Dynamic Optimal Strategies for Multiple Pollutants in Transboundary Pollution Game between Two Asymmetric Regions

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Abstract: Under the fact that there are multiple pollutants, non-cumulative and cumulative pollutants, generated by two adjacent asymmetric regions, which result in transboundary pollution, we proposed a dynamic transboundary pollution treatment model to study how two adjacent asymmetric regions make their pollution treatment strategies under their self-interested behaviors while the pollution of both regions are treated optimally. The optimal investment policies under non-cooperation and cooperation are obtained through theoretic analysis. It is found that only when local governments cooperate to treat transboundary pollution, the damages caused by non-cumulative pollutants to adjacent regions will be taken into their consideration. The capital stock of pollution treatment investment of each region under the non-cooperative treatment is equal to that under the cooperative treatment.

1. Introduction
With the rapid economic development and the improvement of environmental protection awareness, various countries have paid more and more attention to environmental pollution. Now the research on transboundary pollution treatment has formed a growing part of the literature in environment protection. Li pointed out that transboundary pollution exists world wildly as environmental pollution can be transmitted as far as thousands kilometers [1]. Kaitala et al. compared the pollutant treatment policies of Finland and Soviet Union under cooperation and non-cooperation, and found that cooperative treatment is good for Finland, but not for the Soviet Union [2]. Yeung proposed a differential game of cooperative treatment of cross-border industrial pollution under the assumption that governments cooperate to treat environmental pollution while the industrial sectors still maintain competition [3]. Jørgensen et al. used a differential game model that includes emissions and investments in abatement technology as control variables to study how two neighboring countries control transboundary pollution emission and constructed [4]. However, all the above literatures assumed that there is only one kind pollutant, while, in fact, there are more than one kind of pollutant emitted by industries in one region, and they damage the environment of local and adjacent region. In recent years, transboundary pollution control under the coexistence of multiple pollutants has been studied widely and deeply. Yang considered that fossil fuel generates multiple pollutants in combustion, and studied how to use tax or subsidy to regulate transboundary pollution [5]. Gunther et al. analyzed how stable the International Environmental Agreements in a repetitive game framework is, and obtained the sufficient and necessary conditions for its stability when environmental pollution
impacts are both regional and global [6]. Wang showed that water pollutants are not uniformly distributed in space, which leads to differences in environmental damages [7]. Fullerton et al. studied the increase of taxes on one type of pollutant, while other pollutants would face tax or permit policies, and demonstrated the difference between taxes and permits [8]. However, all the papers above studied how to reduce the emission of multiple pollutants. In reality, local governments not only try to reduce the pollutant emission through regulation, but invest a great amount of capital to treat the emitted pollutants to improve the environment. Therefore, it is worth of exploring the impact of abatement capital.

2. Basic model

2.1. Revenue function
There are two asymmetric neighboring regions in the transboundary environmental pollution game. For region $i$ ($i = 1, 2$), let $q_i(t) \geq 0$ denote the rate of production, and $U_i(q_i(t))$ express the instantaneous gains achieved under the production rate $q_i(t)$ at time $t \in [0, +\infty)$. Following Jorgensen et al. [9], the instantaneous return function can be expressed in the form of a function of the production rate $q_i(t)$ as: $U_i(q_i(t)) = \ln q_i(t)$. The revenue function is increasing and strictly concave. Furthermore, it satisfies $U'_i(0) = +\infty$ which means that zero production is unprofitable.

