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Research Article

Modeling and Computation of Transboundary Pollution Game Based on Joint Implementation Mechanism

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In the paper, we use the differential game method to test the impact of joint implementation (JI) mechanism on pollution control in two bilateral countries. The Hamilton-Jacobi-Bellman (HJB) equations of the models are obtained by using the dynamic programming principle. We obtain the optimal emissions, optimal local and foreign investments in environment projects, optimal revenues, and optimal trajectories of carbon stock under three situations, namely, situation without JI, with JI (noncooperative), and with JI (cooperative), of the two countries by solving these equations. We also compare their optimal Nash equilibrium solutions. We find that the introduction of JI mechanism can slow down the growth of the carbon stocks by reducing emissions or increasing investment in emission reduction projects, compared to the situation without JI mechanism. However, the JI mechanism does not reduce the revenue of the two countries under certain conditions. Finally, some numerical tests are provided to illustrate the theoretical results.

1. Introduction

Climate warming has become a global issue. The level of environmental governance and cooperation among countries should be increased to cope with global warming. The international community exerted unremitting efforts to reach a consensus and resolve climate change. One hundred fifty-four countries signed the United Nations Framework Convention on Climate Change (UNFCCC) at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992. The UNFCCC lays down measures to reduce greenhouse gas emissions. The Kyoto Protocol of 1997, which is an important annex of UNFCCC, established three mechanisms, namely, joint implementation (JI), clean development mechanism (CDM), and international emissions trading (ED). These mechanisms are aimed at reducing emissions. JI and CDM are based on the concept of allowing one country (investor) to fulfil its reduction targets by carrying out reduction measures on the territory of another country (host). JI applies to investments in Annex I countries, and CDM applies to investments in green house gas abatement in developing countries (Fichther et al. 2001 [1]). The JI mechanism allows project sponsors to invest in emission reduction projects and obtain emission reduction units. JI is one way of reducing global greenhouse gas (GHG) emissions through international cooperation.

More recently, in 2015, the UNFCCC took place in Paris, from which the so-called Paris Agreement came into being. One hundred eighty-eight countries committed to control their GHG emissions in this binding agreement. In response to climate change commitments, the Chinese government has introduced a series of ambitious laws and policies to prevent further deterioration of air quality. The Chinese government implemented air pollution control measures nationwide, incorporated air quality improvement and emission control into the local government performance evaluation system, and launched the Air Pollution Prevention and Control Action Plan comprehensively (Wang, Zhang, and Pilot et al. 2018 [2]). However, on June 1, 2017, U.S. President Trump announced the withdrawal of the U.S. from the Paris Agreement. His decision triggered a strong concern on the issue of climate change. This paper focuses on the impact of the JI mechanism, which partly allows countries to offset their national carbon abatement commitment by investing in emission reduction projects abroad. We will discuss in depth the need for international cooperation in carbon reduction.

2. Literature Review

In terms of transboundary pollution, carbon emissions, as a by-product of industrial production, continue to accumulate in the atmosphere and leave a continuous impact on the environment. Differential game and optimal control method are one of the effective tools for studying the transboundary pollution problem. At the beginning of the nineties, van der Ploeg and de Zeeuw (1991 [3], 1992 [4]), Hoel (1992 [5], 1993 [6]), Long (1992 [7]), and Kaitala et al. (1995 [8]) formulated transnational pollution as a differential game among governments. Literature on game theory that examined transboundary pollution issues is summarized by Jogensen (2010 [9]). Differential game method is applied to study transboundary pollution issues mainly from the aspects of carbon taxation, technology R&D and transfer, carbon trading mechanisms, joint implementation mechanisms and clean development mechanisms.

From the perspective of carbon tax, Martin et al. (1993 [10]) applied the differential game method to study transboundary pollution in two asymmetric players and assess the cost of achieving a carbon concentration target. They first assumed that the two players have different attitudes toward global climate issues. They concluded that one player will benefit from the game, whereas the other will suffer losses with a negative overall impact. Yanase (2007 [11], 2009 [12]) set up a differential game model between two countries that trade polluting good, this study discussed the dynamic policy of the two countries under the government's control of pollution through the use of carbon taxes and other means. A competitive international market is considered in the first article, and a duopoly market is considered in the second article. This study founded that the emission tax game generates more pollution and lower welfare than the emission quota game.

From the perspective of R&D and transfer of technologies, Xepapadeas (1995 [13]) used a differential game method based on an endogenous carbon emission reduction technology to study pollution control issues. This result holds when the effectiveness of resources depends on technology and technology can be changed through labor. Fuentes-Albero and Rubio ([14] 2010) used the game method to study environmental pollution in two cases where the two countries have different abatement cost and environmental damage. Both cases assumed transfer in one country and no transfer in another. This study concluded the asymmetric case does not affect the scope cooperation relative to the symmetric case when the difference is founded only in terms of abatement costs. The scope of cooperation can be improved through transfer when there is difference in environmental damage. From the perspective of carbon tax regulation, Liu,, Zheng, and Gong et al. (2017 [15]) studied the impact of carbon tax on the low-carbon promotion level and profitability of manufacturers and retailers in the supply chain. The results show that carbon tax regulation can encourage manufacturers to improve the sustainability of their products. At the same time, the government should set a reasonable carbon tax based on the investment coefficient of supply chain members to promote the overall efficiency of the supply chain and reduce the carbon emissions of the entire supply chain.

Several studies were conducted on environmental pollution from the perspective of the three mechanisms of carbon reduction. Lee et al. (1997 [16]) used game theory to establish a game framework under the joint implementation emission reduction mechanism; They also examined the transboundary pollution problem. This analysis concluded that a system that allows joint implementation mechanism results in better social welfare than the one that does not. The most important economic benefit is achieving emission reduction goals at the lowest cost. Janssen (1999 [17]) analyzed the problem of carbon emission reduction under the joint implementation and clean development mechanisms from the perspective of noncooperative game; This study presented two solutions for cooperation game. Breton et al. (2006 [18]) provided a game-theoretic interpretation of joint implementation in environmental projects; They studied the optimal mitigation strategies, conducted comparisons in three scenarios, and assessed the merit of the strategies. Yanase (2010 [19]) used the differential game method to compare the impact on trade when one country used a national carbon tax and another country used carbon emission trade to control emissions. The effects of trade on global pollution and welfare are ambiguous because policy games can yield multiple equilibria. He et al. (2012 [20]) used game theory to compare the effectiveness and efficiency of cap-and-trade and tax systems in controlling carbon emission. Cap-and-trade and four variations of carbon taxes were incorporated into the game theory model to assess its impact on investment in renewable energy generation capacity. Bertinelli et al. (2014 [21]) used differential game to analyze the optimal emission reduction strategies of two countries in the face of carbon dioxide pollution by considering the trading mechanism for carbon emission. The result shows that feedback strategy may lead to lesser social waste than when the countries adopt open-loop strategy. Based on the carbon trading mechanism, Qin, Zhao, and Xia (2018 [22]) analyzed the carbon emission reduction strategies of manufacturers and retailers, the cost sharing contract and the greening financing in the case that manufacturers have certain carbon emission reduction quotas and limited carbon emission reduction capital. The results show that the government should carefully weigh the relationship between carbon trading prices and emissions permit allocation to promote the overall efficiency of the supply chain while controlling the carbon emissions level of the entire supply chain.

In this paper, we consider a finite planning horizon and two nonidentical counties. We assume that each one of two countries can reduce industrial production and/or implement environmental projects to reduce emissions at home or abroad (JI). The aim of this paper is to analyze investments and emission strategies and the revenues of both countries in joint implementation mechanism in a dynamic context. This study also aims to characterize the influence of the introduction of the joint implementation mechanism. The remainder of the paper is organized as follows. Section 3 introduces the model and situations. The different equilibria are derived and discussed in Section 4. Some comparative results are provided in Section 5. A numerical example is provided in Section 6. Finally, conclusions are given in Section 7.

3. Model Formulation

3.1. Model Notations and Assumptions. We consider the bilateral situation in our model, namely, the game involving two countries $i = 1, 2$.

Notations

T : the whole period of environmental project investment.

$x(t)$: the carbon stock, $t \in [0, T]$.

$q_i(t)$: the industrial production of country i, $t \in [0, T]$.

$e_i(t)$: the gross emission from the industrial production of country i, $t \in [0, T]$.

$I_{ii}(t)$: the investment effort on emission reduction projects at home of country i, $t \in [0, T]$.

$I_{ij}(t)$: the investment effort by country i (investor) on emission reduction projects in country j (host), $t \in [0, T]$, it means the investment effort abroad of country i.

r : the interest rate, it is a positive constant.

$N_i(t)$: the net emission of country i, $t \in [0, T]$.

$Te(t)$: the total net emission of both countries, $t \in [0, T]$.

The subscripts A, N and C in the model denote the three different situations, which are without JI, with JI (noncooperation), and with JI (cooperation) discussed in the article.

Assumptions

(1) Each country produces one domestically consumed good, $q_i(t)$, with a given fixed endowment of factors of production and a given technology. Production of $q_i(t)$ results in an amount of emissions, $e_i(t)$. Following Forster (1973 [23]) and List et al. (2001 [24]), the emission-consumption trade-off function has the following form:

$$q_i(t) = M_i(e_i(t)), \quad (1)$$

where the "technology" M_i accounts for items such as the use of abatement equipment and the dissipation of emissions before entering the environment. We assume that this technology is time-invariant, increasing, and weakly concave. Exploiting the relation between $q_i(t)$ and $e_i(t)$ allows us to express revenue in terms of $e_i(t)$. According to List et al. (2001 [24]), Breton et al. (2006 [18]), Yeung (2007 [25]), Li (2014 [26]) and Chang et al. (2015 [27]) the revenue function of country i is strictly concave and quadratic:

$$R(e_i(t)) = b_i e_i(t) - \frac{1}{2} e_i^2(t), \quad e_i(t) \in (0, b_i), \quad (2)$$

where b_i is a given positive parameter. As the emissions increase, the revenue continues to grow, while the marginal revenue continues to decline. If the country wants to get more revenue, it must emit more emissions.

(2) According to List et al. (2001 [24]), Breton et al. (2006 [18]), the local investment cost of emission reduction of the country i is assumed convex and increasing:

$$C_i(I_{ii}(t)) = \frac{1}{2} a_i I_{ii}^2(t), \quad a_i > 0. \quad (3)$$

In the model, we assume that the host country has a first option in choosing the available environmental project, and the investor country has only access to the emission reduction units after the host has collected its local ones. According to Breton et al. (2006 [18]), the cost of abroad investment of country i on emission reduction in country j is assumed to be

$$C_i(I_{ij}(t)) = \frac{1}{2} a_j \left((I_{jj}(t) + I_{ij}(t))^2 - I_{jj}^2(t) \right), \quad a_j > 0, \ i \neq j. \quad (4)$$

This functional form captures the idea that the cost for investor i in host country j depends on the latter's current investment.

(3) According to Jorgensen et al. (2001 [28]), Labriet and Loulou (2003 [29]), Yeung (2007 [25]), and Li (2014 [26]), the pollution damage suffered by country i at time t is assumed to be linear to the carbon stock $x(t)$

$$D_i(t) = d_i x(t), \quad (5)$$

where d_i is a positive parameter. The parameter d_i can be interpreted as the relative importance the country i attaches to the environmental damage in relation to the revenue of the action. Without loss of generality, we let $d_1 > d_2$, this characterizes the difference in the two countries of capacity in bearing damages from the carbon stock $x(t)$.

