The strategy of a uniform carbon tax in the self-enforcing international environmental agreements with free trade

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Abstract: The topic of how to create an effective international environmental agreement has been a significant challenge in climate negotiations. Recently, carbon tax instrument has become increasingly popular with economists. The paper examines the effects of negotiating a uniform carbon tax in international environmental agreements on climate cooperation by developing a three-stage game model. Innovatively, we capture the strategic interaction that countries choose their carbon taxes or emissions caps strategically by taking into account the terms-of-trade effects of their own policies, and assume that firms have access to the technologies of abatement. Comparing with the emissions caps instrument, we show that the uniform carbon tax instrument enhances more ambitious international climate cooperation with less severe emissions damage, and may even form a grand coalition. If the emission damage is more severe, the uniform carbon tax instrument contributes to significantly promoting participation in agreements, but the contribution to improvement in social emissions and social welfare is not obvious.

Keywords: International environmental agreements; Free trade; Uniform carbon tax; Emissions caps; Strategy

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1 Introduction

Global climate change is among the most challenging issues the human faces in this century. According to the IPCC's report of Climate Change 2022: Mitigation of Climate Change, the average annual global greenhouse gas emissions from 2010 to 2019 were at their highest levels in human history, and without immediate and deep emissions reductions across all sectors, limiting global warming to 1.5°C is beyond reach (IPCC, 2022). Although some economies, such as China, the United States, the European Union, have declared their own climate ambitions, the free-riding incentive attached to the global public good of climate mitigation has seriously hampered global climate action (Nordhaus, 2015). How reach an effective international climate treaty to prevent the tragedy of the commons is an urgent and challenging issue (Barrett, 2020).

Two climate treaties based on quantity mandates have been reached in the evolution of the global climate governance system over three decades (Zhang and Zhang, 2021), namely the Kyoto Protocol and the Paris Agreement. But, the failure of the Kyoto Protocol and widespread concerns about the lack of climate ambitions in the Paris Agreement (Allen et al., 2015; Rogelj et al., 2016). Economists are turning to carbon pricing instruments, proposing to negotiate an international carbon price (i.e., a carbon tax) that may promote more ambitious climate cooperation (e.g., Cramton et al., 2015; McKibbin et al., 2014; Parry, 2021; Weitzman, 2014, 2015, 2017). The purpose of our paper is to investigate the role of a uniform carbon tax[1] instrument in climate cooperation.

The advocate for an international carbon tax to combat global warming is not recent. Pearce (1991) discusses the advantages and disadvantages of carbon taxes and calls that additional and more careful analytical studies of carbon taxes are urgently needed. Hoel (1992) compares the internationally harmonized domestic taxes with the international carbon taxes which are designed in a way that the government of each

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[1] The uniform carbon tax means a single carbon tax rate, which is also called the harmonized domestic carbon tax in the literature (e.g., Hoel, 1992, 1993a; Nordhaus, 2006).

country pays a carbon tax to an international agency, and the tax revenue is reimbursed to the governments of the participating countries according to a set of fixed reimbursement shares. He shows such an international carbon tax for all countries will give an allocation of emissions that is very close to the allocation in the first-best optimum (Hoel, 1993b), but the internationally harmonized domestic taxes are politically more realistic (Hoel, 1993a). Van der Ploeg and de Zeeuw (1992) adopt the cost-benefit approach to demonstrating that a uniform carbon tax can improve the environment compared to the outcome that the market is left to its own devices. Nordhaus (2006, 2007) carefully analyze the uniform carbon tax and suggest the uniform carbon tax is more effective than emissions caps to slow global warming. The argument is made more persuasive by Weitzman (2014, 2015, 2017) that show negotiating a uniform carbon tax can internalize climate externality. He argues that a uniform carbon tax provides a focal point compared to negotiating different emissions caps, what's more, the carbon tax has a "double dividend" of reducing emissions and offsetting other distorting taxes, which have been empirically confirmed by McKitrick (1997) and Parry and Bento (2000).

However, the above literature is either conceptual (e.g., Nordhaus, 2006, 2007; Pearce, 1991) or based on the models in non-cooperation and full cooperation (e.g., Hoel, 1992, 1993a,b; van der Ploeg and de Zeeuw, 1992; Weitzman, 2014, 2015, 2017). The requirement that all countries are regulated by a uniform carbon tax ignores the voluntariness of countries participating in agreements and the case of partial cooperation. Given the sovereign independence and geopolitics of countries, and the absence of supranational institutions that can enforce regulations on countries to coordinate collective and individual incentives, it is difficult to reach a globally uniform carbon tax agreement. International cooperation on global environmental issues is more often achieved in the form of self-enforcing international environmental agreements (Barrett, 1994, 2005), such as the Montreal Protocol on ozone depletion.

There is little literature that examines the effects on climate cooperation of negotiating a uniform carbon tax in international environmental agreements (e.g., McEvoy and McGinty, 2018; Nordhaus, 2015; Schmidt and Ockenfels, 2021). Based on the work of Weitzman (2014) and taking into account the voluntary participation of countries, McEvoy and McGinty (2018) show that, with symmetric countries, the uniform carbon tax instrument will result in the same size of the stable coalition and abatement level as the emissions caps instrument. However, the opposite conclusion is obtained by Schmidt and Ockenfels (2021). Combining a game analysis and a laboratory experiment with human subjects, they provide causal evidence that negotiating a uniform carbon tax can promote more ambitious climate cooperation than negotiating different emissions caps when participation is voluntary. The inconsistency in conclusion suggests that the claim that a uniform carbon tax instrument promotes more cooperation than the emissions caps instrument is still debatable. Besides, they depict the global economy in a rudimentary fashion, and ignore the aspect that countries choose their taxes strategically by taking into consideration the terms-of-trade effects of their own policies, as carbon taxes tend to raise concerns about losing competitiveness of domestic industries, especially emissions-intensive and trade-exposed industries (EITE) (Böhringer et al., 2017a,b; Zhang, 2018). Nordhaus (2015) considers the trade structure and shows that the climate club induces a large stable coalition with high levels of abatement by using a Coalition Dynamic Integrated model of Climate and the Economy (C-DICE), but the uniform carbon tax is exogenously given, which does not embody the strategic interaction.

In light of these considerations, our paper considers the voluntariness of countries participating in agreements and the strategic interaction that countries choose their taxes strategically by taking into consideration the terms-of-trade effects of their own policies. We assume a simple market structure where each country has a representative firm and consumer, and the dirty good is produced by the firm and traded in each segmented market. In such a market economy that allows free trade, we examine the effects on climate cooperation of negotiating a uniform carbon tax in international environmental agreements by developing a three-stage game that extends the intra-industry trade model introduced by Brander (1981).

We measure the stability and effectiveness of the coalition under the uniform carbon tax instrument and further investigate the working mechanism, which is our first stage. Consider a coalition formation game, all countries simultaneously and non-cooperatively decide whether to join the coalition that negotiates a uniform carbon tax. Countries that join the coalition are called signatories, and countries that remain outside are called non-signatories. We assume that the coalition is open members and self-enforcing, which means that any country can join freely and can withdraw without punishment and embodies the voluntariness of participating in agreements.

We analyze the strategic interaction between signatories and non-signatories, which is our second stage. Countries choose their taxes strategically by taking into account the terms-of-trade effects of their own policies. Specifically, the signatories choose the uniform carbon tax to maximize the joint welfare, and the non-signatories non-cooperatively choose their own carbon taxes to maximize their own welfare simultaneously. Here we impose a non-negative constraint on carbon taxes due to focusing on the effects of the uniform carbon tax.

We examine the effects of carbon taxes on the strategic choices of firms, which is our third stage. Firms that produce a homogeneous traded good and sell it in segmented markets play the imperfect competition in each segmented market. Rather than relocating when firms are faced with ever-stringent regulations, we assume that the location of each firm is fixed and that firms respond to carbon taxes through abatement efforts utilizing end-of-pipe technologies (Olajire, 2010; Yamaji, 1998).

Following the three-stage game framework, we additionally examine the effects on climate cooperation of negotiating different emissions caps in international environmental agreements for comparative analysis. We compare the output of firms, emissions, and welfare under two instruments and investigate the mechanism difference in coalition formation to attempt to answer whether the uniform carbon tax instrument promotes more ambitious climate cooperation than the emissions caps instrument.

Our results show that an increase in own country’s carbon tax weakens the competitiveness of own country's firm and increases the abatement cost of the firm. Anticipate the terms-of-trade effects of their own countries' carbon tax, we demonstrate that, for a range of parameter values, the dominant strategy of non-signatories is not to implement carbon taxes to regulate the emissions of firms, while the signatories choose the same strategy as non-signatories unless the size of the coalition is large enough to generate positive benefits for signatories. Then, the signatories will implement a positive uniform carbon tax, and the larger the size of the coalition, the more prone to enact a tougher uniform carbon tax to regulate the emissions of firms. Compared with the emissions caps instrument, we further show that the uniform carbon tax instrument is more modest, which narrows the benefits gap between signatories and non-signatories, more likely to promote participation. But the degree of improvement in social welfare and social emissions shows great differences, which decrease in the parameters of emissions damage. Therefore, the uniform carbon tax instrument promotes climate cooperation only when the emission damage is less severe. If the emission damage is more severe, the role of the uniform carbon tax instrument is only to increase participation in agreements, and additional incentives are needed to achieve deep emission reductions.

Our paper benefits from two strands of literature: carbon taxes and international environmental agreements. Carbon taxes are proposed as a policy instrument to control carbon emissions as early as the 20th century (e.g., Nordhaus, 1976) based on the seminal work of Pigou (1920), which suggests taxation to correct negative environmental externalities. Since then, carbon taxes have attracted the interest of researchers and policymakers, and a corpus of carbon tax literature has accumulated to address a variety of issues over the last three decades[2]. In addition to the uniform carbon tax literature mentioned earlier, our paper is also related to the issue that the policy reform of emissions taxes to reduce emissions under imperfect competition (e.g., Gautier, 2013a,b, 2017; Lahiri and Symeonidis, 2007). Lahiri and Symeonidis (2007) investigate the implications of policy reform of emissions taxes on global

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[2] See review (Timilsina, 2018; Zhang et al., 2016).

emissions, but they do not consider the effects on welfare. Furthermore, Gautier (2013a,b, 2017) examine the effects of policy reform of emissions taxes on welfare, and the analysis contributes to previous works by factoring changes in abatement cost and production cost into the policy reform of emissions taxes. We extend their model from two countries to n countries and consider the coalition formation, but maintaining the same market structure and abatement technologies. Moreover, we do not get into the effects on welfare and emissions of policy reform of emission taxes, because that has been covered in the aforementioned literature, instead focusing on the strategic interaction between signatories and non-signatories, as well as the effects of negotiating a uniform carbon tax on effectiveness and stability of the coalition.

