Acid rain in China is mostly caused by emissions of sulfur dioxide by power plants. According to Sinton (1996), coal combustion is responsible for 94% of all sulfur dioxide emissions, power plants are the largest contributors and less than a half a dozen of China's hundreds of power plants utilizes desulfurization technology. Because stack heights are usually very high, however, power plants' emissions contribute more to regional than to local acid rain (Sinton et al. (2000)). Furthermore, sulfur dioxide emissions are rising due to the continued growth in energy consumption. Figure 1 illustrates the upward trend in annual sulfur emissions from 1985 to 1995. While the annual figure for 1985 was below 15 million tons, the annual figure for 1995 was near 20 million tons – a growth rate of 33% in ten years! However, the downward trend in emissions of particulates from industrial processes,
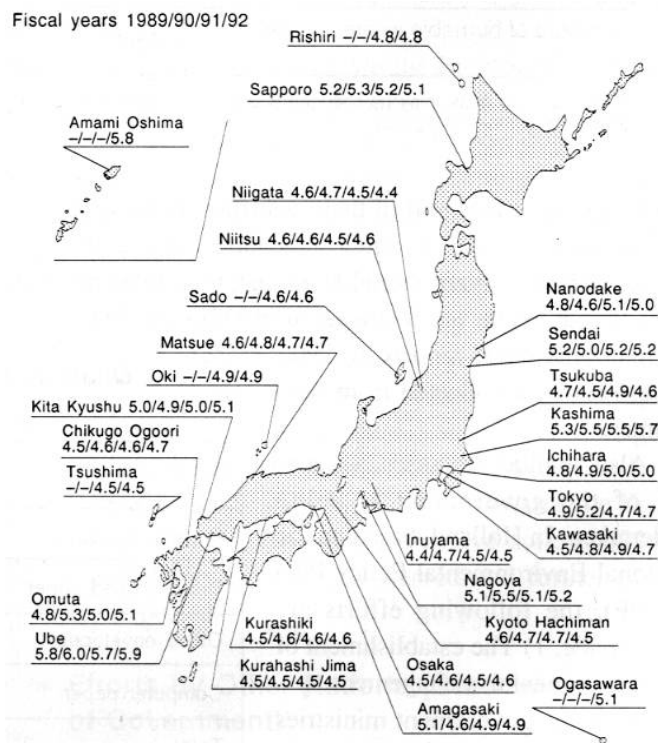
Figure 1. Sulfur Dioxide and Particulate Emissions in China*
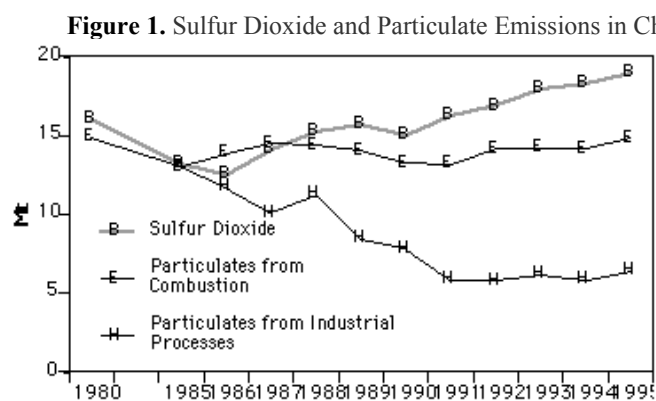
*Figures exclude rural industry, but do include estimates for the household sector.

Source: See Sinton (1996).

1

which are large contributors to urban air pollution, is notable. This pattern is largely due to effective governmental regulations on particulates' emissions (Sinton (1996), Sinton et al. (2000)). Domestic damages caused by sulfur dioxide emissions in China are substantial and comparable to damages suffered by severely acidified regions in North America and Europe. For example, estimates show that air pollution causes near 4,000 deaths per year in Chongqing and Beijing (Dasgupta et al. (1997)). Most of the damages are concentrated in four provinces, Guangdong, Guangxi, Guizhou, and Sichuan. The total annual damages in these provinces in the latter half of the 1980s were estimated to be US$ 2 billion (Sinton (1996)).

Japan is also seriously afflicted by acid rain. As Figure 2 clearly demonstrates, the Western Japanese regions are relatively more affected by acid rain than the Eastern regions. The reported pH level of rain in 1992 was 4.6 or below in Niigata, Niitsu, Sado, Tsushima, Kurashiki, Kurahashi Jima, Osaka, Kyoto, Inuyama and Tsukuba.

Figure 2: Rain pH level in Japan (The Second Survey for Acid Rain Measures)

Fiscal years 1989/90/91/92

Rishiri –/–/4.8/4.8
Sapporo 5.2/5.3/5.2/5.1
Amami Oshima –/–/–/5.8
Niigata 4.6/4.7/4.5/4.4
Niitsu 4.6/4.6/4.5/4.6
Sado –/–/4.6/4.6
Matsue 4.6/4.8/4.7/4.7
Oki –/–/4.9/4.9
Kita Kyushu 5.0/4.9/5.0/5.1
Chikugo Ogoori 4.5/4.6/4.6/4.7
Tsushima –/–/4.5/4.5
Nanodake 4.8/4.6/5.1/5.0
Sendai 5.2/5.0/5.2/5.2
Tsukuba 4.7/4.5/4.9/4.6
Kashima 5.3/5.5/5.5/5.7
Ichihara 4.8/4.9/5.0/5.0
Tokyo 4.9/5.2/4.7/4.7
Kawasaki 4.5/4.8/4.9/4.7
Inuyama 4.4/4.7/4.5/4.5
Nagoya 5.1/5.5/5.1/5.2
Omuta 4.8/5.3/5.0/5.1
Ube 5.8/6.0/5.7/5.9
Kurashiki 4.5/4.6/4.6/4.6
Kurahashi Jima 4.5/4.5/4.5/4.5
Kyoto Hachiman 4.6/4.7/4.7/4.5
Osaka 4.5/4.6/4.5/4.6
Ogasawara –/–/–/5.1
Amagasaki 5.1/4.6/4.9/4.9

Source: Japan's Environment Agency

However, Figure 2 also makes it clear that acid rain is ubiquitous in Japan. Only in Ube the pH level of rains was consistently above 5.6 in the four-year period 1989-1992. As in China, the damages caused by acid rain are believed

to be comparable to damages caused to severely acidified regions in North America and Europe, amounting to billions of dollars. In Tokushima, for example, rains with a pH level no greater than 4.4 led to the destruction of trees and corrosion of several bridges and statues.

Climate scientists agree that emissions of sulfur dioxide in Northeastern China contribute to sulfur depositions in Western Japan. Ichikawa and Fujita (1995), for example, estimate that China's contributions to wet sulfate deposition in Japan represent 50% of the total. The transboundary pollution problem will likely become more serious in the near future because energy consumption levels in Beijing, Tianjin and Shanghai, major industrial cities in Northeastern China, have been growing very rapidly and Chinese energy supplies come mostly from coal-burning power plants. Japanese damages originating with Chinese-produced acid rain may in fact reach catastrophic levels by 2020. The Regional Air Pollution Information System for Asia (RAINS-ASIA) model predicts that, under business-as-usual conditions, Chinese energy consumption in the Northeastern region will reach in the year 2020 a level that is three times higher than its 1990 level (Streets (1997)).

Both China and Japan appear to have been following air pollution control strategies that best fit their current concerns about domestic and international environmental degradation. To date, the measures adopted by the Chinese government to control air pollution have been geared towards reducing domestic damages caused by sulfur dioxide and particulate emissions, with special emphasis placed on reducing air pollution damages in large urban areas. With the exception of a few desulfurization projects at power plants (see some examples in Table 1), sulfur dioxide emissions have not been controlled at all (Sinton et al. (2000)). China has also been reluctant to enter in any international agreement that limits its emissions of acidic pollutants (Sinton (1996)). Japan, on the other hand, has aggressively controlled its own emissions of acidic pollutants over the last 30 years. Laws and regulations to control air pollution were first enacted in the 1960s. Taxes on sulfur emissions were introduced in 1973, national standards regulating quantities of sulfur dioxide emissions were put in practice in 1974 and by 1975 investment in pollution abatement technology accounted for 18% of total investment in Japan (Committee on Japan's Experience in the Battle against Air Pollution (1996)). In addition, perhaps due to its unfavorable downwind geographic position, Japan has also been one of the world leaders in international development of desulfurization technology. Table 1 gives us a measure of Japan's participation in the development of desulfurization technology in China.

Table 1. Japanese Desulfurization Technology in China

3

Location	Facility	Demonstrated Technology	Status
Chongqing, Sichuan	Luohuang Power Plant (2 x 360 MW)	wet lime injection (Mitsubishi)	In operation since 1991
Qingdao, Shandong	Huangdao Power Plant	Semi-dry lime injection	In operation
Taiyuan, Shanxi	Taiyi Power Plant	simplified wet lime injection	In operation
Chengdu, Sichuan	power plant	electrostatic removal	under construction
Weifang, Shandong	industrial boiler	Unknown	In operation
Chongqing, Sichuan	industrial boiler	Unknown	In operation
Nanning, Guangxi	industrial boiler	Unknown	In operation

Source: See Sinton (1996).

The pattern we have observed to date regarding Chinese and Japanese acid rain control strategies may have been the result of a strategic game played by both countries. It is not clear, however, whether China or Japan has played the role of policy leader in this game. China's well known disposition against controlling sulfur dioxide emissions may, in fact, represent a policy leadership position vis-à-vis other Asian countries, in particular Japan. On the other hand, some observers may interpret Japan's long-standing contributions to air pollution abatement production in China as a signal of policy commitment and hence policy leadership in the setting of environmental policy. To clearly understand the current state of affairs, it is, therefore, imperative that we study strategic policy games under which one country is the policy leader. The equilibrium strategies of leader-follower policy games will surely shed some light on the current behaviors displayed by China and Japan. These games will also enable us to predict how these countries will behave in international schemes designed to "solve" domestic and international acid rain problems.

To our knowledge, our game theoretic analysis of the China-Japan acid rain problem is a primer. We examine environmental policy making in China and Japan under two policy settings, fully decentralized and partially decentralized. In the fully decentralized policy setting, each country decides on its own the environmental policy agenda that it will follow. There is no policy coordination or interference from any type of supranational organization. In the partially decentralized setting, however, we include an international agency (IA) whose sole objective is to implement redistributive income transfers from Japan to China. We envision an agency mirrored after the Global Environment Facility (GEF) and consisting of a mix of Chinese and Japanese officials. To facilitate comparisons, we assume that the policy instruments controlled by each country are the same as in the fully decentralized setting. Although they retain control over the same policy instruments, China and Japan behave differently in this new policy setting. Their choices of environmental policy agendas are affected by the way the IA responds to their actions.

