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Abstract: This study analyzes how the Green Climate Fund (GCF) should raise and allocate funds to achieve Pareto optimality in climate governance globally and its own fiscal balance. To make the conclusion more suitable for global climate governance analysis, this study modifies the hypothesis of the public externality model constructed by Baumol and Oates. Subsequently, by comparing the Pareto optimality model of global climate governance and market equilibrium model, this study infers the unique price conditions to induce the market to satisfy Pareto-optimality requirements. Subsequently, this study deduces the rules and the possible ways that must be followed for raising capital and allocating of GCFs while considering global Pareto optimality and fiscal balance. The study observes that the equilibrium results of the international climate game will not achieve the global Pareto-optimality and the financial balance of GCF simultaneously when each country anticipates that the GCF aims to Pareto optimality in climate governance globally and its own fiscal balance.

Keywords: Green Climate Fund; Capital Raising and Allocation; Global Pareto Optimality; Fiscal Balance; Mathematical Model.

JEL: Q54; Q58; H23; C62; P45

Introduction

Climate change caused by excessive greenhouse gas (GHG) emissions affect the survival and development of all mankind. Therefore, controlling and mitigating GHG emissions and adapting to climate change have become a global public concern. As a global public externality, it would be essential to adopt a concerted and comprehensive approach across the globe to reduce GHG emissions. Therefore, in June 1992, the United Nations Conference on Environment and Development was held in Rio de Janeiro, Brazil, which initiated the practice of global climate governance. In this meeting, 154 countries or regions signed the United Nations Framework Convention on Climate Change (UNFCCC). According to the provisions of the UNFCCC, since 1995, the international community has been convening a conference of parties to the UNFCCC every year to discuss specific GHG reduction actions and institutional arrangements.

Although the international environmental agreement on climate governance has not yet been formed, according to the dynamic game analysis of Chander (2010, 2017) and Chander &Wooders (2010), a grand coalition is an equilibrium coalition structure, and the only way to achieve a Pareto efficient outcome in the game would be to negotiate appropriate benefit transfer among countries across the globe. In fact, the global distribution of losses caused by climate change is uneven, and different countries have different historical responsibilities for global warming. Developed countries, as main emitters of GHGs, have an inescapable historical responsibility toward global warming (Lianbiao et al., 2015). In addition, differences in the economic development, science, technology, or the state of the ecological environment, among others, in each country leads to substantial differences in their GHG-reduction potential. Therefore, inter-state financial support and technical assistance are necessary to coordinate responsibility and GHG mitigation in all countries around the world. It is in this context that international climate financing comes into the picture.

Currently, several international environmental funds are involved in addressing climate change, such as the Global Environment Facility (GEF), Special Climate Change Fund (SCCF), Least Developed Countries Fund (LDCF), and Adaptation Fund (AF), among others (Lianbiao, 2014; Qian et al., 2015). However, these international environmental funds are limited in size and are yet to constitute a stable source of long-term funding. Therefore, it would be difficult to construct a systematic and comprehensive mechanism that can coordinate global participation and contribute toward resolving differences in interests in global climate governance through these funds. In addition, it is difficult for the capital sources of these traditional international environmental funds to achieve long-term funding goals (Lv ye and Yang Pu, 2017). Therefore, the Green Climate Fund (GCF) was proposed at the 2009 Convention’s Conference of Parties (COP) in Copenhagen (COP16) ， which is expected to play a key role in the governance of the long-term finance pledge (Fridahl and Linnér, 2016). The GCF was further negotiated at COP17 in Cancun in 2010, and it was finally agreed to start GCF’s operations at COP18 in Durban in 2011 (Qian et al., 2015; Lattanzio, 2014). According to the requirements of the *Copenhagen Accord* and *the Cancún Agreements,* developed countries were required to invest US$30 billion to accelerate the commencement of the GCF between 2010 and 2012, and to provide long-term funds amounting to US$100 billion annually by 2020 for helping developing countries cope with climate change (Fridahl and Linnér, 2016). However, until 2017, the developed countries have only injected capital totaling to US$10.3 billion to the GCF—far from the agreed target (Manzanares, 2017). Therefore, since inception, the GCF has been one of the crucial topics for the international community, governments, and academia.

The academia has carried out in-depth discussions on the establishment purpose, operation mechanism, raising and allocation of funds, and fund use of the GCF, among others; however, fund raising and fund allocation remain the core issues of the GCF. Table I lists several major academic perspectives on these two core issues. Some studies have also simulated the implementation effect of various fund raising and allocation schemes (Cui et al., 2014; Antimiani et al., 2014).

Table I: A summary of the main ideas of the raising of funds and the allocation of GCF in existing literature

	Program	
	Serial number	Name
Fund raising	1	Financing scheme by auctioning the initial international GHG emission rights (Hof et al., 2011)
	2	Financing scheme by collecting the international aviation and marine carbon tax (Hof et al.., 2011)
	3	Financing scheme by collecting the international carbon tax (Hof et al., 2011; Silverstein, 2013)
	4	Financing scheme that taxes the clean development mechanism (CDM) transactions (Hof et al., 2011)
	5	Financing scheme based on the special drawing rights (SDR) of the International Monetary Fund (IMF) (Zonglu, 2013)
	6	Financing schemes for developed countries based on historical emissions responsibility Cui et al., 2015)
	7	Financing schemes based on economic strength (Cui et al., 2015)

		Program
	8	Financing schemes based on the United Nations' membership dues (Cui et al., 2015)
	9	Financing schemes based on Official the Development Assistance (ODA) (Cui et al., 2015)
	10	Financing schemes based on Global Environment Facility (GEF) funding program (Cui et al., 2015)
Allocation of funds	1	GCFs are allocated according to the principle of carbon emission reduction contribution. (Cui et al., 2015)
	2	GCFs are allocated according to the adaptation needs and emission reduction potential of developing countries. (Silverstein, 2013)
	3	GCFs are allocated according to the national climate loss and economic strength (Cui et al., 2014)
	4	GCFs are allocated based on the fairness of results and procedural justice (Grasso, 2010)

Source: This study is organized.

While the existing literature discusses the raising of capital and allocation of GCF, it has certain gaps; this study aims to fill these gaps in the existing literature.

First, the goal of GCF will affect the ways and means of raising and distributing funds. Currently, the main purpose of GCF is to help developing countries adapt to climate change. However, the unsatisfactory financing situation of GCF shows that such goal guidance seems hard to be fully accepted by all countries in the world, and therefore it is difficult to establish a long-term stable international climate interest coordination mechanism. The international community places great expectations on the GCF, hoping it become the main channel of funding under the UNFCCC after 2020 to deal with climate change caused by excessive GHG emissions. So the core task of GCF is to solve the problem of climate change on the basis of understanding the causes of excessive greenhouse gas emissions. The root cause of the climate change problem is the fact that GHGs brings immediate benefits to the emitting country, but increases the stock of GHGs in the atmosphere which affects the present and future welfare of all countries. In the absence of any cooperation among the countries, each country when deciding its emissions takes account of only its own benefits and costs. As a result, the total emissions from all countries are too high compared to the Pareto optimal emissions (Parkash, 2017). Therefore, this study thinks that the goal of GCF is to coordinate global GHG emission and reduction behavior and eventually realize the Pareto optimality in climate governance globally.