2.2. Pollution emission rate
The process of industrial production is always accompanied by a large number of by-products, i.e., pollutants emission. Then let us use $E_i(t) \geq 0$ to indicate the rate of pollution emission and $K_i(t) \geq 0$ to represent the stock of environmental pollution abatement capital of region $i$ at time $t$. Then following Ploeg et al. [10], we can express pollution emission rate $E_i(t)$ as a concrete function of pollution abatement capital stock $K_i(t)$ and production rate $q_i(t)$ at time $t$, namely, $E_i(t) = Y_i(K_i(t))q_i(t)$. Obviously, the pollution emission rate $E_i(t)$ of each region is proportional to the production rate $q_i(t)$. Notice that the proportionality factor $Y_i(K_i(t))$ decreases with the decrease of the pollution control capital stock $K_i(t)$, that is, $Y_i''(K_i(t)) < 0$. Meanwhile, to take into account the decline in returns on the various activities of pollution abatement, we assume $Y_i''(K_i(t)) > 0$. Accordingly, following Jorgensen et al. [9], we assume that $Y_i(K_i(t))$ can be described in the following function form: $Y_i(K_i(t)) = \beta_i e^{-\mu_i K_i(t)}$, where $\beta$ and $\mu$ are positive constants. According to Li [1], we set $\beta_i = \beta, \beta_2 = m\beta, \mu_i = \mu$ and $\mu_2 = n\mu$, where $m$ and $n$ are positive constants and measure the gaps between two regions’ ability in obtaining benefit from pollution control under the capital stock $K_i(t)$.

2.3. The dynamics of pollution abatement capital stock
The dynamics of pollution control capital stock evolves: $K_i(t) = I_i(t) - \alpha_i K_i(t), K_i(0) = K_i^0 \geq 0$, where $\alpha_i > 0$ represents the constant positive rate of depreciation of region $i$. Similarly, we set $\alpha_i = \alpha$ and $\alpha_2 = s\alpha$, in which $s$ is a non-negative parameter and it mainly measures the gap between two regions in the consumption rate of pollution abatement capital stock (The more it accelerates the depreciation of environmental pollution abatement capital stock, the greater efforts of pollution control of each region will make). $I_i(t)$ represents the investment rate in region $i$. Following Yeung [3], the
cost of environmental pollution abatement in region $i$ can be expressed by the following functional form: $C_i \left( I_i(t) \right) = \frac{1}{2} c_i I_i^2(t)$, where $c_i > 0$ is the marginal pollution abatement cost slope of region $i$.

Analogously, we set $c_1 = c$ and $c_2 = dc$, in which $d$ is a non-negative parameter and it mainly measures the gap in the capacity of environmental pollution abatement technologies owned by the two regions (the more advanced pollution treatment technologies each region has, the lower cost of pollution control will be).

### 2.4. The dynamics of pollution stock

Current emission of cumulative pollutants promotes the gradual evolution of pollution stock in a standard manner: $\dot{x}(t) = E_i(t) + E_2(t) - \delta x(t)$, $x(0) = x_0, x(t) \geq 0$, where $\delta > 0$ is the natural decomposition rate of pollutants. Following Yeung [3], the environmental pollution damage $D_i(x(t))$ suffered by region $i$ can be expressed as a function of pollution stock $x(t)$ in the following way: $D_i(x(t)) = h_i x(t)$, $D(0) = 0$, where $h_i > 0$ is the damage parameter of region $i$. Similarly, without losing generality, this paper assumes $h_1 = h$ and $h_2 = vh$, where $v$ is a non-negative constant and it mainly weighs the difference in the marginal damage of pollution stock between the two regions.

### 2.5. Local and global environmental impact

Industrial activities will lead to multiple pollutants that may damage the environment through two ways, that is, the impact of global cumulative pollutants and regional non-cumulative pollutants. We focus on the fact that these two types of pollutants are produced together from a source of pollution, but cause different damage. Therefore, we believe that the regional non-cumulative pollutants will destroy its own region and adjacent areas, and cause regional environmental problems. For example, the acid rain produced by industrial activities in a region will mainly cause more damage to the source region and neighbouring areas. Consequently, we hold that for the pollution emission of $E_i(t)$ produced by region 1, it will result in the regional non-cumulative environmental damage of $\varepsilon_{1i} E_i(t)$ on region 1 and $\varepsilon_{2i} E_i(t)$ on region 2. Analogously, for the pollution emission of $E_2(t)$ produced by region 2, it will result in the regional non-cumulative environmental damage of $\varepsilon_{22} E_2(t)$ on region 2 and $\varepsilon_{21} E_2(t)$ on region 1. Notice that $\varepsilon_{ii} (i = 1, 2)$ indicates the extent of damage caused by regional non-cumulative pollution emission to its own region and $\varepsilon_{ij} (i \neq j) (i = 1, 2)$ represents the degree of damage caused by regional non-cumulative pollution emission to its nearby areas.