4

In the fully decentralized setting, we examine three games, a Cournot-Nash (simultaneous) policy game and two Stackelberg (leader-follower) policy games. China's strategies are the domestic quantities produced of sulfur emissions and pollution abatement. Japan's strategies are the quantity of pollution abatement imported from China as well as the domestic quantities produced of sulfur dioxide emissions and pollution abatement. We show that in the Cournot-Nash equilibrium both countries determine their environmental policy agendas in order to optimally address their domestic needs. Japan decides to import pollution abatement from China rather than producing it at home because China's product is much cheaper and Japan's localized benefit (i.e., reduced damage) associated with pollution abatement in China is substantial. When Japan is the policy leader, it decides against importation of pollution abatement from China. Japan does this in order to induce China to increase its pollution abatement expenditure (and hence domestic provision). Japan anticipates that China will cutback its domestic provision of pollution abatement at a one-to-one rate with the Japanese-financed pollution abatement production in China. China's pollution abatement provision is, however, independent of Japan's domestic pollution abatement provision due to the unidirectional character of the transboundary pollution. Hence, Japan opts for providing pollution abatement at home rather than importing it from China. Finally, when China is the policy leader, it commits to an environmental policy agenda of no intervention. It neither reduces sulfur dioxide emissions nor expends resources in the production of pollution abatement. China anticipates that such a commitment will induce Japan to finance pollution abatement enterprises in China and that the level of Japanese-financed pollution abatement production in China will suffice to address the Chinese acid rain problems! Given China's commitment, Japan's best course of action is indeed, as in the simultaneous Cournot-Nash game, to import pollution abatement from China rather than producing it at home. However, the quantity of pollution abatement imported by Japan in this sequential-policy scenario is larger than in the simultaneous-policy scenario.

In keeping with the fully decentralized setting, we consider three international schemes in the partially decentralized policy setting. These three international schemes share one characteristic in common, namely, the IA implements its policy after it observes both the Chinese and Japanese environmental policy agendas. In game theoretic terminology, the IA is a common follower. In the first international scheme, both countries choose their environmental policies simultaneously in anticipation of the IA's policy responses. This is a two-stage game whereby the countries play a Cournot-Nash game in the first stage and the IA determines its policy in the second stage. The remaining two

5

international schemes are represented by three-stage games. Japan is the policy leader in one game and China is the policy leader in the other. We find that each game has a Pareto efficient subgame perfect equilibrium and that the allocation of resources implied by each equilibrium corresponds to each other. Because the equilibria allocations are isomorphic, there is no "first-mover advantage" in policy setting! This result stands in deep contrast with our results for the fully decentralized policy setting, since in that setting the equilibrium allocation of resources is sensitive to the identity of the policy-leader country. In the fully decentralized policy setting, there is a clear first-mover advantage.

The two desirable implications of the equilibria allocations in the partially decentralized policy setting – namely, efficiency and inexistence of first-mover advantage – make our proposed international schemes especially attractive to policy makers interested in crafting a mutually advantageous and efficient international agreement between China and Japan. Our analysis, however, demonstrates that such an effective and efficient international agreement is possible only if there is an international agency responsible for making mutually satisfactory redistributive income transfers from Japan to China – i.e., transfers that induce China to undergo adjustments necessary for efficiently controlling its sulfur dioxide emissions and are acceptable from Japan's perspective.

This paper is organized as follows. Section 2 describes the basic theoretical model. Section 3 examines the three games under fully decentralized policy making. Section 4 derives Pareto efficient allocations and demonstrates that the fully decentralized allocations examined in section 3 are inefficient. The inefficiency of the fully decentralized allocations motivates our design of individually rational and efficient international schemes in section 5. Section 6 concludes.

2. The Basic Model

Imagine an economy consisting of two nations, indexed by j, j = 1,2, and two politically autonomous national governments. There are two private goods, x and y. Good x is a numéraire and good y is >electricity=. We assume that each nation possesses a single power plant. Production of electricity generates sulfur dioxide, which is emitted in the atmosphere. For simplicity, the relationship between electricity generation and emission of sulfur dioxide is taken to be one to one, that is, if the power plant in nation j produces Y_j units of electricity, it also produces Y_j units of sulfur dioxide. Power plants, however, can use a clean up technology to abate their emissions of sulfur dioxide. If the power plant in nation j produces Y_j units of electricity and reduces its emission of sulfur dioxide by Z_j units, the level of sulfur dioxide which is emitted in the atmosphere – denoted E_j – is simply $Y_j - Z_j$. Power plants can produce electricity and pollution abatement up to capacity levels Y_0 and Z_0, respectively. We shall assume that these capacity levels are sufficiently high so that they are never reached in the equilibria studied in this paper. This assumption allows us to omit the capacity constraints in the analysis that follows, since they are never binding.

Emission of sulfur dioxide in each nation is subsequently transformed into acid rain. The level of acid rain that precipitates in nation j shall be denoted D_j. The national acid rain levels are defined as follows:

$$D_1 \equiv hE_1 \equiv h(Y_1 - Z_1), \tag{1a}$$

$$D_2 \equiv (1-h)E_1 + E_2 \equiv (1-h)(Y_1 - Z_1) + Y_2 - Z_2. \tag{1b}$$

Identity (1a) tells us that of the level of sulfur dioxide emitted in nation 1 a fraction h becomes acid rain in this nation while a fraction $(1-h)$ becomes acid rain in nation 2. Identity (1b) shows that no fraction of the level of sulfur dioxide emitted in region 2 is transported to region 1. Hence, in what follows, nation 1 will be called "China" and nation 2 will be called "Japan."

The fixed populations of China and Japan are, respectively, n_1 and n_2. Within each nation, we assume that the residents are identical. An individual who resides in nation j derives the following utility from consumption of x_j units of the numéraire good, y_j units of electricity and D_j units of acid rain:

$$U(x_j, y_j, D_j) = u(x_j + f(y_j) - v(D_j)) \tag{2}$$

where we assume that u and f are strictly increasing and concave and v is increasing and strictly convex. For

tractability reasons, we model the utility functions as (strict) concave transformations of quasilinear functions. Linearity in the numéraire good and separability in the three goods enable us to sign all partial derivatives in the comparative statics analyses below. These partial derivatives are response functions, which will illustrate how the economic agents react to changes in environmental policy variables.

The numéraire good is used for consumption and as an input in the production of electricity and pollution abatement in each nation. The power plant in nation j can produce Y_j units of electricity and Z_j units of pollution abatement at a total cost of

$$K_j + p_j Y_j + s_j Z_j$$

where $K_j > 0$ is a fixed cost, $p_j > 0$ is the cost per unit of electricity produced and $s_j > 0$ is the cost per unit of pollution abatement produced. Henceforth, we assume that the nations do not trade quantities of electricity or the numéraire good with each other and that, in equilibrium, nation j=s electricity supply is always equal to this nation=s demand for electricity; namely, $Y_j = n_j y_j$. National government j sells electricity to its residents at marginal cost, p_j. Both fixed and domestic abatement production costs are financed with national head taxes.

As we discussed in the introduction, Japan finances production of pollution abatement in China. To account for this fact, we postulate that Japan finances a portion of the Chinese total pollution abatement expenditure. Let a_{21} represent the amount of pollution abatement produced in China with Japanese financial support. That is, this quantity represents the amount of pollution abatement that Japan imports from China. The total pollution abatement expenditure incurred by Japan in this international joint venture is thus $s_1 a_{21}$. Let a_{jj} denote the quantity of pollution abatement produced by nation j=s power plant which is financed by its own government. Hence, national government j=s domestic pollution abatement expenditure is $s_j a_{jj}$. For future reference, it is important to note that $Z_1 = a_{11} + a_{21}$ and $Z_2 = a_{22}$.

Let $I_j > 0$ denote nation j's income, which we assume is fixed. Since we also assume that all residents of nation j are identical, nation j's representative resident is endowed with I_j / n_j units of income. The budget constraint for the representative Chinese resident is

8

$$x_1 + p_1 y_1 + \frac{K_1 + s_1(a_{11} + a_{21})}{n_1} = \frac{I_1 + s_1 a_{21}}{n_1} \, .$$

The resident's total expenditure is given in the left side and his total income, including the per-capita transfer received from Japan for the importation of pollution abatement, is given in the right side. For convenience, we shall use the budget constraint to express the quantity of the numéraire good consumed as a function of the environmental policy variables:

$$x_1(y_1, a_{11}) = \frac{I_1 - K_1 - s_1 a_{11}}{n_1} - p_1 y_1 \, . \tag{3a}$$

Similarly, we use the budget constraint for the representative Japanese resident to write

$$x_2(y_2, a_{21}, a_{22}) = \frac{I_2 - K_2 - s_2 a_{22} - s_1 a_{21}}{n_2} - p_2 y_2 \, . \tag{3b}$$

The meaning for the right side of equation (3b) is similar to the meaning for the right side of equation (3a), except that the per-capita cost of importing pollution abatement from China is also subtracted from per-capita income.

3. Decentralized Simultaneous and Sequential Acid Rain Games

In this section, we examine two different types of Aacid rain games,@ simultaneous and sequential games. In analyses of transboundary pollution, it is customary to examine the (simultaneous and noncooperative) Cournot-Nash game played by the politically autonomous governments. The Cournot-Nash equilibrium illustrates the typical pitfalls involved with self-interested behavior in the presence of externalities. It also enables us to capture the effects of governmental policy commitments when we compare it with equilibria for sequential games, in which one national government makes a commitment to follow a given environmental policy prior to the other national government=s choice of environmental policy.

As we mentioned in the introduction, sequentiality seems to very important in the China-Japan acid rain problem. Some observers may interpret China's reluctance in controlling its sulfur dioxide emissions as a policy commitment. Others may argue that the Japanese-financed pollution abatement projects in China is a clear indication of policy leadership. To better understand the current state of affairs, we will study two two-stage games whereby one country is the Stackelberg policy leader and the other is the Stackelberg policy follower. In the first sequential game, Japan is the Stackelberg leader. This will characterize Japan=s commitment to an environmental policy agenda, since

by the time China chooses its own environmental policy it will do so knowing Japan=s choices of environmental policy variables. In the second sequential game, China is the Stackelberg leader. Subgame perfection is our choice of equilibrium concept for the sequential games.

3.1. The Simultaneous Cournot-Nash Game

The Chinese government chooses nonnegative quantities $\{x_1, y_1, a_{11}\}$ to maximize

$$u(x_1 + f(y_1) - v(h(n_1 y_1 - a_{11} - a_{21}))) \tag{4a}$$

subject to (3a), taking $\{x_2, y_2, a_{21}, a_{22}\}$ as given. Similarly, the Japanese government chooses nonnegative quantities $\{x_2, y_2, a_{21}, a_{22}\}$ to maximize

$$u(x_2 + f(y_2) - v((1-h)(n_1 y_1 - a_{11} - a_{21}) + n_2 y_2 - a_{22})) \tag{4b}$$

subject to (3b), taking $\{x_1, y_1, a_{11}\}$ as given.

Substituting (3a) and (3b) into objective functions (4a) and (4b), respectively, we obtain:

$$u(x_1(y_1, a_{11}) + f(y_1) - v(h(n_1 y_1 - a_{11} - a_{21}))), \tag{5a}$$

$$u(x_2(y_2, a_{21}, a_{22}) + f(y_2) - v((1-h)(n_1 y_1 - a_{11} - a_{21}) + n_2 y_2 - a_{22})). \tag{5b}$$

Hence, the Chinese government's problem becomes the choice of nonnegative quantities $\{y_1, a_{11}\}$ to maximize (5a), taking $\{y_2, a_{21}, a_{22}\}$ as given. Given $\{y_1, a_{11}\}$, the Japanese government's problem is now the choice of nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (5b).

