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A Non-cooperative Game Theoretic Approach to Dust and Sand Storm in North East Asia**

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국문요약

Song and Nagaki(2007)에 나타나 있는 것과 같은 동북아지역의 황사(먼지모래폭풍:DSS) 저감을 위한 비용부담 공조체제는 참여국의 협정불이행으로 실행가능성에 문제가 제기된다. 만일 비협조적 전략이 각국에게 보다 현실적이라면, 내쉬균형이 실현가능한 비용분담 게임의 결과를 예측하게 하여줄 수 있다. 본 연구에 따르면, 연속전략게임의 경우, ADB의 황사저감사업의 비용이 각국 투자에 의해 조달된다는 가정하에 무한한 내쉬균형이 발견된다. 또한, 비연속전략은 3각형 평면으로 나타나는 연속전략의 내쉬균형의 꼭짓점으로 나타나게 되며, 공조적 게임의 결과는 무한한 균형점들을 1개의 점으로 수렴하게 된다.

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Abstract

The cooperative cost sharing scheme for Dust and Sand Storm (DSS) in North East Asia, as suggested in Song and Nagaki (2007), may not be feasible due to possible defection(s) of participating countries. If non-cooperative strategies are more plausible, Nash equilibrium can suggest possible outcomes of the cost sharing game. The result from the continuous strategy model shows that there exists an infinite number of Nash equilibrium such that the summation of investment from each country is always equal to the required budget of the ADB pilot project. It is also discussed that the discrete strategy model points to only 3 Nash equilibria in continuous strategy game outcome and the cooperative game solution may be just one of the infinite equilibria.

❙ Keywords ❙ non-cooperative game, dust and sand storm, Nash equilibrium, discrete and continuous strategies, North East Asia.

I Introduction

Like the other trans-boundary pollutions such as SOx (Song et al, 2001), Dust and Sand Storm (DSS, a.k.a. Yellow Sand) affect not only China but also neighboring countries of Korea and Japan. Noting the issue becomes serious among 3 North East Asian countries, ADB plans to launch a 10 year pilot project to fight back the desertification in China (UN, 2004; ADB, 2005). However, the interested parties are not under the same jurisdiction. This complicates the design of cooperative mechanism and makes enforcement of the project difficult. This leads to this study of non-cooperative game. That is, even a cooperative cost sharing scheme can be provided as in Song and Nagaki (2007), it is still under the questionable assumption of enforcement possibility. In other words, if an enforcement mechanism is not effective, cooperation may fail and the DSS phenomenon may worsen. That is, the fact that a cooperative cost sharing mechanism is not realized implies that an enforcement mechanism is non-existent. If it is non-existent, non-cooperative game can perform better in explaining the current DSS situation and possible breakthrough.

Another possibility is a partial participation in the project in which case a disgruntled country asks for more active cooperation from partially participating or non-participating countries. This is what is stalling the progress of the ADB's pilot DSS project. Therefore, in this study, a non-cooperative game model is developed to draw implications for the DSS project. The outcome of the model may shed light on possible strays of the project and hopefully provide a way to cooperation. The basic assumptions are as follows.

The first assumption is that a country or countries will fight back the DSS phenomena. The cost sharing game for DSS in North East Asia can be classified as a "War of Attrition." In the classical context, roommates wait until the other roommate cleans up the room. In the end, the roommate with lower tolerance level for dirty environment gives up and cleans up the room (Dixit and Skeath, 2004). The situation is comparable to the DSS problem in North East Asia in the sense that three countries suffer from DSS (piled garbage in the roommate game) and each country knows that fighting back DSS not only benefits the participating country but also non-participating, free-riding countries as well (cleaning up the room will benefit the roommate with higher tolerance level for dirty environment as well). Therefore, the three countries wait for other countries to act first just as in the roommate game but they will act in the end.

In addition, it is assumed that the ADB project will be fully financed. In the roommate game, it is assumed that one of the roommates will clean up the room (or take out the garbage). There is no consideration for partial clean-up (a roommate cleans up only a part of the room, for example) or over clean-up (remodeling or decoration). The same assumption is made in this study; if just a country or countries decides to participate, the participating country(s) will finance the whole ADB project. That is, with only a partial participation, the project can not be launched and, in that case, incentive for a partial participation disappears.

In the following, a brief literature review on DSS and DSS cost estimation and policy are provided. In the model and results, two non-cooperative game models of discrete strategy and continuous strategy are introduced along with results and their implications. The section closes after discussion on possible refinements of the multiple Nash equilibrium. Lastly in the conclusion, summarization of the major findings and implications of the study are discussed.

Ⅱ Literature Review

Meteorological studies on DSS are overwhelming since the phenomenon has become an international issue of trans-boundary pollution. Limiting the literature to DSS of North East Asia, the following studies stand out. In(2003), Ruchi(2000) and Hara et al (2004) are three major studies that report the status of DSS and transportation modeling in Korea, China and Japan. Other than these, governmental or intergovernmental reports and action plans contain valuable information on the impacts of DSS (Chu et al, 2003 Kang, 2002, Kang et al 2005; JMOE, 2004, 2005; UN, 2004). Websites also provide up-to-date information on DSS. A Chinese website, www.duststorm.com.cn provides the historical number of DSS occurrence and the website functions as a portal for DSS in North East Asia. Japanese websites, www.jma.go.jp/jp/kosa/ and www.env.go.jp/earth/dss/ provide data on DSS and reports. Korea provides on-line information on DSS at yellow.metri.re.kr. Finally, UN provides information on DSS at www.asiansandstorm.org.