### 2.6. The objective function of local government

The utility functions and corresponding constraints pursued by region $i$ $(i = 1, 2)$ can be given by

$$\begin{align*}
W_i = \max_{E_i(t), I_i(t)} & \int_{0}^{\infty} e^{-rt} \left[U_i(q_i(t)) - C_i(I_i(t)) - \varepsilon_{ii} E_i(t) - \varepsilon_{ij} E_j(t) - D_i(x(t))\right]dt, \\
S.t. & \begin{cases} 
\dot{K}_i(t) = I_i(t) - \alpha K_i(t), K_i(0) = K_i^0, K_i(t) \geq 0, \\
\dot{x}(t) = E_i(t) + E_2(t) - \delta x(t), x(0) = x_0, x(t) \geq 0,
\end{cases}
\end{align*}$$

where $r$ is the constant discount rate, and $W_i$ is the net revenue of region $i$. According to the model setting, we exploit the relation between $q_i(t)$ and $E_i(t)$ and allow us to express the benefit of regional government in the form of a function of $E_i(t)$. Hence, the current important goal of region $i$ is to reasonably determine the rate of pollution emission $E_i(t)$ and the level of investment $I_i(t)$ in pollution
abatement, so as to maximize its own interest. Subsequently, this paper will make full use of the theory of optimal control to obtain these two areas’ non-cooperative and cooperative optimal emission rates and pollution abatement investment policies so that the net revenues of each region will be maximized. Besides, for the sake of brevity, we omit the time $t$ that does not affect the results.

3. Non-cooperative and cooperative optimal strategies

3.1. Non-cooperative outcomes
We first pay attention to the game mode of non-cooperative governance of environmental pollution between the two regions. Then each region will maximize its net income by considering multiple factors to select the optimal pollution emission rate $E_i(t)$ and the optimal environmental pollution abatement investment rate $I_i(t)$. Hence, we express the utility functions and corresponding constraints of region $i$ ($i = 1, 2$) as:

$$
W_i^N = \max_{E_i(t), I_i(t)} \int_{t_0}^{\infty} e^{-\eta t} \left( \ln E_i + \mu K_i - \ln \beta_i - \epsilon_i E_i - \epsilon_i(x_{i-1})x_{i-1} - \frac{1}{2} c_i I_i^2 - h_i x \right) dt,
$$

subject to

$$
\dot{K}_i = I_i - \alpha_i K_i, K_i(0) = K_i^0, K_i \geq 0,
$$

$$
\dot{x} = E_i + E_{i-1} - \delta x, x(0) = x_0, x \geq 0,
$$

where $W_i^N (i = 1, 2)$ indicates the net income of region $i$ ($i = 1, 2$) under the case of non-cooperative governance. The equation (2) is the problems of optimal control under a series of constraints. The control variables of equation (2) are respectively the emission rate $E_i(t)$ and pollution governance investment level $I_i(t)$, and the state variables are respectively the pollution dynamic stock $x(t)$ and capital stock $K_i(t)$. Now our goal is to seek out the best path of emission $E_i(t)$ and investment rate $I_i(t)$ so that $W_i^N$ is maximized. In addition, non-cooperative governance equilibrium results are distinguished by the superscript “N”.