It seems reasonable to assume that in the Cournot-Nash equilibrium both countries produce and consume positive quantities of electricity. If, in addition, we assume that both countries spend resources on pollution abatement, we may describe the Cournot-Nash equilibrium as in Proposition 1.

Proposition 1: If $y_1 > 0, y_2 > 0, a_{11} > 0, a_{21} + a_{22} > 0$ in the Cournot-Nash equilibrium, the equilibrium allocation is characterized by conditions (3a), (3b) and the following:

$$f'(y_1) = p_1 + n_1 h v'(D_1), \tag{6a}$$

$$f'(y_2) = p_2 + n_2 v'(D_2), \tag{6b}$$

$$n_1 h v'(D_1) = s_1, \tag{6c}$$

10

$$n_2(1-h)v'(D_2) - s_1 = 0 \quad \text{if} \quad a_{21} > 0, \tag{6d}$$

$$n_2 v'(D_2) - s_2 = 0 \quad \text{if} \quad a_{22} > 0. \tag{6e}$$

Proof. Optimizing (5a) with respect to y_1 and assuming that $y_1 > 0$ immediately yields (6a). Similarly, optimizing (5b) with respect to y_2 and assuming that $y_2 > 0$ immediately yields (5b). Equation (6c) follows from optimization of (5a) with respect to a_{11} and the assumption that $a_{11} > 0$. Since we assume that $a_{21} + a_{22} > 0$, then either $a_{21} > 0$ or $a_{22} > 0$. Conditions (6d) and (6e) are thus the necessary first order conditions associated with maximization of (5b) with respect to $\{a_{21}, a_{22}\}$. $\square$

Equation (6a) demonstrates that the Chinese government should regulate electricity consumption (and hence production) so that the total electricity quantity consumed is set at the level at which the (per-capita) marginal national benefit from electricity consumption – left side of (6a) – is just equal to the (per-capita) marginal national cost of electricity provision – right side of (6a). The marginal national cost of electricity provision is the sum of the marginal cost of production and the marginal national damage caused by the regional sulfur dioxide emission, the by-product of electricity production. The Chinese government may regulate electricity production with either quantity (command and control) or market-based policy instruments. It could, for example, levy an emission tax equal to the equilibrium value of the marginal national pollution damage. In what follows, we will assume that both national governments are endowed with policy instruments that enable them to regulate electricity provision. We will not, however, specify which policy instruments should be used because the choice of policy instruments is not the focus of this paper.

Equation (6b) is similar to equation (6a) and thus requires little comment. It states that it is optimal for Japan to consume electricity at the level at which its marginal benefit equals its marginal cost. The Japanese marginal national cost – right side of (6b) – is the sum of its marginal production cost and its marginal pollution damage. Equation (6c) shows that the Chinese government produces abatement at the level that equates the Chinese marginal acid rain damage to the Chinese marginal cost of abatement production. The Chinese marginal benefit from abatement production equals the marginal acid rain damage saved due to the production of an extra unit of abatement in the nation.

Equations (6d) and (6e) demonstrate to us how the Japanese government decides which levels of pollution abatement it should import from China and produce at home. It is important to note that, in general, Japan will not

11

simultaneously import pollution abatement from China and produce pollution abatement at home. Japan will typically choose the option that has the lowest effective marginal cost. Let us prove this claim. Assume, contrary to the claim, that $a_{21} > 0$ and $a_{22} > 0$ in the Cournot-Nash equilibrium. From (6d) and (6e) we obtain:

$$s_1/(I - h) = n_2 v'(D_2) = s_2 .$$

Since the marginal unit of sulfur dioxide emission saved in China reduces the damage caused to Japan by $1 - h$ units, Japan=s effective cost of the marginal unit of abatement imported from China is $s_1/(1 - h)$. Japan=s effective cost of the marginal unit of abatement produced at home is s_2. Hence, the equations above tell us that Japan will import pollution abatement from China and produce pollution abatement from China if and only if the effective marginal costs of the two options are equal. However, the effective marginal costs will generally differ. When these costs differ, Japan chooses the option with the lowest effective marginal cost. In fact, close inspection of the Chinese and Japanese data concerning abatement production costs and the transboundary component of the Japanese acid rain associated with Chinese sulfur dioxide emissions reveals that not only the marginal cost of abatement production is lower in China – Streets (1997) estimates that the marginal cost of abatement may be eight times larger in Japan – but also the fraction of the Chinese sulfur dioxide emissions exported to Japan may be significant – according to Ichikawa and Fujita (1995), 50% of the total wet sulfate deposition in Japan originates from Chinese sulfur emission sources. It seems reasonable, therefore, to postulate that

$$s_1/(1 - h) < s_2 . \tag{7}$$

Given (7), it is optimal for the Japanese government to import pollution abatement from China and produce no pollution abatement at home; that is, $a_{21} > 0$ and $a_{22} = 0.$ To prove this, assume contrary to the claim that $a_{22} > 0.$ From (6e) and (7), we have

$$n_2 v'(D_2) = s_2 > \frac{s_1}{1 - h} .$$

But, the inequality above violates condition (6d). Hence, $a_{22} > 0$ is inconsistent with $a_{21} > 0.$

In sum, adding assumption (7) to the set of assumptions employed in Proposition 1 leads us to the conclusion that the Cournot-Nash equilibrium is characterized by conditions (3a), (3b), (6a), (6b), (6c), (6d) and

$$a_{22} = 0 . \tag{8}$$

12

3.2. Multistage Game 1: Decentralized Sequential Game with Japan as the Stackelberg Leader

In this two-stage game, the Japanese government is able to commit to its environmental policy agenda prior to the Chinese government deciding its own environmental policy agenda. The Japanese government anticipates the Chinese government's policy choices and behaves accordingly. This implies that the Chinese government's policy-response functions influence the design of environmental policy in Japan. Formally, the two-stage game can described as follows:[1]

Stage 1: Japan chooses nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (5b) subject to $y_1 = y_1^1(y_2, a_{21}, a_{22})$

and $a_{11} = a_{11}^1(y_2, a_{21}, a_{22})$.

Stage 2: Given $\{y_2, a_{21}, a_{22}\}$, China chooses nonnegative quantities $\{y_1, a_{11}\}$ to maximize (5a).

Consider the second stage of the game. Assuming an interior solution, the conditions that characterize the optimal policy choices for the Chinese government are the same as in the Cournot-Nash game:

$$f'\left(y_1^1(y_2, a_{21}, a_{22})\right) = p_1 + n_1 h v'\left(h\left(n_1 y_1^1(y_2, a_{21}, a_{22}) - a_{11}^1(y_2, a_{21}, a_{22}) - a_{21}\right)\right) \tag{9a}$$

$$n_1 h v'\left(h\left(n_1 y_1^1(y_2, a_{21}, a_{22}) - a_{11}^1(y_2, a_{21}, a_{22}) - a_{21}\right)\right) = s_1 \tag{9b}$$

where, in writing the optimal conditions, we have already made use of the fact that these conditions implicitly define the Chinese policy-response functions $y_1 = y_1^1(y_2, a_{21}, a_{22})$ and $a_{11} = a_{11}^1(y_2, a_{21}, a_{22})$. A straightforward exercise in comparative statics yields:

$$\frac{\partial y_1^1}{\partial y_2} = 0 = \frac{\partial a_{11}^1}{\partial y_2}, \tag{10a}$$

$$\frac{\partial y_1^1}{\partial a_{21}} = 0, \tag{10b}$$

$$\frac{\partial a_{11}^1}{\partial a_{21}} = -1, \tag{10c}$$

$$\frac{\partial y_1^1}{\partial a_{22}} = 0 = \frac{\partial a_{11}^1}{\partial a_{22}}. \tag{10d}$$

---

[1] Superscripts in the policy-response functions refer to the number of the multistage game that is being played. Hence, the policy-response functions in this game have the superscript "1".

Equations (10a) and (10b) tell us that the Chinese policy instruments are not functions of the amounts of electricity and pollution abatement produced in Japan. These quantities do not affect China because China is located upwind from Japan and the two countries do not trade electricity with each other. Equation (10b) shows that the quantity of electricity provided in China does not vary with the amount of pollution abatement imported by Japan. This is an immediate consequence of our modeling assumptions, namely: (i) quasilinearity and separability of the utility functions; and (ii) linearity and separability of the production functions. Although these assumptions are certainly limiting to the analysis, they enable us to highlight the key incentives underlying environmental policy making in both China and Japan. These incentives will be fully captured by the decisions of both countries concerning pollution abatement strategies. Equation (10c), for instance, shows that the Chinese government will cutback its provision of pollution abatement in a one-to-one rate with the quantity of pollution abatement imported by Japan. Because the Chinese government views these two quantities as perfect substitutes, its incentives are to free ride on the Japanese contribution to pollution abatement in China!

Consider now the first stage of the game. Assuming that Japan finds it optimal to produce a positive amount of electricity as well as to either import or produce a positive amount of pollution abatement, we claim that the conditions that characterize Japan=s optimizing behavior are (6b), (6e) and

$$a_{21} = 0. \tag{11}$$

Let us prove this claim. First, note that the first order condition with respect to y_2 must be the same as in the Cournot-Nash equilibrium because the Chinese policy-response functions are not functions of y_2. Thus, we obtain equation (6b). Second, the first order (Kuhn-Tucker) condition with respect to a_{21} is as follows:

$$a_{21}\left\{-\frac{s_1}{n_2} + (1-h)v'(D_2)\left[1 + \frac{da_{11}^1}{da_{21}}\right]\right\} = a_{21}\left\{-\frac{s_1}{n_2}\right\} = 0 \Rightarrow a_{21} = 0.$$

Plugging in equation (10c) into the first equation above yields the second equation and the inevitable conclusion that Japan decides against importing pollution abatement from China. Now, to finish the proof, the first order condition with respect to a_{22} gives us equation (6e) because we assume that Japan finds it desirable to spend resources on pollution abatement.

Proposition 2 summarizes the results of this subsection.

14

Proposition 2: Assume that $y_1 > 0$, $y_2 > 0$, $a_{11} > 0$ and $a_{21} + a_{22} > 0$ in the subgame perfect equilibrium for

Multistage Game 1, whereby Japan is the Stackelberg leader and China is the Stackelberg follower. Then, the

equilibrium allocation is characterized by conditions (3a), (3b), (6a), (6b), (6c), (6e) and (11).

The remarkable feature of Proposition 2 is that Japan decides against importing pollution abatement from

China even though it is cheaper to purchase pollution abatement from China than to produce it at home. That is, the fact

that inequality (7) holds is <u>irrelevant</u> for the results of this subsection. It is easy to explain why this is the case. Japan

knows that China will cutback its pollution abatement expenditure at a one-to-one rate with the quantity of pollution

abatement imported by Japan. Japan also knows that China=s decision of how much to spend in pollution abatement

does not depend on the Japanese pollution abatement production. Since Japan benefits from China=s pollution

abatement production and since Japan=s commitment of not importing pollution abatement from China forces China

to produce pollution abatement to meet its own domestic needs, Japan=s option of producing pollution abatement at

home <u>strongly</u> dominates Japan=s option of importing pollution abatement from China.