The cost estimation of DSS and cooperative measures to fight back the phenomenon are recent endeavors. However, only Kang et al (2005) successfully estimate the damage cost of DSS in monetary terms. Unfortunately, reports of DSS cost are not available for Japan or China in Kang et al (2005). Instead, qualitative or limited quantitative damage costs are reported along with meteorological studies (Ruchi and Woobo, 2003). Especially, Kang et al (2005) measures the DSS cost using various methods of contingent valuation method (CVM), bottom-up approach and benefit transfer approach. The estimated yearly cost of DSS to Korea ranges from 3,847 billion Won to 7,301 billion Won. In Song and Nagaki (2007), the average cost approach (benefit transfer approach) is used to estimate the DSS damage costs for three countries, which is the approach to estimate the cost of DSS in this study for the three countries as well. Ruchi and Woobo (2003) contains some economics analysis of DSS but very limited. ADB(2005) propose a pilot project for DSS and its financial plan, even though no concrete plan to raise money for the project is discussed.

In relation to the DSS cost measurement for North East Asian countries, studies on cost sharing mechanism are harder to find. In Song and Nagaki (2007), the Shapley Value, a cooperative game solution, is used to design a project cost sharing scheme. Derivation of the payoff functions to define characteristic functions for the Shapley Value is detailed in the appendix because the same payoff functions are used in this study. The technical distinction of this study to Song and Nagaki (2007) is as follows. Even though Song and Nagaki (2007) and this study use the same payoff functions, the payoff functions are used to draw the best response functions for Nash equilibrium in this study, where as the payoff functions are used to draw the characteristic functions for Shapley Value in Song and Nagaki (2007). The Shapley Value of i represents the average marginal worth of player i to the coalitions and can be represented as the following. For details, please refer to Shubik (1991) and Roth (1988).

$$sh_i(N,v)=\sum_{\substack{K\subset N\\ \{i\}\subset K}}\frac{(|K|-1)!(N-|K|)!}{|K|!}\left[v(K)-v(K/\{i\})\right]$$

As a conclusion, Song and Nagaki (2007) suggest that China should pay 35.06% of the project cost, Japan pay 43.07%, Korea pay 21.87% when considering bargaining positions. Compared to cost sharing scheme according to benefits received (China 27.52%, Japan 52.92, Korea 19.56%), China should pay 7.54% point more, Japan pay 9.85% point less, and Korea pays 2.31% point more. However, as discussed in the introduction, this study is under optimistic assumption of enforcement possibility.

In contrast to DSS cost and cost sharing mechanism, there are many meteorological studies are done and international organizations have plans for counter-measures such as early-warning system and reforestation but very few studies mention the financial feasibility and method of financing the projects. When it comes to the cost sharing scheme of the project cost, the literature is sparser. Therefore, the focus of this study is limited to the scope of the ADB pilot project. Especially, the focus is on the division scheme of the pilot project budget, which is given exogenously out of the game model.

Ⅲ Model and Results

Discrete Strategy Game

This game model is developed as an one-shot game in the sense that the ADB pilot project is executed only once. It is possible that the ADB might launch a series of projects of this kind in the future. In that case, the model should be extended to include the dynamic aspect of the game. Also, the game is an imperfect information game in the sense that each country is not aware of other country's strategic choice. If there is any case in which the three countries closed a negotiation and cooperated for the same issue, it will be possible to guess the strategic choice in the next stage of the game. However, no such experience has been gained. Therefore, it is reasonable to construct the model as an imperfect information/simultaneous move game.

The net benefit of a participating country from the pilot project is defined as the difference between the benefit of participation and the cost of participation. The benefit of participation is defined as the difference between the cost caused by DSS when there is no project and the cost caused by DSS when there is a project; the decreased cost of DSS due to the project. The cost of DSS for China, Korea and Japan are estimated as in Song and Nagaki (2007). A schematic presentation of the cost estimations are detailed in appendix 1.

To begin with, it is assumed that decreased area of desert area due to the pilot project, A_D^{wp}, is defined as

$$A_D^{wp} = \frac{X}{\overline{C}^{unit}}, \tag{1}$$

where the constraint assumed is $X = \sum x_i$ and x_i is the investment of country i and $\overline{C}^{unit}$ is the unit cost to convert 1 km^2 of desert area into grass land so that the occurrence of DSS phenomenon decreases. X, the budget needed to execute the project, is decided exogenously and assumed to be fully financed. As a constraint, the assumption can be presented as $X = \sum x_i$. In this study, X is given by ADB(2005) and the total project budget is \$46.83 million. The objective of this study is to investigate the cost sharing strategies of three countries for the budget. Then the increased desert area with the project, A_I^{wp}, is

$$A_I^{wp} = A_I^{wop} - A_D^{wp}, \tag{2}$$

or simply,

$$a_0 - \frac{X}{b_0} = A_I^{wp} \tag{3}$$

where $a_0 = A_I^{wop}$ is the increased desert area without the project (assumed to be a constant) and the unit cost of conversion is a constant ($b_0 = \overline{C}^{unit}$) as well. Also, from Song and Nagaki (2007), the number of DSS occurrence for China, Korea and Japan are defined as functions of A_I^{wp}, O_{Ch}^{wp} (DSS occurrence in China with project) and again O_{Ch}^{wp} respectively. In explicit functional forms that provide the greatest R[1] in estimations, occurrence of DSS in China, Korea, and Japan with project can be represented as