Second, concerning the raising of funds and the allocation of GCF, the existing literature focused primarily on empirical analysis and principle discussion, and gave less attention to theoretical modeling. As analyzed above, the GCF will ultimately pursue pareto optimality in global climate governance. Therefore, the key to theoretical model analysis is to find out the answer to the question that how should GCF raise and allocate funds to ensure that the market equilibrium can achieve the global Pareto optimal efficiency. However, the existing literature on modeling global climate governance has mainly concentrated on the game analysis of international environmental agreement on global climate governance, the global environmental policy, and local environmental policy coordination analysis, among others. Baumol and Oates (1988) constructed the mathematical model of public externality and demonstrated the only price conditions required to make the market equilibrium realize Pareto optimal. Concerning the global public externality, in principle, the conclusions of Baumol and Oates (1988) also apply to the global climate governance analysis. However, the conclusions of Baumol and Oates (1988) are based on a hypothetical condition that there exist a commodity consumed or produced by any economic entity, and the commodity has a unified transaction price, namely, the commodity can be the value measurement standard of a different economic entity. They (1988) assert that the assumptions in the real economy are tenable; for example, leisure (labor) is such an item that is used by every economic entity (no one can work 24 hours per day, and every vendor needs to use labors), that is, labor can be a common value standard. In the real economy, however, a unified global labor market and labor price does not exist. Therefore, when analyzing global public externalities, such as climate change, the assumptions do not seem to hold. To this end, this study expands the hypothetical condition into hypothesis 3, which makes the conclusion of this study more suitable for the global public externality analysis.

Third, to ensure long-term operations, as a non-profit international climate financing mechanism, the GCF must consider the raising of capital and allocation of GCF as a whole while considering the fiscal balance of payments. Existing literature has not explored much about how such a precondition constraint affects the raising of capital and the allocation of GCF. In fact, the Pigovian tax is slightly different when considering the balance of payments as compared to considering the fiscal balance of payments (Baumol and Oates, 1988). Thus, based on the only price condition to induce the market to satisfy the Pareto optimality requirements and by considering the fiscal balance of GCF, this study deduces he rules and the possible ways that must be followed for raising capital and allocating of GCF while considering global Pareto optimality and fiscal balance. Then, this study further discusses the way to determine the value of the variables affecting the implementation of fund-raising and allocation plan of the GCF.

Finally, when countries anticipate that the policy adopted by GCF should achieve both Pareto-optimal of global climate governance and financial balance of GCF, what will be the result of international climate game? There is no literature to analyze this problem. This study constructs an international climate game model that incorporates policy expectations and reveals that the game equilibrium result will not achieve the financial balance of GCF and the global Pareto-optimality simultaneously.

The contents of the remaining part of the paper are as follows: Section 2 describes the basic problem, basic idea, and basic assumption of this paper. Section 3 infers the necessary and sufficient price conditions to render identical the competitive equilibrium and Pareto optimality conditions. Section 4 deduces he rules and the possible ways that must be followed for raising capital and allocating of GCF while considering global Pareto optimality and fiscal balance. Section 5 discusses the decision of relative parameters that determine the raising of capital and allocation of GCF. Section 6 presents the conclusion and policy recommendations.

2 Basic Questions, Ideas, and Assumptions

2.1 Basic questions

There are I countries producing and consuming K products in the world, using i and $\bar{i}$ as the index of the country, k as the index of the product. $x_{ki} \geq 0$ and y_{ki} denote the amount of goods (resource) k consumed and produced (used), respectively, by country i. r_{ki} denotes the initial quantity of goods(resource) k available to country i. s_i , S_0 and $S = S_0 + \sum_i s_i \geq 0$ denote the amount of GHGs emitted by country i, the initial stock of GHGs and the final stock of GHGs, respectively, then $\frac{\partial S}{\partial s_i} = 1$. We assume that each unit of GHG emissions would need to use one unit of GHG emissions permit. $f_i(y_{1i}, \cdots, y_{Ki}, s_i)$ is country i's production function and $f_i(y_{1i}, \cdots, y_{Ki}, s_i) \leq 0$ is country i's production set.

$U_i(x_{1i},\cdots,x_{Ki},S)$ is country i's utility, which is determined by the number of K products consumed by country i and the global stock of GHGs S; as for $\frac{\partial S}{\partial s_i}=1$, we can obtain $\frac{\partial U_i}{\partial s_i}=\frac{\partial U_i}{\partial S}\bullet\frac{\partial S}{\partial s_i}=\frac{\partial U_i}{\partial S}$. While x_{ki}, y_{ki}, and s_i are flow variables, S is a stock variable as formally defined below.

The problem that this study attempts to solve is how the GCF can raise and allocate funds to achieve both the Pareto optimality of global climate governance and the fiscal balance of the GCF.

2.2 Basic ideas

In order to solve the basic problems mentioned above, this paper will follow the following train of thought.

First, referring to the model of Baumol and Oates(1988) and Marchiori et al.(2017), and based on the nonlinear programming theory, the study builds the Pareto optimal model of global climate governance and the market equilibrium model; additionally, according to the K-T theorem, the study obtains the Pareto optimal condition and the market equilibrium condition.

Second, by comparing Pareto optimal conditions and market equilibrium conditions, the study aims to ascertain what price conditions should be met to make the market equilibrium achieve Pareto optimality, which is defined as optimal equilibrium prices below.

Third, according to the optimal equilibrium prices, the study added fiscal balance constraints and deduced the plan for raising and allocation of GCF.

2.3 Basic assumptions

There are four basic hypotheses involved in this study:

Hypothesis 1: Each country pursues its own welfare maximization.

Hypothesis 2: The GCF seeks to balance the Pareto optimality of global climate governance with its own fiscal balance. As discussed above, the goal of GCF is to coordinate global GHG emission and reduction behavior and eventually realize the Pareto optimality in climate governance globally. According to the pareto rules(Baumol and Oates, 1988), there is a need to tax or subsidize the activities that make or cut externalities, thereby internalizing the external costs or benefits of making or cutting externalities. In the process of implementing such pareto rules, all the subsidies to countries for their reducing GHG emissions come from all countries in the world, and all the taxes paid by countries for their emitting GHGs are applied to all countries in the world. Therefore, the total net subsidies of all countries should be equal to zero. In other words, as a non-profit international organization, in addition to achieving Pareto optimal GHG emissions globally, the GCF must also consider its fiscal balance to maintain its own operations.

Hypothesis 3: The feasible set of consumption complexes for each country is convex, closed, bounded from below in the $x's$, and contains the null vector; the utility function that represents each country's preferences is twice differentiable, quasi-concave, and increasing in the $x's$; the feasible production set for each country is defined by a set of technical constraints that are twice differentiable and define a convex production possibility set. Under these circumstances, as is well-known, the solution to the maximization problem that is about to be described, exists and is unique (Baumol and Oates, 1988).