3.3. Multistage Game 2: Decentralized Sequential Game with China as the Stackelberg Leader

For the sake of comparison, we will now examine the sequential game whereby the Chinese government is able to

commit to an environmental policy agenda prior to the Japanese government selecting its own environmental policy

agenda. The timing for this two-stage game is as follows:

Stage 1: China chooses nonnegative quantities $\{y_1, a_{11}\}$ to maximize (5a) subject to $y_2 = y_2^2(y_1, a_{11})$,

$\quad a_{21} = a_{21}^2(y_1, a_{11})$ and $a_{22} = a_{22}^2(y_1, a_{11})$.

Stage 2: Given $\{y_1, a_{11}\}$, Japan chooses nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (5b).

Consider the second stage of the game. Since Japan takes $\{y_1, a_{11}\}$ as given, it behaves as in the Cournot-Nash

game. It is thus optimal for Japan to import pollution abatement from China rather than producing it at home. Hence,

we obtain equation (8). Further, assuming that the two relevant policy variables take positive values in equilibrium, the

additional conditions that characterize Japan=s optimizing behavior are

$$f'\big(y_2^2(y_1, a_{11})\big) = p_2 + n_2 v'\big((1-h)\big(n_1 y_1 - a_{21}^2(y_1, a_{11}) - a_{11}\big) + y_2^2(y_1, a_{11})\big), \tag{12a}$$

$$n_2(1-h)v'\big((1-h)\big(n_1 y_1 - a_{21}^2(y_1, a_{11}) - a_{11}\big) + y_2^2(y_1, a_{11})\big) - s_1 = 0. \tag{12b}$$

The optimal conditions (12a) and (12b) are identical to conditions (6b) and (6d), respectively, except that they have

been written with the police-response functions, $y_2^2(y_1, a_{11})$ and $a_{21}^2(y_1, a_{11})$, already inserted into them. These

functions are implicitly defined by equations (12a) and (12b). Differentiation of equations (12a) and (12b) yields:

$$\frac{\partial y_2^2}{\partial y_1} = \frac{\partial y_2^2}{\partial a_{11}} = 0,$$ (13a)

$$\frac{\partial a_{21}^2}{\partial y_1} = n_1 > 0,$$ (13b)

$$\frac{\partial a_{21}^2}{\partial a_{11}} = -1.$$ (13c)

Equations (13a) inform us that Japan's electricity regulation is not influenced by China's environmental policy choices.

Equations (13b) and (13c), however, show that China's environmental policy choices do influence the quantity of

pollution abatement imported by Japan. From equation (13b), we know that Japan will demand more pollution

abatement from China if electricity consumption expands in China. A marginal increase in per-capita electricity

consumption in China will motivate the Japanese government to expand the quantity of pollution abatement imported

by n_1 units in order to offset the impact on Japan's acid rain level caused by the growth in electricity usage in China.

Furthermore, equation (13c) demonstrates that Japan views its quantity of pollution abatement imported from China

and China's own provision of pollution abatement as perfect substitutes. A marginal increase in China's provision of

pollution abatement leads to a marginal decrease in the quantity of pollution abatement imported by Japan of the same

magnitude.

We are now ready to examine the first stage of the game. China knows how Japan will react to its

environmental policy choices and takes this into account when it solves its maximization problem. Assuming an

interior solution for the level of electricity consumption, China=s optimal environmental policy choices are determined

by the following conditions:

$$\left\{ f'(y_1) - p_1 - h v'(D_1) \left(n_1 - \frac{\partial a_{21}^2}{\partial y_1} \right) \right\} = 0 \Rightarrow f'(y_1) = p_1,$$ (14a)

$$a_{11} \left\{ h v'(D_1) \left(1 + \frac{\partial a_{21}^2}{\partial a_{11}} \right) - \frac{s_1}{n_1} \right\} = 0 \Rightarrow a_{11} \left\{ -\frac{s_1}{n_1} \right\} = 0 \Rightarrow a_{11} = 0.$$ (14b)

The second equation in (14a) shows that the Chinese government will set the level of electricity consumption at the

16

quantity which equates the marginal national benefit to the marginal cost of electricity production. The first equation in (14a) makes it clear why this is the case: Japan responds to a marginal expansion of sulfur dioxide emission in China by increasing its quantity of pollution abatement imported from China at a level that exactly matches the increase in the Chinese sulfur dioxide emission. Hence, China's environmental damages caused by its electricity consumption are completely taken care of by Japan! Equation (14b) shows that China finds it optimal to bear no cost with pollution abatement production, since it knows that Japan will decrease its imported quantity of pollution abatement at a one-to-one rate with any quantity of pollution abatement production financed by the China.

Proposition 3 summarizes the results of this subsection.

Proposition 3: If $y_1 > 0$, $y_2 > 0$, $a_{21} > 0$ and $a_{22} > 0$ in the subgame perfect equilibrium for Multistage Game 2, whereby China is the Stackelberg leader and Japan is the Stackelberg follower, the equilibrium allocation is described by conditions (3a), (3b), (6b), (6d), (8), (14a) and (14b).

China's ability to commit to an environmental policy agenda prior to Japan determining its environmental policy agenda enables it to completely rely on Japanese-financed pollution abatement to deal with its environmental problems. Anticipating that Japan will demand more pollution abatement from China as the level of Chinese sulfur dioxide emission expands, the Chinese government has no incentive to regulate electricity consumption (or production).

This second leader-follower scenario appears to describe well the current state of affairs, since to date China has not reduced sulfur dioxide emissions and its production of sulfur dioxide abatement has been largely dependent on foreign aid or direct investment. Japan, perhaps due to its downwind geographic location, may have been unable to credibly commit to an acid rain policy that induces China to fully finance the development and implementation of desulfurization technology. The facts seem to contradict the alternative hypothesis that Japan has taken a leadership position vis-à-vis China in acid rain policy making because Japan's continual financial support of desulfurization projects in China is not consistent with a position of policy leadership. Japan's resulting equilibrium strategy in the previous sequential game is to provide no support to such projects.

4. Pareto Efficiency

For a fixed parameter $\theta \in (0,1)$, we can determine a Pareto efficient allocation by choosing nonnegative

17

$\{x_1, x_2, y_1, y_2, a_1, a_2\}$ to maximize

$$\theta u(x_1 + f(y_1) - v(D_1)) + (1-\theta)u(x_2 + f(y_2) - v(D_2)) \tag{15}$$

subject to:

$$n_1(x_1 + p_1 y_1) + n_2(x_2 + p_2 y_2) + s_1 a_{11} + s_2 a_{22} + K_1 + K_2 = I_1 + I_2, \tag{16}$$

$$D_1 = h(n_1 y_1 - a_{11} - a_{21}), \quad D_2 = (1-h)(n_1 y_1 - a_{11} - a_{21}) + n_2 y_2 - a_{22}. \tag{17}$$

By varying the parameter θ between 0 and 1, we can derive the whole Pareto frontier. Assuming an interior solution, the Pareto efficient allocation for a given θ satisfies the overall resource constraint (16) and the following conditions:

$$\frac{\theta u'(w_1)}{n_1} = \frac{(1-\theta)u'(w_2)}{n_2}, \tag{18a}$$

$$f'(y_1) = p_1 + n_1 h v'(D_1) + n_2(1-h)v'(D_2), \tag{18b}$$

$$f'(y_2) = p_2 + n_2 v'(D_2), \tag{18c}$$

$$n_1 h v'(D_1) + n_2(1-h)v'(D_2) = s_1, \tag{18d}$$

$$n_2 v'(D_2) = s_2, \tag{18e}$$

where

$$w_j \equiv x_j + f(y_j) - v(D_j).$$

Equation (18a) tells us that it is efficient to transfer income from one nation to another until the weighted national marginal utilities of income are equalized. Since per capita income in Japan is much larger than per capita income in China, we postulate throughout that income transfers will flow from Japan to China. The weights depend on the parameter θ and on the regional population sizes. A transfer of one unit of income from Japan to China, for example, costs $1/n_2$ to the representative Japanese resident and yields a benefit of $1/n_1$ to the representative Chinese resident. All else the same, the parameter θ influences the size of the overall international income transfer; the larger the value of this parameter is, the larger will be the efficient level of the income transfer that flows from Japan to China.

Equation (18b) demonstrates that the efficient level of electricity consumption in China is found from equalization of the Chinese marginal benefit from consumption of electricity and the international marginal cost of electricity production in China. This cost is the sum of the marginal production cost and the marginal pollution

damages incurred by China and Japan. Equation (18c) is similar in spirit. It states that the efficient level of electricity consumption in Japan follows from equalization of the Japanese marginal benefit from consumption and the Japanese marginal cost of production. The marginal cost is given by the sum of marginal production cost and the marginal pollution damage faced by Japan.

Equation (18d) informs us that the efficient level of pollution abatement production in China is determined by equating the international marginal benefit of pollution abatement production in China to the Chinese marginal cost of pollution abatement production. The marginal benefit of pollution abatement production is measured by the international pollution damage saved with production of pollution abatement. Equation (18e) says that in Japan the efficient level of pollution abatement production follows from equalization of the Japanese marginal benefit from pollution abatement production in Japan to the Japanese marginal production cost of pollution abatement production.

It is important to note that none of the decentralized equilibria studied in the previous section is Pareto efficient. The equilibria fail to satisfy several of the efficiency conditions, including efficiency condition (18a). The simultaneous Cournot-Nash equilibrium satisfies efficiency condition (18c) but fails to satisfy efficiency conditions (18b), (18d) and (18e) because China does not internalize the transboundary pollution caused by its sulfur dioxide emissions and because Japan finds it attractive to finance pollution abatement production in China instead of producing it at home. The subgame perfect equilibrium for the Multistage Game 1, whereby Japan is the Stackelberg leader, satisfies efficiency conditions (18c) and (18e) but does not satisfy efficiency conditions (18b) and (18d). The sole difference between this equilibrium allocation and the Cournot-Nash equilibrium is that Japan finds it desirable to produce pollution abatement at home rather than purchasing it from China. Finally, the subgame perfect equilibrium for the Multistage Game 2, where China is the Stackelberg leader, satisfies efficiency condition (18c) but fails to satisfy efficiency conditions (18b), (18d) and (18e). In this equilibrium allocation, China finds it desirable to impose no restriction in its electricity consumption and to spend no resources in pollution abatement production. It produces pollution abatement, but the cost of production is financed in its entirety by Japan.

5. Efficient International Schemes

The fact that the decentralized equilibria are inefficient motivates us to study situations whereby an International Agency (IA), presumably an agency consisting of a mix of Chinese and Japanese officials, is in charge of designing an

19

international scheme that induces voluntary participation and efficient behavior by both nations. The agency has limited political and economical powers. It is neither able to commit to policy strategies nor is endowed with environmental policy instruments. It only controls instruments to effect international transfers. In game theoretic terms, the international agency is a common Stackelberg follower, which observes the environmental policies of both countries prior to choosing the international transfer to be made.