The game-theoretic analysis of international environmental agreements dates back to Barrett (1994) and Carraro and Siniscalco (1993), who conduct pioneering work on the formation and stability of international environmental agreements. Carraro and Siniscalco (1993) develop a classic standard model of international environmental agreements that considered a two-stage open membership game in Cournot timing. In the first stage, countries simultaneously and non-cooperatively decide whether to join the coalition and then countries decide on equilibrium emissions in the second stage. Barrett (1994) uses abatement rather than emissions as the decision variable and considers the coalition acts as Stackelberg leader in the second stage. Based on the standard model, the research on international environmental agreements has been developed in multiple aspects[3], such as asymmetry (e.g., Hagen and Eisenack, 2019, McGinty, 2007), uncertainty (e.g., Barrett, 2013; Finus and Pintassilgo, 2013; Na and Shin, 1998), dynamics (e.g., Rubio and Casino, 2005; Rubio and Ulph, 2007), etc. But these models take reduced form and only depict the global economy in a rudimentary fashion. Barrett (1997) and Eichner and Pethig (2013) extend the basic model and link international trade to climate negotiations to capture the market economy. However, previous research that takes the form of emissions caps as climate policy still has yet to identify a successful mechanism for climate cooperation.

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[3] More in detail see the review of Finus (2008) and Amrita and Marrouch (2016)

Our model builds on Barrett (1997) and the contribution is that we consider carbon taxes as climate policy and assume the members of the coalition negotiate a uniform carbon tax. Some literature combines international environmental agreements with trade and carbon taxes (e.g., Khourdajie and Finus, 2020; Eichner and Pethig, 2014, 2015). With a perfectly competitive world market setting, Eichner and Pethig (2014) investigate the effects of mixed fossil-fuel supply taxes and demand-side caps-and-trade policy on the effectiveness of international environmental agreements, and Eichner and Pethig (2015) compare the demand-side carbon taxes and demand-side caps policy. Unlike their model setting, we consider the supply-side carbon taxes and set an imperfectly competitive segmented market in a partial equilibrium framework, which is similar to Khourdajie and Finus (2020). However, they focused on examining the effects of carbon border adjustments on the effectiveness of international environmental agreements and comparing the carbon taxes with and without border tax adjustments. The main aim of our paper is to examine the effects on climate cooperation of negotiating a uniform carbon tax in international environmental agreements and to compare it with the emissions caps instrument. Besides, we innovatively consider emissions variables and abatement efforts of firms, which are usually assumed that there are no abatement technologies, and use output reduction as an alternative to emissions reduction in the traditional international environmental agreement literature. Finally, unlike Khourdajie and Finus (2020), which allow the carbon taxes to be negative because they don’t care about absolute values but comparative values, we impose a non-negative constraint on carbon taxes due to analyzing the strategic interaction of countries.

In summary, the main contributions of this paper are at the intersection of the aforementioned literature. First, we develop the model for negotiating a uniform carbon tax in the self-enforcing international environmental agreement that considers the abatement efforts of firms and captures the aspect that countries choose their taxes strategically by taking into account the terms-of-trade effects of their own policies, which complements the growing uniform carbon tax theoretical literature. Second, we analyze the strategic interaction between coalition and fringe and derive the mechanism that how the uniform carbon tax instrument encourages participation by comparing it with the emissions caps instrument, which contributes as a guide for the proposal that negotiates a uniform carbon tax coalition. Last but not least, we clarify the role of climate cooperation of negotiating a uniform carbon tax in international environmental agreements with free trade and determine the conditions under which the uniform carbon tax instrument can promote more ambitious international climate cooperation.

The rest of this paper is organized as follows. Section 2 introduces the model framework. Section 3 solves the three-stage game and analyzes the results. Section 4 compares the emission caps instrument and the uniform carbon tax instrument. Section 5 summarizes the paper, points out the limitations, and puts forward future research.

2. Methodology

2.1. Model

Consider N ex-ante symmetric countries, indexed by $i \in N = \{1,2,\dots,n\}$. We assume each country has a representative firm and consumer, and the location of the firm is fixed. Each firm produces a homogeneous traded good and sells it in segmented markets, so the firms play Cournot competitive in each segmented market. The output of the firm located in country i in the market of the country j denoted as x_{ij}, $i,j \in N$, throughout the paper the first subscript indicates the firm in which the good is produced, and the second subscript indicates the market in which the good is consumed, then the total output x_i^p of firm i is given by:

$$x_i^p = \sum_{j=1}^{n} x_{ij}. \tag{1}$$

The total consumption x_i^c of market i is given by:

$$x_i^c = \sum_{j=1}^{n} x_{ji}. \tag{2}$$

The social total production and consumption meet the conditions for market clear:

$$\sum x_i^p = \sum x_i^c. \tag{3}$$

We assume a linear inverse demand function which in country i is given by:

$$p_i(x_i^c) = a - x_i^c, \tag{4}$$

where p_i is the good's price faced by the consumer in country i, and $a > 0$ is a market size parameter.

Carbon emissions are a by-product of the output of the firms. We assume that all firms have the same production technology and emissions are proportional to output. The country i imposes a carbon tax t_i on emissions per unit, the firms respond by abatement efforts with end-of-pipe technologies. Following Gautier (2013a) and Lahiri and Symeonidis (2007), we consider a simple cost function of end-of-pipe for tractability, that is:

$$C_i(x, e) = cx_i^p + \frac{(x_i^p - e_i)^2}{2}, \tag{5}$$

where e_i is the ultimate carbon emissions of firm i, i.e., the release of emissions into the atmosphere. The first item of Eq.(5) is the production cost of firm i, and the marginal production cost is $c > 0$. The second item of Eq.(5) is the abatement cost of firm i, and the marginal abatement cost is $x_i^p - e_i$, which equals the abatement in our paper.

The carbon emissions are global pollution, thus, the ultimate social emissions consist of all firms' ultimate carbon emissions, that is:

$$E = \sum_{i=1}^{n} e_i. \tag{6}$$

Damage caused by global carbon emissions is the same for each country, we assume a liner damage function, that is:

$$D(E) = \gamma E, \tag{7}$$

where $\gamma > 0$ is the marginal damage parameter of carbon emissions.

Assuming that other costs of firms are away as usual, such as export transportation and tariffs, etc., the profit function of the firm i is given by:

$$\pi_i = \sum_{j=1}^{n} p_j\left(x_j^c\right)x_{ij} - C_i(x, e) - t_i e_i, \tag{8}$$

where the first item is the sales revenue of firm i, the second item is the cost of the firm i consisting of production cost and abatement cost, and the third item is the carbon tax faced by the firm i due to carbon emissions.

Next, consider the welfare of country i, which is given by:

$$W_i = CS_i + PS_i + CR_i - D, \tag{9}$$

where CS_i represents the consumer surplus of country i, PS_i represents the producer surplus of country i, CR_i represents the carbon tax revenue of country i from carbon emissions of the domestic firm, and D is the damages caused by global carbon emissions.

The consumer surplus of country i is given by:

$$CS_i = ax_i^c - \frac{1}{2}(x_i^c)^2 - p_i(x_i^c)x_i^c, \tag{10}$$

where the first two items are consumer utility functions that exclude the effect of income, and the last item is consumer spending.

The producer surplus of country i is the profit of the firm i, that is:

$$PS_i = \pi_i. \tag{11}$$

The carbon tax revenue of country i from carbon emissions of the domestic firm is given by:

$$CR_i = t_i e_i. \tag{12}$$

2.2. The rule of the game

The first stage is coalition formation: all countries simultaneously and non-cooperatively decide whether to join the coalition regulated by the uniform carbon tax. We consider there are m countries that join the coalition, called signatories, which are set as $S = \{1,2, \dots m\}$, and the remaining countries called non-signatories act as singletons, which are set as $NS = \{1,2, \dots n-m\}$, $1 \le m \le n$.

The second stage is the strategic interaction of carbon tax between the coalition and the fringe. The signatories choose the uniform carbon tax t_s by maximizing the joint welfare of the coalition, that is $max \sum_{s=1, s\in S}^{m} W_s$. The non-signatories $f \in NS$ choose their individual carbon tax t_f by maximizing the own welfare, that is $max\, W_f$.

The third stage is imperfect competition among firms. All firms simultaneously and non-cooperatively choose the abatement taking their own country's carbon tax as given and the output in each segmented market taking the output of other firms in each segmented market as given to maximize the profit, that is $max\, \pi_i$, $i \in N$.

The game is solved by backward induction.

3. Analysis

3.1. The strategy of firms

In this section, we analyze the strategic interaction of firms, which includes product strategy and abatement strategy. For product strategy, the firm chooses the output in each segmented market taking the output of other firms as given. For the abatement strategy, if the firm fails to reduce emissions, it will face a higher carbon tax cost. Therefore, the firm i takes its carbon tax and the segmented outputs of other firms as given to choose the abatement and the output in market k to maximize profit, that is $max\,\pi_i, i \in N$. The first-order conditions (for an interior solution) are:

$$\frac{\partial \pi_i}{\partial x_{ik}} = a - c - 3x_{ik} - \sum_{j=1,j\neq i}^{n} x_{jk} - \sum_{j=1,j\neq k}^{n} x_{ij} + e_i = 0,\ i,k = 1,2,\dots n \tag{13}$$

$$\frac{\partial \pi_i}{\partial e_i} = \sum_{j=1}^{n} x_{ij} - e_i - t_i = 0,\ i = 1,2,\dots n \tag{14}$$

where Eq.(13) states that the firm i will expand the output in market k until marginal revenue in market k, i.e., $a - \sum_{i=1}^{n} x_{ik} - x_{ik}$ equals the marginal costs, i.e., $c + \sum_{j=1}^{n} x_{ij} - e_i$, which consists of marginal abatement cost $\sum_{j=1}^{n} x_{ij} - e_i$ and marginal product cost c. Eq.(14) shows that the firm will decrease emissions until the marginal abatement cost $\sum_{j=1}^{n} x_{ij} - e_i$ equals the carbon tax t_i. The result reveals that abatement equals carbon tax in our model setting.It is easy to verify that the second-order Hessian matrix is negative, so there is a unique equilibrium solution. Solve the $n(n+1)$ equation above, we determine the equilibrium emissions and the equilibrium output in the market k of firm i, respectively. Given the coalition structure S, and the uniform carbon tax of signatories $t_{s\in S} = t_s$, then the equilibrium output of the signatory's firm $s \in S$ and non-signatory's firm $f \in NS$ in the market k are given respectively by:

$$x_{sk} = \frac{a-c-(n-m+1)t_s+\sum_{f=1}^{n-m} t_f}{(n+1)}, \tag{15}$$

$$x_{fk} = \frac{a-c+mt_s-nt_f+\sum_{j=1,j\neq f,j\in NS}^{n-m} t_j}{(n+1)}. \tag{16}$$

Eq.(15) and Eq.(16) state that the output of each firm in each segmented market is the same, but the non-signatories' firms sell more than signatories' firms in each segmented market when $t_s \geq t_f$. Besides, the output of signatories' firms in each segmented market decreases in the uniform carbon tax ($\frac{\partial x_{sk}}{\partial t_s} = -\frac{n-m+1}{n+1} < 0$) and increases in non-signatories' carbon taxes ($\frac{\partial x_{sk}}{\partial t_f} = \frac{1}{n+1} > 0$). Similarly, the output of non-signatories' firms decreases in their own country's carbon tax ($\frac{\partial x_{fk}}{\partial t_f} = -\frac{n}{n+1} < 0$) and increases in the uniform carbon tax ($\frac{\partial x_{fk}}{\partial t_s} = \frac{m}{n+1} > 0$) and other non-signatories' carbon taxes ($\frac{\partial x_{fk}}{\partial t_j} = \frac{1}{n+1} > 0$). But, the addition of a unit of the uniform carbon tax will have a greater effect on the output of non-signatories' firms than on signatories' firms when $m > \frac{n+1}{2}$. Same as the literature on how carbon taxes affect the competitiveness of firms (e.g., Aldy and Pizer, 2015), the competitiveness of firms is negatively affected by the own country's carbon tax and positively affected by the other countries' carbon taxes.