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$$O_{Ch}^{wp} = a_1\left(A_I^{wp}\right)^3 + b_1\left(A_I^{wp}\right)^2 + c_1\left(A_I^{wp}\right) + d_1,$$
$$O_{Kor}^{wp} = a_2\left(O_{Ch}^{wp}\right)^{b_2},$$
$$O_{Jap}^{wp} = a_3 e^{b_3 O_{Ch}^{wp}}. \quad (4)$$

If we assume that unit amount of PM(Particulate Matter) per DSS occurrence for i, the total PM traveled to country i is

$$TPM_i = PM_i^{unit} \cdot O_i^{wp}. \quad (5)$$

The total annual cost(C_i^{wp}) can be obtained by multiplying the unit costs per ton of PM for i (C_i^{unit}) with the total PM to i (TPM_i) and it can be represented as

$$C_i^{wp} = C_i^{unit} TPM_i. \quad (6)$$

Then the benefit of the pilot project for China, Korea and Japan can be represented as

$$B_i = C_i^{wop} - C_i^{wp}. \quad (7)$$

Finally, the payoffs (or net benefits) can be represented as

$$\pi_i = B_i - x_i. \quad (8)$$

Table 1 shows the payoffs in this game for discrete strategy.

Table 1. Payoff Tables for the Discrete Strategy Game (million USD)

China Cooperates		Japan	
		Cooperate	Defect
Korea	Cooperate	17437, 12394, 33531	17422, 12384, 33556
	Defect	17434, 12403, 33525	17403, 12403, 33556
China Defects		Japan	
		Cooperate	Defect
Korea	Cooperate	17450, 12390, 33522	17450, 12356, 33556
	Defect	17450, 12403, 33509	0, 0, 0

To repeat, an assumption is that the pilot project can be fully financed. Details are provided in appendix 1. Following the convention, payoffs are represented in the order of China, Korea and Japan.

There are three Nash equilibria(bolded) in this game. That is, if any one country decides to participate, other two countries do not participate at all. This is the reason why this kind of international cooperation is hard to be realized; if any one country signals its intention to participate, the other countries lose incentive to participate.

Another issue is the attitude of the playing countries toward risk. As can be seen in the payoff tables, there are not much differences between two payoffs of cooperation or defection. For example, when China participates and Japan defects, Korea should compare the payoffs of two alternative strategies; cooperate or defect. In this case, the payoff for Korea is $12384 mil if Korea cooperates and $12403 mil if otherwise. The difference is only a fraction ($19 mil, about 0.15% of total payoff). This may be simply caused by estimation errors of benefit or cost of DSS. Cost of losing credential in international cooperation may be much bigger than this amount. If this risk factor is reflected in the payoff table then the result may be quite different. Trouble is that the effect of worsen reputation can not be measured easily. A Bayesian game can deal with this issue but that is not the central issue here.

Continuous Strategy Game

More explicitly and continuously than discrete strategy model, the payoffs for each country for continuous strategy game are as follows.

$$\pi_{Ch} = C_{Ch}^{wop} - PM_{Ch}^{unit} \cdot C_{Ch}^{unit}\left[a_1\left(a_0 - \frac{X}{b_0}\right)^3 + b_1\left(a_0 - \frac{X}{b_0}\right)^2 + c_1\left(a_0 - \frac{X}{b_0}\right) + d_1\right] - x_{Ch},$$
$$\pi_{Kor} = C_{Kor}^{wop} - PM_{Kor}^{unit} \cdot C_{Kor}^{unit} \cdot a_2\left(O_{Ch}^{wp}\right)^{b_2} - x_{Kor},$$
$$\pi_{Jap} = C_{Jap}^{wop} - PM_{Jap}^{unit} \cdot C_{Jap}^{unit} \cdot a_3 e^{b_3 O_{Ch}^{wp}} - x_{Jap}. \tag{9}$$

To derive the best response function for i, the payoff functions are differentiated w.r.t. x_i, which results in the same conditions below. Derivation of the best response functions is detailed in appendix 1.

$$\frac{\partial \pi_{Ch}}{\partial x_{Ch}} = 0 \Rightarrow a_0 - \frac{X}{b_0} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 12a_1k_1}}{6a_1} = a_{13}$$
$$\frac{\partial \pi_{Kor}}{\partial x_{Kor}} = 0 \Rightarrow a_0 - \frac{X}{b_0} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 12a_1k_2}}{6a_1} = a_{14}$$
$$\frac{\partial \pi_{Jap}}{\partial x_{Jap}} = 0 \Rightarrow a_0 - \frac{X}{b_0} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 12a_1k_3}}{6a_1} = a_{15} \tag{10}$$