Let t_j, $j = 1,2$, denote the income transfer received (if positive) or paid (if negative) by country j. Although we will not focus our attention on the magnitude of the income transfer that flows from Japan to China, it is straightforward to make such a computation in each of the following schemes if one wishes to do so. It is easy to construct simple but realistic numerical examples where the size of the transfer China receives from Japan depends on the mutually agreeable distribution of the gains resulting from implementation of the international scheme.

When we introduce income transfers in the model, the budget constraints for the representative Chinese and Japanese residents, equations (3a) and (3b), respectively, become:

$$x_1(y_1, a_{11}, t_1) = \frac{I_1 + t_1 - K_1 - s_1 a_{11}}{n_1} - p_1 y_1, \tag{19a}$$

$$x_2(y_2, a_{21}, a_{22}, t_2) = \frac{I_2 + t_2 - K_2 - s_2 a_{22} - s_1 a_{21}}{n_2} - p_2 y_2. \tag{19b}$$

Since the income transfers are redistributive

$$t_1 + t_2 = 0. \tag{19c}$$

For future reference, it is convenient to rewrite the utilities for the representative residents as follows:

$$u(w_1(y_1, a_{11}, a_{21}, t_1)) \equiv u(x_1(y_1, a_{11}, t_1) + f(y_1) - v(h(n_1 y_1 - a_{11} - a_{21}))), \tag{20a}$$

$$u(w_2(y_1, y_2, a_{11}, a_{21}, a_{22}, t_2)) \equiv u(x_2(y_2, a_{21}, a_{22}, t_2) + f(y_2) - v((1-h)(n_1 y_1 - a_{11} - a_{21}) + n_2 y_2 - a_{22})). \tag{20b}$$

We postulate that the IA's objective function is a weighted sum of the utilities of the representative residents:

$$\theta u(w_1(y_1, a_{11}, a_{21}, t_1)) + (1-\theta) u(w_2(y_1, y_2, a_{11}, a_{21}, a_{22}, t_2)), \tag{21}$$

where the weight, θ, is taken as given. A reasonable interpretation for the objective function (21) is that it represents the way in which the constitution of the international scheme allocates the benefits from participation. The weight given to each country's welfare may have resulted from a bargaining game played by both countries prior to the

20

ratification of the international scheme. Although such a game is undoubtedly very interesting, we will defer its analysis to future work. We assume that both countries agree that expression (21) is the IA's objective function.

We examine three different multistage games in what follows. Each game represents an international scheme whereby the IA is a common follower and its sole policy duty is to transfer income from one country to the other. The games obey the same timing of governmental policy decisions as the decentralized simultaneous and sequential policy games. In the first game, with only two stages, we investigate a scenario whereby China and Japan are both Stackelberg leaders. In the other two games, consisting of three stages, we model situations where either Japan or China is the Stackelberg leader. The timing for the first two stages of the second game correspond exactly to Multistage Game 1 and the timing for the first two stages of the third game are identical to Multistage Game 3. We show that each game has Pareto efficient subgame perfect equilibria and that the equilibrium allocations are isomorphic. Therefore, unlike our previous results, the results of this section imply that governmental policy commitments play no role in the allocation of resources.

5.1. Multistage Game 3: Efficient Scheme with China and Japan as Stackelberg Leaders

Consider a setting where China and Japan simultaneously choose their environmental policies, taking each other's choices as given, but in anticipation of the international transfer policy to be implemented by the IA. We assume that the transfer policy of the IA must not violate each country's participation constraint. This can be interpreted as one of the mandates of the constitution underlying the scheme. Formally, the game is as follows:

Stage 1: China chooses nonnegative quantities $\{y_1, a_{11}\}$ to maximize (20a) subject to $t_1 = t_1^3(y_1, y_2, a_{11}, a_{21}, a_{22})$,

taking Japan's choices as given. Japan chooses nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (20b)

subject to $t_2 = t_2^3(y_1, y_2, a_{11}, a_{21}, a_{22})$, taking China's choices as given.

Stage 2: Having observed $\{y_1, y_2, a_{11}, a_{21}, a_{22}\}$, the IA chooses $\{t_1, t_2\}$ to maximize (21) subject to: (17), (19a), (19b),

(19c) and

$$u(w_1(y_1, a_{11}, a_{21}, t_1)) \geq u_1^0, \tag{22a}$$

$$u(w_2(y_1, y_2, a_{11}, a_{21}, a_{22}, t_2)) \geq u_2^0, \tag{22b}$$

where $u_j^0, j = 1, 2,$ denotes the per capita welfare level obtained by country j in the Cournot-Nash equilibrium.

Conditions (22a) and (22b) are participation constraints. They state that each country will voluntarily participate in the

21

scheme if and only if it gets no less utility from participation than in the status quo. Since a reasonable description of the status quo in this case is the situation where the countries simultaneously choose their environmental policies, taking each other's choices as given, the relevant reservation utility levels are the payoffs received by the countries in the Cournot-Nash equilibrium.

We proceed with the working hypothesis that the participation constraints are satisfied slack in the subgame perfect equilibrium. If, as indeed we show below, the subgame perfect equilibrium is Pareto efficient, the equilibrium allocation may represent a Pareto improvement relative to the Cournot-Nash equilibrium allocation. Whether or not this is the case will essentially depend on the weight θ placed on China's welfare (and hence also on the weight $1-\theta$ placed on Japan's welfare). Since there is a range of values for the weight θ such that both countries are strictly better off if they participate in the international scheme, our working hypothesis will be satisfied in equilibrium provided the weight is properly determined.

Ignoring the participation constraints, the IA's optimal international income transfer policy satisfies:

$$\frac{\theta u'\left(w_1\left(y_1, a_{11}, a_{21}, t_1\right)\right)}{n_1} = \frac{(1-\theta) u'\left(w_2\left(y_1, y_2, a_{11}, a_{21}, a_{22}, t_2\right)\right)}{n_2} \tag{23}$$

$$t_1 + t_2 = 0 \tag{19c}$$

It is important to note that conditions (23) corresponds to equation (18a) and that condition (19c) implies equation (16) given equations (19a) and (19b). Equations (19c) and (23) implicitly define the IA's policy-response functions, $t_j^3\left(y_1, y_2, a_{11}, a_{21}, a_{22}\right)$, j = 1,2.

Let us now examine the first stage of the game. China's optimal policies are given by:

$$f'(y_1) = p_1 + n_1 h v'(D_1) - \left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^3}{\partial y_1}\right) \qquad \qquad if \quad y_1 > 0 \qquad \qquad (24a)$$

$$n_1 h v'(D_1) + \frac{\partial t_1^3}{\partial a_{11}} = s_1 \qquad \qquad if \quad a_{11} > 0 \qquad \qquad (24b)$$

Equations (24a) and (24b) clearly demonstrate that China's environmental policy depends on the IA's policy responses. We show below that, in equilibrium, the implied IA's marginal responses correspond to the marginal damage caused to Japan by Chinese sulfur emissions. Japan's optimal policies are determined by:

$$f'(y_2) = p_2 + n_2 v'(D_2) - \left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^3}{\partial y_2}\right) \qquad \qquad if \quad y_2 > 0 \qquad \qquad (25a)$$

$$n_2(1-h)v'(D_2) + \frac{\partial t_2^3}{\partial a_{21}} = s_1 \qquad \qquad if \quad a_{21} > 0 \qquad \qquad (25b)$$

$$n_2 v'(D_2) + \frac{\partial t_2^3}{\partial a_{22}} = s_2 \qquad \qquad if \quad a_{22} > 0 \qquad \qquad (25c)$$

As in China, Japan's policies depend on the IA's responses. The result below shows that the IA's marginal policy responses induce Japan to fully internalize all externalities:

Proposition 4: Suppose that $y_1 > 0$, $y_2 > 0$, $a_{22} > 0$, either $a_{11} > 0$ or $a_{21} > 0$, and constraints (22a) and (22b) are satisfied slack in a subgame perfect equilibrium for Multistage Game 3, whereby China and Japan are Stackelberg leaders and the IA is the Stackelberg follower. Then, the equilibrium allocation is Pareto efficient.

Proof. As we stated above, equations (19a), (19b) and (19c) together imply equation (16) and equation (23) is identical to equation (18a). We must now show that equations (18b), (18c), (18d) and (18e) are also satisfied by the subgame perfect equilibrium. Differentiating equations (19c) and (23) with respect to y_1 yields

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\frac{\partial t_1^3}{\partial y_1} - p_1 + f'(y_1) - n_1 h v'(D_1)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\frac{\partial t_2^3}{\partial y_1} - n_1(1-h)v'(D_2)\right)$$

$$\frac{\partial t_1^3}{\partial y_1} + \frac{\partial t_2^3}{\partial y_1} = 0 .$$

Given (24a) and the fact that $u'' \neq 0$, we obtain

$$\frac{\partial t_1^3}{\partial y_1} = -n_1 n_2 (1-h)v'(D_2) < 0 , \qquad \qquad (26a)$$

23

$$\frac{\partial t_2^3}{\partial y_1} = n_1 n_2 (1-h)v'(D_2) > 0 .$$ (26b)

Substituting equation (26b) into equation (24a) leads to equation (18b).

Differentiating equations (19c) and (23) with respect to y_2 yields

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^3}{\partial y_2}\right)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^3}{\partial y_2}\right) - p_2 + f'(y_2) - n_2 v'(D_2)\right),$$

$$\frac{\partial t_1^3}{\partial y_2} + \frac{\partial t_2^3}{\partial y_2} = 0 .$$

Given (25a) and the fact that $u'' \neq 0$, the solution to the system of equations above is given by

$$\frac{\partial t_1^3}{\partial y_2} = \frac{\partial t_2^3}{\partial y_2} = 0 .$$ (26c)

Thus, equation (25a) is identical to equation (18c).

Differentiating equations (19c) and (23) with respect to a_{11} yields

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^3}{\partial a_{11}}\right) - \frac{s_1}{n_1} + hv'(D_1)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^3}{\partial a_{11}}\right) + (1-h)v'(D_2)\right),$$

$$\frac{\partial t_1^3}{\partial a_{11}} + \frac{\partial t_2^3}{\partial a_{11}} = 0 .$$

Given (24b) and the fact that $u'' \neq 0$, the solution to the system of equations above is given by

$$\frac{\partial t_1^3}{\partial a_{11}} = n_2 (1-h)v'(D_2) > 0 ,$$ (26d)

$$\frac{\partial t_2^3}{\partial a_{11}} = -n_2 (1-h)v'(D_2) > 0 .$$ (26e)

Substituting equation (26d) into equation (24b) yields equation (18d).