The total output of signatory's firm s and non-signatory's firm f are given respectively by:

$$x_s^p = \frac{n(a-c)-n(n-m+1)t_s+n\sum_{f=1}^{n-m} t_f}{(n+1)}, \tag{17}$$

$$x_f^p = \frac{n(a-c)+nmt_s-n^2 t_f+n\sum_{j=1,j\neq f,j\in NS}^{n-m} t_j}{(n+1)}. \tag{18}$$

The total output of the firm is equivalent to the sum of the output in each segmented market, and as previously analyzed, the output in each segmented market is the same. Consequently, the change in total output is the same as the change in output of the segmented market.

The equilibrium emissions of signatory's firm s and non-signatory's firm f are given respectively by:

$$e_s = \frac{n(a-c)-\left((n+1)+n(n-m+1)\right)t_s+n\sum_{f=1}^{n-m} t_f}{n+1}, \tag{19}$$

$$e_f = \frac{n(a-c)-(n^2+n+1)t_f+n\sum_{j=1,j\neq f,j\in NS}^{n-m} t_j+nmt_s}{n+1}. \tag{20}$$

Eq.(19) and Eq.(20) indicate the non-signatories' firms emit more than the signatories' firms when $t_s \geq t_f$. The emissions of signatories' firms decrease in the uniform carbon tax ($\frac{\partial e_s}{\partial t_s} = -\frac{(n+1)+n(n-m+1)}{n+1} < 0$) and increase in non-signatories' carbon taxes ($\frac{\partial e_s}{\partial t_f} = \frac{n}{n+1} > 0$). Similarly, the emissions of non-signatories' firms decrease in own country's carbon tax ($\frac{\partial e_f}{\partial t_f} = -\frac{n^2+n+1}{n+1} < 0$) and increase in the uniform carbon tax ($\frac{\partial e_f}{\partial t_s} = \frac{nm}{n+1} > 0$) and other non-signatories' carbon taxes ($\frac{\partial e_f}{\partial t_j} = \frac{n}{n+1} > 0$). The addition of a unit of the uniform carbon tax will have a greater effect on the emissions of non-signatories' firms than on signatories' firms when $m > \frac{(n+1)^2}{2n}$.

The social emissions are given by

$$E = \frac{n^2(a-c)-(2n+1)mt_s-(2n+1)\sum_{f=1}^{n-m} t_f}{(n+1)} \tag{21}$$

The social emissions are equivalent to the sum of emissions of each country. Further, Eq.(21) says the social emissions decrease in carbon taxes.

The consumption of signatory s and non-signatory f are given respectively by:

$$x_s^c = \frac{n(a-c)-mt_s-\sum_{f=1}^{n-m} t_f}{(n+1)}, \tag{22}$$

$$x_f^c = \frac{n(a-c)-mt_s-t_f-\sum_{j=1,j\neq f,j\in NS}^{n-m} t_j}{(n+1)}. \tag{23}$$

Eq.(22) and Eq.(23) show the consumption of signatories and non-signatories are the same, and consumption decreases in carbon taxes, whether it is the own country's carbon tax or the other countries' carbon taxes. This is mainly due to the increase in carbon taxes that causes the increase of other firms' output is less than the decrease of own firms' output in this market. For example, consider a signatory's market, the increase in uniform carbon tax that results in the decrease in output of all signatories' firms exceeds the increase in output of all non-signatories' firms, and the increase in non-siggnatories' carbon taxes that results in the decrease in output of all non-signatories' firms exceeds the increase in output of all signatories' firms. The same for a non-signatory market.

3.2. The strategy of countries

In this section, we analyze the strategic interaction of carbon taxes between signatories and non-signatories. They choose carbon taxes strategically by taking into account the terms-of-trade effects of their own policies. Considering the strategic behavior of the country, on the one hand, the country expects to be in a position to reduce the damage caused by carbon emissions using a carbon tax instrument; on the other hand, it expects to keep the competitiveness of the domestic firm. Therefore, given the structure of the coalition, the signatories choose the uniform carbon tax to maximize the joint welfare, and the non-signatories non-cooperatively choose individual carbon tax to maximize their individual welfare simultaneously. We first briefly characterize two benchmarks of the business-as-usual (BAU) scenario and the social optimal scenario and then turn to the self-enforcing climate coalition.

3.2.1. Business-as-usual

Business-as-usual means that each country takes account of the damage to itself caused by its emissions, but does not takes into consideration the damage caused to other countries. In game-theoretic expression, the n countries play the non-cooperative game, and their strategies are countries' carbon taxes and their payoff functions are countries' welfare. The country $i \in N$ chooses the carbon tax to maximize its own welfare W_i taking the other countries' carbon taxes given. The optimization problem is:

$$max\ W_i = \frac{1}{2}(x_i^c)^2 + \sum_{k=1}^{n} x_{ik}\,(a - x_k^c - c) - \frac{\left(x_i^p - e_i\right)^2}{2} - \gamma E$$

$$\text{s.t.}\ \ t_i \geq 0. \tag{24}$$

The Kuhn-Tucker conditions of the optimization problem (24) are:

$$\frac{\partial W_i}{\partial t_i} \leq 0，\ t_i \geq 0，\ t_i \frac{\partial W_i}{\partial t_i} = 0， \tag{25}$$

where

$$\frac{\partial W_i}{\partial t_i} = -\frac{n(3n+2)}{(n+1)^2} t_i + \frac{n+1-n^2}{(n+1)^2} \sum_{j=1,j\neq i}^{n} t_j + \frac{\gamma(2n+1)}{n+1} - \frac{(a-c)n^2}{(n+1)^2}. \tag{26}$$

Eq.(26) shows the effects of a change in country i's carbon tax on country i's welfare. The first term is the direct effect, which indicates that the marginal change in welfare decreases in the own country's carbon tax. The second term is the cross effect, which indicates that the marginal change in welfare decreases in the other countries' carbon taxes. The third term says that the marginal change in welfare increases in the marginal damage of emissions. The fourth term in Eq.(26) says that the marginal change in welfare decreases in the benefit from production and consumption $a-c$. The constraint qualification is satisfied as a result of the constraints being linear. The second-order condition $\frac{\partial^2 W_i}{\partial t_i^2}=-\frac{n(3n+2)}{(n+1)^2}<0$, the solution to the optimization problem (24) exists. The equilibrium carbon taxes of all countries will be the same under the symmetric assumption.

Proposition 1. *Denote the equilibrium carbon tax in business-as-usual* t^u*, then:*

$$t^u=\begin{cases}\frac{-n^2(a-c)+(n+1)(2n+1)\gamma}{(n^3+n^2+2n+1)} & if\ \frac{n^2(a-c)}{(n+1)(2n+1)}<\gamma \\ 0 & if\ \gamma\leq\frac{n^2(a-c)}{(n+1)(2n+1)}\end{cases}. \tag{27}$$

Proof: See Appendix A.1.

From Proposition 1, we know that the carbon tax is determined by the number of countries n, the market size parameter a, the marginal production cost of firms c, and the marginal damage parameter of emissions γ. There exists a threshold $\tilde{\gamma}_1=\frac{n^2(a-c)}{(n+1)(2n+1)}$, when the marginal damage of emissions is less than or equal to this threshold, i.e., $\gamma\leq\tilde{\gamma}_1$, the equilibrium carbon taxes of all countries is zero. Without carbon taxes interventions, the firms will not take the initiative to reduce emissions. When the marginal damage of emissions is greater than this threshold, i.e., $\gamma>\tilde{\gamma}_1$, the countries will enact positive carbon taxes to force firms to reduce emissions. Furthermore, we find the carbon tax decreases in the number of countries ($\frac{\partial\frac{-n^2(a-c)+(n+1)(2n+1)\gamma}{(n^3+n^2+2n+1)}}{\partial n}<0$), and the threshold $\tilde{\gamma}_1$ increases in the number of countries ($\frac{\partial\tilde{\gamma}_1}{\partial n}>0$), which implies that the increase in the number of countries weakens the motivation of countries to implement carbon taxes and abatement.

3.2.2. Social optimum

Social optimum means that each country takes account of the damage to society caused by the emissions of all countries, which implies that all countries are regulated by a global uniform carbon tax in our setting. In game-theoretic expression, the n countries play the full cooperative game, and their strategies are the uniform carbon tax and their payoff functions are social welfare. All countries choose the global uniform carbon tax t^c to maximize social welfare $\sum_{i=1}^{n} W_i$, and $\sum_{i=1}^{n} W_i = nW_i$ under the symmetric assumption. The optimization problem is:

$$max \sum_{i=1}^{n} W_i = n\left(\frac{1}{2}(x_i^c)^2 + \sum_{k=1}^{n} x_{ik}\,(a - x_k^c - c) - \frac{\left(x_i^p - e_i\right)^2}{2} - \gamma E\right)$$

$$\text{s.t. } t^c \geq 0. \tag{28}$$

The Kuhn-Tucker conditions of the optimization problem (28) are:

$$\frac{\partial nW_i}{\partial t^c} \leq 0,\ t^c \geq 0,\ t^c \frac{\partial nW_i}{\partial t^c} = 0, \tag{29}$$

where

$$\frac{\partial nW_i}{\partial t^c} = n\left[-\frac{2n^2+2n+1}{(n+1)^2}t^c + \frac{\gamma n(1+2n)}{n+1} - \frac{(a-c)n}{(n+1)^2}\right]. \tag{30}$$

Eq.(30) shows the effects of a change in uniform carbon tax on social welfare. The first term is the direct effect, which indicates that the marginal change in social welfare decreases in the uniform carbon tax. The second term says that the marginal change in social welfare increases in marginal damage of emissions. The third term says that the marginal change in social welfare decreases in the benefit from production and consumption. The constraint qualification is satisfied as a result of the constraints being linear. The second-order condition $\frac{\partial^2 nW_i}{\partial t^{c2}} = -n\frac{2n^2+2n+1}{(n+1)^2} < 0$, the solution to the optimization problem (28) exists.

Proposition 2. *Denote the equilibrium carbon tax in social optima t^c, then:*

$$t^c = \begin{cases} \frac{-n(a-c)+n(2n+1)(n+1)\gamma}{2n^2+2n+1} & if\ \frac{(a-c)}{(n+1)(2n+1)} < \gamma \\ 0 & if\ \gamma \leq \frac{(a-c)}{(n+1)(2n+1)} \end{cases}. \tag{31}$$

Proof: See Appendix A.2

From Proposition 2, we know that there also exists a threshold $\tilde{\gamma}_2 = \frac{(a-c)}{(n+1)(2n+1)}$, when the marginal damage of emissions is less than or equal to this threshold, i.e., $\gamma \leq \tilde{\gamma}_2$, the uniform carbon tax is zero, and thus the abatement is zero. When the marginal damage of emissions is greater than this threshold, i.e., $\gamma > \tilde{\gamma}_2$, the uniform carbon tax is positive and the firms will make abatement efforts under the carbon tax intervention. Furthermore, we find that the uniform carbon tax increases in the number of countries ($\frac{\partial \frac{-n(a-c)+n(2n+1)(n+1)\gamma}{2n^2+2n+1}}{\partial n} > 0$), and the threshold $\tilde{\gamma}_2$ decreases in the number of countries ($\frac{\partial \tilde{\gamma}_2}{\partial n} < 0$), which implies the increase in the number of countries strengthens the motivation of countries to implement carbon taxes and the level of abatement.