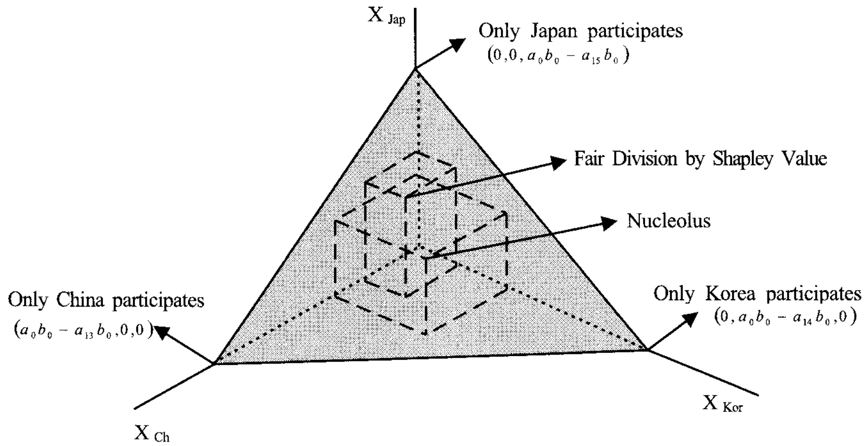
Therefore, the best response functions for i are,

$$x_{Ch} = a_0b_0 - a_{13}b_0 - x_{Kor} - x_{Jap}$$
$$x_{Kor} = a_0b_0 - a_{14}b_0 - x_{Ch} - x_{Jap}$$
$$x_{Jap} = a_0b_0 - a_{15}b_0 - x_{Kor} - x_{Ch}. \tag{11}$$

Solving the above three best response functions, it is found that $a_{13} = a_{14} = a_{15}$. Therefore, the Nash equilibrium is any combination of investments by countries that sums up to the cost of the project, $a_0b_0 - a_jb_0$, where j=13, 14, or 15.[2)] In Figure 1, the Nash equilibrium is graphically represented as a grayed triangular plane.

As can be seen in Figure 1, the Nash equilibria for the discrete strategy game are three apexes of the gray triangular plane. Also, cooperative game solutions, Shapley Value and Nucleolus in Song and Nagaki (2007) are presented to show possible equilibria for the cooperative games. In the continuous strategy game, any combination, including the three apexes, that sums up to the pilot project cost is a Nash equilibrium (thus, a plane). That is, there exist an infinite number of Nash equilibria. Question is, which point(s) will be chosen? Or can we find a focal point in this game?

Figure 1 Nash Equilibrium for DSS Cost Division Game



When there are multiple equilibria in a game, a focal point often can lead the game to a game with unique equilibrium. However, a focal point can be socio-cultural in many cases and very hard to include it into a game formally. Therefore, the following possible focal points are discussed but not included in the game. In this sense, discussion on the refinements of the Nash equilibria in this section is merely a sketch.

2) In the appendix, an additional implication of the Nash equilibrium condition is discussed. That is, at the Nash equilibrium, the marginal benefits of all three countries are equal.

Possible focal points can be the following. Japan is the richest country among three and three countries share the feeling that Japan owes Korea and China for its invasion and exploitation during the World War II. Therefore, Japan should take the full responsibility. In addition, Japanese are known to be more hygiene sensitive than Chinese and Korean and care more about environment degradation. In fact, Japan is involved in several private projects to fight back desertification and its ODA(Official Development Assistance) funds are utilized at governmental level when relatively little investments are made by Korea and China to fight back desertification in China.

Second plausible focal point may be the idea of "Polluters Pay," which is frequently used paradigm to resolve environmental conflicts. In this case, China should bear all the cost to correct the problem. The question is, "did China cause DSS to happen?" It is partly related to reckless use of land by Chinese farmers and/or global warming. Even in the case that we admit that deforestation is caused by China but the direction of wind that carries dust and sand are not Chinese responsibility. Most of all, China is an independent country and the two countries have no jurisdiction in China to directly ask for the correction of the problem.

Third possibility is that three countries share the idea of equal division of the cost. In this case, all three countries pay the same amount to finance the project. In this game, this will coincide with the nucleolus of the game as shown in Figure 1.[3] But this does not consider the asymmetric benefits to each country from the pilot project and bargaining power.

Fourth refinement idea is to share the project cost according to the ratio of the benefit each country gains. It is a very appealing idea because it sounds fair in the sense of utilitarian justice and it can be done through intuitively straight forward calculation procedure. At ministerial level talks for DSS, this may be the most plausible resolution scheme.

The last cost division scheme is to divide the cost according to the bargaining power in negotiation process as shown in Figure 1. As described in Song and Nagaki (2007), without institutional cooperation from China, financial coalition by Korea and Japan alone can not guarantee the implementation of the project. Therefore, China is the stake holder in this game and its bargaining power is greatest. Therefore, China pays relatively less amount of the cost.

3) The Nucleolus is one of the cooperative game solutions and regarded as a fair division (Friedman, 1990, p. 256). It is a center of the core and if the core does not exist, it's the "latent" position of the core (Shubik, 1991, p. 339). It becomes an equal division because the core is symmetrical in this game.

Ⅳ Conclusion and scope of further study

It is possible to extend the classical example of 'War of Attrition' in the context of this study. That is, not only the roommates clean up the room but also they decide to decorate or remodel the room for mutual benefits. In the same manner, the model in this study can be expanded to include the possibility that each country joins an international project for DSS beyond the ADB pilot project. In this case, the scope of the project is dependent on the collective budget provided. The problem in doing so is that there is no definite knowledge on how each country will behave in provision of necessary budget. This was the reason why the model in this study is limited to the ADB pilot project. In the future when more tangible contributions from concerning countries are realized, the model can be extended.