**Theorem 1.** The feedback Nash equilibrium results in region $i$ ($i = 1, 2$) under steady state can be obtained as:

(i) the optimal pollution emission rates $E_i^N (t)$ ($i = 1, 2$) are shown by

$$
E_1^N = \frac{1}{\epsilon_1 + h + r + \delta}, E_2^N = \frac{1}{\epsilon_2 + rh + s + \delta}.
$$

(ii) the optimal pollution control investment rates $I_i^N (t)$ ($i = 1, 2$) are listed by

$$
I_1^N = \frac{\mu}{(r + \alpha)c}, I_2^N = \frac{n\mu}{(r + s\alpha)d c}.
$$

(iii) the optimal environmental pollution abatement capital stocks $K_i^N (t)$ ($i = 1, 2$) are expressed by

$$
K_1^N = \frac{\mu}{\alpha(r + \alpha)c}, K_2^N = \frac{n\mu}{s\alpha(r + s\alpha)d c}.
$$

**Proof 1.** In order to obtain the optimal conditions for the optimal control problems in equation (2), we apply the Pontryagin’s maximum principle. Thus the present value Hamiltonians are:

$$
H_i = \ln E_i + \mu_i K_i - \ln \beta_i - \epsilon_i E_i - \epsilon_i(x_{i-1})x_{i-1} - \frac{1}{2} c_i I_i^2 - h_i x + \lambda_i (E_i + E_{i-1} - \delta x) + \theta_i (I_i - \alpha_i K_i)
$$
where $\lambda_i$ and $\theta_i$ are the dynamic adjoint variables related to the state equations about $x$ and $K_i(t)$, respectively, and the Hamiltonian $H_i$ mainly denotes the instantaneous equilibrium. Therefore, the necessary optimum conditions for solving the optimal control problems in equation (2) are that the optimal emission rate $E_i$ and the optimal pollution control investment policy $I_i$ should be decided to maximize the Hamiltonian $H_i$. For the current value Hamiltonian $H_i$, we find that the necessary conditions include

$$\dot{\lambda}_i = (r+\delta)\lambda_i + h_i, \quad (6)$$
$$\dot{\theta}_i = (r+\alpha_i)\theta_i - \mu_i. \quad (7)$$

According to specific definition of differential equation, the conditions of steady state should satisfy $\dot{x} = \dot{\lambda}_i = 0$ and $\dot{K}_i = \dot{\theta}_i = 0$, then from equations (6) and (7), we have

$$\lambda_i = -\frac{h_i}{r+\delta}, \quad (8)$$
$$\theta_i = \frac{\mu_i}{r+\alpha_i}. \quad (9)$$

According to the first-order optimal condition $\frac{\partial H_i}{\partial E_i} = 0$, we can get the optimal path of pollution emission $E_i^N$, and then substituting $\lambda_i$ into $E_i^N$ leads to the formulas (3); from optimality condition $\frac{\partial H_i}{\partial I_i} = 0$, we have the optimal investment rate $I_i^N$, and then substituting $\theta_i$ into $I_i^N$ leads to the formulas (4); depending on the steady state condition $\dot{K}_i = 0$ under the non-cooperative governance game, we obtain the optimal pollution abatement capital stock $K_i^N$, and then substituting $I_i^N$ into $K_i^N$ leads to the formulas (5).

### 3.2. Cooperative arrangements

Now we consider the situation where two asymmetric adjacent regions are willing to cooperate to combat environmental pollution and agree to take joint action, so that the optimization of collective action can be achieved. The joint utility function and constraints of these two areas can be written by

$$W^C = \max_{E_1^N, I_1^N} \int_0^\infty e^{-rt}[Ln E_1 - (e_{11} + e_{12})E_1 + Ln E_2 - (e_{22} + e_{21})E_2 - (1+v)hx$$

$$+ \mu K_1 + n\mu K_2 - \frac{1}{2} c_1^2 - \frac{1}{2} c_2^2 - Ln m \beta \gamma]dt$$

$$S.t. \begin{cases} \dot{K}_1 = I_1 - \alpha K_1, K_1(0) = K_1^0 \geq 0, \\ \dot{K}_2 = I_2 - s\alpha K_2, K_2(0) = K_2^0 \geq 0, \\ \dot{x} = E_1 + E_2 - \delta x, x(0) = x_0, x \geq 0, \end{cases}$$