3.2.3. Climate coalition

The climate coalition means partial cooperation and divides the countries into two groups, namely signatories $S = \{1,2, \dots m\}$ and non-signatories $NS = \{1,2, \dots n - m\}$. It is the case under business-as-usual for $m = 0$ or 1, and social optima for $m = n$. Thus, the case of $1 < m < n$ is considered here. The signatories choose the uniform carbon tax t_s to maximize the welfare of the coalition $\sum_{s=1}^{m} W_{s \in S} = mW_s$, and the non-signatories $f \in NS$ choose the individual carbon tax t_f to maximize own welfare W_f. The optimization problem of signatories is:

$$max\ \ mW_s = \frac{m}{2}(x_s^c)^2 + m\sum_{k=1}^{n} x_{sk}\,(a - x_k^c - c) - \frac{m\left(x_s^p - e_s\right)^2}{2} - m\gamma E$$

$$\text{s.t.}\ \ t_s \geq 0. \tag{32}$$

The Kuhn-Tucker conditions of the optimization problem (32) are:

$$\frac{\partial mW_s}{\partial t_s} \leq 0, t_s \geq 0, t_s\frac{\partial mW_s}{\partial t_s} = 0, \tag{33}$$

where

$$\frac{\partial mW_s}{\partial t_s} = m\begin{bmatrix} \frac{(2n+1)m^2-2n(n+1)m-(n+1)^2}{(n+1)^2}t_s + \frac{(2n+1)m-n(n+1)}{(n+1)^2}\sum_{f=1}^{n-m} t_f \\ +\frac{\gamma m(1+2n)}{n+1} - \frac{(a-c)n(n-m+1)}{(n+1)^2} \end{bmatrix}. \tag{34}$$

Eq.(34) is the effects of a change in uniform carbon tax on the welfare of the coalition. The first term is the direct effect, which indicates that the marginal change in the welfare of the coalition decreases in the uniform carbon tax. The second term is the cross effect, which indicates that the marginal change in the welfare of the coalition increases (decreases) in non-signatories' carbon taxes when $m > (<) \frac{n(n+1)}{2n+1}$. The equilibrium carbon taxes of non-signatories will be the same under the symmetric assumption, the Eq.(34) can be rewritten as:

$$\frac{\partial mW_s}{\partial t_s} = m\left[\begin{matrix}\frac{(2n+1)m^2-2n(n+1)m-(n+1)^2}{(n+1)^2}t_s - \frac{(2n+1)m^2-n(3n+2)m+n^2(n+1)}{(n+1)^2}t_f \\ +\frac{\gamma m(1+2n)}{n+1} - \frac{(a-c)n(n-m+1)}{(n+1)^2}\end{matrix}\right]. \quad (35)$$

Second-order condition $\frac{\partial^2 mW_s}{\partial t_s^2} = m\frac{(2n+1)m^2-2n(n+1)m-(n+1)^2}{(n+1)^2} < 0$ hold on $m \in (0, n)$, the solution to the optimization problem (32) exists.

The optimization problem of non-signatory f is:

$$max\ W_f = \frac{1}{2}\left(x_f^c\right)^2 + \sum_{k=1}^{n} x_{fk}\left(a - x_k^c - c\right) - \frac{\left(x_f^p - e_f\right)^2}{2} - \gamma E$$

$$\text{s.t.}\ \ t_f \geq 0, \quad (36)$$

The Kuhn-Tucker conditions of the optimization problem (36) are:

$$\frac{\partial W_f}{\partial t_f} \leq 0, t_f \geq 0, t_f\frac{\partial W_f}{\partial t_f} = 0, \quad (37)$$

where

$$\frac{\partial W_f}{\partial t_f} = -\frac{n(3n+2)}{(n+1)^2}t_f + \frac{n+1-n^2}{(n+1)^2}\sum_{j=1,j\neq f}^{n-m} t_j + \frac{m(n+1-n^2)}{(n+1)^2}t_s + \frac{\gamma(2n+1)}{n+1} - \frac{(a-c)n^2}{(n+1)^2}. \quad (38)$$

Eq.(38) is the effects of a change in non-signatory f's carbon tax on own country's welfare. The first term is the direct effect, which indicates that the marginal change in non-signatories' welfare decreases in their own country's carbon tax. The second term and the third term in Eq.(38) are the cross effect, which indicates that the marginal change in non-signatories' welfare decreases in other countries' carbon taxes. Recall the equilibrium carbon taxes of non-signatories will be the same under the symmetric assumption, and the signatories choose the uniform carbon tax t_s. Thus, the Eq.(38) can be rewritten as:

$$\frac{\partial W_f}{\partial t_f} = \frac{m(n+1-n^2)}{(n+1)^2}t_s - \frac{(n+1-n^2)m+n^3+n^2+2n+1}{(n+1)^2}t_f + \frac{\gamma(2n+1)}{n+1} - \frac{(a-c)n^2}{(n+1)^2}. \quad (39)$$

Second-order condition $\frac{\partial^2 W_f}{\partial t_f^2} = -\frac{(n+1-n^2)m+n^3+n^2+2n+1}{(n+1)^2} < 0$ hold on $m \in (0, n)$, the solution to the optimization problem (37) exists.

We determine the solutions to carbon taxes of signatories and non-signatories by joint Eq.(33), Eq.(35), Eq.(37), and Eq.(39).

Proposition 3. *Denote the uniform carbon tax of signatories* t_s*, and the carbon tax of non-signatories* t_f *in coalition formation. Then there exist three solutions:*

internal solution $(t_s > 0，\ t_f > 0)$*, signatories' interior and non-signatories' corner solution* $(t_s > 0，\ t_f = 0)$*, and double corner solution* $(t_s = 0，\ t_f = 0)$*. The three solutions are as follows:*

(1) *Internal solution*[4] $(t_s > 0，\ t_f > 0)$:

$$t_s = \frac{b(m)}{h(m)}, t_f = \frac{g(m)}{h(m)}, if\ b(m) > 0 \text{ and } g(m) > 0， \tag{40}$$

(2) *Signatories interior and non-signatories corner solution* $(t_s > 0，\ t_f = 0)$:

$$t_s = \frac{[n(n+1)-nm](a-c)-[(n+1)(2n+1)m]\gamma}{(2n+1)m^2-2n(n+1)m-(n+1)^2}, if\ \frac{(n^2+n-nm)(a-c)}{(n+1)(2n+1)m} < \gamma \tag{41}$$

(3) *Double corner solution:*

$$t_s = 0, t_f = 0, if\ \gamma \leq \frac{(n^2+n-nm)(a-c)}{(n+1)(2n+1)m}. \tag{42}$$

Proof: See Appendix A.3.

From Proposition 3, we know that the countries have three possible strategic behaviors under coalition formation. Intending to determine more precisely the choice of strategies, we analyze more thoroughly the conditions under which the various solutions are implemented.

For internal solution, we find that when $m \geq 3$, $g(m) < 0$, so the internal solution is only achieved at $m = 2$, where $\gamma > \frac{n(3n^2-n-2)(a-c)}{(n+1)^2(2n+1)}$. The marginal damage of emissions is larger than the benefit of consumption and production. As a result, the country will adopt a strict carbon tax to regulate the carbon emissions of the firm, including requiring the firm to stop production activities. For signatories' interior and non-signatories' corner solution and double corner solution, there is a threshold $\tilde{\gamma}_3(m) = \frac{(n^2+n-nm)(a-c)}{(n+1)(2n+1)m}$. When the marginal damage of emissions is greater than this threshold, i.e., $\tilde{\gamma}_3(m) < \gamma$, the equilibrium solution is signatories' interior and

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[4] $h(m) = -(n+1)^3m^2 + (n(n+1)(n^2+n+4)+1)m + (n+1)(n^3+n^2+2n+1)$

$$b(m) = [n(n+1)m^2 - n^3m - n(n+1)^2](a-c)$$
$$+[-nm^2 + (n^2+3n+1)m - n^2](n+1)(2n+1)\gamma$$

$$g(m) = [n(n+1)m^2 - n(n^2+n+1)m - n^2(n+1)](a-c)$$
$$+[-nm^2 + 2nm + (n+1)](n+1)(2n+1)\gamma$$

non-signatories' corner solution. When the marginal damage of emissions is less than or equal to this threshold, i.e., $\tilde{\gamma}_3(m) > \gamma$, the equilibrium solution is the double corner solution.

Moreover, if we strictly limit the space of the parameters $\gamma \le \frac{2(n+1)(a-c)}{(2n+1)^2}$, only signatories' interior and non-signatories' corner solution and double corner solution are available, then $t_f = 0$ is the dominant strategy of non-signatories. The result indicates that regardless of which strategy the signatories choose, the best strategy for non-signatories is not to regulate carbon emissions. However, the strategic choice of the signatories depends on the size of the coalition, the marginal damage of emissions, the number of countries, and the benefit of production and consumption. If we fix the size of the coalition, then when the marginal damage of emissions is less than or equal to the threshold $\tilde{\gamma}_3(m)$, the signatories choose the same strategy as non-signatories, i.e., they do not regulate the carbon emissions of firms. When the marginal damage of emissions is greater than the threshold $\tilde{\gamma}_3(m)$, the signatories will implement a positive carbon tax to regulate carbon emissions. Further, we find carbon taxes increases in the size of the coalition ($\frac{\partial \frac{[n(n+1)-nm](a-c)-[(n+1)(2n+1)m]\gamma}{(2n+1)m^2-2n(n+1)m-(n+1)^2}}{\partial m} > 0$), and the threshold $\tilde{\gamma}_3$ decreases in the size of the coalition ($\frac{\partial \tilde{\gamma}_3(m)}{\partial m} < 0$), which implies the signatories are prone to enact a tougher uniform carbon tax as the size of the coalition increases.

3.3. Coalition formation

In this section, we analyze the effectiveness and stability of the coalition and solve for the size of the stable coalition. Following the concept of coalition stability developed by d'Aspremont et al. (1983) which has been widely used in the literature of international environmental agreements, a stable coalition has to satisfy two conditions. The first condition is internal stability, which means that countries within the coalition have no incentive to withdraw from the coalition, and the second condition is external stability, which means that fringe has no incentive to join the coalition. In addition, we follow Barrett (1997) and assume that a country will join the coalition if it is not made worse off. Using an axiomatic expression, considering a coalition S, after solving the optimal equilibrium solution for the first two stages, the welfare of the signatories and non-signatories can be expressed as a function of the size of coalition m. The coalition S is stable if for any country i, there have:

$$W_{i\in S}(m) \geq W_{i\notin S}(m-1). \tag{43}$$

$$W_{j\notin S}(m) > W_{j\in S}(m+1). \tag{44}$$

Eq.(43) is an internal stability condition, the welfare of country i within the coalition is greater than or equal to the welfare of it withdrawing from the coalition, so countries within the coalition will not choose to leave the coalition. Eq.(44) is an external stability condition, the welfare of fringe j is greater than the welfare of it joining the coalition, so the fringe will not choose to join the coalition.