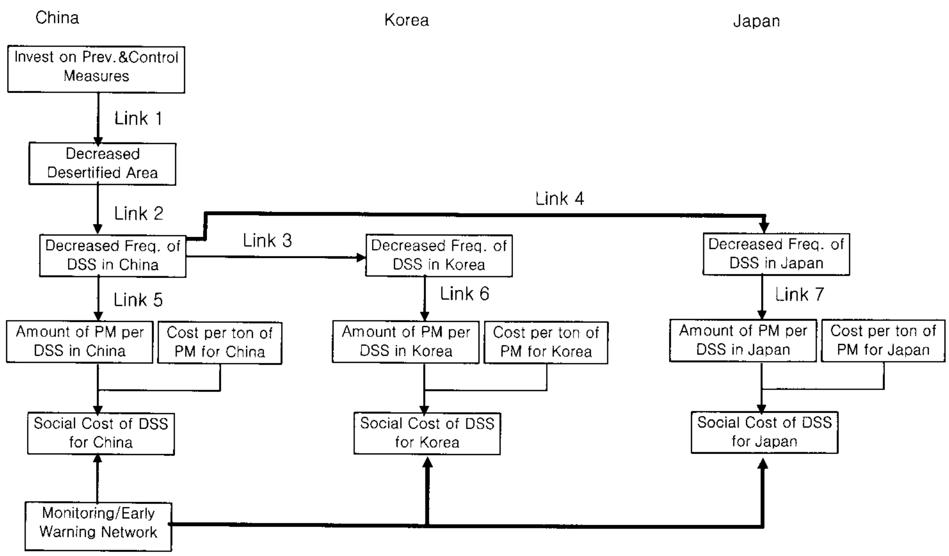
The result from the discrete strategy model implies that only one country will pay for the whole project and any country can be the paying player if we disregard history, political and/or cultural aspect. If we expand the model to continuous strategy model, the model suggests that as long as the project is financed, regardless of who pay how much, three countries will be satiated. However, as discussed, no one focal point is dominant. In other words, if there is no agreed enforcement mechanism, any Nash equilibrium can result in equilibrium. Therefore, establishing an enforcement mechanism is the key to the successive counter measures for DSS.

If an enforcement mechanism is established, a cooperative game, the Shapley Value, suggests that three countries should divide the cost in the ratio of 35% by China, 43% by Japan and 22% by Korea for the division to be fair (Song and Nagaki, 2007). Again the question is "will this normative criterion be accepted at the negotiation table?" The answer can be provided by Sen (1970); *What should happen will happen.*

Appendix 1. Detailed Description of the Model

To illustrate the model, a schematic model is reproduced from Song and Nagaki (2007) in figures A1 and A2. The figure A1 shows how investing in the pilot project would decrease the DSS cost in each country. It starts from the top－left corner of the figure. The joint investment in the project leads to decreased desert area in China (2nd box, column China), which will lead to reduced occurrence of DSS in China, and then subsequently, Korea and Japan. Then, yearly amount of PM dropped will be reduced in each country and the DSS cost will drop. The decreased DSS cost is defined as the benefit of participating in the project. Monitoring/Early Warning Network will also lessen the DSS cost in each country, but not considered in this study.

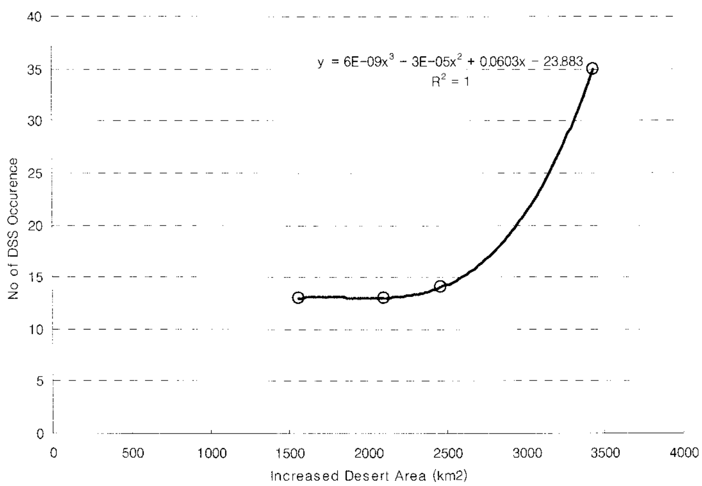
Figure A1. A Schematic Presentation of the DSS Cost Estimation Model



The first link between 'investment on prevention and control measures' and 'decreased desertificated area' can established as follows. The ADB pilot project aims to decrease the desert area by reforestation. Thus it is assumed that the ADB project works as planed. Taking the average of per hectare cost of reforestation by China and ADB, it is assumed that it cost $814 to convert 1 hectare of desert land into forest land (Song and Nagaki, 2007). The target area of the ADB pilot project sums up to 57,530 hectare with total investment of $46,833,000.

The second link is established as the following. A key assumption is that increased(or decreased) desert area is positively related with increase(or decrease) in DSS occurrence; the smaller the area gets, the less often the DSS occurs, as shown in Figure A2 (Ruchi, 2000, reproduced from Song and Nagaki, 2007). Because there are only 4 observations available in Ruchi(2000), the estimation may not be reliable. However, there is no other study that shows the relationship between the increased desert area and DSS occurrence. Given this limitation on data, the relationship is estimated and presented in the figure. It can be noted that once the increased desert area passes the threshold of 2,500 square km, DSS occurrence explodes in China, which is a recent event in 90's.