(4) The benefit of the environmetal investment lies in so-called emissions reduction units $ERU(t)$, according to Breton et al. (2006 [18]), the local and abroad emission reduction units are assumed to be proportional to the investment

$$\begin{aligned} ERU_{ii}(t) &= \gamma_i I_{ii}(t), \\ ERU_{ij} &= \gamma_j I_{ij}(t), \end{aligned} \quad (6)$$

where γ_i is a positive parameter, and it could be interpreted as the efficiency of the emission reduction technology of county i. Here, we have chosen to let the emission reduction units depend on the conditions in the host country. The abroad reduction units are assumed dependent on the location of the project and not on investor's technology. Another possibility would be to let the abroad reduction depend on the investor's technology or on both players' conditions.

(5) Following Bertinelli et al. (2014 [21]), the countries can reduce the rate of accumulation of the carbon stock by employing the abatement strategy; that is,

$$\begin{aligned} \dot{x}(t) = {} & e_1(t) + e_2(t) - \gamma_1 (I_{11}(t) + I_{21}(t)) \\ & - \gamma_2 (I_{22}(t) + I_{12}(t)) - \rho x(t), \end{aligned} \quad (7)$$

where ρ represents the exponential decay rate of carbon, and the net emission of country i, $N_i(t)$, is $e_i(t) - \gamma_i I_{ii} - \gamma_j I_{ij}(t))$.

3.2. Model and Situations. Three situations are considered in our paper.

(1) Situation without JI Mechanism. In this situation, only local investments in carbon emission reduction projects are allowed. Each country then invests exclusively in local environmental projects. The net revenue flow of country i at period $0 \leq t \leq T$ is

$$F_i^A(t) = R_i(e_i(t)) - C_i(I_{ii}(t)) - d_i x(t). \tag{8}$$

Thus, we can obtain the present value of net revenue in county i at time t

$$\int_t^T F_i^A(w) \exp^{-r(w-t)} dw. \tag{9}$$

The current objective of country i is to find the optimal emission path and the optimal local investment to maximize the present value of net revenue.

In the absence of JI mechanism participation, because bilateral countries only reduce emissions from domestic environmental projects, then the cumulative rate of carbon stock includes carbon emissions of both countries, subtracting the amount of carbon emissions reductions and of natural attenuation of carbon. So the cumulative rate of change of carbon stock in the situation without JI mechanism is

$$\begin{aligned}\dot{x}^A(t) &= e_1^A(t) + e_2^A(t) - \gamma_1 I_{11}^A(t) - \gamma_2 I_{22}^A(t) \\ &\quad - \rho x^A(t), \quad x^A(t) > 0, \ x^A(0) = x_0.\end{aligned} \tag{10}$$

The optimal performance function is

$$V_i^A(x^A, t) = \max_{e_i^A, I_{ii}^A} \int_t^T F_i^A(w) \exp^{-r(w-t)} dw, \tag{11}$$

s.t.

$$\begin{aligned}\dot{x}^A(t) &= e_1^A(t) + e_2^A(t) - \gamma_1 I_{11}^A(t) - \gamma_2 I_{22}^A(t) \\ &\quad - \rho x^A(t), \quad x^A(t) > 0, \ x^A(0) = x_0.\end{aligned} \tag{12}$$

(2) Situation With JI Mechanism (Noncooperative Game). In this situation, local or abroad investments in carbon emission reduction projects are allowed to collect emission reduction units. Countries can both invest at home and abroad. Each country chooses its own emissions, local and foreign investments strategies so as to optimize its own net revenue, but they do not cooperate.

Because of the introduction of JI mechanism, bilateral countries can reduce emissions from both local and foreign environmental projects, then the cumulative rate of carbon stock includes carbon emissions of both countries, subtracting the amount of carbon emissions reductions of local and foreign environmental projects and of natural attenuation of carbon. So the cumulative rate of change of carbon stock in the situation of with JI mechanism is

$$\begin{aligned}\dot{x}^N(t) &= e_1^N(t) - \gamma_1 I_{11}^N(t) - \gamma_2 I_{12}^N(t) + e_2^N(t) \\ &\quad - \gamma_2 I_{22}^N(t) - \gamma_1 I_{21}^N(t) - \rho x^N(t), \\ &\quad x^N(t) > 0, \ x^N(0) = x_0.\end{aligned} \tag{13}$$

Then the optimal performance function is

$$V_i^N(x^N, t) = \max_{e_i^N, I_{ii}^N, I_{ij}^N} \int_t^T F_i^N(w) \exp^{-r(w-t)} dw, \tag{14}$$

s.t.

$$\begin{aligned}\dot{x}^N(t) &= e_1^N(t) - \gamma_1 I_{11}^N(t) - \gamma_2 I_{12}^N(t) + e_2^N(t) \\ &\quad - \gamma_2 I_{22}^N(t) - \gamma_1 I_{21}^N(t) - \rho x^N(t), \\ &\quad x^N(t) > 0, \ x^N(0) = x_0,\end{aligned} \tag{15}$$

where

$$\begin{aligned}F_i^N(t) &= R_i(e_i^N(t)) - C_i(I_{ii}^N(t)) - C_i(I_{ij}^N(t)) \\ &\quad - d_i x^N(t).\end{aligned} \tag{16}$$

(3) Situation with JI Mechanism (Cooperative Game). In this last situation, the two countries play a cooperative game and seek the optimal emissions and investments paths to optimize their joint net revenue. The assumption here is that they jointly invest their carbon emission reduction projects as if they were one single player. In this situation, the cumulative rate of carbon stock is as same as in the noncooperative game model. Then the optimization problem can be written as follows:

$$V^C(x^C, t) = \max_{e_1^C, e_2^C, I_{11}^C, I_{12}^C, I_{22}^C, I_{21}^C} \int_t^T F^C(w) \exp^{-r(w-t)} dw \tag{17}$$

s.t.

$$\begin{aligned}\dot{x}^C(t) &= e_1^C(t) - \gamma_1 I_{11}^C(t) - \gamma_2 I_{12}^C(t) + e_2^C(t) \\ &\quad - \gamma_2 I_{22}^C(t) - \gamma_1 I_{21}^C(t) - \rho x^C(t), \\ &\quad x^C(t) > 0, \ x^C(0) = x_0,\end{aligned} \tag{18}$$

where

$$\begin{aligned}F^C(t) &= \sum_{i=1, i\neq j}^{2} \Big(R_i(e_i^C(t)) - C_i(I_{ii}^C(t)) - C_i(I_{ij}^C(t)) \\ &\quad - d_i x(t)^C\Big) = \sum_{i=1, i\neq j}^{2} \Big(R_i(e_i^C(t)) \\ &\quad - \frac{1}{2} a_i (I_{ii}^C(t) + I_{ji}^C(t))^2 - d_i x^C(t)\Big).\end{aligned} \tag{19}$$

In the cooperative game, the investment decisions are the sum $I_{ii}^C(t) + I_{ji}^C(t)$, so the optimal performance function becomes:

$$V^C(x, t) = \max_{e_1^C, e_2^C, I_{11}^C + I_{21}^C, I_{12}^C + I_{22}^C,} \int_t^T F^C(w) \exp^{-r(w-t)} dw. \tag{20}$$

4. Equilibrium

4.1. Nash Equilibrium of Situation without JI Mechanism. In this situation, countries act independently from one another and invest in carbon emission reduction projects exclusively at the local level. The following proposition characterizes the Nash equilibrium solutions of situation without JI, optimal net revenue, and carbon stock trajectory.

Proposition 1. *Denote $e_i^{A*}(t), I_{ii}^{A*}(t), i = 1,2$ be the Nash equilibrium solutions of the control variables in the situation without JI. Then*

(1) The optimal emissions and local investments in environmental projects of country $i = 1,2$ are

$$\begin{aligned} e_i^{A*}(t) &= \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i; \\ I_{ii}^{A*}(t) &= -\frac{\gamma_i}{a_i}\frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right); \end{aligned} \tag{21}$$

(2) The optimal revenue of country $i = 1,2$ are

$$\begin{aligned} V_i^A\left(x^A, t\right) = {} & \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x^A \\ & - \frac{\mu_i^A}{r+2\rho}\exp^{-2(r+\rho)(T-t)} \\ & - \frac{\nu_i^A}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta_i^A}{r} \\ & + \left(\frac{\mu_i^A}{r+2\rho} + \frac{\nu_i^A}{\rho} - \frac{\theta_i^A}{r}\right)\exp^{-r(T-t)}, \end{aligned} \tag{22}$$

where $\mu_i^A = (1/2)(1+\gamma_i^2/a_i)(d_i/(r+\rho))^2 + (1+\gamma_j^2/a_j)(d_id_j/(r+\rho)^2)$, $\nu_i^A = -2\mu_i^A + (b_i+b_j)(d_i/(r+\rho))$ and $\theta_i^A = \mu_i^A - (b_i+b_j)(d_i/(r+\rho)) + (1/2)b_i^2$.

(3) The state variable $x^A(t)$ is

$$\begin{aligned} x^A(t) = {} & \frac{\alpha^A}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^A}{\rho} \\ & + \left(x_0 - \frac{\beta^A}{\rho} - \frac{\alpha^A}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t}, \end{aligned} \tag{23}$$

where $\alpha^A = (1+\gamma_1^2/a_1)(d_1/(r+\rho)) + (1+\gamma_2^2/a_2)(d_2/(r+\rho))$ and $\beta^A = b_1 + b_2 - \alpha^A$.

Proof. See Appendix. □

Remark 2. We assume that emissions $e_i^{A*}(t)$ are positive, which requires

$$b_i > \frac{d_i}{r+\rho}\left(1 - \exp^{-(r+\rho)T}\right), \quad i = 1,2. \tag{24}$$

The following corollaries can be easily observed:

(1) Solution (21) shows that optimal emissions $e_i^{A*}(t) < b_i$. This conclusion is very consistent with the actual situation, because the revenue function in the model hypothesis is a quadratic function of carbon emissions. When the emissions exceed b_i, the revenue will decrease, so no country will adopt a production strategy with emissions greater than b_i.

(2) Optimal emissions $e_i^{A*}(t)$ are strictly increasing at time t, whereas optimal local investments $I_{ii}^{A*}(t)$ are strictly decreasing. This finding shows that the two countries will only seek to maximize their own revenues if there is no JI mechanism. Under this circumstance, although the two countries also need to bear certain environmental pollution costs, they will increase emissions, expand production, and reduce carbon emission reductions while pursuing maximum of economic benefits. At this time, emissions will continue to increase and, emission reductions continue to decrease, thereby resulting in the deterioration of the environment;

(3) The optimal emissions $e_i^{A*}(t)$ is increasing in revenue parameter b_i and decreasing in marginal damage cost d_i. The larger b_i is, the greater marginal revenue is, and, with the larger b_i, both countries will inevitably increase the production to obtain more revenue. While the larger d_i is, the higher the environmental damage cost of each country is, so with larger d_i, both countries will reduce production and promote environmental improvement to increase their revenue.