Intending to measure the effectiveness of the coalition that negotiates a uniform carbon tax, we consider a relative measurement following Eyckmans and Finus (2006), who proposed a closing the gap index (CGI) to measure to what extent a stable coalition closes the gap between the social optimum and the business-as-usual. Specifically, we defined the closing the gap index of welfare (WCGI) and the closing gap index of emission (ECGI) as follows respectively:

$$\mathrm{WCGI} = \frac{\sum_{i=1}^{n} W_i(m) - \sum_{i=1}^{n} W_i(1)}{\sum_{i=1}^{n} W_i(n) - \sum_{i=1}^{n} W_i(1)} \times 100. \tag{45}$$

$$\mathrm{ECGI} = \frac{\sum_{i=1}^{n} E_i(1) - \sum_{i=1}^{n} E_i(m)}{\sum_{i=1}^{n} E_i(1) - \sum_{i=1}^{n} E_i(n)} \times 100. \tag{46}$$

Although we have simplified the model by assumptions to keep tractability, solving for an analytical solution is still complicated. Here we rely on numerical simulation to analyze the stability and effectiveness of the coalition, which has been widely used in the literature of international environmental agreements (e.g., Khourdajie and Finus, 2020; Barrett, 1994; Eichner and Pethig, 2013).

3.4. Simulation results

We strictly limit the parameter space $\gamma \leq \frac{2(n+1)(a-c)}{(2n+1)^2}$ to ensure that the output and emissions are non-negative. Then non-signatories choose the dominant equilibrium strategy $t_f = 0$.

When $\gamma \leq \frac{(a-c)}{(n+1)(2n+1)}$, the marginal damage of emissions is small, and the effect on the environment is negligible. Then signatories and non-signatories will choose the zero-carbon tax strategy that will not regulate the emissions of firms. Each country is either a signatory or a non-signatory.

When $\frac{(a-c)}{(n+1)(2n+1)} < \gamma \leq \frac{2(n+1)(a-c)}{(2n+1)^2}$, the strategic choice of the signatories depends on the parameters. Khourdajie and Finus (2020) have shown that the absolute values of the parameters a, c, and γ have no bearing on the outcome, what matters is their ratio. Thus, we assumes that the marginal production cost $c = 0$, the market size is normalized to 1, i.e., $a = 1$, and the number of countries $n = 10$. Then marginal damage of emissions $\gamma \in (0.0043，0.0499]$, which is divided into 5 value with equal intervals such that $\Delta = \frac{\overline{\gamma} - \underline{\gamma}}{4}$. The $\underline{\gamma} = 0.0043$ represents the lower bound, and the $\overline{\gamma} = 0.0499$ represents the upper bound. We choose the values at quarter γ_3, half γ_2, and three-quarters γ_1 for simulation, i.e., $\gamma_3 < \gamma_2 < \gamma_1$.

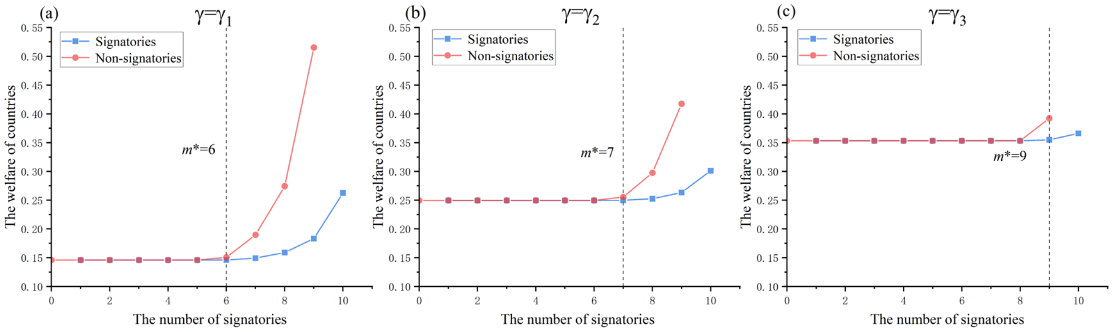

Fig. 1. Welfare of countries with different sizes of coalition

Fig.1a,b,c illustrate the welfare of signatories and non-signatories with different sizes of coalition. Take the marginal damage of emissions $\gamma = \gamma_1$ as an example. Fig.1a shows that the welfare of signatories and non-signatories is the same when $m \leq 5$, and that comes from the same carbon tax strategy, i.e., $t_s = t_f = 0$. When $m > 5$, the signatories change the strategy from $t_s = 0$ to $t_s > 0$, and ever then, the welfare of the signatories and non-signatories has progressively increased, but the growth of non-signatories far exceeds that of signatories as a consequence of free-riding. At $m = 6$, for any country i within the coalition, the welfare $W_{i \in S}(6) = 0.14594$, if it stays within the coalition; the welfare $W_{i \notin S}(5) = 0.14587$, if it withdraws from the coalition. $W_{i \in S}(6) > W_{i \notin S}(5)$ implies the internal stability condition Eq.(43) is satisfied, i.e., the countries within the coalition will not withdraw from the coalition. For any country j outside the coalition, the welfare $W_{j\notin S}(6) = 0.15054$, if it stays outside the coalition; the welfare $W_{j\in S}(7) = 0.14911$, if it joins the coalition. $W_{j\notin S}(6) > W_{j\in S}(7)$ implies that the external stability condition Eq.(44) is satisfied, i.e., the countries outside the coalition will not join the coalition. Therefore, the size of the stable coalition is m^* =6. Similarly, when $\gamma = \gamma_2$, $\gamma = \gamma_3$, the size of the stable coalition is m^* =7 and m^* =9, respectively. It appears that at least half of the countries join the coalition, and the smaller the marginal damage, the larger the size of the stable coalition, and possibly even the grand coalition. This result seems counterintuitive at first glance, but we provide a plausible explanation from the following dimensions.

First, the marginal damage of emissions is limited to our parameter space, which ensures that the damage caused by emissions is not so small that it is ignored by countries, nor it is so large that the countries must stop the production activities of firms. Second, as analyzed in Section 3.2.2, the carbon tax strategies of signatories depend on the threshold $\tilde{\gamma}_3(m)$, and when the marginal damage of emissions is less than or equal to the threshold $\tilde{\gamma}_3(m)$, the signatories choose the same strategy as non-signatories, i.e., $t_s = t_f = 0$. When the marginal damage of emissions is greater than the threshold $\tilde{\gamma}_3(m)$, the signatories choose $t_s > 0$. From Figure 1, we know that the welfare of countries increases in the uniform carbon tax, so a stable coalition is only possibly achieved under the strategy $t_s > 0$. Furthermore, the threshold $\tilde{\gamma}_3(m)$ decreases in the size of the coalition m. Thus, when the marginal damage of emissions γ is smaller, the size of coalition m needs to be larger to guarantee that the marginal damage of emissions γ is greater than the threshold $\tilde{\gamma}_3(m)$.

The strategic interaction described above perfectly reflects the mechanism of a uniform carbon tax instrument to mitigate free riding. To clarify this mechanism, we further analyze the composition of welfare, i.e., consumer welfare, producer welfare, carbon tax revenue, and damage of emissions, as shown in Fig 2a,b,c,d. An increase in the uniform carbon tax will benefit signatories from less damage and carbon tax revenue, but it will also have negative effects on consumer and producer welfare.

Signatories increase the uniform carbon tax only if the gains from the reduction in damages and carbon tax revenues are greater than the reductions in consumer welfare and producer welfare. As analyzed in Section 3.1, the reduction in damages and carbon tax revenues increase in the size of the coalition m, so there exists a value, i.e., $\gamma = \tilde{\gamma}_3(m)$, such that the gains equal the loss. This clarifies why the signatories choose $t_s = 0$ when $\gamma \leq \tilde{\gamma}_3(m)$, and reveals how a uniform carbon tax instrument works to encourage participation: though non-signatories enjoy the same reduction in damage at no cost and the increase in producer welfare as a consequence of free-riding, they cannot enjoy the benefits of free-riding when the size of the coalition is not large enough to generate positive benefits for signatories.

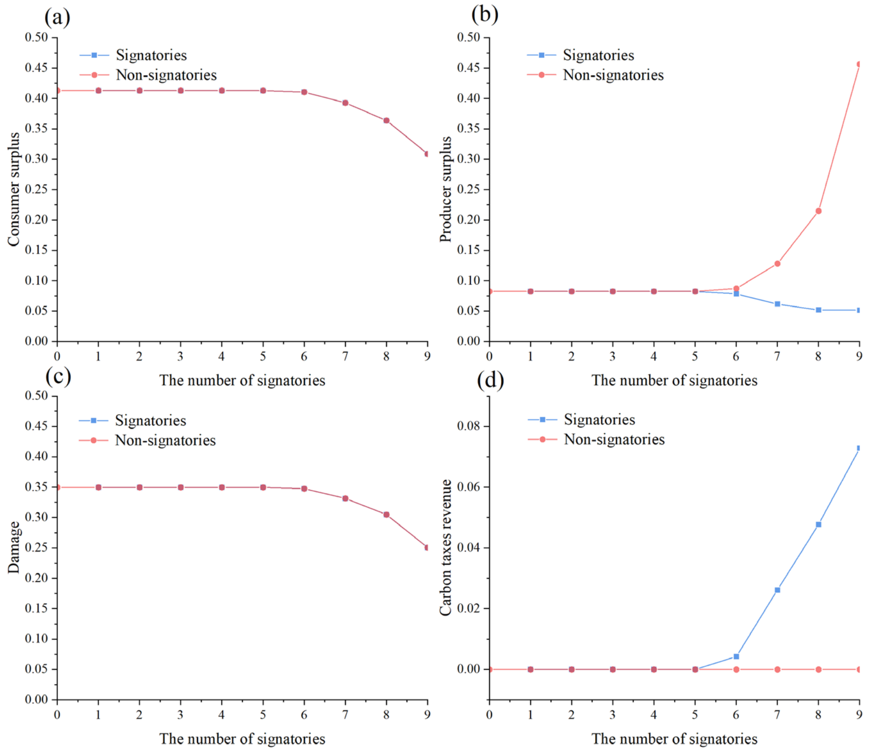

Fig. 2. Composition of welfare with different sizes of coalition ($\gamma = \gamma_1$)

Fig. 3a,b,c illustrate the emissions of signatories and non-signatories with different sizes of coalition. The emissions of signatories and non-signatories are the same when the signatories choose the same strategy as non-signatories, i.e., $t_s = t_f = 0$, where the firms are not regulated by carbon taxes. The emissions of signatories decrease due to the abatement efforts of firms regulated by the uniform carbon tax when the signatories choose $t_s > 0$. However, the emissions of non-signatories increase and the increase in the emissions from non-signatories is greater than the decrease in the emissions from signatories as a consequence of the free-riding, which increases the risk of carbon leakage. In addition, we find that emissions of signatories increase as the marginal damage of emissions γ decreases, while emissions of non-signatories decrease as the marginal damage of emissions γ decreases. This is primarily because the uniform carbon tax decreases as the marginal damage of emissions decreases, as determined by Eq.(41). The smaller the uniform carbon tax, the less the abatement of signatories' firms, which results in higher emissions. Conversely, the smaller the uniform carbon tax, the less competitive the non-signatories have in the market, which results in fewer emissions they emit. Changes in emissions of signatories and non-signatories with respect to the uniform tax can also be obtained directly from Eq.(19) and Eq.(20).