Figure A2. DSS Occurrence and Desertification Area (Song and Nagaki, 2007)



Once the second link is established, link 3 and 4 should be established. To do so, it is also assumed that higher frequency of DSS in China leads to higher DSS frequencies in Japan and Korea. However, the recording protocols of DSS occurrence are different in three countries. That is the reason why the raw data from each country's DB is not directly used in this study to establish the relationships among DSS occurrences in three countries. Also, Japanese territory is about 3 time longer than Korea and DSS moves in a stream so that the probability that DSS pass through Japan is higher (thus more DSS occurrences) than Korea, depending on the direction of the winds. This might explain why more frequent DSS is observed in Japan than Korea.

Table A1. Average Frequency of DSS (Song and Nagaki, 2007)

Period	China	Korea	Japan
1960 - 1969	8	8	18
1970 - 1979	13	7	21
1980 - 1989	14	6	18
1990 - 1999	23	9	25
2000 - 2006	32	16	40

* Source: China; UNEP, Environmental Emergencies News, Issue 4, April 2005. For the period of 2000 - 2006, 2003 data is used. Korea; Frequencies are calculated from DSS occurrence Database (date/place) from yellow.metri.re.kr/new_kor/datadb05_1.php. Japan; www.data.kishou.go.jp/obs - env/kosahp/kosa_table_1.html

Reproduced from Song and Nagaki (2007), table A1 shows that the 10 year average DSS occurrences are increasing in three countries since 80's. However, except for China, the DSS occurrences have decreased from 60's to 80's in Korea and the DSS occurrences in Japan increased from 60's to 70's, then decreased in 80's. To reflect the current trend of increasing DSS occurrences, only the data after mid 80's are used to estimate 1) the relationships between DSS occurrences in China and DSS occurrences in Korea and 2) the relationship between DSS occurrences in China and DSS occurrences in Japan. Estimated functions are presented below. The functional forms are chosen in such a way that the R^2 is greatest.

$$O_{Kor}^{wp} = 1.4427\left(O_{Ch}^{wp}\right)^{0.1097},$$
$$O_{Jap}^{wp} = 8.0191e^{0.0546 \cdot O_{Ch}^{wp}}. \qquad \text{(A1)}$$

Lastly, link 5, 6, and 7 should be established. Once the DSS occurrences in Korea and Japan as functions of DSS occurrences in China are estimated, PM per DSS occurrence in China, Korea and Japan needs to be estimated. This way, the total PM dropped in each country can be calculated and, by employing benefit transfer approach as in Kang et al (2005), the yearly cost of DSS in each country can be calculated. The levels of PM caused by DSS are different in three countries. When DSS occurs in China and travels to neighboring countries, the level of total PM decreases. Therefore, a PM transportation model needs to be developed to simulate the particle movements. As discussed in Song and Nagaki (2007), there are several such models. However, the transportation models are too algebraically complex to manage in this model. Therefore, as a second best, a simple assumption replaces the model in the study; PM(ton) per DSS occurrence is assumed to be 1 million ton in China (Song, 2002). Ratio of dust transported from Gobi desert to Beijing, Korea and Japan are assumed to be 0.1, 0.05 and 0.03 (Jung, 2006).[4] Once PM per DSS is calculated, it is multiplied by the yearly number of DSS occurrences to give the yearly total PM dropped in each country.

An observed total PM dropped in Korea in March and April of 2002 was 260,925 ton (Lee, 2004; recited from Kang et al, 2005, p103). The model used in this study simulates that a total yearly PM dropped in Korea is 364,812 ton. Considering the latter estimate is a yearly measure, the model simulates the phenomenon with an acceptable margin of error. Using the estimated yearly PM and cost per ton of PM in this model, the yearly DSS cost for Korea is 8,000 billion KW(Korean won), which is close to 7,300 billion KW in Kang et al (2005) in year 2002 for Korea, using Markandya's approach (1998). Equations (1) to (6) in the main text of this paper describe the calculation procedure. Using equation (7) and (8), columns 2, 3 and 4 in Table A2 can be calculated.

Table A2. Benefits and Project Cost (PC) Division Rule under Full/Partial Participation.

	DSS Cost w/o Project (A)	DSS Cost with Project (B)	Benefit with Project (A-B)	PC Share Ratio K-C	PC Share Ratio K-J	PC Share Ratio C-J	PC Share Ratio C-J-K
China	36,715,	19,265	17,450	0.5845		0.3421	0.2752
Japan	56,267,	22,711	33,556		0.7301	0.6579	0.5292
Korea	20,481	8,078	12,403	0.4155	0.2699		0.1956
Total	113,463	50,055	63,408	1.0000	1.0000	1.0000	1.0000

4) A simulation model of PM transportation can be used. However, there are too parameters and variables to use the simulation models in this study. Therefore, a sensitivity analysis has been executed to compensate the lack of generality. For recent developments in the dust transportation modeling, refer to Hara et al (2004) and In (2003).

As discussed, it is assumed that the ADB pilot project can be fully financed even from participation of only one country. Then the 2nd column, 'Cost w/o Project,' represents the DSS cost when there is no DSS project (a status of quo or no country participates). The 3rd column, 'Cost with Project,' represents the DSS cost when the DSS project is accomplished. The difference of these two columns is the benefit of the DSS project (4th column). Up to 4th column, it is assumed that all three countries participate (full participation). The cost sharing ratio is proportional to the benefit ratio and presented in the last column.