Differentiating equations (19c) and (23) with respect to a_{21} leads to

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^3}{\partial a_{21}}\right) + hv'(D_1)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^3}{\partial a_{21}}\right) - \frac{s_1}{n_2} + (1-h)v'(D_2)\right),$$

$$\frac{\partial t_1^3}{\partial a_{21}} + \frac{\partial t_2^3}{\partial a_{21}} = 0 .$$

24

Given (25b) and the fact that $u'' \neq 0$, the solution to the system of equations above is as follows:

$$\frac{\partial t_1^3}{\partial a_{21}} = -n_1 hv'(D_1) < 0, \tag{26f}$$

$$\frac{\partial t_2^3}{\partial a_{21}} = n_1 hv'(D_1) > 0. \tag{26g}$$

Substituting equation (26g) into equation (25b) yields equation (18d). Since a_{11} and a_{21} are perfect substitutes, equation (18d) holds provided that at least one of these quantities is strictly positive in equilibrium.

Differentiating equations (19c) and (23) with respect to a_{22} yields

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^3}{\partial a_{22}}\right)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^3}{\partial a_{22}}\right) - \frac{s_2}{n_2} + v'(D_2)\right),$$

$$\frac{\partial t_1^3}{\partial a_{22}} + \frac{\partial t_2^3}{\partial a_{22}} = 0.$$

Given (25c) and the fact that $u'' \neq 0$, the solution to the system of equations above is given by

$$\frac{\partial t_1^3}{\partial a_{22}} = \frac{\partial t_2^3}{\partial a_{22}} = 0. \tag{26h}$$

Thus, equation (25c) is identical to equation (18e).∎

The IA's international income transfer policy is powerful enough to nullify both countries' incentives to behave inefficiently. This conclusion is immediate once one notices that the game just examined is similar to the Cournot-Nash game, except that it has an additional stage whereby an extra player (i.e., the IA) makes international income transfers after the countries choose their environmental policies. More specifically, the IA's international income transfer policy leads to changes in all aspects of China's environmental policy and in Japan's decisions of how much pollution abatement to import or produce at home. Equation (26a) informs us that the IA' response to a marginal increase in China's sulfur emission is to penalize China with a monetary cost equal to the marginal damage caused to Japan by China's emissions. The international transfer policy, therefore, forces China to fully acknowledge the full cost of electricity provision. Equation (26d), on the other hand, tells us that the IA rewards China for a marginal increase in its abatement provision with a monetary transfer equal to the marginal benefit that such a marginal expansion generates in Japan. For Japan, equation (26g) reveals that the IA rewards Japan for a marginal increase in its

25

quantity of abatement imported from China with a monetary transfer equal to the marginal benefit that such an expansion creates in China. Given the IA's rewards, both countries view the quantities of abatement produced in China as perfect substitutes – i.e., both countries use equation (18d) to determine their choices. Hence, there is a continuum of (Cournot-Nash) equilibria in the first stage of the game. It is also worth noting that Japan's choices of quantities of electricity and abatement to produce at home are not directly influenced by the IA because the conditions used by Japan to determine these quantities are efficient.

It is quite possible (and indeed likely) that both countries decide to participate in the international scheme. Prior to their participation decisions, the countries fully anticipate that there are "gains from trade": the monetary transfer that flows from Japan to China may more than fully compensate China for incurring the additional costs associated with internalization of the transboundary pollution and the effect felt by Japan from such an internalization may translate in a monetary benefit amount that is larger than the amount of income transferred. There is a range of θ values under which both countries benefit from this trade; the exact value of this parameter depends on the abilities of both players (China and Japan) in the bargaining game (not modeled). However, once an agreement is reached, we immediately obtain the IA's objective function and the scheme is fully implementable.

5.2. Multistage Game 4: Efficient Scheme with Japan as the Stackelberg Leader

We now examine a setting whereby Japan is able to commit to an environmental policy agenda prior to China. Japan, China and the IA play a three-stage game, with the timing for the first two stages being identical to the timing for Multistage Game 1. The IA determines its international income transfer policy in the third stage. Formally, the game is as follows:

Stage 1: Japan chooses nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (20b) subject to: $t_2 = t_2^4(y_1, y_2, a_{11}, a_{21}, a_{22})$,

$y_1 = y_1^4(y_2, a_{21}, a_{22})$ and $a_{11} = a_{11}^4(y_2, a_{21}, a_{22})$.

Stage 2: Given $\{y_2, a_{21}, a_{22}\}$, China chooses nonnegative quantities $\{y_1, a_{11}\}$ to maximize (20a) subject to:

$t_1 = t_1^4(y_1, y_2, a_{11}, a_{21}, a_{22})$.

Stage 3: Having observed $\{y_1, y_2, a_{11}, a_{21}, a_{22}\}$, the IA chooses $\{t_1, t_2\}$ to maximize (21) subject to: (17), (19a), (19b), (19c) and

$$u(w_1(y_1, a_{11}, a_{21}, t_1)) \geq u_1^1, \qquad (27a)$$

$$u\big(w_2\big(y_1,y_2,a_{11},a_{21},a_{22},t_2\big)\big) \geq u_2^1 , \tag{27b}$$

where u_j^1, $j=1,2,$ denotes the per capita welfare level obtained by country j in the Multistage Game 1. Conditions (27a) and (27b) are the analogues of conditions (22a) and (22b), respectively. They represent the relevant participation constraints in this game, since they require that the per capita welfare levels in equilibrium for the current game be no less than the per capita welfare levels implied by the subgame perfect equilibrium for the sequential game where Japan is the Stackelberg leader and China is the Stackelberg follower.

.   We again assume that the participation constraints are satisfied slack in equilibrium. Since the subgame perfect equilibrium for Multistage Game 1 is inefficient and we demonstrate below that a subgame perfect equilibrium for the current game is efficient, there is a range of θ values under which both countries end up strictly better off if they participate. As in the previous game, given slack participation constraints, the solution to the IA's problem is given by equations (19c) and (23). These equations implicitly define $t_j^4\big(y_1,y_2,a_{11},a_{21},a_{22}\big)$, $j=1,2$.

Consider now China's choices. Anticipating the international income transfer policy to be implemented by the IA, China's optimal quantities are determined by the following conditions:

$$f'\big(y_1\big) = p_1 + n_1 h v'\big(D_1\big) - \left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^4}{\partial y_1}\right) \qquad\qquad if \quad y_1 > 0 \tag{28a}$$

$$n_1 h v'\big(D_1\big) + \frac{\partial t_1^4}{\partial a_{11}} = s_1 \qquad\qquad if \quad a_{11} > 0 \tag{28b}$$

Because conditions (28a) and (28b) are similar to conditions (24a) and (24b) of the previous game, respectively, the incentives faced by China in this game are essentially the same. One should, therefore, expect that China will find it desirable to fully internalize the transboundary pollution. Equations (28a) and (28b) implicitly define China's policy responses, $y_1 = y_1^4\big(y_2,a_{21},a_{22}\big)$ and $a_{11} = a_{11}^4\big(y_2,a_{21},a_{22}\big)$.

Japan knows how China and the IA will respond to its policy choices. Acknowledging the responses of the other players, Japan's optimal quantities are given by

$$f'\big(y_2\big) = p_2 + n_2 v'\big(D_2\big) + \big(1-h\big)v'\big(D_2\big)\left(n_1\left(\frac{\partial y_1^4}{\partial y_2}\right) - \frac{\partial a_{11}^4}{\partial y_2}\right) - \left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^4}{\partial y_2} + \left(\frac{\partial t_2^4}{\partial y_1}\right)\left(\frac{\partial y_1^4}{\partial y_2}\right) + \left(\frac{\partial t_2^4}{\partial a_{11}}\right)\left(\frac{\partial a_{11}^4}{\partial y_2}\right)\right)$$

$$if \quad y_2 > 0 \tag{29a}$$

27

$$n_2(1-h)v'(D_2) + \frac{\partial t_2^4}{\partial a_{21}} = s_1 + n_2(1-h)v'(D_2)\left(n_1\left(\frac{\partial y_1^4}{\partial a_{21}}\right) - \frac{\partial a_{11}^4}{\partial a_{21}} - \left(\left(\frac{\partial t_2^4}{\partial y_1}\right)\left(\frac{\partial y_1^4}{\partial a_{21}}\right) + \left(\frac{\partial t_2^4}{\partial a_{11}}\right)\left(\frac{\partial a_{11}^4}{\partial a_{21}}\right)\right)\right)$$

$$\text{if} \quad a_{21} > 0 \qquad (29b)$$

$$n_2 v'(D_2) + \frac{\partial t_2^4}{\partial a_{22}} = s_2 + n_2(1-h)v'(D_2)\left(n_1\left(\frac{\partial y_1^4}{\partial a_{22}}\right) - \frac{\partial a_{11}^4}{\partial a_{22}} - \left(\left(\frac{\partial t_2^4}{\partial y_1}\right)\left(\frac{\partial y_1^4}{\partial a_{22}}\right) + \left(\frac{\partial t_2^4}{\partial a_{11}}\right)\left(\frac{\partial a_{11}^4}{\partial a_{22}}\right)\right)\right)$$

$$\text{if} \quad a_{22} > 0 \qquad (29c)$$

We start by computing the IA's marginal response functions. As in the previous game, differentiation of equations (19c) and (23) with respect to y_1 yields a system of two linear equations in two variables whose solution, given (28a) and the fact that $u'' \neq 0$, is given by

$$\frac{\partial t_1^4}{\partial y_1} = -n_1 n_2(1-h)v'(D_2) < 0, \qquad (30a)$$

$$\frac{\partial t_2^4}{\partial y_1} = n_1 n_2(1-h)v'(D_2) > 0. \qquad (30b)$$

Also as in the previous game, differentiation of equations (19c) and (23) with respect to a_{11} yields a system of two linear equations in two variables whose solution, given (28b) and the fact that $u'' \neq 0$, is as follows:

$$\frac{\partial t_1^4}{\partial a_{11}} = n_2(1-h)v'(D_2) > 0, \qquad (30c)$$

$$\frac{\partial t_2^4}{\partial a_{11}} = -n_2(1-h)v'(D_2) > 0. \qquad (30d)$$

Since the procedure to determine the remaining IA's marginal response functions is different than the one used in the previous game, we will demonstrate it in detail. Differentiating equations (19c) and (23) with respect to y_2 leads to

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^4}{\partial y_2}\right)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^4}{\partial y_2}\right) - p_2 + f'(y_2) - n_2 v'(D_2)\right),$$

$$\frac{\partial t_1^4}{\partial y_2} + \frac{\partial t_2^4}{\partial y_2} = 0.$$

The solution to this system of equations is

$$\frac{\partial t_1^4}{\partial y_2} = \frac{\left(\dfrac{(1-\theta)u''(w_2)(f'(y_2) - p_2 - n_2 v'(D_2))}{n_2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}, \tag{30e}$$

$$\frac{\partial t_2^4}{\partial y_2} = -\frac{\left(\dfrac{(1-\theta)u''(w_2)(f'(y_2) - p_2 - n_2 v'(D_2))}{n_2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}. \tag{30f}$$