Hypothesis 4: There is a group of goods: (1) any of this group of goods is produced or consumed by at least one country; (2) any country produced at least one of goods in the group and consumed at least one of goods in the group; (3) each country can have direct or indirect economic relations with any other country through this group of goods; (4) there is a unified market for any goods in the group. An example of this hypothesis is as following. Supposing there are four countries. Both country 1 and country 2 have produced or consumed goods A. Both country 3 and country 4 have produced or consumed goods B. If neither country 1 nor country 2 have produced or consumed same goods with country 3 or country 4, that is there is no direct or indirect economic connection between country 1, country 2 and country 3, country 4, so this scenario doesn't satisfy Hypothesis 4(see Figure 1.a). If at least one country of country 1 and country 2 has produced or consumed at least one same goods with at least one country of country 3 and country 4, arbitrarily say both country 1 and country 3 have produced or consumed the goods C, then Any of the four countries has a direct or indirect relationship with any other country in this scenario which satisfy Hypothesis 4. Goods A, Goods B and Goods C comprise the group of goods in Hypothesis 4. This assumption ensures that all countries can measure and compare values through interrelated markets. Baumol and Oates (1988) assumed that there exist a commodity consumed or produced by any economic entity, and the commodity has a unified transaction price. They (1988) think that leisure (labor) is just such a commodity. In the real economy, however, a unified global labor market and labor price does not exist. Therefore, when analyzing global public externalities, such as climate change, the assumptions do not seem to hold. This Hypothesis 4 is more general, and is more realistic portrayal of the real world.

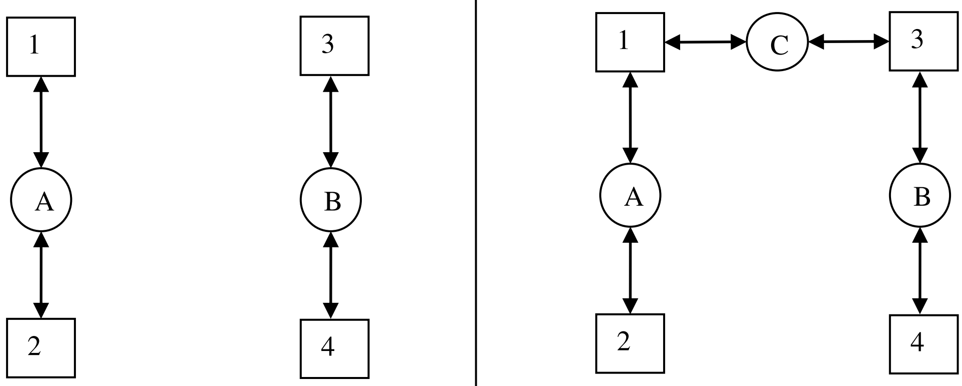

Figure 1.a scenario not satisfying hypothesis 4

Figure 1.b scenario satisfying hypothesis 4

Figure1 The graphic description of hypothesis 4

3 Comparative Analyses of Global Pareto Optimality and Market Equilibrium

3.1 Global Pareto optimality model

We can formulate the global Pareto optimality problem as model (1):

$$\begin{aligned} \max &: U_1(x_{11},\cdots,x_{K1},S) \\ s.t. &: U_i(x_{1i},\cdots,x_{Ki},S) \ge \bar{U}_i \quad (\forall i = 2,3,\cdots,I), \\ & \quad f_i(y_{1i},\cdots,y_{Ki},s_i) \le 0 \quad (\forall i), \\ & \quad \sum_i x_{ki} \le \sum_i (y_{ki}+r_{ki}) \quad (\forall k). \end{aligned} \tag{1}$$

Model (1) maximizes the utility of any arbitrarily chosen country, say country 1, subject to the requirements that there be no consequent loss to any other country, and that the constraints constituted by the production functions($f_i(y_{1i},\cdots,y_{Ki},s_i) \le 0 \quad (\forall i)$) and the availability of resources ($\sum_i x_{ki} \le \sum_i (y_{ki}+r_{ki}) \quad \forall k$) are satisfied.

We obtain the Lagrangian as follows:

$$L_1 = \sum_i \lambda_i [U_i(\bullet) - \bar{U}_i] - \sum_i \mu_i f_i(\bullet) - \sum_k \{\omega_k [\sum_i x_{ki} - \sum_i (y_{ki}+r_{ki})]\} \tag{2}$$

The Greek letters(λ_i 、 μ_i 、 ω_k)in (2) all represent Lagrange multipliers. Differentiating in turn with respect to the x_{ki}, y_{ki}, and s_i, we obtain the Kuhn-Tucker conditions ((5°)—(7°)) given in the first column of Table I.

3.2 Market equilibrium model

Our objective is to determine the characteristics of the prices, assuming that they exist, which will induce the behavior patterns necessary (and sufficient) for the satisfaction of our Pareto optimality conditions and determine whether that set of prices is unique. Thus, it is more convenient to first consider the corresponding market equilibrium requirements.

We can formulate the welfare maximization problem of country i as model (3):

$$\begin{aligned} &\min : \sum_k [p_k * (x_{ki} - y_{ki} - r_{ki})] + t * (s_i - \bar{s}_i) - T_i * S \\ &s.t. \quad : U_i(x_{1i}, \cdots, x_{Ki}, S) \geq \bar{U}_i \\ &\qquad\quad f_i(y_{1i}, \cdots, y_{Ki}, s_i) \leq 0. \end{aligned} \tag{3}$$

In model (3), we use the following notation:

p_k = the price of good (resource) k;

t = the price of GHG emission rights;

$\bar{s}_i$ = the quantity of initial GHG emission rights possessed by country i;

$\bar{S} = \sum_i \bar{s}_i$ = the global total quantity of initial GHG emission rights;

T_i = the subsidies assigned to country i for per unit of GHGs stock that exceeds $\sum_i \bar{s}_i$.

The country i in the model (3) is taken to minimize the expenditure necessary to achieve any given level of the utility, $\bar{U}_i$, subject to the constraints of the production function, $f_i(y_{1i}, \cdots, y_{Ki}, s_i) \leq 0$, so that in Lagrangian form the problem is to find the saddle value of

$$L_2 = \sum_k [p_k * (x_{ki} - y_{ki} - r_{ki})] + t * (s_i - \bar{s}_i) - T_i * (\sum_i s_i - \sum_i \bar{s}_i) - \alpha_i [U_i(\bullet) - \bar{U}_i] + \beta_i f_i(\bullet)$$
(4)

(where α_i is a Lagrange multiplier). We immediately obtain the Kuhn-Tucker conditions ((5^c)—(7^c)) given in the second column of Table II.