where $W^C$ denotes the joint net profit of region 1 and 2. The equation (10) is the problem of optimal control under a series of constraints. The control variables of equation (10) are the emission level $E_i(t)$ and investment rate $I_i(t)$, and the state variables are the pollution stock $x(t)$ and capital stock $K_i(t)$. Now our important goal is to find the optimal emission path $E_i(t)$ and investment policy $I_i(t)$ so that $W^C$ is maximized. Besides, the equilibrium results in cooperation are identified by the
Theorem 2. The optimal equilibrium results of region \(i = 1, 2\) under steady state in the cooperative governance game can be obtained as follows:

(i) the optimal pollution emission policies \(E_{i1}^C(t)\) are expressed as:

\[
E_{1}^C = \frac{1}{\varepsilon_{11} + \varepsilon_{12} + \frac{(1 + v)h}{r + \delta}},\quad E_{2}^C = \frac{1}{\varepsilon_{22} + \varepsilon_{21} + \frac{(1 + v)h}{r + \delta}}.
\] (11)

(ii) the optimal pollution abatement investment strategies \(I_{i}^C(t)\) are shown as:

\[
I_{1}^C = \frac{n\mu}{(r + \alpha)c}, \quad I_{2}^C = \frac{n\mu}{(r + \mu + \alpha)c}.
\] (12)

(iii) the optimal pollution control capital stocks \(K_{i}^C(t)\) are the following:

\[
K_{1}^C = \frac{\mu}{\alpha(r + \alpha)c}, \quad K_{2}^C = \frac{n\mu}{s(\alpha + r + s)\alpha}.
\] (13)

Proof 2. The proof of Theorem 2 is similar to the proof of Theorem 1, which will not be described again.

4. Comparing of Non-cooperative and Cooperative Governance Game

Theorem 3. The optimal pollution emission rate of each region under the non-cooperative governance game is higher than the one under cooperative governance.

Proof 3. We compare the optimal pollution emission path of region \(i = 1, 2\) under the non-cooperative game with those under the cooperative governance game. From formulas (3) and (11), we can have

\[
E_{i1}^N - E_{i1}^C = \frac{1}{\varepsilon_{i1} + \frac{h}{r + \delta}} - \frac{1}{\varepsilon_{i1} + \varepsilon_{i2} + \frac{h + h_{i}}{r + \delta}} > 0, i = 1, 2.
\]

Thus the conclusion in Theorem 3 is verified, which completes the proof of Theorem 3.

Theorem 3 means that regional cooperation in pollution control is more conducive to improving environmental quality. This is mainly because there are significant differences between the non-cooperative and cooperative pollution emission rates in each region. The rate of pollution emission is only affected by the regional non-cumulative pollutants damage to its own region \(\varepsilon_i\) under the non-cooperative governance game. However, the level of pollution emission is affected by the regional non-cumulative pollutants damage to its own region \(\varepsilon_i\) and neighboring areas \(\varepsilon_{i(i-1)}\) under the cooperative governance game.

Theorem 4. The stock of environmental pollution under the non-cooperative governance is higher than that under the cooperative governance.

Proof 4. According to the equation (6) and the steady state condition \(\dot{x} = 0\), we have

\[
x^N = \frac{E_{11}^N + E_{21}^N}{\delta}, \quad x^C = \frac{E_{11}^C + E_{21}^C}{\delta}.
\]

Then we can obtain

\[
x^N - x^C = \frac{E_{11}^N + E_{21}^N}{\delta} - \frac{E_{11}^C + E_{21}^C}{\delta} = \frac{1}{\delta}\left[(E_{11}^N - E_{11}^C) + (E_{21}^N - E_{21}^C)\right].
\]

Because of \(\delta > 0\), simultaneously
in connection with formula \( E_i^N - E_i^C > 0 \), we can get \( x^N - x^C > 0 \). Thus the conclusion of Theorem 4 is satisfied, which finishes the proof.