(4) The optimal local investments $I_{ii}^{A*}(t)$ in environmental projects are always positive. Optimal local investments $I_{ii}^{A*}(t)$ are increasing in the technological efficiency parameter γ_i and decreasing in the parameter of cost in emission reduction a_i. The larger γ_i indicates higher emission reduction technology, so the larger γ_i is, the higher the country's revenue from emission reduction is. As γ_i increases, the country will choose more emission reductions to obtain the higher revenue. The larger a_i indicates higher abatement costs, so the larger a_i, the lower the country's revenue from emission reduction is. As a_i increases, the country will choose less emission reduction to make the revenue higher.

4.2. Nash Equilibrium of Situation with JI Mechanism (Noncooperative Game). In this situation, the countries can invest locally and abroad in carbon emission reduction projects, and collect emissions reduction units. Each country chooses its optimal emissions and, local and foreign investments to optimize its own net revenue.

Proposition 3. *Denote $e_i^{N*}(t), I_{ii}^{N*}(t), I_{jj}^{N*}(t), I_{ij}^{N*}(t), i = 1,2; j = 2,1$ be the Nash equilibrium solutions of the control variables in the situation with JI mechanism (noncooperative). We then obtain the following.*

(1) The optimal emissions of country $i = 1,2$ are

$$e_i^{N*}(t) = \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i; \tag{25}$$

The optimal local investments in environmental projects are

$$I_{ii}^{N*}(t) = -\frac{\gamma_i}{a_i}\left(\frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)\right). \tag{26}$$

(2) According to the above assumption $d_1 > d_2$, the optimal foreign investments of country $i = 1, 2$ are

$$\begin{aligned} I_{12}^{N*}(t) &= \frac{\gamma_2}{a_2}\left(\frac{d_1 - d_2}{r+\rho}\right)\left(1 - \exp^{-(r+\rho)(T-t)}\right); \\ I_{21}^{N*}(t) &= 0; \end{aligned} \tag{27}$$

(3) The optimal revenue of country $i = 1, 2$ are

$$\begin{aligned} V_i^N\left(x^N, t\right) &= \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x \\ &\quad - \frac{\mu_i^N}{r+2\rho}\exp^{-2(r+\rho)(T-t)} \\ &\quad - \frac{\nu_i^N}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta_i^N}{r} \\ &\quad + \left(\frac{\mu_i^N}{r+2\rho} + \frac{\nu_i^N}{\rho} - \frac{\theta_i^N}{r}\right)\exp^{-r(T-t)}, \end{aligned} \tag{28}$$

where $\mu_i^N = (1/2)(1 + \gamma_i^2/a_i + \gamma_j^2/a_j)(d_i/(r+\rho))^2 + (d_i d_j/(r+\rho)^2) + (1/2)(\gamma_j^2/a_j)(d_j/(r+\rho))^2$, $\nu_i^N = -2\mu_i^N + (b_i + b_j)(d_i/(r+\rho))$ and $\theta_i^N = \mu_i^N - (b_i + b_j)(d_i/(r+\rho)) + (1/2)b_i^2$.

(4) The state variable $x^N(t)$ is

$$\begin{aligned} x^N(t) &= \frac{\alpha^N}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^N}{\rho} \\ &\quad + \left(x_0 - \frac{\beta^N}{\rho} - \frac{\alpha^N}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t}, \end{aligned} \tag{29}$$

where $\alpha^N = (1 + \gamma_1^2/a_1 + \gamma_2^2/a_2)(d_1/(r+\rho)) + (d_2/(r+\rho))$, $\beta^N = b_1 + b_2 - \alpha^N$.

Proof. See Appendix. □

The following corollaries can be easily observed:

(1) $e_i^{A*}(t) = e_i^{N*}(t)$, $I_{ii}^{A*}(t) = I_{ii}^{N*}(t)$, this means the introduction of JI mechanism will not change the optimal emissions and local investments in the environmental projects of both countries. The introduction of the JI mechanism will not reduce emissions, and industrial production will remain unchanged. Thus it will not affect people's living standards.

(2) When the damage cost $d_1 > d_2$, foreign investment $I_{21}(t) = 0$, $I_{12}(t) > 0$. This finding shows that Country 1 will also need to invest in Country 2 on the basis of maintaining its local investment in carbon reduction projects. This finding is attributed to the fact that the marginal cost of local investment is greater than that in Country 2, which means that the country 1 has more incentive to decrease carbon stock than country 2. Country 1 will use the lower cost of emission reduction and other resources in the foreign country to reduce emissions. The amount of investment in environmental projects abroad depends on the difference of damage cost parameter $d_1 - d_2$ and the size of parameter γ_i/a_i. This result means that the country with a greater degree of penalties for air pollution has stronger willingness to invest in carbon reduction projects abroad, and vice verse. The introduction of JI mechanism will push one country to invest in carbon reduction projects in another country, thereby reducing the penalty cost, and promoting environmental improvement.

4.3. Nash Equilibrium of Situation with JI Mechanism (Cooperative Game). In this case, the two countries agree to play a cooperative game, that is, they accept to coordinate their emissions and investment strategies and agree on a rule for sharing the total cooperative reward. Under a cooperative framework, the two countries seek the optimal emission levels and, local and foreign investments to maximize the joint net revenue.

Proposition 4. *Denote $e_i^{C*}(t), I_{ii}^{C*}(t), I_{ij}^{C*}(t), i = 1, 2; j = 2, 1$ be the Nash equilibrium solutions of the control variables in the cooperative game case. We then obtain*

(1) The optimal emissions of country $i = 1, 2$ are

$$e_i^{C*}(t) = \frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i; \tag{30}$$

(2) The sum of optimal local and foreign investments investments in environmental projects of country $i = 1, 2$ are

$$\begin{aligned} &I_{ii}^{C*}(t) + I_{ji}^{C*}(t) \\ &\quad = -\frac{\gamma_i}{a_i}\left(\frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)\right); \end{aligned} \tag{31}$$

(3) The optimal joint revenue is

$$\begin{aligned} V^C(x, t) &= \frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x \\ &\quad - \frac{\mu^C}{r+2\rho}\exp^{-2(r+\rho)(T-t)} \\ &\quad - \frac{\nu^C}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta^C}{r} \\ &\quad + \left(\frac{\mu^C}{r+2\rho} + \frac{\nu^C}{\rho} - \frac{\theta^C}{r}\right)\exp^{-r(T-t)}, \end{aligned} \tag{32}$$

where $\mu^C = (1 + (1/2)(\gamma_1^2/a_1) + (1/2)(\gamma_2^2/a_2))((d_1 + d_2)/(r+\rho))^2$, $\nu^C = -2\mu^C + (b_1 + b_2)((d_1 + d_2)/(r+\rho))$ and $\theta^C = \mu^C - (b_1 + b_2)((d_1 + d_2)/(r+\rho)) + (1/2)(b_1^2 + b_2^2)$.

(4) The state variable $x^C(t)$ is

$$\begin{aligned} x^C(t) &= \frac{\alpha^C}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^C}{\rho} \\ &\quad + \left(x_0 - \frac{\beta^C}{\rho} - \frac{\alpha^C}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t}, \end{aligned} \tag{33}$$

where $\alpha^C = (2 + \gamma_1^2/a_1 + \gamma_2^2/a_2)((d_1 + d_2)/(r+\rho))$, $\beta^C = b_1 + b_2 - \alpha^C$.

Proof. See Appendix. □

The following corollaries can be easily observed.

(1) Optimal emissions $e_i^{C*}(t) < b_i$, and the sum of optimal local and foreign investments in environmental projects $I_{ii}^{C*}(t) + I_{ji}^{C*}(t)$ are always positive.

(2) Optimal emissions $e_i^{C*}(t)$ are strictly increasing in time t, whereas optimal investments $I_{ii}^{C*}(t)+I_{ji}^{C*}(t)$ are strictly decreasing;

(3) Both the optimal emissions, the sum of optimal local and foreign investments are increasing in the revenue parameter b_i and decreasing in the marginal damage cost d_i.

(4) The sum of local and foreign investments $I_{ii}^{C*}(t) + I_{ji}^{C*}(t)$ are increasing in the technological efficiency parameter γ_i and decreasing in the parameter of cost in emission reduction a_i.

5. Comparison of Equilibrium

In this section we compare the results obtained under the three situations in order to assess the impact of Joint Implementation mechanism on emission reductions and revenues for the two countries.

Proposition 5. (1) *Gross emissions of country $i = 1,2$ are compared as follows:*

$$e_i^{A*}(t) = e_i^{N*}(t) > e_i^{C*}(t), \quad i = 1,2; \tag{34}$$

(2) *The local investments in environmental projects of country $i = 1,2$ are compared as follows:*

$$I_{ii}^{A*}(t) = I_{ii}^{N*}(t), \quad i = 1,2; \tag{35}$$

(3) *Foreign investments in environmental projects are compared as follows ($d_1 > d_2$):*

$$\begin{aligned} I_{12}^{N*}(t) &= \frac{\gamma_2}{a_2}\frac{d_1 - d_2}{r+\rho}\left(1 - \exp^{-(r+\rho)(T-t)}\right) > I_{12}^{A*}(t) \\ &= 0, \end{aligned} \tag{36}$$

$$I_{21}^{A*}(t) = I_{21}^{N*}(t) = 0.$$

(4) *Net emissions of country $i = 1,2$ are compared as follows ($d_1 > d_2$):*

$$\begin{aligned} N_1^{A*}(t) &= N_1^{N*}(t) > N_1^{C*}(t); \\ N_2^{A*}(t) &> N_2^{N*}(t) > N_2^{C*}(t). \end{aligned} \tag{37}$$

Proof. See Appendix. □

Proposition 5(1) means that the introduction of Joint Implementation noncooperative mechanisms can not change emission levels in both sides of the game. From another perspective, Joint Implementation mechanism will not decrease or increase the production of both sides. However, the cooperative mechanism will cause the two sides to decrease their emissions.

Proposition 5(2) means that the Joint Implementation noncooperative mechanism will not affect local investments in environmental projects.

Proposition 5(3) means that only Country 1 choose the foreign investment, because we assume that the damage cost parameter of Country 1 is larger than that of Country 2. Country 1 takes more incentive to invest the carbon emission reduction projects in Country 2. This finding means that the total amount of investment in the emission reduction projects of Country 2 will increase from $(\gamma_2/a_2)(d_2/(r+\rho))(1-\exp^{-(r+\rho)(T-t)})$ to $(\gamma_2/a_2)(d_1/(r+\rho))(1-\exp^{-(r+\rho)(T-t)})$ at time t.

Proposition 5(4) shows that the introduction of Joint implementation noncooperative mechanism will not change the net emission reduction in Country 1, but it can decrease the net emission reduction in Country 2. Cooperative mechanism will decrease the net emission reductions of both countries.

Proposition 6. *(1) The total net emissions of two countries are compared as follows:*

$$Te^{A*}(t) > Te^{N*}(t) > Te^{C*}(t); \tag{38}$$

(2) Carbon stocks are compared as follows:

$$x^A(t) > x^N(t) > x^C(t). \tag{39}$$

Proof. See Appendix. □

The introduction of the JI mechanism reduces total net emissions, in terms of cooperation and noncooperation, thereby improving the atmospheric environment. In the case of noncooperative games, the carbon emissions used for production will not change, and the improvement of the environment will be achieved through the increase of investment in foreign carbon reduction projects in one country. In the cooperative game scenario, the amount of carbon emission used for production is also reduced. Thus, carbon stocks are reduced more quickly.