Table II: Kuhn-Tucker conditions for optimality with climate change

Variable	Pareto optimality	Market equilibrium	Prices
x_{ki}	$\lambda_i \frac{\partial U_i}{\partial x_{ki}} - \omega_k \le 0$ $x_{ki} \bullet (\lambda_i \frac{\partial U_i}{\partial x_{ki}} - \omega_k) = 0$ (5^o)	$p_k - \alpha_i \frac{\partial U_i}{\partial x_{ki}} \ge 0$ $x_{ki} \bullet (p_k - \alpha_i \frac{\partial U_i}{\partial x_{ki}}) = 0$ (5^c)	$p_k = \omega_k$ $\alpha_i = \lambda_i$ (5^e)
y_{ki}	$\omega_k - \mu_i \frac{\partial f_i}{\partial y_{ki}} \le 0$ $y_{ki}(\omega_k - \mu_i \frac{\partial f_i}{\partial y_{ki}}) = 0$ (6^o)	$p_k - \beta_i \frac{\partial f_i}{\partial y_{ki}} \le 0$ $y_{ki}(p_k - \beta_i \frac{\partial f_i}{\partial y_{ki}}) = 0$ (6^c)	$p_k = \omega_k$ $\mu_i = \beta_i$ (6^e)
s_i	$\mu_i \frac{\partial f_i}{\partial s_i} = \sum_i \lambda_i \frac{\partial U_i}{\partial s_i}$ (7^o)	$\beta_i \frac{\partial f_i}{\partial s_i} = T_i - t + \alpha_i \frac{\partial U_i}{\partial s_i}$ (7^c)	$\alpha_i = \lambda_i$ $\mu_i = \beta_i$ (7^e) $T_i - t = \sum_{\bar{i} \ne i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i})$

Data source: Research consolidation

3.3 The price-tax solution

We define prices that sustain a competitive equilibrium that is Pareto-optimal as optimal equilibrium prices.

Proposition 1: We can infer that price conditions (5^e)—(7^e) are optimal equilibrium prices. In addition, for all $x_{ki} > 0$ 、 $y_{ki} > 0$ **, the price condition (5^e)—(7^e) is the necessary and sufficient condition to induce each country to select Pareto-optimal activity levels.**

Proof: See Appendix A.

While for all x_{ki}=0、 y_{ki}=0 price conditions, (5^{e})—(7^{e}) is not the only sufficient condition to yield equality between the market and Pareto-optimal activity levels, other policies for good i are not relevant to countries that do not consume or produce any good i. In fact, when we do not know if x_{ki} and y_{ki} are greater than 0 or equal to 0 beforehand, the price condition (5^{e})—(7^{e})tends to be the only necessary and sufficient condition that can induce each country to select Pareto-optimal activity levels. In other words, they are optimal equilibrium prices.

4 The Green Climate Fund: Fund Raising and Allocation Plan

4.1 Analysis on global Pareto-optimal conditions

The GCF is set to achieve the goal of coordinating the national GHG emissions reduction benefits and ultimately achieve global Pareto optimality. As the optimal equilibrium price condition is the necessary and sufficient condition for the market equilibrium to achieve Pareto optimality, for calculating GCF subsidies or taxes on the national GHG emissions, Eq. (7^{e}) needs to be satisfied and that is

$$T_i - t = \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i}) = \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S}) \tag{8}$$

Subject to Eq. (8), to achieve Pareto optimal GHG emissions globally, the GCF must meet Pareto rules during the raising of funds and allocation of GCF. The reduction (increase) of a unit of GHG emissions must be subsidized, wherein the net subsidies must be equal the total marginal benefit offered by the unit of GHG to all other countries across the world. If the total marginal benefit is positive, then the net subsidy would be positive, and vice versa, that is, where the net subsidy is negative, tax levy would be required for that country.

4.2 Analysis of global Pareto optimality and fiscal balance of GCF

As a non-profit international organization, in addition to achieving Pareto optimal GHG emissions globally, the GCF must also consider its fiscal balance to maintain its own operations. The restraint of fiscal balance can be described by Eq. (9)

$$\sum_{i=1}^{I}[t*(\bar{s}_i - s_i) + T_i*(\sum_i s_i - \sum_i \bar{s}_i)] = C - D \tag{9}$$

where $\sum_{i=1}^{I}[t*(\bar{s}_i - s_i) + T_i*S]$ specifies the total net subsidies to all countries given by the GCF; D denotes all other revenues (including public fund donations, private donations, and grants from various agencies) unrelated to GHG emissions acquired by the GCF; C expresses all other expenditures (including operating costs of GCF and research expenditures) unrelated to GHG emissions paid by the GCF.

Subject to Eqs. (8) and (9), we can obtain the only solution of t and T_i (refer to Appendix B for the derivation process).

$$t = \sum_{\bar{i}}(\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S}) \tag{10}$$

It must be noted that $\sum_i s_i - \sum_i \bar{s}_i \neq 0$ is crucial. In the real economy, $S > 0$, $I > 1$, $S_0 > 1$ and $\bar{S} \geq 0$, that is, the global total net GHG emissions are greater than zero, the number of countries participating in the GCF is greater than one, and the global total initial GHG emission quota is greater than or equal to zero. Therefore, we can conclude that $S(1-I) - \bar{S} - S_0 < 0$.

Subject to Eqs. (8) and (10), we obtain

$$T_i = \lambda_i \frac{\partial U_i}{\partial S} \tag{11}$$

In the Eqs. (10) and (11), $\bar{S}$ denotes the global total initial GHG emissions quota, S expresses the global final total GHG emissions, $\lambda_i \frac{\partial U_i}{\partial S}$ specifies the marginal damage caused by per unit stock of GHGs to a country, $\sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S})$ measures the global total marginal damage caused by per unit stock of GHGs. Based on Eq. (10), the price of GHG emissions permit (t) can be divided into two parts:

$$\frac{S(I-1)\sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0} \tag{12}$$

And

$$\frac{C-D}{S(1-I)-\bar{S}-S_0} \tag{13}$$

where (12)denotes basic prices of GHG emissions rights and(13) expresses price adjustment according to the income surplus that is not related to GHG emissions in order to maintain the fiscal balance of GCF. Similarly, according to Eq. (11), the subsidies assigned to country i for per unit stock of GHGs (T_i)can be divided into two parts:

$$-\lambda_i \frac{\partial U_i}{\partial S} - \frac{\bar{S}\sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}} \tag{14}$$

and

$$\frac{C-D}{S(1-I)-\bar{S}-S_0} \tag{15}$$

where (14)denotes the basic subsidies.

Eq. (8) is the only necessary and sufficient condition for market equilibrium to achieve the global Pareto optimality, and Eq. (9) is the only equation that describes the balance of fiscal revenue and expenditure, that is, both are unique. Thus, the only set of solutions—Eqs. (10) and (11) derived from Eqs. (8) and (9)—are also unique.

4.3 Fund-raising and allocation plan for the GCF

Based on Eqs. (10) and (11), we can obtain the financial surplus of the GCF:

$$\begin{aligned}
&D-C-\sum_{i=1}^{I}\{\frac{C-D+S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}*(\bar{s}_i-s_i)+[\lambda_i\frac{\partial U_i}{\partial S}+\frac{D-C+\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0}]*S\} \\
&=\sum_i\{\frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}*(s_i-\bar{s}_i)+[-\lambda_i\frac{\partial U_i}{\partial S}-\frac{\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0}]*S\} \\
&=\sum_i\{\theta(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})*(s_i-\bar{s}_i)-[\lambda_i\frac{\partial U_i}{\partial S}-(1+\theta)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})]*S\} \\
&=0
\end{aligned} \tag{16}$$

where $\theta=\frac{S(I-1)}{S(1-I)-\bar{S}-S_0}$; θ can be defined as a balance factor of fiscal revenue and expenditure that are related only with the global total initial GHG emissions quota $\bar{S}$, the global final total GHG emissions S, and the number of global countries I [1]. θ is proportional to $\bar{S}$ and S_0, but inversely proportional to S and I. Therefore, we can obtain the plan for the raising of capital and allocation of GCF based on both global Pareto optimality and fiscal balance.