Similarly, it is straightforward to show that

$$\frac{\partial t_1^4}{\partial a_{21}} = \frac{\left(\dfrac{(1-\theta)u''(w_2)(n_2(1-h)v'(D_2) - s_1)}{n_2^2}\right) - \left(\dfrac{\theta u''(w_1)(n_1 h v'(D_1))}{n_1^2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}, \tag{30g}$$

$$\frac{\partial t_2^4}{\partial a_{21}} = -\frac{\left(\dfrac{(1-\theta)u''(w_2)(n_2(1-h)v'(D_2) - s_1)}{n_2^2}\right) - \left(\dfrac{\theta u''(w_1)(n_1 h v'(D_1))}{n_1^2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}, \tag{30h}$$

$$\frac{\partial t_1^4}{\partial a_{22}} = \frac{\left(\dfrac{(1-\theta)u''(w_2)(n_2 v'(D_2) - s_2)}{n_2^2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}, \tag{30i}$$

$$\frac{\partial t_2^4}{\partial a_{22}} = -\frac{\left(\dfrac{(1-\theta)u''(w_2)(n_2 v'(D_2) - s_2)}{n_2^2}\right)}{\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) + \left(\dfrac{(1-\theta)u''(w_2)}{n_2^2}\right)}. \tag{30j}$$

Let us now determine China's marginal response functions in the second stage. First, note that by inserting equations (30a) and (30c) into equations (28a) and (28b), respectively, we obtain:

$$f'(y_1^4(y_2, a_{21}, a_{22})) = p_1 + n_1 h v'(h(n_1 y_1^4(y_2, a_{21}, a_{22}) - a_{11}^4(y_2, a_{21}, a_{22})))$$

$$+ n_2(1-h)v'((1-h)(n_1 y_1^4(y_2, a_{21}, a_{22}) - a_{11}^4(y_2, a_{21}, a_{22})) + n_2 y_2 - a_{22})$$

$$if \quad y_1 > 0 \tag{31a}$$

$$n_1 h v'(h(n_1 y_1^4(y_2, a_{21}, a_{22}) - a_{11}^4(y_2, a_{21}, a_{22}))) + n_2(1-h)v'((1-h)(n_1 y_1^4(y_2, a_{21}, a_{22}) - a_{11}^4(y_2, a_{21}, a_{22})) + n_2 y_2 - a_{22}) = s_1$$

29

$$\text{if} \quad a_{11} > 0 \qquad (31b)$$

Equations (31a) and (31b) are identical to equations (18b) and (18d), respectively, except that we have already inserted China's policy response functions into them. A straightforward exercise in comparative statics yields the following results:

$$\frac{\partial y_1^4}{\partial y_2} = \frac{\partial y_1^4}{\partial a_{21}} = \frac{\partial y_1^4}{\partial a_{22}} = 0, \qquad (32a)$$

$$\frac{\partial a_{11}^4}{\partial y_2} = \frac{n_2^2 (1-h) v''(D_2)}{h(n_1 h v''(D_1) + n_2 (1-h) v''(D_2))} > 0, \qquad (32b)$$

$$\frac{\partial a_{11}^4}{\partial a_{21}} = -1, \qquad (32c)$$

$$\frac{\partial a_{11}^4}{\partial a_{22}} = -\frac{n_2 (1-h) v''(D_2)}{h(n_1 h v''(D_1) + n_2 (1-h) v''(D_2))} < 0. \qquad (32d)$$

Given equations (30d) and (32a), we may rewrite equation (29a) as follows:

$$f'(y_2) = p_2 + n_2 v'(D_2) - \left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^4}{\partial y_2}\right) \qquad \text{if} \quad y_2 > 0 \qquad (33a)$$

Substituting equation (30f) into (33a) yields the following expression after some algebra:

$$\left(\frac{\theta u''(w_1)}{n_1^2}\right)(f'(y_2) - p_2 - n_2 v'(D_2)) = 0 \qquad \text{if} \quad y_2 > 0 \qquad (33b)$$

Since $\left(\dfrac{\theta u''(w_1)}{n_1^2}\right) \neq 0$, equation (33b) implies equation (18b).

Given equations (30d) and (32a), we may rewrite equations (29b) and (29c) as follows:

$$n_2 (1-h) v'(D_2) + \frac{\partial t_2^4}{\partial a_{21}} = s_1 \qquad \text{if} \quad a_{21} > 0 \qquad (33c)$$

$$n_2 v'(D_2) + \frac{\partial t_2^4}{\partial a_{22}} = s_2 \qquad \text{if} \quad a_{22} > 0 \qquad (33d)$$

Inserting equations (30h) and (30j) into equations (33c) and (33d), respectively, yields

$$\left(\frac{\theta u''(w_1)}{n_1^2}\right)(n_1 h v'(D_1) + n_2 (1-h) v'(D_2) - s_1) = 0 \qquad \text{if} \quad a_{21} > 0 \qquad (33e)$$

30

$$\left(\frac{\theta u''(w_1)}{n_1^2} \right) \left(n_2 v'(D_2) - s_2 \right) = 0 \qquad\qquad if \quad a_{22} > 0 \qquad (33f)$$

Since $\left(\dfrac{\theta u''(w_1)}{n_1^2} \right) \neq 0$, equations (33e) and (33f) imply equations (18d) and (18e), respectively.

We may summarize the results above with the following proposition:

Proposition 5: Suppose that $y_1 > 0$, $y_2 > 0$, $a_{22} > 0$, either $a_{11} > 0$ or $a_{21} > 0$, and constraints (27a) and (27b) are satisfied slack in a subgame perfect equilibrium for Multistage Game 4, whereby Japan moves first, China moves second and the IA is the common Stackelberg follower. Then, the equilibrium allocation is Pareto efficient.

It is again the ability of the IA of transferring income from Japan to China after the countries choose their environmental policy agendas that induces both countries to behave efficiently. Given the income transfer policy, the incentives faced by both countries are exactly the same as in the previous game. As we discussed above, this conclusion is immediate in the case of China, since the equations that determine the optimal environmental policy in this country are identical to the equations that determined the optimal environmental policy in the previous game. In the case of Japan, the conclusion is not as immediate, but it goes through after some simplification of the algebraic expressions. The ability of committing to an environmental policy prior to China does not give Japan any particular advantage, since its optimal environmental policy agenda in this game is identical to Japan's environmental policy agenda in the previous game.

5.3. Multistage Game 5: Efficient Scheme with China as the Stackelberg Leader

We now reverse the order of moves for the countries by considering a game where China is the Stackelberg leader. Japan observes China's choices and chooses its environmental policy agenda. Both countries make their decisions knowing how the IA will respond. The IA observes the actions taken by the countries and determines the optimal transfer policy from its point of view. The game is as follows:

Stage 1: China chooses nonnegative quantities $\{y_1, a_{11}\}$ to maximize (20a) subject to: $t_1 = t_1^5 (y_1, y_2, a_{11}, a_{21}, a_{22})$,

$y_2 = y_2^5 (y_1, a_{11})$, $a_{21} = a_{21}^5 (y_1, a_{11})$ and $a_{22} = a_{22}^5 (y_1, a_{11})$.

Stage 2: Given $\{y_1, a_{11}\}$, Japan chooses nonnegative quantities $\{y_2, a_{21}, a_{22}\}$ to maximize (20b) subject to:

$t_1 = t_1^5 (y_1, y_2, a_{11}, a_{21}, a_{22})$.

Stage 3: Having observed $\{y_1, y_2, a_{11}, a_{21}, a_{22}\}$, the IA chooses $\{t_1, t_2\}$ to maximize (21) subject to: (17), (19a), (19b), (19c) and

$$u\big(w_1(y_1, a_{11}, a_{21}, t_1)\big) \geq u_1^2, \tag{34a}$$

$$u\big(w_2(y_1, y_2, a_{11}, a_{21}, a_{22}, t_2)\big) \geq u_2^2, \tag{34b}$$

where u_j^2, $j = 1,2$, denotes the per capita welfare level obtained by country j in the Multistage Game 2. Conditions (34a) and (34b) are participation constraints. The relevant reservation utility levels are the payoffs received by the countries in the setting where China is the Stackelberg leader and Japan is the Stackelberg follower.

As before, we proceed by assuming that in equilibrium the participation constraints are satisfied slack. Given this assumption, equations (19c) and (23) again characterize the IA's optimal international income transfer policy. These equations implicitly define the response functions, $t_j^5(y_1, y_2, a_{11}, a_{21}, a_{22})$, $j = 1,2$.

Japan anticipates the effects brought about by the IA's income transfer policy and determines its optimal environmental policy agenda accordingly. The equations that illustrate Japan's optimizing behavior are:

$$f'(y_2) = p_2 + n_2 v'(D_2) - \left(\frac{1}{n_2}\right)\left(\frac{\partial t_2^5}{\partial y_2}\right) \qquad if \quad y_2 > 0 \tag{35a}$$

$$n_2(1 - h)v'(D_2) + \frac{\partial t_2^5}{\partial a_{21}} = s_1 \qquad if \quad a_{21} > 0 \tag{35b}$$

$$n_2 v'(D_2) + \frac{\partial t_2^5}{\partial a_{22}} = s_2 \qquad if \quad a_{22} > 0 \tag{35c}$$

As one should expect, these equations are similar to the equations that characterized Japan's optimizing behavior in Multistage Game 3. Japan faces the same incentives in this scenario as in that other scenario.

Knowing how both Japan and the IA will behave, China chooses its environmental policy agenda. China's optimal choices satisfy the following equations:

$$f'(y_1) = p_1 + n_1 h v'(D_1) - \left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^5}{\partial y_1} + \left(\frac{\partial t_1^5}{\partial y_2}\right)\left(\frac{\partial y_2^5}{\partial y_1}\right) + \left(\frac{\partial t_1^5}{\partial a_{22}}\right)\left(\frac{\partial a_{22}^5}{\partial y_1}\right)\right) - \left(\left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^5}{\partial a_{21}}\right) + h v'(D_1)\right)\left(\frac{\partial a_{21}^5}{\partial y_1}\right)$$

$$if \quad y_1 > 0 \tag{36a}$$

$$n_1 h v'(D_1) + \frac{\partial t_1^5}{\partial a_{11}} = s_1 - \left(\left(\frac{\partial t_1^5}{\partial y_2} \right) \left(\frac{\partial y_2^5}{\partial a_{11}} \right) + \left(\frac{\partial t_1^5}{\partial a_{22}} \right) \left(\frac{\partial a_{22}^5}{\partial a_{11}} \right) \right) - \left(\frac{\partial t_1^5}{\partial a_{21}} + n_1 h v'(D_1) \right) \left(\frac{\partial a_{21}^5}{\partial a_{11}} \right) \qquad if \quad a_{11} > 0 \qquad (36b)$$

It is straightforward to show that conditions (35) and (36), together with equations (19c) and (23), imply the Pareto efficient conditions. It should now be clear to the reader that differentiation of equations (19c) and (23) with respect to $\{y_2, a_{21}, a_{22}\}$ gives rise to the following marginal response functions:

$$\frac{\partial t_1^5}{\partial y_2} = \frac{\partial t_2^5}{\partial y_2} = 0, \qquad (37a)$$

$$\frac{\partial t_1^5}{\partial a_{21}} = -n_1 h v'(D_1) < 0, \qquad (37b)$$

$$\frac{\partial t_2^5}{\partial a_{21}} = n_1 h v'(D_1) > 0, \qquad (37c)$$

$$\frac{\partial t_1^5}{\partial a_{22}} = \frac{\partial t_2^5}{\partial a_{22}} = 0. \qquad (37d)$$

Given equations (37a), (37c) and (37d), we may rewrite equations (35a), (35b) and (35c) as

$$f'\left(y_2^5(y_1, a_{11})\right) = p_2 + n_2 v'\left((1-h)\left(n_1 y_1 - a_{11} - a_{21}^5(y_1, a_{11})\right) + n_2 y_2^5(y_1, a_{11}) - a_{22}^5(y_1, a_{11})\right) \qquad if \quad y_2 > 0 \qquad (38a)$$

$$n_1 v'\big(h\big(n_1 y_1 - a_{11} - a_{21}^5(y_1, a_{11})\big)\big) + n_2(1-h)v'\big((1-h)\big(n_1 y_1 - a_{11} - a_{21}^5(y_1, a_{11})\big)\big) + n_2 y_2^5(y_1, a_{11}) - a_{22}^5(y_1, a_{11})\big) = s_1$$

$$if \quad a_{21} > 0 \qquad (38b)$$

$$n_2 v'\big((1-h)\big(n_1 y_1 - a_{11} - a_{21}^5(y_1, a_{11})\big)\big) + n_2 y_2^5(y_1, a_{11}) - a_{22}^5(y_1, a_{11})\big) = s_2 \qquad if \quad a_{22} > 0 \qquad (38c)$$

Equations (38a), (38b) and (38c) correspond to equations (18b), (18d) and (18e), respectively, except that Japan's policy response functions are inserted into them.