Proposition 7. *If $d_1 > d_2$, then $V_2^N(x^N, t) > V_2^A(x^A, t)$.*

Proof. See Appendix. □

This proposition suggests that the introduction of JI mechanism will increase the present value of net revenue any time if the country has lower damage cost. This conclusion is accurate because emission level and emission reductions of Country 2 do not change in the case of noncooperative game. Otherwise, the additional efforts made by Country 1 in terms of emission reduction improved the environment, which resulted in the improved benefits of country 2.

Proposition 8. *We can find a sufficient large T to make*

(1) $V_i^N(x_0^N, 0) > V_i^A(x_0^A, 0), i = 1, 2$.

(2) $V^C(x_0, 0) > V_1^N(x_0, 0) + V_2^N(x_0, 0)$.

Proof. See Appendix. □

Table 1: Parameters' values for numerical solution.

Parameters	a_1	a_2	b_1	b_2	d_1	d_2	γ_1	γ_2	r	ρ	T
	0.08	0.02	224.26	116.80	1	0.15315	0.3	0.2	0.04	0.0083	30

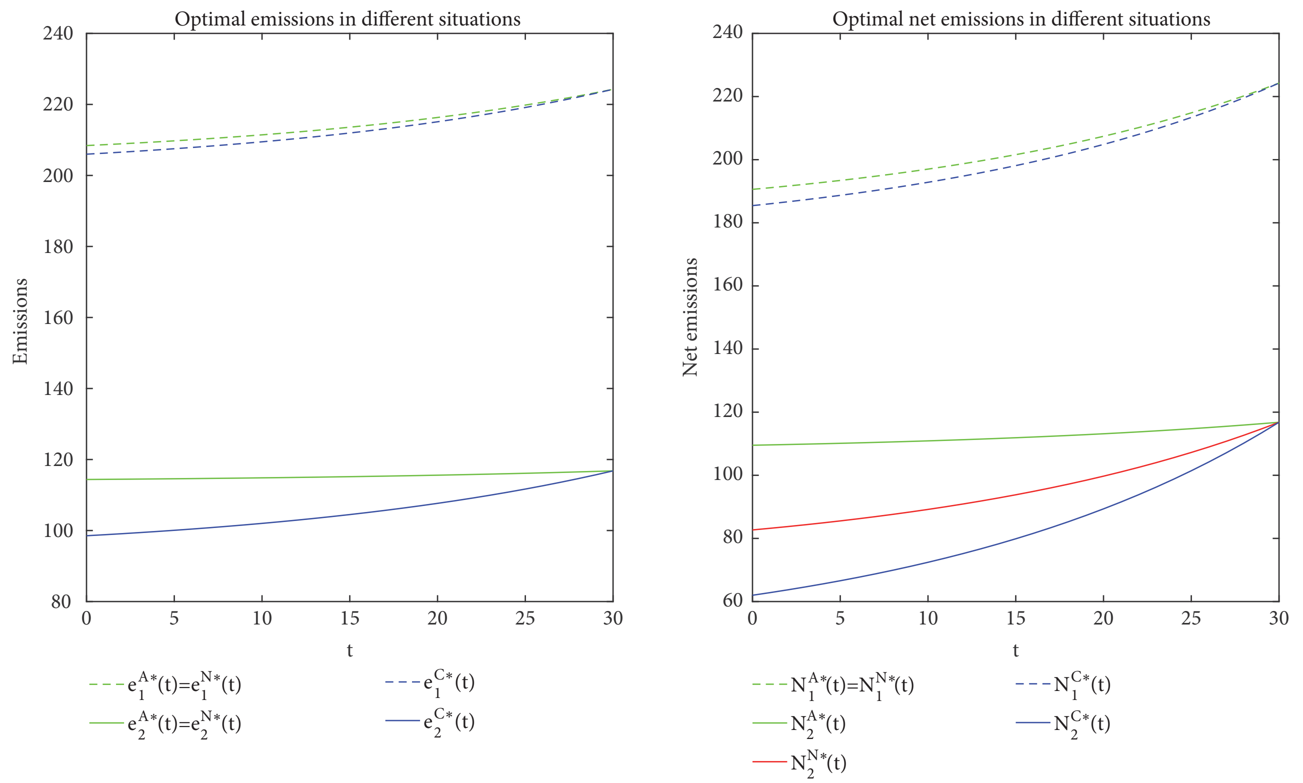

Figure 1: The optimal emissions and net emissions in the case study.

From the perspective of long-term mechanism, these propositions suggest that the introduction of JI mechanism (both noncooperative and cooperative) will increase the welfare of bilateral countries. From another point of view, if United Nations aim to leave positive impact on the economy and the environment of both countries, the JI mechanism must last for a relatively long time.

6. Numerical Example

In this section, we will show the theoretical results of our differential game model through a numerical example. Before proceeding to the simulations, according to the references List et al. (2001 [24]), Athanassoglou et al. (2012 [30]), Mcclellan et al. (2012 [31]) and Manoussi et al. (2017 [32]), we set the important parameters of the model in Table 1. In this case, we assume that d_1 is greater than d_2, and in order to ensure the establishment of Proposition 8, we assume that T is sufficiently large for 30 years. Because in the theoretical framework, we get the optimal decision and optimal state and optimal revenues of both countries of the game, so the main purpose of numerical calculation is to better explain the results of the model so that the reader can better understand.

Firstly, we study the optimal emissions, optimal net emissions, optimal carbon stocks and their respective revenue of both countries in the game over time. We also compare their optimal values in three different situations (without JI, with JI no-cooperation and cooperation), explore the impact of joint implementation noncooperative or cooperative mechanism on environmental improvement and country's revenue.

(1) The optimal emissions and optimal net emissions of two countries under different scenarios are shown in Figure 1. The first figure of Figure 1 shows that the optimal emissions are monotonically increasing and reach the maximum value b_i at time T. It can be seen from the figure that under the cooperative game mechanism, the carbon emissions of each country are lower at each moment than those in the noncooperative game. Thus, Proposition 5(1) holds true. The second figure of Figure 1 shows that the net emissions are also monotonically increasing. It can be seen from the figure that for country 1, under the JI noncooperative mechanism, its net emissions are the same as that without JI mechanism, but higher than that of the cooperative game mechanism. For country 2, due to the introduction of the joint implementation mechanism, country 1 increased the investment in country 2 on environmental projects, so the net emissions under the JI noncooperative game mechanism are lower than

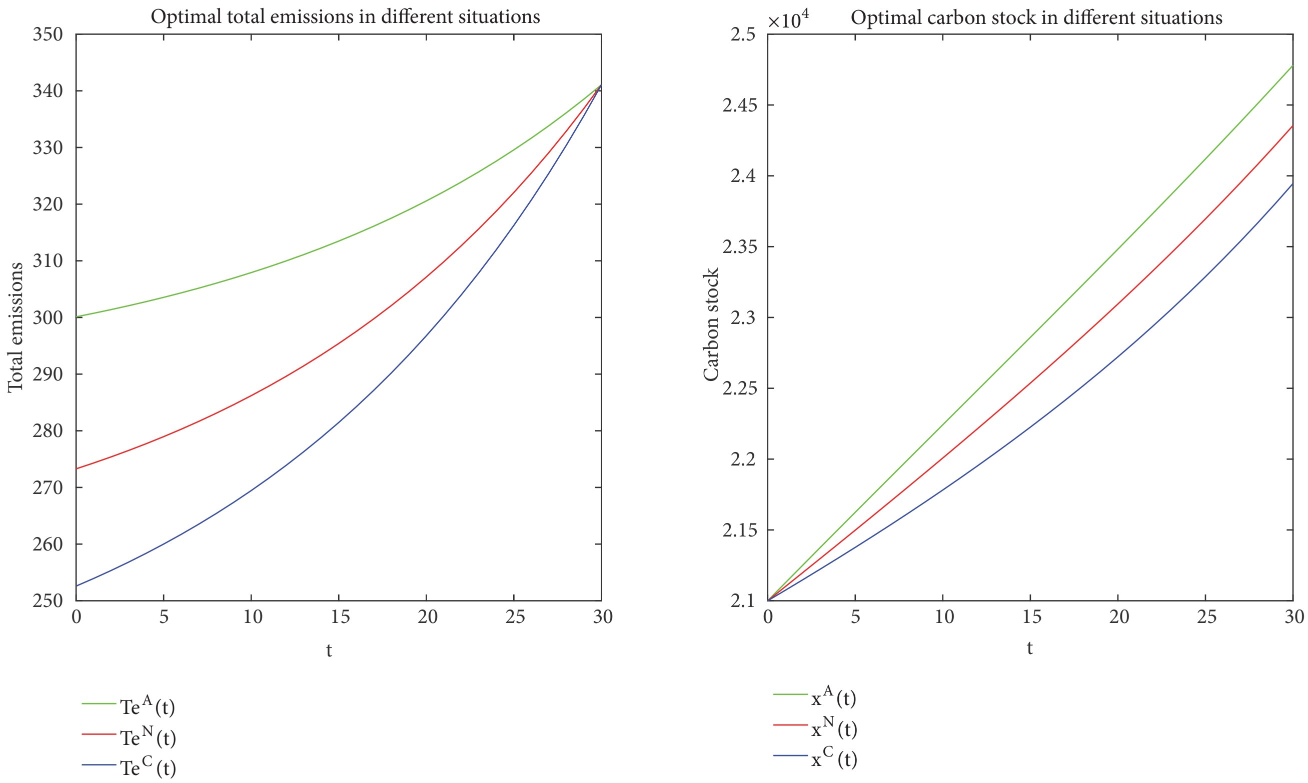

Figure 2: The optimal total net emissions and carbon stocks in the case study.

those without JI mechanism. While when the two countries play a cooperative game, the net emissions of the country 2 are further reduced and Proposition 5(4) holds true.

(2) The first figure of Figure 2 shows the trends in optimal total emissions of different countries under different situations. It can be seen from the figure that the total amount of emissions increases with time in all three situations, the trend is increasing. However, it can be clearly seen that it is the highest in the absence of a joint implementation mechanism, followed by the noncooperative game mechanism, and the cooperative game mechanism is the lowest, which shows that Proposition 6(1) holds true. The second figure of Figure 2 shows the trends in carbon stock under different situations, As a result of changes in emissions and emission reductions in two countries in three different situations, carbon stocks have changed. It can also be clearly seen from the figure that the carbon stock under JI cooperation game mechanism is lower than that of the noncooperative game mechanism at every moment, and is lower than that of the situation without JI mechanism, which shows that Proposition 6(2) holds true. So the introduction of JI mechanism (both noncooperative and cooperative situations) can reduce total net emissions, to improve the atmosphere environment. The second figure of Figure 2 shows that the introduction of JI mechanism in noncooperative situation can reduce the amount of carbon stock, but it can not change the increasing trend. However, the JI mechanism in cooperative game situation can cause the carbon stock to decline rapidly and slowly return to a stable level. Therefore, bilateral countries must reach a high degree of consistency to address environmental problems.