(I) Given below are four main ways that can be employed to raise funds for the GCF:

Way 1: When $\frac{C-D}{S(1-I)-\bar{S}-S_0}+\frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}\geq 0$, countries with excessive historical net GHG emissions and those exceeding their initial emission rights should pay the

[1] To be precise, I should be the number of countries involved in the GCF mechanism; this study assumes that all countries in the world will participate in the GCF mechanism.

climate funds to GCF, that is, if $s_i - \bar{s}_i > 0$ in country i, then this country should contribute $[\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}]*(s_i - \bar{s}_i)$ amount of climate funds to the GCF.

Way 2: When $\frac{C-D}{S(1-I)-\bar{S}} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}} < 0$, countries whose historical net GHG emissions are lesser than their initial emission rights should pay the climate funds to GCF, that is, if $s_i - \bar{s}_i < 0$ in country i, then this country should contribute $[\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}]*(s_i - \bar{s}_i)$ amount of climate funds to the GCF.

Way 3: If $\frac{C-D}{S(1-I)-\bar{S}-S_0} - \lambda_i\frac{\partial U_i}{\partial S} - \frac{\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0} > 0$ in country i, then this country should contribute $[\frac{C-D}{S(1-I)-\bar{S}-S_0} - \lambda_i\frac{\partial U_i}{\partial S} - \frac{\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0}]*S$ amount of climate funds to the GCF.

Way 4: The GCF acquires all other revenues unrelated to GHG emissions, including public fund donations, private donations, or grants from various agencies.

(II) Given below are four main ways to allocate funds for the GCF:

Way 1: When $\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0} \geq 0$, countries that are active in reducing GHG emissions and whose net emissions are less than their initial emission rights should receive climate subsidies from the GCF, that is, if $s_i - \bar{s}_i < 0$ in country i, then the GCF should allocate $[\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}]*(\bar{s}_i - s_i)$ amount of climate subsidies to this country.

Way 2: When $\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0} < 0$, countries with excessive historical net GHG emissions and those exceeding their initial emission rights should receive climate subsidies from the GCF, that is, if $s_i - \bar{s}_i > 0$ in country i, then the GCF should allocate $[\frac{C-D}{S(1-I)-\bar{S}-S_0} + \frac{S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}]*(\bar{s}_i - s_i)$ amount of climate subsidies to this country.

Way 3: If $\frac{D-C}{S(1-I)-\bar{S}-S_0} + \lambda_i\frac{\partial U_i}{\partial S} + \frac{\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0} > 0$ in country i, then the GCF should allocate $[\frac{D-C}{S(1-I)-\bar{S}-S_0} + \lambda_i\frac{\partial U_i}{\partial S} + \frac{\bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I)-\bar{S}-S_0}]*S$ amount of climate subsidies to this country.

Way 4: The GCF pays all other expenditures unrelated to GHGs emissions, including the operating costs of GCF or other research expenditures.

5 Further Discussions on Fund-raising and Allocation Plan of the GCF

5.1 Discussion of variable settings

According to Eqs. (10), (11), and (16), to implement GCF's plan of raising the capital and allocation, and ultimately to achieve both Pareto-optimal climate governance globally and financial balance in the Green Climate Fund Organization, we need to determine the 5 variables described as following:

①C denotes the expenditures paid by the GCF and not related to GHG emissions. It cannot be pre-determined, but it can be gradually determined with the operation of the GCF.

②D denotes the revenues acquired by the GCF and unrelated to GHG emissions. It cannot be pre-determined, but it can be gradually determined with the operation of the GCF.

③S denotes the expected final global stock of GHGs. It is preset according to the goals of the GCF. There are two possible scenarios. If the GCF pursues Pareto optimality in global climate governance, then scientific research should be conducted to assess the global Pareto-optimal stock of GHGs. If the GCF pursues the periodic goal of global climate governance, then it will need to facilitate consultations among the countries of the world to determine S[1].

④I denotes the number of countries participating in the GCF. Since the climate change due to GHG emissions affects all the countries across the world, I should be set as the number of all countries in the world.

⑤$\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S}$ denotes the impact of a unit of stock of GHGs on the country $\bar{i}$ and needs to be determined through scientific research.

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[1] The global climate has been making progress in each planning period, since several years. For example, progress was witnessed in the first commitment period of the Kyoto protocol, which was from 2008 to 2012, and, subsequently, in the second commitment period of the Kyoto protocol, which was from 2013 to 2020. In the future, global climate governance will be difficult, but it will be more feasible with periodical planning.

⑥ $\overline{s}_i$ ($\overline{S}$) denotes country i's initial GHG emission rights. It needs to be negotiated at a global level. Currently, there are the following three main viewpoints on the determination of each country's initial GHG emission rights:

(I)The initial GHG emission rights of each country are zero, that is, $\overline{s}_i=0$.

(II)Each country's initial GHG emission rights are determined through the grandfather principle, that is, the initial GHG emission rights are determined based on existing GHG emissions of each country.

(III)Countries independently declare their own right to emit GHGs. When the final global stock of GHGs is given, the global permissive GHG emissions is then set. In the case of this scenario, the main purpose of countries involved in the international climate game is to obtain more GHG emission rights to maximize their own welfare. That is to say that the actions of all the countries are focused on maximizing their own interests, including self-declaration to determine their initial GHG emission rights. The first order conditions (FOCs) for ($\overline{s}_i$) to be an optimum are:

$$\frac{\partial L_2}{\partial \overline{s}_i}=\frac{\partial t}{\partial \overline{s}_i}*(s_i-\overline{s}_i)-t-\frac{\partial T_i}{\partial \overline{s}_i}*S=0 \tag{17}$$

Substituting the Eqs. (10) and (11) into Eq. (17), we have (Refer to Appendix C for specific details):

$$\overline{s}_i = s_i + \overline{S}+S(I-2) \text{ (when } C-D+S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}}\frac{\partial U_{\overline{i}}}{\partial S})\neq 0 \text{ and } \overline{S}\neq S(1-I)-S_0\text{)} \tag{18}$$

Summarizing all countries' $\overline{s}_i$, we obtain:

$$\overline{S}=S(1-I)-S_0 \tag{19}$$

In the case where (19) is established, the denominator of Eqs. (10) and (11) is zero, that is, t and T_i cannot be obtained. This shows that the equilibrium results of the international climate game will not achieve the global Pareto-optimality and the financial balance of GCF simultaneously when each country anticipates that the GCF aims to Pareto optimality in climate governance globally and its own fiscal balance.