Differentiation of equations (38a), (38b) and (38c) yields the following marginal policy responses:

$$\frac{\partial y_2^5}{\partial y_1} = \frac{\partial y_2^5}{\partial a_{11}} = 0, \qquad (39a)$$

$$\frac{\partial a_{22}^5}{\partial y_1} = \frac{\partial a_{22}^5}{\partial a_{11}} = 0, \qquad (39b)$$

$$\frac{\partial a_{21}^5}{\partial y_1} = n_1, \qquad (39c)$$

$$\frac{\partial a_{21}^5}{\partial a_{11}} = -1. \qquad (39d)$$

Given equations (37b), (39a) and (39b), we may rewrite equations (36a) and (36b) as

$$f'(y_1) = p_1 + n_1 h v'(D_1) - \left(\frac{1}{n_1}\right)\left(\frac{\partial t_1^5}{\partial y_1}\right) \qquad if \quad y_1 > 0 \qquad (40a)$$

$$n_1 h v'(D_1) + \frac{\partial t_1^5}{\partial a_{11}} = s_1 \qquad if \quad a_{11} > 0 \qquad (40b)$$

Differentiating (19c) and (23) with respect to y_1 yields

$$\left(\frac{\theta u''(w_1)}{n_1}\right)\left(\left(\frac{1}{n_1}\right)\frac{\partial t_1^5}{\partial y_1} - p_1 + f'(y_1) - n_1 h v'(D_1)\right) = \left(\frac{(1-\theta)u''(w_2)}{n_2}\right)\left(\left(\frac{1}{n_2}\right)\frac{\partial t_2^5}{\partial y_1} - n_1(1-h)v'(D_2)\right)$$

$$\frac{\partial t_1^5}{\partial y_1} + \frac{\partial t_2^5}{\partial y_1} = 0.$$

Given (40a) and the fact that $u'' \neq 0$, we obtain

$$\frac{\partial t_1^5}{\partial y_1} = -n_1 n_2(1-h)v'(D_2) < 0, \qquad (41a)$$

34

$$\frac{\partial t_2^5}{\partial y_1} = n_1 n_2 (1-h) v'(D_2) > 0 . \tag{42b}$$

Substituting equation (41b) into equation (40a) implies equation (18b).

Differentiating (19c) and (23) with respect to a_{11} we obtain:

$$\left(\frac{\theta u''(w_1)}{n_1} \right) \left(\left(\frac{1}{n_1} \right) \left(\frac{\partial t_1^5}{\partial a_{11}} \right) - \frac{s_1}{n_1} + h v'(D_1) \right) = \left(\frac{(1-\theta) u''(w_2)}{n_2} \right) \left(\left(\frac{1}{n_2} \right) \left(\frac{\partial t_2^5}{\partial a_{11}} \right) + (1-h) v'(D_2) \right),$$

$$\frac{\partial t_1^5}{\partial a_{11}} + \frac{\partial t_2^5}{\partial a_{11}} = 0 .$$

Given (40b) and the fact that $u'' \neq 0$, we have

$$\frac{\partial t_1^5}{\partial a_{11}} = n_2 (1-h) v'(D_2) > 0 , \tag{41c}$$

$$\frac{\partial t_2^5}{\partial a_{11}} = -n_2 (1-h) v'(D_2) > 0 . \tag{41d}$$

Substituting equation (41c) into (40d) yields equation (18d).

The following proposition summarizes the results above:

Proposition 6: Suppose that $y_1 > 0$, $y_2 > 0$, $a_{22} > 0$, either $a_{11} > 0$ or $a_{21} > 0$, and constraints (34a) and (34b) are satisfied slack in a subgame perfect equilibrium for Multistage Game 5, whereby China moves first, Japan moves second and the IA is the common Stackelberg follower. Then, the equilibrium allocation is Pareto efficient.

The incentive effects introduced by the IA's international income transfer policy are again strong enough to nullify each nation's incentives to behave inefficiently. As in the other two international schemes examined above, a subgame perfect equilibrium allocation in the current setting induces China to internalize the transboundary pollution and Japan to correctly value the marginal benefit associated with its importation of abatement from China. Since China and Japan agree on the marginal benefits and costs associated with abatement provision in China, the two types of abatement provided by China are perfect substitutes. There is a continuum of subgame perfect equilibria. All subgame perfect equilibria that satisfy the restrictions imposed by Proposition 6, however, are Pareto efficient and result in the same distribution of welfare levels between the nations. The equilibria differ only with respect to the allocation of abatement costs and income transfers.

35

In sum, Propositions 4 - 6 tell us that, under similar restricting circumstances, the subgame perfect equilibria for Multistage Games 3 - 5 are identical to each other in the sense that they result in the same (real) allocation of resources. This conclusion may be stated as follows:

Proposition 7: Provided Propositions 4 - 6 hold, there is no "first-mover" advantage. That is, the ability of either Japan or China of committing to an environmental policy agenda does not affect the allocation of resources.

Proposition 7 is good news for policy makers who wish to find reasonable solutions to the China-Japan acid rain problem. If we are indeed correct in characterizing the current state of affairs as the scenario in which China is the policy leader, China's current leading position will certainly work in its favor in the (political) bargaining game that shall decide how the gains from the agreement should be divided between the two countries. If China continues to be the leader even after an international agreement is brokered should not cause much concern to Japan. Provided both countries agree on a mutually satisfactory rule (constitution) for the distribution of the gains, the agreement will be efficient and policy leadership will be worthless.

6. Conclusion

Acid rain is a problem of current and future concern in both China and Japan. A fraction of Japan's sulfur depositions originates from sulfur dioxide emissions in China. Since Chinese sulfur dioxide emissions are expected to escalate by a significant amount in the near future, the environmental quality of already severely acidified Chinese and Japanese regions will certainly worsen under business-as-usual conditions, perhaps reaching catastrophic levels by 2020. Effective Chinese and Japanese acid rain control strategies are desperately needed to improve current and future environmental conditions.

To date, China has not effectively controlled its own sulfur dioxide emissions. With the exception of a few foreign-financed desulfurization projects in China, there does not appear to be any governmental action in promoting sulfur abatement activities. China's current position of not interfering with the production of sulfur dioxide and not spending resources in sulfur abatement activities may represent a policy commitment vis-à-vis Japan. Perhaps due to its disadvantageous downwind geographic position, Japan appears to be unable to credibly commit to a policy of no financial support to development and implementation of desulfurization projects in China. The current state of affairs seems to be described well by a strategic leader-follower game in which China plays the role of policy leader.

The equilibrium for the game that is currently being played by China and Japan is undoubtedly inefficient.

There is scope for growth in the welfare of both countries if they agree to "trade" with each other. Not only per capita income is substantially larger in Japan than in China, but also Japan derives enormous benefits from both reduction of sulfur dioxide emissions and provision of sulfur abatement in China. Japan is surely able to compensate China for switching from its current inefficient behavior to a behavior consistent with internalization of the transboundary pollution. The needed adjustments to be carried out in the Chinese economy can be financed with Japanese funds by an international agency consisting of a mix of Chinese and Japanese officials. This agency may be mirrored after the Global Environment Facility.

If the international agency is delegated authority to transfer income from Japan to China and the income transfer policy is effected after the countries choose their environmental agendas – i.e., the international agency implements redistributive transfers, similarly to the Global Environment Facility – it is possible that both countries feel motivated to choose efficient environmental policies. The transfer policy has implicit punishments and rewards built into it. In the analysis of this paper, the marginal punishments and rewards consisted of efficient (Pigouvian) pollution taxes and subsidies.

The international agency may be restricted to follow the rules embedded in the constitution of the international agreement by the founding fathers (i.e., China and Japan). The constitution, for example, may explicitly orient the agency on how the "gains from trade" (participation) shall be divided by both countries. The rule for the division of the gains from trade will then determine the size of the income transfer to be made from Japan to China. The constitution may also have explicit safeguards that prohibit the implementation of income transfers that violate either country's participation constraint.

The drafting of the constitution will certainly depend on the abilities of China and Japan in the playing of a political bargaining game. It is likely that China will have a better bargaining position in such a game due to its current policy leadership status. The resulting constitution, emphasizing that fairness is an issue of extreme importance, may subsequently require that Japan not only finance a fraction of sulfur abatement expenditures in China but also provide (compensatory) income transfers. This noticeable increase in the degree of Japan's economic responsibilities relative to the status quo is nevertheless perfectly consistent with an increase in Japanese welfare. Furthermore, policy leadership, currently a very valuable resource, may bring little (if any at all) benefit to China after the international scheme is launched.

References

Committee on Japan's Experience in the Battle against Air Pollution (1996). *Japan's Experience in the Battle against Air Pollution: Working towards Sustainable Development*, Pollution-Related Health Damage Compensation and Prevention Association, Japan.

Dasgupta, S., Wang H., and Wheeler, D. (1997). *Surviving Success: Policy Reform and the Future of Industrial Pollution in China*. Washington, D.C.: Policy Research Department, The World Bank.

Ichikawa, Y. and Fujita, S. (1995), "An Analysis of Wet Deposition of Sulfate Using a Trajectory Model for East Asia," *Water, Air, Soil, Pollution*, 85, 192.

Sinton, J.E. (1996), "China's View of Acid Rain in Northeast Asia and Regional Cooperation Strategies for Mitigation," Energy Analysis Program, Lawrence Berkeley National Laboratory.

Sinton, J.E., Fridley, D.G., Logan, J., Yuan, G., Bangcheng W. and Qing, X. (2000), "China Energy, Environment and Climate Study: Background Issues Paper," prepared for the World Resources Institute.

Streets, D.G. (1997), "Energy and Acid Rain Projections for Northeast Asia," Nautilus of America / The Nautilus Institute.