(3) The first figure of Figure 3 shows the welfare of different countries in situation without JI mechanism and with JI mechanism (noncooperative game). This finding demonstrates that the welfare of each country under JI mechanism is higher than that in situation without JI mechanism. The second figure of Figure 3 shows the total welfare of both countries in three different situations. This figure demonstrates that the total welfare under JI cooperative situation is the highest followed by, total welfare under JI noncooperative situation, and the total welfare under situation without JI is the lowest. This finding means that the introduction of cooperative mechanism will improve the environment by reducing the level of production in each country and by increasing the investment in environmental projects. These approaches will also increase the overall economic benefits of both countries.

Secondly, we will further analyze the impact of various key parameters, such as $d_1, d_2, \gamma_1, \gamma_2$, on carbon stock changes in the three different situations.

(1) Let $\Delta x^{AN}(t)$ denote the percentage of carbon stock reduction in JI noncooperative mechanism, compared with that without JI mechanism over time t. We have the form that

$$\Delta x^{AN}(t) = \frac{x^{A}(t) - x^{N}(t)}{x^{A}(t)} \cdot 100\%. \quad (40)$$

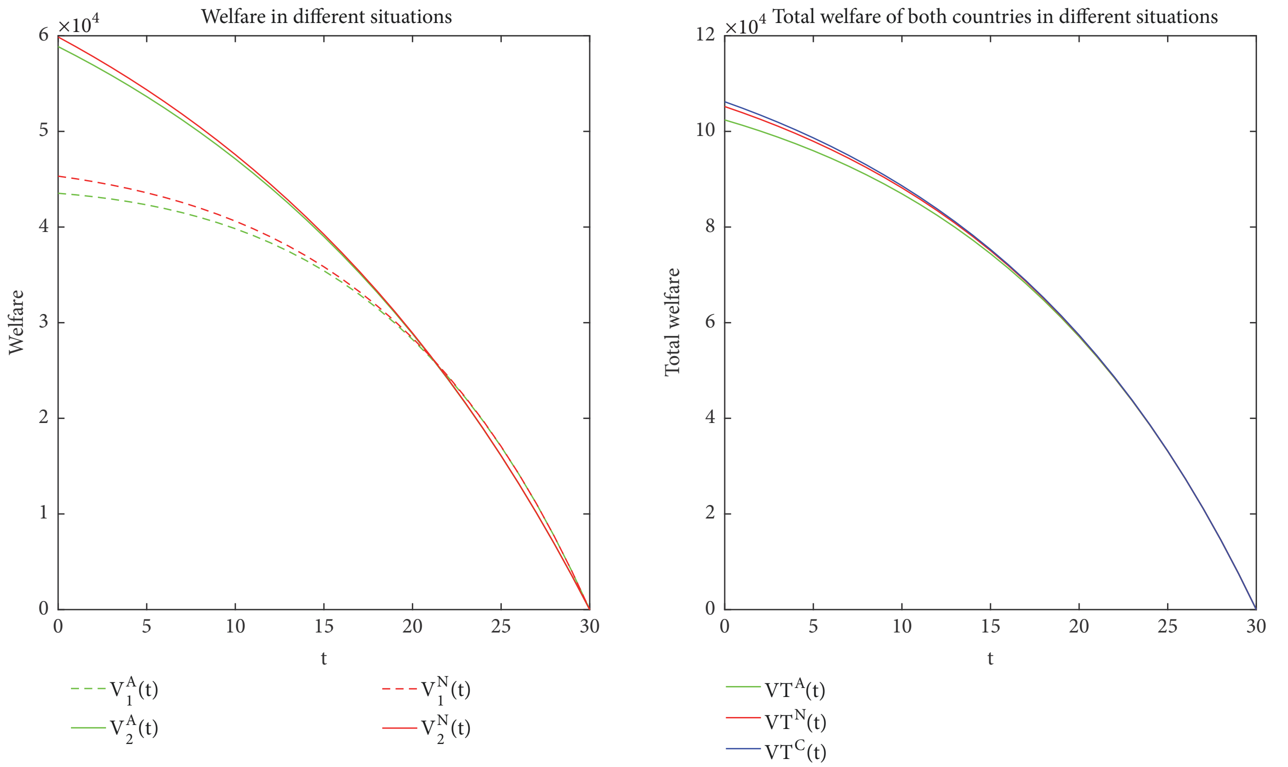

Figure 3: The welfare in the case study.

Let Δx^{AC} denote the percentage carbon reduction of JI cooperative mechanism, compared with that of without JI mechanism over time t. We have the form that

$$\Delta x^{AC}(t) = \frac{x^A(t) - x^C(t)}{x^A(t)} \cdot 100\%. \tag{41}$$

The behavior of $\Delta x^{AN}(t)$ and $\Delta x^{AC}(t)$ can be seen from Figures 4 and 5, as d_1 and d_2 change, respectively. The larger d_1, the greater is the percentage of carbon stocks reduction in the situation of JI noncooperative game and cooperative game, compared to the situation of without joint implementation mechanism. Due to $d_1 > d_2$, in the noncooperative game situation, the introduction of the joint implementation has enabled country 1 to increase the investment in environmental projects to country 2, while the cooperation game mechanism makes both countries pay more attention to carbon emission reduction, so the carbon stock is reduced and the environment is improved. Among them, when d_1 is equal to 1.1, the percentage $\Delta x^{AN}(t)$ can be up to 1.9%; the percentage $\Delta x^{AC}(t)$ can be up to 3.8%. The larger d_2, the greater is the percentage of carbon stocks reduction in the situation of JI noncooperative game, compared to the situation of without joint implementation mechanism. On the contrary, the larger d_2, the smaller is the percentage of carbon stocks reduction in the situation of JI cooperative game. This is because when d_2 becomes larger and d_1 remains unchanged, the gap between them is smaller. At this time, in the cooperative game situation, the promotion effect on both countries is lower. But even then, under the same parameters, cooperative games are more conducive to the reduction of carbon stocks than noncooperative games. Among them, when d_2 is equal to 0.1, the percentage $\Delta x^{AN}(t)$ can be up to 1.8%; when d_2 is equal to 0.4, the percentage $\Delta x^{CN}(t)$ can be up to 4%. It can be seen from the Figures 3 and 4 that the sensitivity of d_1 and d_2 to the percentage of carbon stock reduction is relatively close. This suggests that increasing the country's damage cost for each country has the same effect on environmental improvements.

The behavior of $\Delta x^{AN}(t)$ and $\Delta x^{AC}(t)$ can be seen from Figures 6 and 7, as γ_1, γ_2 changes respectively. The larger γ_1 and γ_2, the greater the percentage of carbon stocks reduction is in the situation of JI noncooperative game and cooperative game, compared to the situation of without JI mechanism. Obviously, the higher the emission reduction technology, the more reduction of carbon stock. Among them, when γ_1 is equal to 0.4, the percentage $\Delta x^{AN}(t)$ can be up to 1.7%; the percentage $\Delta x^{AC}(t)$ can be up to 3.7%. While when γ_2 is equal to 0.4, the percentage $\Delta x^{AN}(t)$ can be up to 7%; the percentage $\Delta x^{AC}(t)$ can be up to 9.7%. It can be clearly seen from the Figures 6 and 7 that γ_2 is more sensitive to the percentage of carbon stock reduction and γ_1 is relatively less sensitive to it. This is because in the JI mechanism, Country 1 will invest in Country 2, and the efficiency of investment depends on the local technology level. Therefore, in order to improve the environment, it is necessary to increase the level of emission reduction technology of the invested countries.

The figures and their characteristics offer the following important conclusions: The introduction of JI mechanism

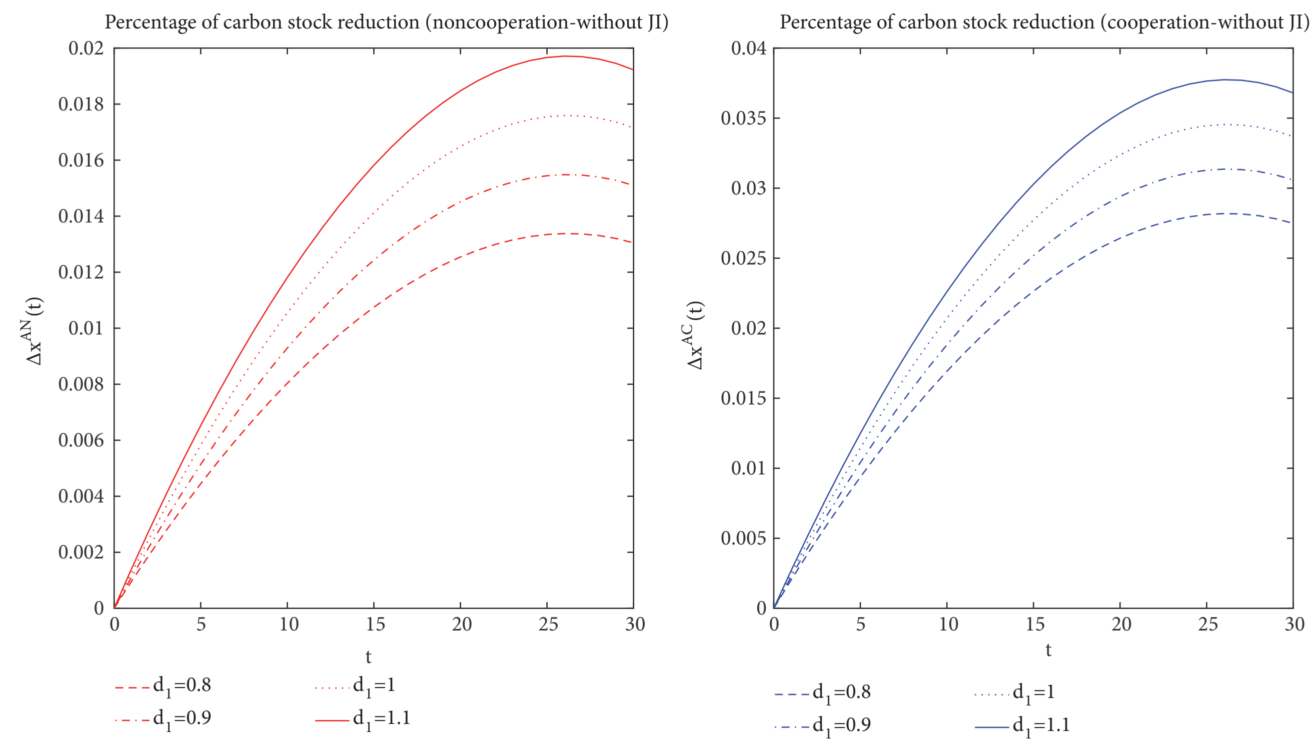

FIGURE 4: The behavior of percentage of carbon stock reduction as d_1 changes.