5.2 Conditions that set $t = 0$ must be met

For $t = 0$, according to Eq. (10),

$$t = \frac{C - D + S^*(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S^*})}{S(1-I) - \bar{S} - S_0} = 0 \quad (17)$$

then

$$D - C = S^*(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S^*}) \quad (18)$$

When $t = 0$,

$$T_i = \sum_{\bar{i} \neq i}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S^*}) \quad (19)$$

It should be noted that, only to meet the formula (18), t will be equal to zero. According to the analysis of Appendix C, formula (18) is almost impossible to meet in the real economy; therefore, $t=0$, generally, cannot be set.

5.3 Conditions that set $T_i = 0$ must be met

For $T_i = 0$, according to Eq. (11),

$$\lambda_i \frac{\partial U_i}{\partial S} = -\frac{D - C + \bar{S}\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I) - \bar{S} - S_0} \quad (20)$$

Therefore, it can be seen that $T_i = 0$ must meet the following two conditions at the same time (Refer to Appendix D for specific details): 1) $\lambda_i \frac{\partial U_i}{\partial S} = \lambda_j \frac{\partial U_j}{\partial S}$ $(i \neq j)$, that is, a unit stock of GHGs has the same marginal impact on countries. 2) The global total quantity of initial GHG emission rights must be set as $\bar{S} = \frac{D-C}{(1+I)\lambda_i \frac{\partial U_i}{\partial S}} + \frac{S_0 + S + IS}{(1+I)}$. In the real economy, however, such conditions can hardly be satisfied. Under the conditions $T_i = 0$, we have $t = \frac{(I-1)(D-C)}{S_0 + \bar{S} - S - I\bar{S} - IS}$.

6 Conclusion and Policy Recommendations

In this study, first, the Pareto optimal model and market equilibrium model of global climate management are constructed; subsequently, the Pareto optimal conditions and market equilibrium conditions are obtained. The two conditions are compared to achieve the optimal equilibrium prices, which induce the market to satisfy the Pareto optimality requirements. In other words, the reduction (increase) of a unit of GHG emissions must be subsidized, wherein the net subsidies would be equal to the total marginal benefit offered by the unit of GHGs to all other countries of the world; additionally, if the total marginal benefit is positive, then the net subsidy would be positive, and vice versa.

Subsequently, by adding fiscal balance constraints to the optimal equilibrium prices, this study deduces the price condition that the GCF must meet when it raises and allocates funds to achieve Pareto optimality globally and fiscal balance of payments. This leads to the formulation of the plan of raising capital and allocating the GCF. At the same time, the study also discusses ways to determine different economic variables for the implementation of the plan of raising capital and allocating the GCF. It is noteworthy that the equilibrium results of the international climate game will not achieve the global Pareto-optimality and the financial balance of GCF simultaneously when each country anticipates that the GCF aims to Pareto optimality in climate governance globally and its own fiscal balance. This means that it is not feasible to determine the initial amount of GHG emissions rights in the form of voluntary emissions reduction under the premise that the GCF pursues the goal of achieving global Pareto optimality and its own fiscal balance in future.

Therefore, this study concludes with the following policy recommendations for the further development of the GCF:

I) Clear short-term and long-term GCF funding and distribution of funds

Currently, due to the lack of scientific and technological information, the specific influence of GHG emissions on countries has not yet achieved a unified consensus; however, the international community has a clear understanding that the developed countries should have more historical responsibility than developing countries. In addition, the real economy, generally, has $S>0$、$I>1$、$\bar{S}\geq 0$、$\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial S})<0$、$C-D<S(1-I)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})$， Therefore, $\frac{C-D+S(I-1)\sum_{\bar{i}}(\lambda_{\bar{i}}\frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I)-\bar{S}-S_0}\geq 0$. During the beginning of the operations, the GCF could mainly follow Way 1 and Way 4 to raise funds; that is, the corresponding operational funds were provided by the developed countries with more historical responsibilities and through the contributions from various public welfare funds, private donations, and funds of various institutions. The GCF could allocate funds mainly through Way 1 and Way 4. With a clarity on the relevant information and a consensus, in the long-term, the GCF can also follow Way 3 to raise funds and can allocate funds using the Way 3.

II) Initiate related research and negotiations to determine various parameters of fund collection and allocation of the GCFs

First, on the basis of construction of the GCF, carry out the research of S^* (the global Pareto optimal stock of GHGs) and $\lambda_i \frac{\partial U_i}{\partial S}$ (impact of a unit of stock of GHGs on country i). Second, start negotiations on the world's initial GHG emission rights, and subsequently, on the accounting of $\overline{S}$.

In particular, under the premise that the GCF pursues the goal of achieving global pareto optimality and its own fiscal balance in future, it is not feasible to determine the initial amount of GHG emission rights in the form of voluntary emission reduction. However, the following should be considered: (1) other ways of determining each country's initial amount of GHG emission rights or (2) before targeting the global Pareto optimality and fiscal balance of GCF, each country's initial amount of GHG emission rights was determined.

Finally, on the basis of various parameter assessment and initial greenhouse gas emission rights negotiation, the basic price of GHG emission rights and the basic subsidies to country i for per unit stock of GHGs can be estimated according to the formulas of Eqs. (12) And (14), respectively. Subsequently, in each financial cycle of the GCF, according to the Eq. (13) or Eq. (15), estimate the price adjustment according to the income surplus unrelated to GHG emissions and subsequently adjust the long-term basic price, appropriately.

Appendix A : Proof of Proposition 1

We will prove first that the conditions(5^e)—(7^e) in table II are sufficient to induce the market to satisfy the Pareto optimality requirements. Substituting the value of p_k, T_i, and t from (5^e)—(7^e) into (5^c)—(7^c), we see that the system of inequalities and equations determining the competitive equilibrium becomes identical with the system of inequalities and equations that determine the Pareto-optimal solution—$x^o_{ki}, y^o_{ki}, s^o_{ki}, \lambda_i$, and β_i. Thus, these systems will have the same solutions, so that if they are unique, then we have $x^o_{ki} = x^c_{ki}, y^o_{ki} = y^c_{ki}, s^o_i = s^c_i$.

We may ask whether conditions (5^e)—(7^e) are absolutely required for achieving optimality. The answer is that they are, if we accept the plausible Hypothesis 4.

To deal with this issue, the uniqueness of the prices solution (5^e)—(7^e), we must assume that there is a set of prices that yield equality between the market and Pareto-optimal activity levels (i.e., that there exists $x^o_{ki} = x^c_{ki}, y^o_{ki} = y^c_{ki}, s^o_i = s^c_i, S^o = S^c$). Subsequently, we ask what values of the p_k, t, and T_i are consistent with these relationships. Assume goods $k=1,2,\cdots,K_1$ （$1 \le K_1 \le K$） satisfied the Hypothesis 4, and let $p_k = p_1, p_2, \cdots, p_{K_1}$ represent the prices of this set of goods, respectively.