Theorem 4 shows that regional cooperation can reduce global cumulative pollution stock and improve environmental quality. Cooperative governance in environmental pollution control is currently the most effective course of action and plays an active role in environmental management.

**Theorem 5.** The environmental pollution abatement investment rate and capital stock of each region under the non-cooperative governance game is equal to the cooperative governance game.

**Proof 5.** From formulas (4) and (12), we can get the following differences of optimal pollution control investment policies between non-cooperative and cooperative governance game:

\[
I_i^N - I_i^C = \frac{\mu_i}{(r + \alpha_i) c_i} - \frac{\mu_i}{(r + \alpha_i) c_i} = 0, \quad i = 1, 2. 
\]

From formulas (5) and (13), we can get the following differences of optimal capital stocks between non-cooperative and cooperative governance game:

\[
K_i^N - K_i^C = \frac{\mu_i}{\alpha_i(r + \alpha_i) c_i} - \frac{\mu_i}{\alpha_i(r + \alpha_i) c_i} = 0, \quad i = 1, 2. 
\]

Thus the conclusion of Theorem 5 is satisfied, which finishes the proof.

Theorem 5 indicates that the optimal pollution mitigation investment level and capital stock under steady state in the case of non-cooperative governance game are consistent with the ones obtained in the cooperative governance game. This is mainly due to the structural design of our model where there is no good interaction in environmental pollution abatement investment decisions between two asymmetric adjacent areas. In addition, we should note that it is a rather rare phenomenon that the result of cooperative governance game automatically turns into the Nash equilibrium. However, this kind of property has also appeared in some game studies of pollution control [4].

**Theorem 6.** The total revenue between the two regions under the cooperative governance game is higher than that under the non-cooperative governance game.

**Proof 6.** We have the return \( W^C = W_1^C + W_2^C \) under the cooperative governance game and \( W^N = W_1^N + W_2^N \) under the non-cooperative governance game. Then we define the cooperative surplus denoted by \( w \) such that

\[
w = W^C - W^N = W_1^C + W_2^C - W_1^N - W_2^N. \quad (15)
\]

Recall that the objective function of region \( i \) \((i = 1, 2)\) in equation (8) was defined and then we can get the benefits \( W_i^N \) \((i = 1, 2)\) and \( W_i^C \) \((i = 1, 2)\) under non-cooperative and cooperative governance, respectively. Apparently, using the characteristics of joint maximization, we can get the fact that \( W^C - W^N > 0 \), that is, the cooperative surplus \( w > 0 \) which finishes the proof.

5. **Conclusion**

We study the problem of transboundary pollution control in two asymmetric adjacent areas under the non-cooperative and cooperative governance game. We hold the opinion that transboundary pollution will damage the two regions in two ways, namely, through the regional non-cumulative pollutants and global cumulative pollutants jointly discharged from a source of pollution. We make full use of the optimal control theory to determine the optimal levels of pollution emission and investment rates under the non-cooperative and cooperative governance game, so that the discounted stream of net revenues of each area is maximized. Optimal control models for transboundary pollution generate four important results. First, the optimal pollutant emission policy of each region under the non-cooperative governance game is higher than that under the cooperative governance game. The optimal emission rate of each region is only affected by the damage degree of regional non-cumulative pollutants to its own region under the non-cooperative governance game, but it is affected by the damage degree of regional non-cumulative pollutants to its own region and adjacent regions under the cooperative governance game. Second, the pollution stock under the non-cooperative governance game is higher than that under the cooperative governance game. Each region will reduce pollutants emission under
the cooperative governance game. Third, the total revenue between two regions under the cooperative governance game is higher than that under the non-cooperative governance game. Fourth, the equilibrium pollution investment rate and capital stock of each region under steady state in the case of non-cooperative governance game are consistent with the ones obtained in the cooperative governance game.

6. References

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