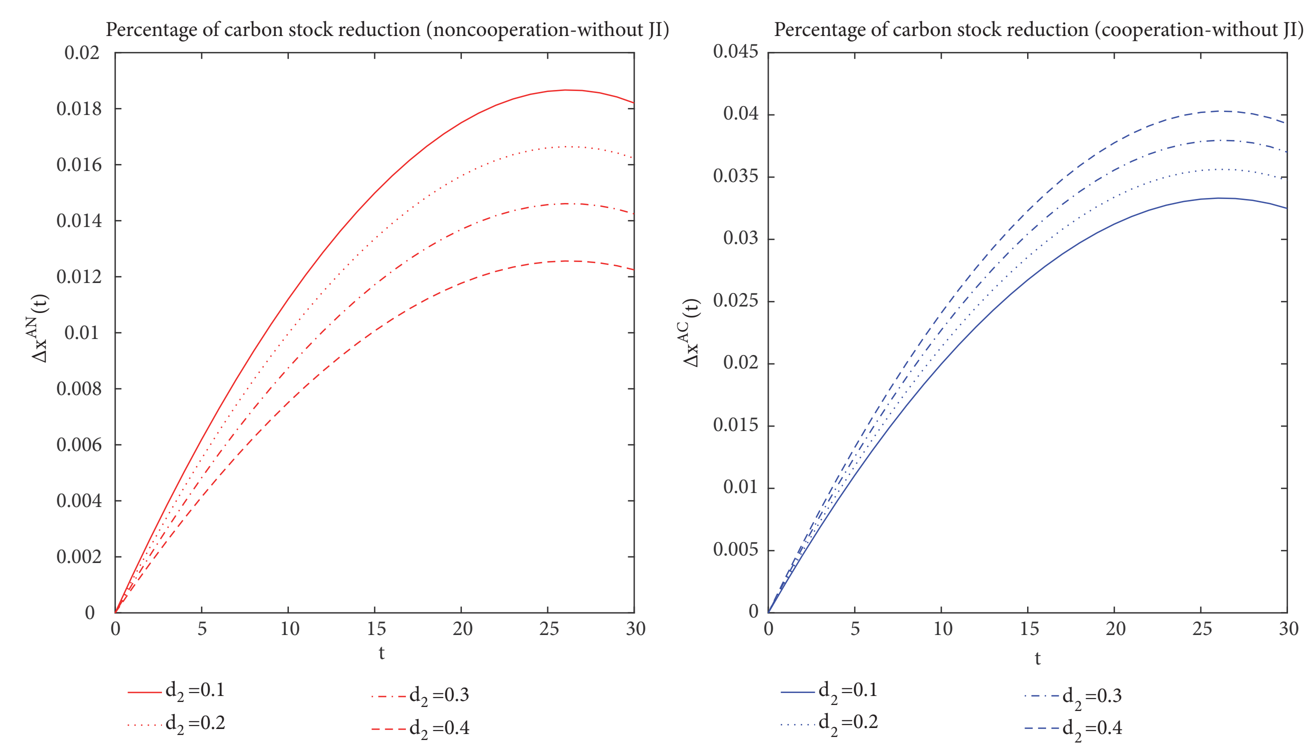

FIGURE 5: The behavior of percentage of carbon stock reduction as d_2 changes.

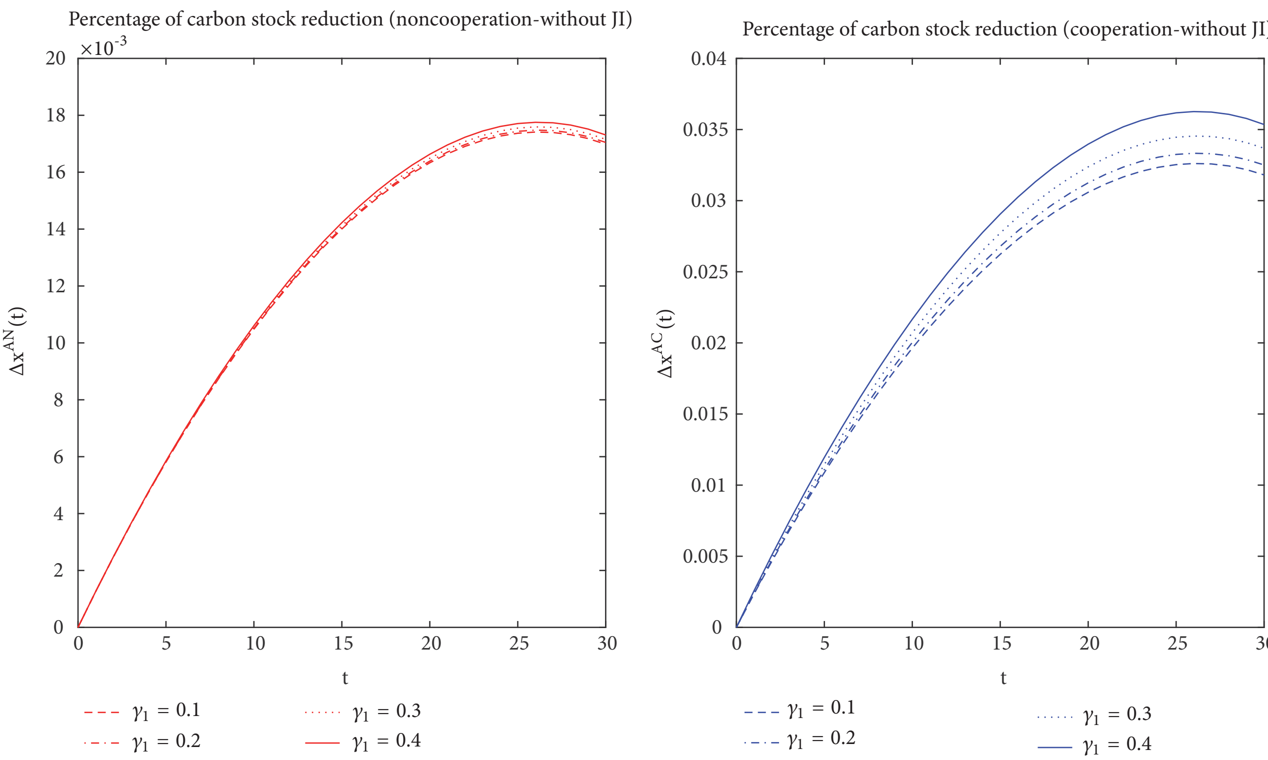

FIGURE 6: The behavior of percentage of carbon stock reduction as γ_1 changes.

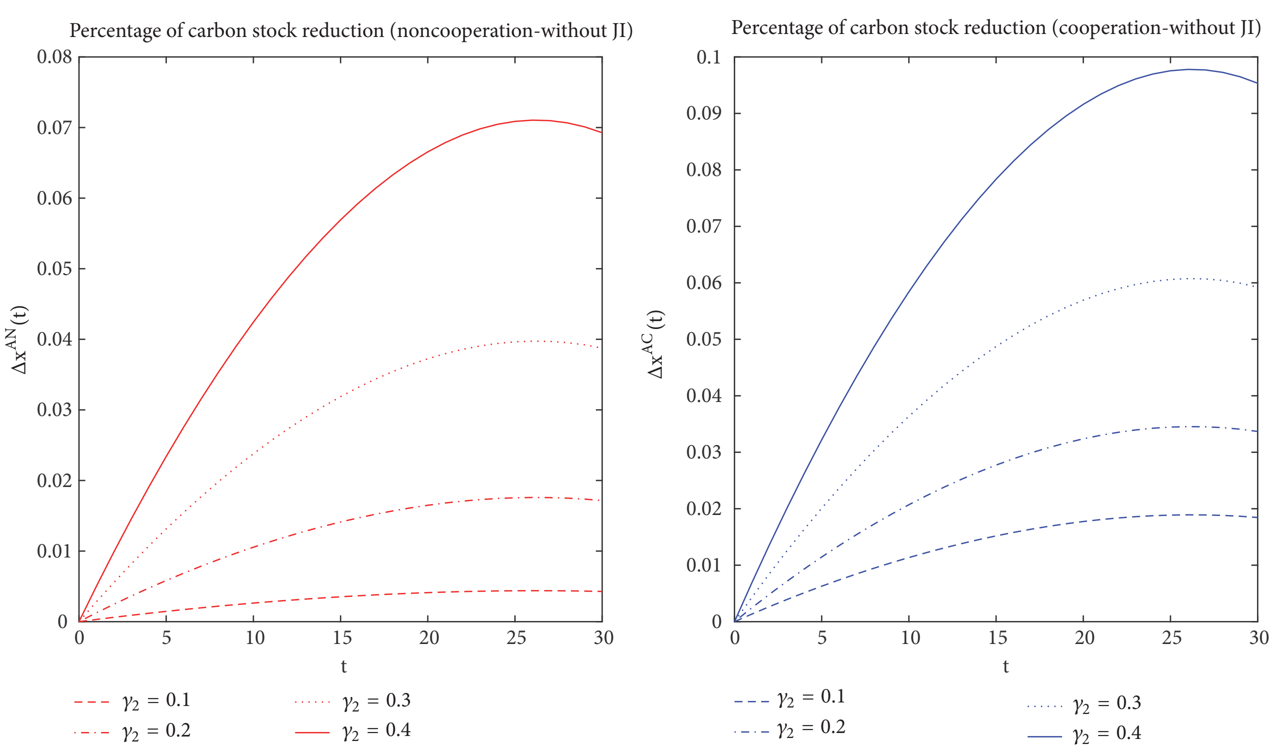

FIGURE 7: The behavior of percentage of carbon stock reduction as γ_2 changes.

(noncooperative game) does not reduce the level of production in various countries and does not change the investment made in local environmental projects of both countries, compared to the situation without JI mechanism. However, Country 1 will make use of the resources of Country 2 to invest in carbon emission reduction projects abroad, to achieve reduction of carbon stock and improve the environment. Foreign investment in emission reduction projects increases, but the welfare of both countries increases due to the introduction of JI mechanism. This outcome is the significance of JI mechanism. In addition, compared with the noncooperative game, the introduction of the cooperative game mechanism will cause both countries to reduce production, and increase the total investment of environmental projects, continuously control the growth of the carbon stock, promote environmental improvement, and do not reduce the welfare of their respective countries. In addition, countries can further expand the percentage of carbon stocks reduction by increasing their environmental awareness and improving carbon emission reduction efficiency, thereby achieve environmental improvement.

7. Conclusion

We discuss the optimal emissions and, optimal investment in environmental projects of two bilateral countries in pollution control problems by using differential game models. First, we consider the basic model of three situations: without JI, with JI noncooperative and cooperative game. We then discuss their Nash equilibrium solutions and reach conclusions by comparing these solutions.

(1) The introduction of JI (noncooperative) mechanisms can not change the emissions and local investments in environmental projects of both countries, compared to the situation without JI. Country 1 with a bigger damage cost parameter will choose foreign investment under the situation of JI noncooperative game. The cooperation mechanism has not changed the emission trends in both countries over time, but the carbon emissions of each country at cooperative situation are lower, and the total investments in environmental projects are more than those in the other two situations.

(2) Since the JI mechanism will not cause country 2 to invest environmental projects in country 1, and country 1 does not change its carbon emissions, so the net emissions of the country 1 have not changed compared to the situation without JI mechanism. However, the introduction of the JI mechanism has enabled country 1 to actively participate in the environmental project investment of country 2, so the introduction of the JI noncooperative game mechanism has reduced the net emissions of country 2. Under the JI cooperative game mechanism, since the two countries have common goals, their net emissions will be effectively reduced compared to the other two situations. Therefore, the growth of carbon stocks has been effectively controlled under the JI noncoopertive or cooperative mechanism, and the quality of the environment is improved.