According to Hypothesis 4, goods $k=1$ is produced or consumed by at least one country, and assuming it is produced or consumed by countries $i = 1、2、\cdots、\bar{I}\,(2 \le \bar{I} \le I)$. If goods $k=1$ is consumed by countries $i = 1、2、\cdots、\bar{I}\,(2 \le \bar{I} \le I)$, then we have

$$\lambda_i \frac{\partial U_i}{\partial x_{1i}} = \omega_1 \quad (i = 1、2、\cdots、\bar{I}) \qquad \text{(A.1)}$$

$$\alpha_i \frac{\partial U_i}{\partial x_{1i}} = p_1 \quad (i = 1、2、\cdots、\bar{I}) \qquad \text{(A.2)}$$

If goods $k=1$ is produced by countries $i = 1、2、\cdots、\bar{I}\,(2 \le \bar{I} \le I)$, then we have

$$\mu_i \frac{\partial f_i}{\partial y_{1i}} = \omega_1 \quad \text{(A.3)}$$

$$\beta_i \frac{\partial f_i}{\partial y_{1i}} = p_1 \quad \text{(A.4)}$$

Taking $\bar{k}$ as our standard of value, we set arbitrarily

$$\omega_{\bar{k}} = p_{\bar{k}} \quad \text{(A.5)}$$

For any country $i \in \{1, 2, \ldots, \bar{I}\}$, if goods k=1 is consumed by country i, then we have obtain (A.6) , and if goods k=1 is produced by country i, then we have obtain (A.7)

$$\lambda_i = \frac{\omega_{\bar{k}}}{\frac{\partial U_i}{\partial x_{\bar{k}i}}} = \frac{p_{\bar{k}}}{\frac{\partial U_i}{\partial x_{\bar{k}i}}} = \alpha_i \quad (i = 1、2、\cdots、\bar{I}) \quad \text{(A.6)}$$

$$\mu_i = \frac{\omega_{\bar{k}}}{\frac{\partial f_i}{\partial y_{\bar{k}i}}} = \frac{p_{\bar{k}}}{\frac{\partial f_i}{\partial y_{\bar{k}i}}} = \beta_i \quad (i = 1、2、\cdots、\bar{I}) \quad \text{(A.7)}$$

From above analysis, it can be seen that equations (A.6) or (A.7) hold for all countries that are economically connected to each other through goods 1.

According to Hypothesis 4, the countries that produced or consumed goods 1 must also produced or consumed other goods besides goods 1, otherwise, they will not have direct or indirect economic relations with countries that do not produce or consume goods 1. Assuming some of the countries that produced or consumed goods 1 also produced or consumed goods 2, suppose goods 2 is produced or consumed by country $i = \bar{I}$. In addition, goods 2 may also be produced or consumed by countries besides countries $i = 1、2、\cdots、\bar{I}$. Suppose countries $i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}$ produced or consumed goods 2. If goods 2 is consumed by countries $i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}$, then we obtain (A.8) and (A.9)

$$\lambda_i \frac{\partial U_i}{\partial x_{2i}} = \omega_2 \quad (i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}) \qquad (A.8)$$

$$\alpha_i \frac{\partial U_i}{\partial x_{2i}} = p_2 \quad (i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}) \qquad (A.9)$$

If goods 2 is produced by countries $i = 1、2、\cdots、\bar{I}\,(2 \le \bar{I} \le I)$, then we obtain (A.9) and (A.10)

$$\mu_i \frac{\partial f_i}{\partial y_{2i}} = \omega_2 \quad (i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}) \qquad (A.10)$$

$$\beta_i \frac{\partial f_i}{\partial y_{2i}} = p_2 \quad (i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}) \qquad (A.11)$$

According to （A.6）、（A.7）, we have $\lambda_{\bar{I}} = \alpha_{\bar{I}}$ or $\mu_{\bar{I}} = \beta_{\bar{I}}$. Therefore, we obtain

$$\omega_2 = \lambda_{\bar{I}} \frac{\partial U_{\bar{I}}}{\partial x_{2i}} = \alpha_{\bar{I}} \frac{\partial U_{\bar{I}}}{\partial x_{2i}} = p_2 \qquad (A.12)$$

or

$$\omega_2 = \mu_{\bar{I}} \frac{\partial f_{\bar{I}}}{\partial y_{2i}} = \beta_{\bar{I}} \frac{\partial f_{\bar{I}}}{\partial y_{2i}} = p_2 \qquad (A.13)$$

Subsequently, If goods 2 is consumed by countries $i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}$, we obtain

$$\lambda_i = \frac{\omega_2}{\frac{\partial U_i}{\partial x_{2i}}} = \frac{p_2}{\frac{\partial U_i}{\partial x_{2i}}} = \alpha_i \qquad (A.14)$$

If goods 2 is produced by countries $i = \bar{I}、\bar{I}+1、\cdots、\bar{\bar{I}}$, we obtain

$$\mu_i = \frac{\omega_2}{\frac{\partial U_i}{\partial x_{2i}}} = \frac{p_2}{\frac{\partial U_i}{\partial x_{2i}}} = \beta_i \qquad (A.15)$$

From above analysis, it can be seen that equations $\lambda_i = \alpha_i$ or $\mu_i = \beta_i$ hold for all countries that are economically connected to each other through goods 1 and goods 2.

According to Hypothesis 4, each economic agent can have direct or indirect economic relations with any other economic agent through the goods $k=1,2,\cdots,K_1$, and any country produced at least one of goods in the group and consumed at least one of goods in the group. Therefore, following the same argument, we can infer that only if hypothesis 4 is true, for all countries, we will have

$$\lambda_i = \alpha_i \quad \text{(A.16)}$$

$$\mu_i = \beta_i \quad \text{(A.17)}$$

Subsequently, by (5^o), (5^c), and (A.16), we must obtain, for any goods k , if it is consumed by country i

$$\omega_k = \lambda_i \frac{\partial U_i}{\partial x_{ki}} = \alpha_i \frac{\partial U_i}{\partial x_{ki}} = p_k \text{, for all } x_{ki} > 0 \quad \text{(A.18)}$$

We can also obtain, for any goods k , if it is used or produced by country i

$$\omega_k = \mu_i \frac{\partial f_i}{\partial y_{ki}} = \beta_i \frac{\partial f_i}{\partial y_{ki}} = p_k \quad \text{(A.19)}$$

Subsequently, by (7^o), (7^c), (A.16), and (A.17), we must have

$$T_i - t = \lambda_i \frac{\partial U_i}{\partial s_i} - \mu_i \frac{\partial f_i}{\partial s_i} = \alpha_i \frac{\partial U_i}{\partial s_i} - \beta_i \frac{\partial f_i}{\partial s_i} = \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i}) \quad \text{(A.20)}$$

By (A.15), (A.16), (A.17), (A.18), and (A.19), we have proved that for all $x_{ki} > 0$, $y_{ki} > 0$, the price conditions (5^e)—(7^e) in Table II are necessary and sufficient conditions to render identical the competitive equilibrium and the Pareto optimality conditions.