If any country defects (not cooperate), then partial participation can occur. If only two countries participate, it is assumed, again, that they will fully finance the project and divide the cost according to the ratio of benefits to them. The 5th column suggests the cost sharing scheme when Korea and China participate. Column 6 and 7 shows the cost sharing ratio when Korea and Japan participate (K－J) and when China and Japan participate (C－J).

Table A3. Payoffs under Various Participation Scenarios (in Million USD)

Participation Scenario	Project Cost			Project Benefit			Payoffs or Net Benefit		
	China	Japan	Korea	China	Japan	Korea	China	Japan	Korea
All participate	13	25	9	17,450	33,556	12,403	17,437	33,531	12,394
Korea	0	0	47	17,450	33,556	12,403	17,450	33,556	12,356
China	47	0	0	17,450	33,556	12,403	17,403	33,556	12,403
Japan	0	47	0	17,450	33,556	12,403	17,450	33,509	12,403
Korea－China	27	0	19	17,450	33,556	12,403	17,422	33,556	12,384
Korea－Japan	0	34	13	17,450	33,556	12,403	17,450	33,522	12,390
China－Japan	16	31	0	17,450	33,556	12,403	17,434	33,525	12,403
All Defects	0	0	0	0	0	0	0	0	0

Using table A2, table A3 can be provided to show the cost and benefit sharing schemes under 8 participation scenarios. These are the payoffs used in Table 1, the payoff table for discrete strategy game. It can be noted that the project cost is just a fraction of the benefit. This extreme benefit/cost ratio is due to the exponential decrease of DSS occurrence when the area that is proposed to be decreased by the project, as illustrated in Figure A2. When a subsequent project is launched, it is expected that the benefit will exponentially decrease.

Appendix 2. Derivation of the Best Response Functions

The payoff functions for China, Korea and Japan are defined below.

$$\begin{aligned}
\pi_{Ch} &= C_{Ch}^{wop} - PM_{Ch}^{unit} \cdot C_{Ch}^{unit}\left[a_1\left(a_0 - \frac{X}{b_0}\right)^3 + b_1\left(a_0 - \frac{X}{b_0}\right)^2 + c_1\left(a_0 - \frac{X}{b_0}\right) + d_1\right] - x_{Ch}, \\
\pi_{Kor} &= C_{Kor}^{wop} - PM_{Kor}^{unit} \cdot C_{Kor}^{unit} \cdot a_2\left(O_{Ch}^{wp}\right)^{b_2} - x_{Kor}, \\
\pi_{Jap} &= C_{Jap}^{wop} - PM_{Jap}^{unit} \cdot C_{Jap}^{unit} \cdot a_3 e^{b_3 O_{Ch}^{wp}} - x_{Jap}.
\end{aligned} \tag{A2}$$

Replacing the constants in the above equations, the following equations can be derived.

$$\begin{aligned}
\pi_{Ch} &= a_{10} - a_4 \cdot a_7\left[a_1\left(a_0 - \frac{X}{b_0}\right)^3 + b_1\left(a_0 - \frac{X}{b_0}\right)^2 + c_1\left(a_0 - \frac{X}{b_0}\right) + d_1\right] - x_{Ch}, \\
\pi_{Kor} &= a_{11} - a_5 \cdot a_8 \cdot a_2\left(O_{Ch}^{wp}\right)^{b_2} - x_{Kor}, \\
\pi_{Jap} &= a_{12} - a_6 \cdot a_9 \cdot a_3 e^{b_3 O_{Ch}^{wp}} - x_{Jap}.
\end{aligned} \tag{A3}$$

Then response functions for country i can be derived by differentiating the above payoff function by x_i and setting it to zero. Therefore, the best response for China should satisfy the following. Using Chain rule,

$$\frac{\partial \pi_{Ch}}{\partial\left(a_0 - \frac{X}{b_0}\right)} \cdot \frac{\partial\left(a_0 - \frac{X}{b_0}\right)}{\partial X} \cdot \frac{\partial X}{\partial x_{Ch}} = -a_4 \cdot a_7\left[3a_1\left(a_0 - \frac{X}{b_0}\right)^2 + 2b_1\left(a_0 - \frac{X}{b_0}\right) + c_1\right] \cdot \left(-\frac{1}{b_0}\right) \cdot 1 - 1 = 0 \tag{A4}$$

which reduces to

$$\left[3a_1\left(a_0 - \frac{X}{b_0}\right)^2 + 2b_1\left(a_0 - \frac{X}{b_0}\right) + c_1\right] = \frac{b_0}{a_4 a_7} \tag{A5}$$