(3) A long-term development of JI noncooperative or cooperative mechanism will not only control the growth of carbon stocks, improve the quality of the environment, but it will also increase the revenue of both countries, according to theoretical and numerical results.

Appendix

Proof of Proposition 1. (1) By using the dynamic programming principle, we can get the HJB equations:

$$\max_{e_i^A, I_{ii}^A} \left(F_i^A(t) + \frac{\partial V_i^A}{\partial x^A} f^A(t) + \frac{\partial V_i^A}{\partial t} - r V_i^A \right) = 0, \tag{A.1}$$

with the terminal condition

$$V_i^A\left(x_T^A, T\right) = 0. \tag{A.2}$$

According to the first-order optimal condition, we know the optimal emission levels $e_i^{A*}(t)$ and the local investment levels $I_{ii}^{A*}(t)$ can be given by the following equations:

$$\begin{aligned} e_i^{A*}(t) &= \frac{\partial V_i^A}{\partial x^A} + b_i, \\ I_{ii}^{A*}(t) &= -\frac{\gamma_i}{a_i} \frac{\partial V_i^A}{\partial x^A} \end{aligned} \tag{A.3}$$

We conjecture that $V_i^A(x^A, t)$ are the linear functions with respect x, that is

$$V_i^A\left(x^A, t\right) = l_i^A(t) x^A + k_i^A(t), \quad i = 1, 2 \tag{A.4}$$

where $l_i^A(t)$ and $k_i^A(t)$ are the functions of t. Substituting the first-order condition (A.3) into the HJB equation (A.1), we get

$$\begin{aligned} &\left(l_i^{A\prime}(t) - (\rho + r) l_i^A(t) - d_i \right) x^A + k_i^{A\prime}(t) - r k_i^A(t) \\ &\quad + g_i^A(t) = 0, \end{aligned} \tag{A.5}$$

where

$$\begin{aligned} g_i^A(t) = {} & \frac{1}{2}\left(1 + \frac{\gamma_i^2}{a_i}\right)\left(l_i^A(t)\right)^2 \\ & + \left(1 + \frac{\gamma_j^2}{a_j}\right) l_i^A(t) l_j^A(t) + \left(b_i + b_j\right) l_i^A(t) \\ & + \frac{1}{2} b_i^2. \end{aligned} \tag{A.6}$$

Noting that the system (A.5) should be satisfied for all $x > 0$, we can determine $l_i^A(t)$ and $k_i^A(t)$ by solving the following ordinary differential equations:

$$\begin{aligned} l_i^{A\prime}(t) - (\rho + r) l_i^A(t) - d_i &= 0, \\ l_i^A(T) &= 0 \end{aligned} \tag{A.7}$$

$$\begin{aligned} k_i^{A\prime}(t) - r k_i^A(t) + g_i^A(t) &= 0, \\ k_i^A(T) &= 0. \end{aligned} \tag{A.8}$$

Then by solving the differential equation (A.7), we get

$$l_i^A = \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) \quad (A.9)$$

then

$$\begin{aligned} e_i^{A*}(t) &= \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i; \\ I_{ii}^{A*}(t) &= -\frac{\gamma_i}{a_i}\frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right). \end{aligned} \quad (A.10)$$

(2) Substituting (A.9) into (A.6), we get

$$g_i^A(t) = \mu_i^A \exp^{-2(r+\rho)(T-t)} + \nu_i^A \exp^{-(r+\rho)(T-t)} + \theta_i^A \quad (A.11)$$

where $\mu_i^A = (1/2)(1+\gamma_i^2/a_i)(d_i/(r+\rho))^2 + (1+\gamma_j^2/a_j)(d_i d_j/(r+\rho)^2)$, $\nu_i^A = -2\mu_i^A + (b_i+b_j)(d_i/(r+\rho))$ and $\theta_i^A = \mu_i^A - (b_i+b_j)(d_i/(r+\rho)) + (1/2)b_i^2$. By solving the differential equation (A.8), we get

$$\begin{aligned} k_i^A(t) &= -\frac{\mu_i^A}{r+2\rho}\exp^{-2(r+\rho)(T-t)} - \frac{\nu_i^A}{\rho}\exp^{-(r+\rho)(T-t)} \\ &\quad + \frac{\theta_i^A}{r} + \left(\frac{\mu_i^A}{r+2\rho} + \frac{\nu_i^A}{\rho} - \frac{\theta_i^A}{r}\right)\exp^{-r(T-t)}. \end{aligned} \quad (A.12)$$

Then

$$\begin{aligned} V_i^A\left(x^A, t\right) &= \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x \\ &\quad - \frac{\mu_i^A}{r+2\rho}\exp^{-2(r+\rho)(T-t)} \\ &\quad - \frac{\nu_i^A}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta_i^A}{r} \\ &\quad + \left(\frac{\mu_i^A}{r+2\rho} + \frac{\nu_i^A}{\rho} - \frac{\theta_i^A}{r}\right)\exp^{-r(T-t)}. \end{aligned} \quad (A.13)$$

(3) Substituting the optimal emissions and local investments (21) into equation (12), by solving it, we get

$$\begin{aligned} x^A(t) &= \frac{\alpha^A}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^A}{\rho} \\ &\quad + \left(x_0 - \frac{\beta^A}{\rho} - \frac{\alpha^A}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t}, \end{aligned} \quad (A.14)$$

where $\alpha^A = (1+\gamma_1^2/a_1)(d_1/(r+\rho)) + (1+\gamma_2^2/a_2)(d_2/(r+\rho))$, $\beta^A = b_1 + b_2 - \alpha^A$. □

Proof of Proposition 3. (1) By using the dynamic programming principle, we can get the HJB equations:

$$\begin{aligned} &\max_{e_i^N, I_{ii}^N, I_{ij^N}} \left(F_i^N(t) + \frac{\partial V_i^N}{\partial x^N} f^N(t) + \frac{\partial V_i^N}{\partial t} - rV_i^N\right) \\ &= 0, \end{aligned} \quad (A.15)$$

with the terminal condition

$$V_i^N\left(x_T^N, T\right) = 0. \quad (A.16)$$

According to the first-order optimal condition, we know the optimal emission levels $e_i^{N*}(t)$ and the local investment levels $I_{ii}^{N*}(t)$ can be given by the following equations:

$$\begin{aligned} e_i^{N*}(t) &= \frac{\partial V_i^N}{\partial x^N} + b_i, \\ I_{ii}^{N*}(t) &= -\frac{\gamma_i}{a_i}\left(\frac{\partial V_i^N}{\partial x^N}\right), \end{aligned} \quad (A.17)$$

and because $d_1 > d_2$, then the foreign investments are given as

$$\begin{aligned} I_{12}^{N*}(t) &= \frac{\gamma_2}{a_2}\left(\frac{\partial V_2^N}{\partial x^N} - \frac{\partial V_1^N}{\partial x^N}\right); \\ I_{21}^{N*}(t) &= 0. \end{aligned} \quad (A.18)$$

We conjecture that $V_i^N(x,t)$ are the linear functions with respect x, that is

$$V_i^N\left(x^N, t\right) = l_i^N(t)\, x^N + k_i^N(t), \quad (A.19)$$

where $l_i^N(t)$ and $k_i^N(t)$ are the functions of t.

Substituting the first-order condition (A.17) and (A.18) into the HJB equation (A.15), we get

$$\begin{aligned} &\left(l_i^{N\prime}(t) - (\rho+r)\, l_i^N(t) - d_i\right)x^N + k_i^{N\prime}(t) \\ &- rk_i^N(t) + g_i^N(t) = 0, \end{aligned} \quad (A.20)$$

where

$$\begin{aligned} g_i^N(t) &= \frac{1}{2}\left(1 + \frac{\gamma_i^2}{a_i} + \frac{\gamma_j^2}{a_j}\right)l_i^2 + l_i l_j + \frac{1}{2}\frac{\gamma_j^2}{a_j}l_j^2 \\ &\quad + \left(b_i + b_j\right)l_i + \frac{1}{2}b_i^2. \end{aligned} \quad (A.21)$$

Noting that the system (A.20) should be satisfied for all $x > 0$, we can determine $l_i^N(t)$ and $k_i^N(t)$ by solving the following ordinary differential equations:

$$\begin{aligned} l_i^{N\prime}(t) - (\rho+r)\, l_i^N(t) - d_i &= 0, \\ l_i^N(T) &= 0; \end{aligned} \quad (A.22)$$

$$\begin{aligned} k_i^{N\prime}(t) - rk_i^N(t) + g_i^N(t) &= 0, \\ k_i^N(T) &= 0. \end{aligned} \quad (A.23)$$

Then by solving the differential equation (A.22), we get

$$l_i^N = \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right). \quad (A.24)$$

Then

$$e_i^{N*}(t) = \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i;$$
$$I_{ii}^{N*}(t) = -\frac{\gamma_i}{a_i}\frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right). \tag{A.25}$$

And for $d_1 > d_2$, we have

$$I_{12}^{N*}(t) = \frac{\gamma_2}{a_2}\left(\frac{d_2 - d_1}{r+\rho}\right)\left(\exp^{-(r+\rho)(T-t)} - 1\right);$$
$$I_{21}^{N*}(t) = 0; \tag{A.26}$$

(2) Substitute (A.24) into (A.21), and we get

$$g_i^N(t) = \mu_i^N \exp^{-2(r+\rho)(T-t)} + \nu_i^N \exp^{-(r+\rho)(T-t)} + \theta_i^N, \tag{A.27}$$

where $\mu_i^N = (1/2)(1 + \gamma_i^2/a_i + \gamma_j^2/a_j)(d_i/(r+\rho))^2 + d_i d_j/(r+\rho)^2 + (1/2)(\gamma_j^2/a_j)(d_j/(r+\rho))^2$, $\nu_i^N = -2\mu_i^N + (b_i + b_j)(d_i/(r+\rho))$ and $\theta_i^N = \mu_i^N - (b_i + b_j)(d_i/(r+\rho)) + (1/2)b_i^2$.

By solving the differential equation (A.23), we get

$$k_i^N(t) = -\frac{\mu_i^N}{r+2\rho}\exp^{-2(r+\rho)(T-t)} - \frac{\nu_i^N}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta_i^N}{r} + \left(\frac{\mu_i^N}{r+2\rho} + \frac{\nu_i^N}{\rho} - \frac{\theta_i^N}{r}\right)\exp^{-r(T-t)}. \tag{A.28}$$

Then

$$V_i^N\left(x^N, t\right) = \frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x - \frac{\mu_i^N}{r+2\rho}\exp^{-2(r+\rho)(T-t)} - \frac{\nu_i^N}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta_i^N}{r} + \left(\frac{\mu_i^N}{r+2\rho} + \frac{\nu_i^N}{\rho} - \frac{\theta_i^N}{r}\right)\exp^{-r(T-t)}. \tag{A.29}$$

(3) Substitute (25) and (27) into (15), and, by solving it, we get

$$x^N(t) = \frac{\alpha^N}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^N}{\rho} + \left(x_0 - \frac{\beta^N}{\rho} - \frac{\alpha^N}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t}, \tag{A.30}$$

where $\alpha^N = (1 + \gamma_1^2/a_1 + \gamma_2^2/a_2)(d_1/(r+\rho)) + (d_2/(r+\rho))$, $\beta^N = b_1 + b_2 - \alpha^N$. □

Proof of Proposition 4. By using the dynamic programming principle, we can get the HJB equations:

$$\max_{e_1^C, e_2^C, I_{11}^C + I_{21}^C, I_{12}^C + I_{22}^C}\left(F^C(t) + \frac{\partial V^C}{\partial x^C} f^C(t) + \frac{\partial V^C}{\partial t} - rV^C\right) = 0. \tag{A.31}$$

with the terminal condition

$$V^C\left(x_T^C, T\right) = 0. \tag{A.32}$$

According to the first-order optimal condition, we know the optimal emission levels $e_i^{C*}(t)$, the local investment levels $I_{ii}^{C*}(t)$ and the foreign investments $I_{ij}^{C*}(t)$ can be given by the following equations:

$$e_i^{C*}(t) = \frac{\partial V^C}{\partial x^C} + b_i,$$
$$I_{ii}^{C*}(t) + I_{ji}^{C*}(t) = -\frac{\gamma_i}{a_i}\left(\frac{\partial V^C}{\partial x^C}\right), \quad i = 1, 2; \tag{A.33}$$

We conjecture that $V^C(x, t)$ is the linear function with respect x, that is

$$V^C\left(x^C, t\right) = l(t)x^C + k(t), \tag{A.34}$$

where $l(t)$ and $k(t)$ are the functions of t.