Appendix B: Proof of t and T_i

The Eq. (9) $\sum_{i=1}^{I}[t*(\bar{s}_i - s_i) + T_i * S] + C - D = 0$ can be expanded as follows：

$$t \bullet \bar{S} - t \bullet S + S \bullet \sum_i T_i + C - D = 0 \quad \text{(B.1)}$$

Summarizing Eq. (8) for all countries, we obtain:

$$\sum_i T_i - t \bullet I = \sum_i \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i}) \quad \text{(B.2)}$$

Both sides of Eq. (B.2) are multiplied by S and subtracted by Eq. (B.1). We obtain:

$$t \bullet (\sum_{i=1}^{I} s_i (1-I) - \bar{S} - IS_0) = S \bullet \sum_i \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i}) \quad \text{(B.3)}$$

Based on Eq. (B.3), we obtain:

$$t = \frac{C - D + S \sum_i \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I) - \bar{S} - S_0} = \frac{C - D + S \sum_i \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I) - \bar{S} - S_0} \quad \text{(B.4)}$$

It must be noted that $\sum_{i=1}^{I} s_i (1-I) - \bar{S} - IS_0 = S(1-I) - \bar{S} - S_0 \neq 0$ is crucial. We have:

$$\sum_i \sum_{\bar{i} \neq i} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S}) = (I-1) \sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S}) \quad \text{(B.5)}$$

Subject to Eq. (B.4) and Eq. (B.5), we obtain:

$$t = \frac{C - D + S(I-1) \sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial S})}{S(1-I) - \bar{S} - S_0} = \frac{C - D + S(I-1) \sum_{\bar{i}} (\lambda_{\bar{i}} \frac{\partial U_{\bar{i}}}{\partial s_i})}{S(1-I) - \bar{S} - S_0} \quad \text{(B.6)}$$

Appendix C: The derivation of $\overline{s}_i$ under the independent declaration

In formula (8), take the derivative of both sides with respect to $\overline{s}_i$, and we have:

$$\frac{\partial T_i}{\partial \overline{s}_i} - \frac{\partial t}{\partial \overline{s}_i} = 0 \tag{C.1}$$

According to Eq. (17) and Eq. (C.1), we have:

$$\frac{\partial t}{\partial \overline{s}_i} * (s_i - \overline{s}_i) - t - \frac{\partial T_i}{\partial \overline{s}_i} * S = \frac{\partial t}{\partial \overline{s}_i} * (s_i - \overline{s}_i - S) - t = 0 \tag{C.2}$$

According to formula (10), we have:

$$\frac{\partial t}{\partial \overline{s}_i} = \frac{C - D + S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S})}{[S(1-I) - \overline{S} - S_0]^2} \tag{C.3}$$

Substituting Eq. (10) and Eq. (C.3) into Eq. (C.2) and sorting out:

$$\frac{C - D + S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S})}{[S(1-I) - \overline{S} - S_0]^2} * (s_i - \overline{s}_i - S) = \frac{C - D + S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S})}{S(1-I) - \overline{S} - S_0} \tag{C.4}$$

when $C - D + S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S}) \neq 0$ and $\overline{S} + S_0 \neq S(1-I)$, we have:

$$\overline{s}_i = s_i + \overline{S} + S^*(I-2) + S_0 \tag{C.5}$$

$C - D$ represent a net pay for GCFs not related to GHGs emissions, which the GCF cannot predict and control. And the probability that it is equal to $-S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S})$ is very small, that is, in the real economy, $C - D + S(I-1)\sum_{\overline{i}}(\lambda_{\overline{i}} \frac{\partial U_{\overline{i}}}{\partial S}) \neq 0$ is basically established.

Appendix D: Conditions that set $T_i = 0$ must be met

Since for all countries, the right side of (23) is equal, we obtain:

$$\lambda_i \frac{\partial U_i}{\partial S} = \lambda_j \frac{\partial U_j}{\partial S} \quad (i \neq j) \tag{D.1}$$

Thus, Eq. (23) can be transformed into:

$$\lambda_i \frac{\partial U_i}{\partial S} = \frac{D - C + \bar{S} I \lambda_i \frac{\partial U_i}{\partial S}}{S_0 + \bar{S} - S(1-I)} \tag{D.2}$$

subsequently, reorganizing Eq. (D.2), we have:

$$\lambda_i \frac{\partial U_i}{\partial S} (S_0 + \bar{S} - S - I\bar{S} - IS) = D - C \tag{D.3}$$

and:

$$\bar{S} = \frac{D - C}{(1+I)\lambda_i \frac{\partial U_i}{\partial S}} + \frac{S_0 + S + IS}{(1+I)} \tag{D.4}$$

References

Antimiani, A., Costantini, V., Markandya, A., Martini, C., Palma, A., & Tommasino, M. C. (2014). A dynamic cge modelling approach for analyzing trade-offs in climate change policy options: the case of green climate fund. *Seeds Working Papers*.

Carmen Marchiori, Simon Dietz & Alessandro Tavoni.(2017). Domestic Politics and the Formation of International Environmental Agreements[J]. *Journal of Environmental Economics & Management*, 81(1):115-131.

Chander P. (2010). Cores of games with positive externalities. *Core Discussion Papers, 30*(1), 78–98.

Chander P. (2017). Subgame-perfect cooperative agreements in a dynamic game of climate change ☆. *Journal of Environmental Economics & Management, 84*, 173-188.

Chander P., & Wooders M. (2010). Subgame perfect cooperation in an extensive game. *Vanderbilt University Department of Economics Working Papers*.

Cui Lianbiao. (2014). *Design and Analysis of the Green Climate Fund*. (Doctoral dissertation, University of Science and Technology of China).

Cui Lianbiao, Song Malin, Zhu lei & Fan Ying. (2015). Financing Burden Sharing of the Green Climate Fund: A Perspective of the Combination of Historical Responsibility and Economic Ability. *Journal of Finance and Economics*, 41(3), 65-76.

Cui, L. B., Zhu, L., Springmann, M., & Fan, Y. (2014). Design and analysis of the green climate fund. *Journal of system science and systems engineering,23*(3), 266-299.

Fridahl, M., & Linnér, B. O. (2016). Perspectives on the green climate fund: possible compromises on capitalization and balanced allocation. *Climate & Development, 8*(2), 105-109.

Grasso M. (2010). An ethical approach to climate adaptation finance. *Global Environmental Change, 20*(1), 74-81.

Hof A. F., Elzen M. G. J. D. & Beltran A. M. (2011). Predictability, equitability and adequacy of post-2012 international climate financing proposals. *Environmental Science & Policy, 14*(6), 615-627.

Lattanzio, R. K. (2011). International climate change financing: the green climate fund (gcf).

Liu Qian, Nian Shuting & Wang Yao. (2015). Global Climate Finance Architecture and the Countermeasure of China. *China Population, Resources and Environment*, 25(10), 30-38.

Li Zonglu. (2013). Analysis of financing ideas based on Special Drawing Rights . *Henan Social Sciences, 21*(1), 48-52.

Manzanares, F. J. (2017). The green climate fund – a beacon for climate change action. *Asian Journal of Sustainability & Social Responsibility*, 1-5.

Shen Lvye & Yang Pu. (2017). A brief analysis of the sources of long-term funds of the green climate fund. *Economic Research Guide*,(6), 61-63.

Silverstein D. N. (2013). A globally harmonized carbon price framework for financing the green climate fund. *Social Science Electronic Publishing*.

William J.Baumol & Wallace E.Oates.(1988). *The theory of environmental policy(Second edition)*. Cambridge :Cambridge University Press.