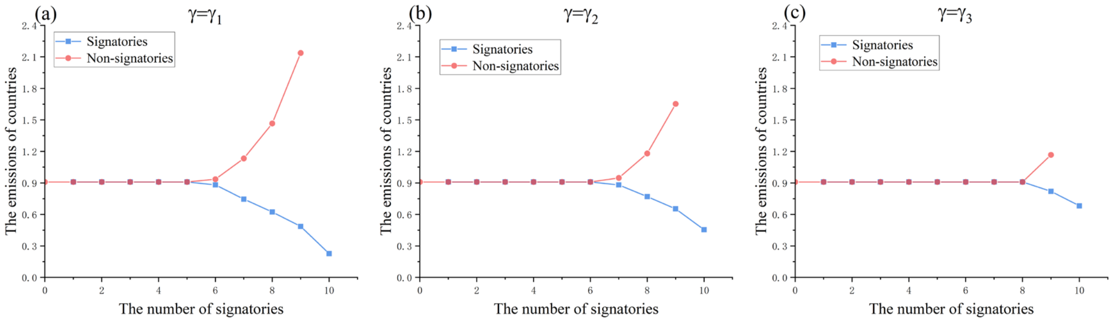

Fig. 3. Emissions of countries with different sizes of coalition

Social emissions and social welfare show the same trend as the emissions and the welfare of signatories with respect to the marginal damage of emissions, as demonstrated in Fig. 4. Besides, the social emissions decrease in the size of the coalition, and the social welfare increases in the size of the coalition. That means that the social emissions and social welfare are improved. However, the degree of improvement in social emissions and social welfare shows great differences when the coalition is stable, which depends on the parameters of emissions damage. Following the closing the gap index of welfare WCGI defined by Eq.(45) and closing the gap index of emissions ECGI defined by Eq.(46), we examine the effectiveness of the stable coalition which is measured by what extent a stable coalition closes the gap between the social optimum and the business-as-usual. The results show that when

$\gamma = \gamma_1$, $\gamma = \gamma_2$, and $\gamma = \gamma_3$, the closing the gap index of welfare is $\mathrm{WCGI} = 1.64\%$, $\mathrm{WCGI} = 3.52\%$, and $\mathrm{WCGI} = 41.78\%$, respectively, and the closing the gap index of emissions is $\mathrm{ECGI} = 0.82\%$, $\mathrm{ECGI} = 1.78\%$, and $\mathrm{ECGI} = 23.93\%$, respectively. The result suggests that the smaller the marginal damage of emissions, the more improver the social emissions and social welfare. In other words, the less the emissions damage, the larger the size and the more effective the stable coalition.

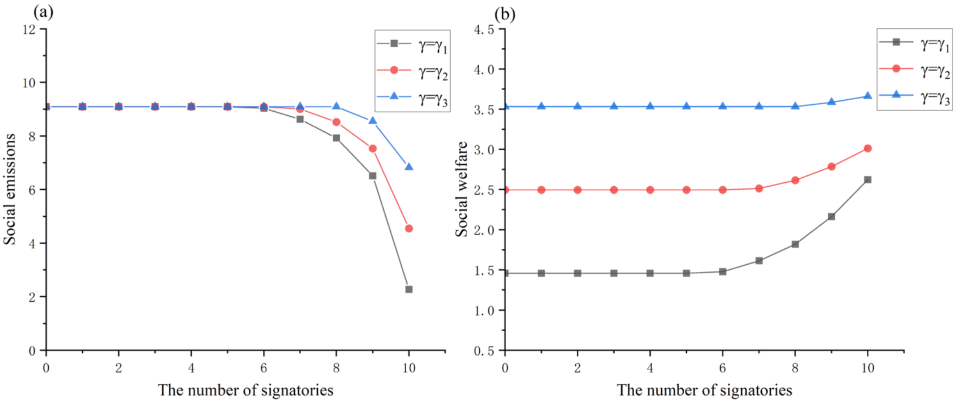

Fig. 4. Social welfare and Social emissions with different sizes of coalition

Table 1 The size and effectiveness of the stable coalition.

	$n = 10$			$n = 20$			$n = 50$		
γ	m^*	WCGI	ECGI	m^*	WCGI	ECGI	m^*	WCGI	ECGI
$\gamma_1(n)$	6	1.64%	0.82%	12	1.19%	0.60%	29	0.13%	0.07%
$\gamma_2(n)$	7	3.52%	1.78%	14	2.44%	1.23%	34	0.40%	0.20%
$\gamma_3(n)$	9	41.78%	23.93%	17	11.51%	5.95%	41	1.87%	0.94%

To investigate the robustness of results about the stability and effectiveness of the coalition, we further choose the number of countries $n = 20$ and $n = 50$ for simulation. Results are displayed in Table 1. We find the parameter γ and the size of the stable coalition m are increased by a factor of 1 from $n = 10$ to $n = 20$ and by moving to $n = 50$, they are increased by a factor of 4. Moreover, the WCGI and ECGI decrease in the marginal damage of emissions for a given n, and they decrease in the number of countries. Therefore, the results turned out to be robust.

4. Caps versus taxes

In this section, we compare the uniform carbon tax instrument and emissions caps instrument to examine whether negotiating a uniform carbon tax can promote international climate cooperation than negotiating different emissions caps. The rules of this game, however, are a little different and are modeled as follows: in the first stage, all countries simultaneously and non-cooperatively decide whether to join the coalition; in the second stage, the members of the coalition choose their own emissions caps to maximize the welfare of the coalition, and fringes choose their own emissions caps to maximize their own welfare; the third stage is still the imperfect competition among firms in segmented markets, and the other settings are the same as in Section 2.1.

Specifically, the ultimate carbon emissions e_i of firm i in Eq.(5) is replaced by the emissions cap $\hat{e}_i$ of country i, which means that firms only determine their own output, and the ultimate carbon emissions are determined by the countries in the absence of carbon trading. Thus, the cost function of end-of-pipe is replaced by:

$$\hat{C}_i(\hat{x},\hat{e}) = c\hat{x}_i^p + \frac{(\hat{x}_i^p-\hat{e}_i)^2}{2}, \tag{47}$$

where the $\hat{x}$ is the output of firms under the emissions caps instrument. Then, the profit function of the firm i is replaced by:

$$\hat{\pi}_i = \sum_{j=1}^n p_j\left(\hat{x}_j^c\right)\hat{x}_{ij} - \hat{C}_i(\hat{x},\hat{e}), \tag{48}$$

the social emissions are given by:

$$\hat{E} = \sum_{i=1}^n \hat{e}_i, \tag{49}$$

finally, consider the welfare of country i, which is given by:

$$\widehat{W}_i = \frac{1}{2}(\hat{x}_i^c)^2 + \sum_{k=1}^n \hat{x}_{ik}\,(a-\hat{x}_k^c-c) - \frac{(\hat{x}_i^p-\hat{e}_i)^2}{2} - \gamma\hat{E}, \tag{50}$$

where the first item is the consumer surplus, the second and third items are the producer surplus, and the final item is the damage caused by global carbon emissions.

We still restrict parameter space $\frac{(a-c)}{(n+1)(2n+1)} < \gamma \leq \frac{2(n+1)(a-c)}{(2n+1)^2}$ here for convenience to compare with the results obtained under the uniform carbon tax instrument. Similarly, we first characterize the output strategies of firms in each segmented market, then describe the strategic interaction of countries in the three scenarios of business as usual, social optimum, and climate coalition, and finally follow Eq.(43)-(46) to measure the stability and effectiveness of the coalition. For more details see Appendix A.4.

Proposition 4. *In the two benchmark scenarios of the business as usual and social optimum, the uniform carbon tax instrument and the emissions caps instrument result in the same levels of output, emissions, and welfare.*

Proof: See Appendix A.4.2.1 and A.4.2.2.

From proposition 4, we demonstrate that the uniform carbon tax instrument and emissions caps instrument are equivalent under business as usual and social optimum, respectively.

Proposition 5. *Denote the emissions caps of signatories* $\hat{e}_s$, *and the emissions caps of non-signatories* $\hat{e}_f$ *in coalition formation. Then there exist two solutions: signatories' interior and non-signatories' corner solution* $(\hat{x}_s^p > \hat{e}_s > 0,\ \hat{e}_f = \hat{x}_s^p)$, *and double corner solution* $(\hat{e}_s = \hat{x}_s^p,\ \hat{e}_f = \hat{x}_s^p)$. *The two solutions are as follows:*

(1) *Signatories' interior and non-signatories' corner solution*[5]:

$$\hat{e}_s = \frac{\hat{b}(m)}{\hat{h}(m)}, \hat{e}_f = \frac{\hat{g}(m)}{\hat{h}(m)}, if\ \frac{(2n^2+n-nm)(a-c)}{(n+1)(2n+1)m} < \gamma \tag{51}$$

(2) *Double corner solution:*

$$\hat{e}_s = \frac{n(a-c)}{n+1}, \hat{e}_f = \frac{n(a-c)}{n+1}, if\ \gamma \leq \frac{(2n^2+n-nm)(a-c)}{(n+1)^2(2n+1)m}. \tag{52}$$

Proof: See Appendix A.4.2.3.

From Proposition 5, we know that the country has two possible strategic behaviors under coalition formation, which depend on the size of the coalition, the marginal damage of emissions, the number of countries, and the benefit of production and consumption. If we fix the parameters n, a, c, then there is a threshold $\tilde{\gamma}_4(m) = \frac{(n^2+n-nm)(a-c)}{(n+1)(2n+1)m}$. When the marginal damage of emissions is greater than the threshold, i.e., $\tilde{\gamma}_4(m) < \gamma$, equilibrium solution is signatories' interior and non-signatories'

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[5] $\hat{h}(m) = (n^2+3n+1)m^2 - (n^3+5n+3n)m - (n+1)(2n+1)$

$\hat{b}(m) = [n(n+1)m^2 - n(n^2+n-1)m - n(n+2)(2n+1)](a-c)$

$\quad -[nm+(n+1)^2](n+1)(2n+1)m\gamma$

$\hat{g}(m) = [(n+1)m^2 - n(n+2)m - (2n+1)]n(a-c) - (n+1)(2n+1)nm^2\gamma$

corner solution, when the marginal damage of emissions is less than or equal to the threshold, i.e., $\tilde{\gamma}_4(m) > \gamma$, the equilibrium solution is the double corner solution. The results reveal that the $\hat{e}_f = \hat{x}_s^p$ is the dominant strategy of non-signatories, which means that the optimal strategy for non-signatories is not to regulate the carbon emissions of firms, regardless of which strategy the signatories choose. The signatories choose the same strategy as non-signatories when the marginal damage of emissions is less than the threshold $\tilde{\gamma}_4(m)$. However, when the marginal damage of emissions is greater than the threshold $\tilde{\gamma}_4(m)$, the signatories will implement the emissions caps to regulate the carbon emissions of firms. Furthermore, we find that the emissions caps decrease in the size of the coalition ($\frac{\partial \hat{e}_s}{\partial m} < 0$), and the threshold $\tilde{\gamma}_4$ decreases in the size of the coalition ($\frac{\partial \tilde{\gamma}_4(m)}{\partial m} < 0$), which implies that the signatories are prone to enact tougher emissions caps as the number of signatories increases.

For the scenario of climate coalition, the simulation technique is employed to compare output, emissions, and welfare under the two instruments of the uniform carbon tax and emissions caps. We keep the same parameter settings and assume that the marginal production cost $c = 0$, the market size $a = 1$, the number of countries $n = 10$, and take the marginal damage of emissions $\gamma = \gamma_1$ as example.