Substituting the first-order condition (A.33) into the HJB equation (A.31), we get

$$\left(l'(t) - (\rho + r)l(t) - (d_1 + d_2)\right)x^C + k'(t) - rk(t) + g(t) = 0, \tag{A.35}$$

where

$$g(t) = \left(1 + \frac{1}{2}\frac{\gamma_1^2}{a_1} + \frac{1}{2}\frac{\gamma_2^2}{a_2}\right)l^2 + (b_1 + b_2)l + \frac{1}{2}\left(b_1^2 + b_2^2\right). \tag{A.36}$$

Noting that the system (A.35) should be satisfied for all $x > 0$, we can determine $l(t)$ and $k(t)$ by solving the following ordinary differential equations:

$$l'(t) - (\rho + r)l(t) - (d_1 + d_2) = 0, \quad l(T) = 0; \tag{A.37}$$

$$k'(t) - rk(t) + g(t) = 0, \quad k(T) = 0. \tag{A.38}$$

By solving the differential equation (A.37), we get

$$l(t) = \frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right). \tag{A.39}$$

Then

$$e_i^{C*}(t) = \frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right) + b_i, \quad i = 1, 2;$$
$$I_{ii}^{C*}(t) + I_{ji}^{C*}(t) = -\frac{\gamma_i}{a_i}\left(\frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)\right), \quad i = 1, 2. \tag{A.40}$$

(2) Substitute (A.39) into (A.36), and we get

$$g^C(t) = \mu^C \exp^{-2(r+\rho)(T-t)} + \nu^C \exp^{-(r+\rho)(T-t)} + \theta^C, \quad (A.41)$$

where

$$\begin{aligned}\mu^C &= \left(1 + \frac{1}{2}\frac{\gamma_1^2}{a_1} + \frac{1}{2}\frac{\gamma_2^2}{a_2}\right)\left(\frac{d_1 + d_2}{r+\rho}\right)^2, \\ \nu^C &= -2\mu^C + (b_1 + b_2)\frac{d_1 + d_2}{r+\rho}, \\ \theta^C &= \mu^C - (b_1 + b_2)\frac{d_1 + d_2}{r+\rho} + \frac{1}{2}\left(b_1^2 + b_2^2\right).\end{aligned} \quad (A.42)$$

By solving the differential equation (A.38), we get

$$\begin{aligned}k^C(t) = &-\frac{\mu^C}{r+2\rho}\exp^{-2(r+\rho)(T-t)} - \frac{\nu^C}{\rho}\exp^{-(r+\rho)(T-t)} \\ &+ \frac{\theta^C}{r} + \left(\frac{\mu^C}{r+2\rho} + \frac{\nu^C}{\rho} - \frac{\theta^C}{r}\right)\exp^{-r(T-t)}\end{aligned} \quad (A.43)$$

Then

$$\begin{aligned}V^C\left(x^C, t\right) = &\frac{d_1 + d_2}{r+\rho}\left(\exp^{-(r+\rho)(T-t)} - 1\right)x \\ &- \frac{\mu^C}{r+2\rho}\exp^{-2(r+\rho)(T-t)} \\ &- \frac{\nu^C}{\rho}\exp^{-(r+\rho)(T-t)} + \frac{\theta^C}{r} \\ &+ \left(\frac{\mu^C}{r+2\rho} + \frac{\nu^C}{\rho} - \frac{\theta^C}{r}\right)\exp^{-r(T-t)}.\end{aligned} \quad (A.44)$$

(3) Substituting (24) and (31) into (18), by solving it, we get

$$\begin{aligned}x^C(t) = &\frac{\alpha^C}{r+2\rho}\exp^{-(r+\rho)(T-t)} + \frac{\beta^C}{\rho} \\ &+ \left(x_0 - \frac{\beta^C}{\rho} - \frac{\alpha^C}{r+2\rho}\exp^{-(r+\rho)T}\right)\exp^{-\rho t},\end{aligned} \quad (A.45)$$

where $\alpha^C = (2 + \gamma_i^2/a_i + \gamma_j^2/a_j)((d_1 + d_2)/(r+\rho))$, $\beta^C = b_1 + b_2 - \alpha^C$. □

Proof of Proposition 5. We can get the first three proposition from the Propositions 1, 3 and 4 straightforward.

For the two countries $i = 1, 2$, we have

$$\begin{aligned}N_i^{A*}(t) &= e_i^{A*}(t) - \gamma_i I_{ii}^{A*}(t), \\ N_i^{N*}(t) &= e_i^{N*}(t) - \gamma_i\left(I_{ii}^{N*}(t) + I_{ji}^{N*}(t)\right)\end{aligned} \quad (A.46)$$

and

$$N_i^{C*}(t) = e_i^{C*}(t) - \gamma_i\left(I_{ii}^{C*}(t) + I_{ji}^{C*}(t)\right), \quad (A.47)$$

then we can get

$$\begin{aligned}N_i^{A*}(t) &= \left(1 + \frac{\gamma_i^2}{a_i}\right)\frac{d_i}{r+\rho}\left(\exp^{-(r+\rho)(T-t)-1}\right) + b_i; \\ N_1^{N*}(t) &= \left(1 + \frac{\gamma_1^2}{a_1}\right)\frac{d_1}{r+\rho}\left(\exp^{-(r+\rho)(T-t)-1}\right) + b_1, \\ N_2^{N*}(t) &= \left(\frac{d_2}{r+\rho} + \frac{\gamma_2^2}{a_2}\frac{d_1}{r+\rho}\right)\left(\exp^{-(r+\rho)(T-t)-1}\right) \\ &\quad + b_2; \\ N_i^{C*}(t) &= \left(1 + \frac{\gamma_i^2}{a_i}\right)\frac{d_i + d_j}{r+\rho}\left(\exp^{-(r+\rho)(T-t)-1}\right) \\ &\quad + b_i.\end{aligned} \quad (A.48)$$

Then

$$N_1^{A*}(t) = N_1^{N*}(t) > N_1^{C*}(t); \quad (A.49)$$

because $d_1 > d_2$, we can get

$$N_2^{A*}(t) > N_2^{N*}(t) > N_2^{C*}(t). \quad (A.50)$$

□

Proof of Proposition 6. (1) For $Te(t) = N_i(t) + N_j(t)$, then by the inequalities (37), we get

$$Te^{A*}(t) > Te^{N*}(t) > Te^{C*}(t). \quad (A.51)$$

(2) Because of $\dot{x}(t) = N_i(t) + N_j(t) - \rho x(t)$, $x(0) = x_0$ and $\rho > 0$, then from the nature of ordinary differential equation, we get

$$x^A(t) > x^N(t) > x^C(t). \quad (A.52)$$

□

Proof of Proposition 7. The welfare is given by

$$\begin{aligned}V_2^A\left(x^A, t\right) &= \int_t^T F_2^A(w)\exp^{-r(w-t)}dw \\ V_2^N\left(x^N, t\right) &= \int_t^T F_2^N(w)\exp^{-r(w-t)}dw\end{aligned} \quad (A.53)$$

Since $e_2^{A*}(t) = e_2^{N*}(t)$, $I_{22}^{A*}(t) = I_{22}^{N*}(t)$, and $I_{21}^{N*}(t) = 0$, then

$$\begin{aligned}&V_2^N\left(x^N, t\right) - V_2^A\left(x^A, t\right) \\ &= \int_t^T \left(F_2^N(w) - F_2^A(w)\right)\exp^{-r(w-t)}dw \\ &= \int_t^T d_2\left(x^A(w) - x^N(w)\right)\exp^{-r(w-t)}dw\end{aligned} \quad (A.54)$$

For $x^A(t) > x^N(t)$, then

$$V_2^N\left(x^N, t\right) > V_2^A\left(x^A, t\right). \quad (A.55)$$

□

Proof of Proposition 8. (1) From (22) and (28), we can get

$$\begin{aligned} &V_i^N(x_0,0)-V_i^A(x_0,0)\\ &=\left(\frac{1}{(r+2\rho)T}\left(1-\exp^{-(r+2\rho)T}\right)\right.\\ &\quad\left.+\frac{2}{\rho T}\left(\exp^{-\rho T}-1\right)+\frac{1}{rT}\left(\exp^{rT}-1\right)\right)\\ &\quad\cdot T\mu_i\exp^{-rT}, \end{aligned} \tag{A.56}$$

where $\mu_i=(1/2)(\gamma_j^2/a_j)((d_i-d_j)/(r+\rho))^2$.

If $T>[\ln 2/(r+\rho)]^+$, we can see that $(2/\rho T)(\exp^{-\rho T}-1)+(1/rT)(\exp^{rT}-1)$ is monotonically increasing about T, then we can find a sufficient large T make

$$\frac{2}{\rho T}\left(\exp^{-\rho T}-1\right)+\frac{1}{rT}\left(\exp^{rT}-1\right)>0. \tag{A.57}$$

And because $(1/(r+2\rho)T)(1-\exp^{-(r+2\rho)T})>0$, then we get

$$V_i^N(x_0,0)>V_i^A(x_0,0),\quad i=1,2. \tag{A.58}$$

(2) From (28) and (32), we can get

$$\begin{aligned} &V^C(x_0,0)-V_1^N(x_0,0)-V_2^N(x_0,0)\\ &=\left(\frac{1}{(r+2\rho)T}\left(1-\exp^{-(r+2\rho)T}\right)\right.\\ &\quad\left.+\frac{2}{\rho T}\left(\exp^{-\rho T}-1\right)+\frac{1}{rT}\left(\exp^{rT}-1\right)\right)\\ &\quad\cdot T\mu\exp^{-rT}, \end{aligned} \tag{A.59}$$

where $\mu=(1/2)(1+\gamma_1^2/a_1)d_1^2+(1/2)(1+\gamma_2^2/a_2)d_2^2$.

So, with the same method of proving of (1), we can can find sufficient long T; make

$$V^C(x_0,0)>V_1^N(x_0,0)+V_2^N(x_0,0). \tag{A.60}$$

□

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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