Then, as defined, replacing $a_0 - \frac{X}{b_0} = A_I^{wp}$ and $c_1 - \frac{b_0}{a_4 a_7} = k_1$ the above condition can be rearranged as

$$3a_1 A_I^{wp^2} + 2b_1 A_I^{wp} + k_1 = 0$$

$$\therefore A_I^{wp} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 4 \cdot 3a_1 \cdot k_1}}{2 \cdot 3a_1} = a_{13}, \quad \text{(A6)}$$

which is a constant. Therefore, the best response function for China is,

$$a_0 b_0 - a_{13} b_0 = X \text{ or } a_0 b_0 - a_{13} b_0 = x_{Ch} + x_{Jap} + x_{Kor} \text{ or}$$

$$x_{Ch} = a_0 b_0 - a_{13} b_0 - x_{Jap} - x_{Kor}. \quad \text{(A7)}$$

The best response function for Korea is derived as follow. Replacing $a_1\left(a_0 - \frac{X}{b_0}\right)^3 + b_1\left(a_0 - \frac{X}{b_0}\right)^2 + c_1\left(a_0 - \frac{X}{b_0}\right) + d_1 = O_{Ch}^{wp}$, the payoff function for Korea can be rearranged as

$$\pi_{Kor} = a_{11} - a_5 \cdot a_8 \cdot a_2 \left[a_1\left(a_0 - \frac{X}{b_0}\right)^3 + b_1\left(a_0 - \frac{X}{b_0}\right)^2 + c_1\left(a_0 - \frac{X}{b_0}\right) + d_1 \right]^{b_2} - x_{Kor}, \quad \text{(A8)}$$

Then using the Chain rule,

$$\frac{\partial \pi_{Ch}}{\partial O_{Ch}^{wp}} \frac{\partial O_{Ch}^{wp}}{\partial\left(a_0 - \frac{X}{b_0}\right)} \cdot \frac{\partial\left(a_0 - \frac{X}{b_0}\right)}{\partial X} \cdot \frac{\partial X}{\partial x_{Kor}} = -a_2 \cdot a_5 \cdot a_8 \cdot b_2 O_{Ch}^{wp^{b_2 - 1}} \left[3a_1\left(a_0 - \frac{X}{b_0}\right)^2 + 2b_1\left(a_0 - \frac{X}{b_0}\right) + c_1 \right] \left(-\frac{1}{b_0}\right) \cdot 1 - 1 = 0 \quad \text{(A9)}$$

Replacing $a_0 - \frac{X}{b_0} = A_I^{wp}$ and $c_1 - \frac{b_0}{a_2 \cdot a_5 \cdot a_8 \cdot b_2 O_{Ch}^{wp^{b_2-1}}} = k_2$, (A9) reduces to,

$$3a_1 A_I^{wp^2} + 2b_1 A_I^{wp} + k_2 = 0$$

$$\therefore A_I^{wp} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 4 \cdot 3a_1 \cdot k_2}}{2 \cdot 3a_1} = a_{14},$$

Therefore the best response function for Korea can be presented as,

$$x_{Kor} = a_0 b_0 - a_{14} b_0 - x_{Jap} - x_{Ch}. \tag{A11}$$

Lastly, the best response function for Japan can be derived as the following. Replacing $b_3 O_{Ch}^{wp}$ with BO, the payoff for Japan is represented by

$$\pi_{Jap} = a_{12} - a_6 \cdot a_9 \cdot a_3 e^{b_3 O_{Ch}^{wp}} - x_{Jap} = a_{12} - a_6 \cdot a_9 \cdot a_3 e^{BO} - x_{Jap}. \tag{A12}$$

Therefore, the payoff maximizing behavior of Japan can be described by the following condition.

$$\frac{\partial \pi_{Jap}}{\partial BO} \frac{\partial BO}{\partial O_{Ch}^{wp}} \frac{\partial O_{Ch}^{wp}}{\partial\left(a_0 - \frac{X}{b_0}\right)} \cdot \frac{\partial\left(a_0 - \frac{X}{b_0}\right)}{\partial X} \cdot \frac{\partial X}{\partial x_{Jap}} = -a_6 \cdot a_9 \cdot a_3 \cdot e^{BO} b_3 \left[3a_1\left(a_0 - \frac{X}{b_0}\right)^2 + 2b_1\left(a_0 - \frac{X}{b_0}\right) + c_1\right]\left(-\frac{1}{b_0}\right) \cdot 1 - 1 = 0 \tag{A13}$$

Replacing $a_0 - \frac{X}{b_0} = A_I^{wp}$ and $c_1 - \frac{b_0}{a_6 \cdot a_9 \cdot a_3 \cdot e^{BO} b_3} = k_3$, (A9) reduces to,

$$3a_1 A_I^{wp^2} + 2b_1 A_I^{wp} + k_3 = 0$$

$$\therefore A_I^{wp} = \frac{-2b_1 \pm \sqrt{4b_1^2 - 4 \cdot 3a_1 \cdot k_3}}{2 \cdot 3a_1} = a_{15},$$

Therefore the best response function for Korea can be presented as,

$$x_{Jap} = a_0 b_0 - a_{15} b_0 - x_{Kor} - x_{Ch}. \quad \text{(A14)}$$

These three best response functions imply that a country's best strategy is to pay whatever amount not paid by the rest of the two countries to make the project fully financed, as illustrated in Figure 1.

Also, when to be a Nash equilibrium (or to solve the three best response functions simultaneously), $a_{13} = a_{14} = a_{15}$, and therefore, $k_1 = k_2 = k_3$. This consecutively implies the following.

$$a_4 a_7 = a_2 a_5 a_8 b_2 O_{Ch}^{b_2 - 1} = a_6 a_9 a_3 e^{BO} b_3. \quad \text{(A15)}$$

This means that the marginal DSS cost per DSS occurrence with the ADB project should be all equal. Because the net benefit or payoff is defined as the difference between the DSS cost without the project and DSS cost with the project, the above condition says, at Nash equilibrium, marginal benefits of all participating countries should be equal.

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