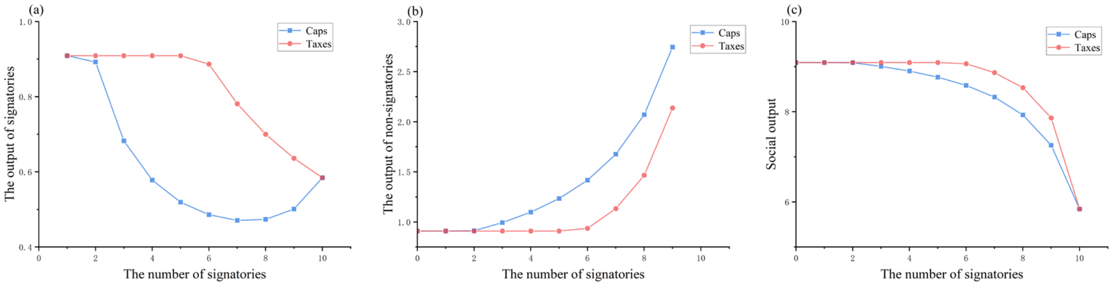

Fig. 5. The output of firms with different sizes of coalition

Fig. 5a,b,c compare the output of signatories, non-signatories, and social total output with different sizes of the coalition under two instruments. Fig. 5(a) shows the output of signatories under the uniform carbon tax instrument is better than that of the emissions caps instrument, and the opposite conclusion for the output of non-signatories, as shown in Fig. 5(b). The result suggests that given the same size of the coalition, compared with the emissions caps instrument, the uniform carbon tax instrument strengthens the competitiveness of the signatories’ firms in each segmented market. Moreover, the effect of the higher output from signatories is stronger than that of the lower output from non-signatories under the uniform carbon tax instrument, which results in social output under the uniform carbon tax instrument being better than that of the emissions caps instrument, as shown in Fig. 5(c).

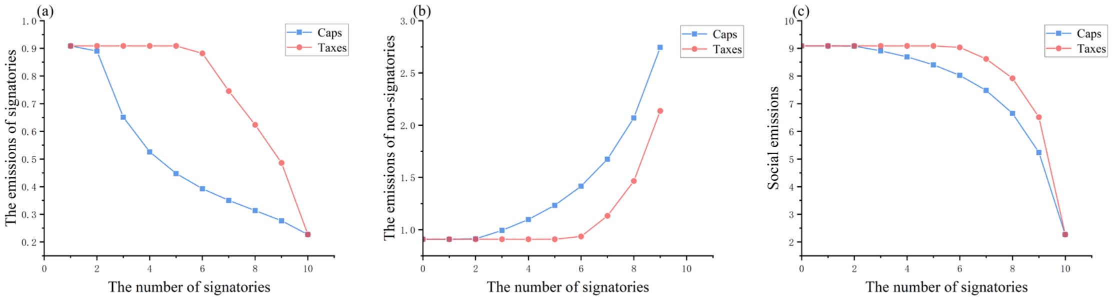

Fig. 6. The emissions of countries with different sizes of coalition

Fig. 6a,b,c compare the emissions of signatories, non-signatories, and social emissions with different sizes of the coalition under two instruments. Fig. 6(a) shows the emissions of signatories under the uniform carbon tax instrument are larger than that of the emissions caps instrument, and the opposite conclusion for the emissions of non-signatories, as shown in Fig. 6(b). This result suggests that the uniform carbon tax instrument is more modest in regulating the emissions of firms than the emissions caps instrument. Correspondingly, the effect of higher emissions from signatories is stronger than that of the lower emissions from non-signatories under the uniform carbon tax instrument, which results in the social emissions under the uniform carbon tax instrument being larger than that of the emissions caps instrument, as shown in Fig. 6(c). Thus, given the same size of the coalition, the emissions caps instrument outperforms the uniform carbon tax instrument owing to the fewer social emissions.

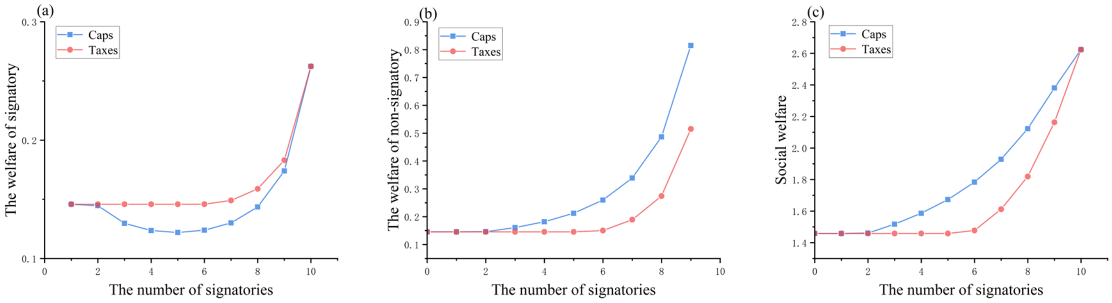

Fig. 7. The welfare of different sizes of coalition

Fig. 7(a) shows the welfare of signatories under the uniform carbon tax instrument is better than that of the emissions caps instrument, and the opposite conclusion for the welfare of non-signatories, as shown in Fig. 7(b). But, the effect of higher welfare from non-signatories is stronger than that of the lower welfare from signatories under the uniform carbon tax instrument, which results in the social welfare under the emissions caps instrument being better than that of the uniform carbon tax instrument, as shown in Fig. 7(c). The result suggests that, given the same size of the coalition, the emissions caps instrument outperforms the uniform carbon tax instrument owing to the higher social welfare.

Table 2 The size of the stable coalition under caps and taxes.

	$n = 10$		$n = 20$		$n = 50$	
γ	taxes	caps	taxes	caps	taxes	caps
$\gamma_1(n)$	$m^* = 6$	$m^* = 1$	$m^* = 12$	$m^* = 2$	$m^* = 29$	$m^* = 2$
$\gamma_2(n)$	$m^* = 7$	$m^* = 2$	$m^* = 14$	$m^* = 3$	$m^* = 34$	$m^* = 3$
$\gamma_3(n)$	$m^* = 9$	$m^* = 4$	$m^* = 17$	$m^* = 5$	$m^* = 41$	$m^* = 6$

m^* denotes the size of stable coalitions.

Overall, given the same size of the coalition, the emissions caps instrument is more effective than the uniform carbon tax instrument due to the higher level of total abatement and social welfare. However, the two instruments cannot achieve the same level of participation in the self-enforcing international environmental agreement. We adopt the simulation and follow Eq.(43)-(46) to measure the stability and effectiveness of the coalition under the emissions caps instrument. Table 2 lists the size of the stable coalition under the two instruments. The result shows that the size of the stable coalition under the uniform carbon tax instrument is significantly larger than that under the emissions caps instrument, which suggests that the uniform carbon tax instrument has a greater capacity to boost participation. Therefore, if countries anticipate suffering from more loss of competitiveness, stricter emissions regulation, and poorer welfare as a signatory under the emissions caps instrument, then they prefer to free ride as non-signatories. The uniform carbon tax instrument is more modest compared to the emissions caps instrument, which narrows the benefits gap between signatories and non-signatories, more likely to promote the willingness of countries to participate in the agreement.

Besides, the closing the gap index of welfare $\mathrm{WCGI} = 0$ and the closing the gap index of emissions $\mathrm{ECGI} = 0$ of the stable coalition under the emissions caps instrument in our model framework, suggests that the stable coalition formed is invalid. Recall the closing the gap indexes of the stable coalition under the uniform carbon tax instrument, as shown in Table 1, are all positive. Therefore, for the stable coalition formed under the two instruments, the uniform carbon tax instrument is superior to the emissions caps instrument in the effectiveness of the stable coalition. Combining with the previous analysis, we conclude that the uniform carbon tax instrument improves participation in agreements, but the effectiveness depends on the parameter of emissions damage. Climate cooperation should consider not only the level of participation in the agreement but also the level of emission reductions and welfare improvements. Thus, when the emissions damage is less severe, the uniform carbon tax instrument enhances international climate cooperation.

5. Conclusions

The free-riding incentive attached to the global public good of climate mitigation has seriously hampered global climate action, so how to create an effective international climate agreement has been a significant challenge in climate change negotiations. This paper examines the effects on climate cooperation of negotiating a uniform carbon tax in international environmental agreements. Specially, we consider the market economy and allow free trade to capture the aspect that countries choose their carbon taxes strategically by taking into account the terms-of-trade effects of their own policies. Besides, we assume that the firms compete in imperfect segmented markets and respond to carbon taxes through abatement efforts. By developing a three-stage game, we first examine the effects of carbon taxes on firms, then analyze the strategic interaction between signatories and non-signatories that considers the above terms-of-trade effects of carbon taxes, and finally measure the stability and effectiveness of coalition and compare the uniform carbon tax instrument with the emissions caps instrument.

The main results of this paper are as follows: First, the effects of carbon taxes embodied via the change in output and emissions. An increase in own country's carbon taxes reduces the output and emissions of its own firms but raises the output and emissions of firms in other countries. Thus, the uniform carbon taxes weaken the competitiveness of the own country's firm and increase the abatement cost of the firm. Moreover, the consumption of the market is decreased whether the increase in own country's carbon taxes or other countries.

Second, for a range of parameter values, anticipating the terms-of-trade effects of their own countries' carbon taxes, the dominant strategy of non-signatories is not to implement carbon taxes to regulate the emissions of firms, while the strategy of signatories is determined by parameter values. There exists a threshold, when the marginal damage of emissions is less than or equal to the threshold, the signatories choose the same strategy as non-signatories, when the marginal damage of emissions is greater than the threshold, the signatories will implement positive carbon taxes, and are prone to enact a tougher uniform carbon tax as the number of signatories increases. The above strategic interaction reveals the mechanism of the uniform carbon tax instrument, i.e., non-signatories cannot enjoy the benefits of free-riding unless the size of the coalition is large enough to generate positive benefits for signatories.

Finally, we answer the question of whether the uniform carbon tax instrument promotes more ambitious climate cooperation than the emissions caps instrument. Given the same size of the coalition, the emissions caps instrument is more effective than the uniform carbon tax instrument on abatement level and welfare improvement. But, the uniform carbon tax instrument is more modest, which narrows the benefits gap between signatories and non-signatories, more likely to form a larger stable coalition. Furthermore, given that the effectiveness depends on the parameter of emissions damage, on the one hand, the uniform carbon tax instrument enhances more ambitious international climate cooperation with less severe emissions damage. On the other hand, the uniform carbon tax instrument significantly increases the participation level of agreements, but with only slight improvements in social welfare and social emissions with more severe emissions damage.

The paper highlights the role in climate cooperation of negotiating a uniform carbon tax in international environmental agreements. Under the structure of a market economy that allows free trade, we conclude a conclusion different from McEvoy and McGinty (2018) and Schmidt and Ockenfels (2021), and provide the conditions under which the uniform carbon tax instrument can promote more ambitious international climate cooperation. Our analysis serves as a guide for the proposal that negotiates a uniform carbon tax. We have demonstrated that the uniform carbon tax instrument can facilitate a larger self-enforcing climate coalition, but cannot achieve higher emissions reductions with more severe emissions damage, hence, additional incentives need to be attached to induce abatement of countries, such as the carbon border adjustments. Of course, which needs to be further examined. Besides, this paper makes some simple assumptions for tractability, though the analytical solution is still complicated. To better reflect the highly complex ongoing international climate negotiations, in the future, we need to relax the assumptions and examine the effects.

Acknowledgments

Appendix A

Proof of Proposition 1

According to the Kuhn Tucker conditions Eq.(25), when $t_i > 0$, $\frac{\partial W_i}{\partial t_i} = 0$. We obtain $t_j = t_i, \forall j \in N, j \neq i$ by the symmetric assumption, so the Eq.(26) can rewritten as:

$$\frac{\partial W_i}{\partial t_i} = -\frac{n^3+n^2+2n+1}{(n+1)^2} t_i + \frac{\gamma(2n+1)}{n+1} - \frac{(a-c)n^2}{(n+1)^2} \tag{A.1}$$

The interior solution is found by setting Eq.(A.1) equal to zero. Solve the $\mathrm{Eq.(A.1)} = 0$, and we get the equilibrium carbon tax $t^u = \frac{-n^2(a-c)+(n+1)(2n+1)\gamma}{(n^3+n^2+2n+1)}$, $t^u > 0 \Rightarrow \gamma > \frac{n^2(a-c)}{(n+1)(2n+1)}$.

When $t_i = 0$, $\frac{\partial W_i}{\partial t_i} \leq 0$, $t_j = t_i = 0, \forall j \in N, j \neq i$ by the symmetric assumption, the solution for $t^u = 0$ is found by setting $t_i = 0$ in Eq.(A.1) and solving for $\frac{\partial W_i}{\partial t_i} = \frac{\gamma(2n+1)}{n+1} - \frac{(a-c)n^2}{(n+1)^2} \leq 0 \Rightarrow \gamma \leq \frac{n^2(a-c)}{(n+1)(2n+1)}$.||

Proof of Proposition 2

According to the Kuhn Tucker conditions Eq.(29), when $t^c > 0$, $\frac{\partial nW_i}{\partial t^c} = 0$. Recall the Eq.(30) as:

$$\frac{\partial nW_i}{\partial t^c} = n[-\frac{2n^2+2n+1}{(n+1)^2} t^c + \frac{\gamma n(1+2n)}{n+1} - \frac{(a-c)n}{(n+1)^2}] \tag{A.2}$$

The interior solution is found by setting Eq.(A.2) equal to zero. Solve the $\text{Eq.}(\text{A}.2) = 0$, and we get the equilibrium carbon tax $t^c = \frac{-n(a-c)+n(2n+1)(n+1)\gamma}{2n^2+2n+1}$, $t^c > 0 \Rightarrow \gamma > \frac{(a-c)}{(n+1)(2n+1)}$.

When $t^c = 0$, $\frac{\partial nW_i}{\partial t^c} \leq 0$, the solution for $t^c = 0$ is found by setting $t^c = 0$ in Eq.(A.2) and solving for $\frac{\partial nW_i}{\partial t^c} = n[\frac{\gamma n(1+2n)}{n+1} - \frac{(a-c)n}{(n+1)^2}] \leq 0 \Rightarrow \gamma \leq \frac{(a-c)}{(n+1)(2n+1)}$.||

Proof of Proposition 3

The solutions are found by jointing the Kuhn Tucker conditions Eq.(33) and Eq.(37):

$$\begin{cases} \frac{\partial mW_s}{\partial t_s} \leq 0, t_s \geq 0, t_s \frac{\partial mW_s}{\partial t_s} = 0 \\ \frac{\partial W_f}{\partial t_f} \leq 0, t_f \geq 0, t_f \frac{\partial W_f}{\partial t_f} = 0 \end{cases} \tag{A.3}$$

(1) When $t_s > 0$ and $t_f > 0$, the Eq.(A.3) can rewritten as:

$$\begin{cases} \frac{\partial mW_s}{\partial t_s} = 0 \\ \frac{\partial W_f}{\partial t_f} = 0 \\ t_s > 0 \\ t_f > 0 \end{cases} \tag{A.4}$$

The interior solution is found by solving Eq.(A.4), we find the solution $t_s = \frac{b(m)}{H(m)}, t_f = \frac{g(m)}{H(m)}$ by solving the $\frac{\partial mW_s}{\partial t_s} = 0$ and $\frac{\partial W_f}{\partial t_f} = 0$. It is easy to verify $H(m) > 0, \forall m \in [0, n]$, thus $t_s > 0 \Rightarrow b(m) > 0$ and $t_f > 0 \Rightarrow g(m) > 0$.

(2) When $t_s > 0, t_f = 0$, the Eq.(A.3) can rewritten as:

$$\begin{cases} \frac{\partial mW_s}{\partial t_s} = 0 \\ \frac{\partial W_f}{\partial t_f} \leq 0 \\ t_s > 0 \\ t_f = 0 \end{cases} \tag{A.5}$$

The signatories' interior and non-signatories' corner solution is found by solving Eq.(A.5), we find the solution $t_s = \frac{[n(n+1)-nm](a-c)-[(n+1)(2n+1)m]\gamma}{(2n+1)m^2-2n(n+1)m-(n+1)^2}$ by solving the $\frac{\partial mW_s}{\partial t_s}|_{t_f=0} = 0$, where it is easy to verify $(2n+1)m^2 - 2n(n+1)m - (n+1)^2 < 0, \forall m \in [0,n]$, thus $t_s > 0 \Rightarrow \frac{(n^2+n-nm)(a-c)}{(n+1)(2n+1)m} < \gamma$. Besides, the condition $\frac{\partial W_f}{\partial t_f} \leq 0 \Rightarrow g(m) \leq 0$. For $m \geq 3$, $g(m) < 0$ holds; for $m = 2$, $g(2) \leq 0 \Rightarrow \gamma \leq \frac{n(3n^2-n-2)(a-c)}{(n+1)^2(2n+1)}$; for $m = 1$, $g(1) \leq 0 \Rightarrow \gamma \leq \frac{n^2(a-c)}{(n+1)(2n+1)}$, but where $t_s > 0$ require $\gamma > \frac{n^2(a-c)}{(n+1)(2n+1)}$, thus the solution does not exist when $m = 1$.

(3) When $t_s = 0, t_f > 0$, the Eq.(A.3) can rewritten as:

$$\begin{cases} \frac{\partial mW_s}{\partial t_s} \leq 0 \\ \frac{\partial W_f}{\partial t_f} = 0 \\ t_s = 0 \\ t_f > 0 \end{cases} \tag{A.6}$$

The signatories' corner and non-signatories' interior solution is found by solving Eq.(A.6), we find the solution $t_{ns} = \frac{-n^2(a-c)+(n+1)(2n+1)d}{(n+1-n^2)m+(n^3+n^2+2n+1)}$ by solving the $\frac{\partial W_f}{\partial t_f}|_{t_s=0} = 0$, where it is easy to verify $(n+1-n^2)m + (n^3+n^2+2n+1) > 0, \forall m \in [0,n]$, thus $t_f > 0 \Rightarrow \frac{n^2(a-c)}{(n+1)(2n+1)} < \gamma$. Besides, the condition $\frac{\partial mW_s}{\partial t_s} \leq 0 \Rightarrow b(m) \leq 0 \Rightarrow \gamma \leq \tilde{\gamma}_5(m) = \frac{[-n(n+1)m^2+n^3m+n(n+1)^2](a-c)}{[-n(2n+1)(n+1)m^2+(n+1)(2n+1)(n^2+3n+1)m-n^2(2n+1)(n+1)]}$. Further, $\frac{\partial \tilde{\gamma}_5(m)}{\partial m} = \frac{(a-c)}{(2n+1)} * \frac{n[(2n+1)^2m^2-2n(2n+1)(n+1)m+(2n+1)(n^3+2n^2+3n+1)]}{-(m^2n-mn^2-3mn+n^2-m)^2(n+1)} < 0$, so there is $\tilde{\gamma}_5(m) \in [\frac{(a-c)}{(n+1)(2n+1)}, \frac{n^2(a-c)}{(n+1)(2n+1)}]$ on $m \in [1,n]$, $\gamma \leq \frac{n^2(a-c)}{(n+1)(2n+1)}$. But $t_f > 0$ requires the $\frac{n^2(a-c)}{(n+1)(2n+1)} < \gamma$, so the signatories' corner and non-signatories' interior solution does not exist.

(4) When $t_s = 0, t_f = 0$, the Eq.(A.3) can rewritten as:

$$\begin{cases} \frac{\partial mW_s}{\partial t_s} \leq 0 \\ \frac{\partial W_f}{\partial t_f} \leq 0 \\ t_s = 0 \\ t_f = 0 \end{cases} \tag{A.7}$$

The $\frac{\partial mW_s}{\partial t_s} \leq 0 \Rightarrow \gamma \leq \frac{n(n-m+1)(a-c)}{(n+1)(2n+1)m}$ and $\frac{\partial W_f}{\partial t_f} \leq 0 \Rightarrow \frac{(a-c)}{(n+1)(2n+1)}$, we identify $\frac{n(n-m+1)(a-c)}{(n+1)(2n+1)m} \leq \frac{(a-c)}{(n+1)(2n+1)}$, so the double corner solution require the $\gamma \leq \frac{n(n-m+1)(a-c)}{(n+1)(2n+1)m}$.||

Proof of Proposition 4

A.4.1. The strategy of firms

The firm i takes the output of other firms as given and chooses its output to maximize profit, that is:

$$\max \hat{\pi}_i = \sum_{j=1}^{n} p_j(\hat{x}_j^c)\hat{x}_{ij} - \hat{C}_i(\hat{x}, \hat{e}) \tag{A.8}$$

The first-order conditions are:

$$\frac{\partial \hat{\pi}_i}{\partial \hat{x}_{ik}} = a - c - 3\hat{x}_{ik} - \sum_{j=1,j\neq i}^{n} \hat{x}_{jk} - \sum_{j=1,j\neq k}^{n} \hat{x}_{ij} + \hat{e}_i = 0, i, k = 1,2, \ldots n \tag{A.9}$$

Solving the n^2 equations above, we determine the equilibrium output of firm i in the market k, that is:

$$\hat{x}_{ik} = \frac{(a-c)(n+1)+2n\hat{e}_i - \sum_{j=1,j\neq i}^{n} \hat{e}_j}{(n+1)(2n+1)}, \tag{A.10}$$

by Eq.(A.10), the output and consumption of firm i are given respectively:

$$\hat{x}_i^p = \frac{(a-c)n(n+1)+2n^2\hat{e}_i - n\sum_{j=1,j\neq i}^{n} \hat{e}_j}{(n+1)(2n+1)}, \tag{A.11}$$

$$\hat{x}_i^c = \frac{(a-c)n(n+1)+(n+1)\sum_{j=1}^{n} \hat{e}_j}{(n+1)(2n+1)}. \tag{A.12}$$

A.4.2 The strategy of emissions caps

A.4.2.1 Business-as-usual

The country $i \in N$ chooses the emissions cap to maximize national welfare W_i taking the other countries' emissions caps given. The optimization problem is:

$$max\ \widehat{W}_i = \frac{1}{2}(\hat{x}_i^c)^2 + \sum_{k=1}^{n} \hat{x}_{ik}\,(a - \hat{x}_k^c - c) - \frac{(\hat{x}_i^p - \hat{e}_i)^2}{2} - \gamma\hat{E}$$

$$\text{s.t. } 0 \leq \hat{e}_i \leq \hat{x}_i^p. \tag{A.13}$$

The Kuhn-Tucker conditions of the optimization problem (A.13) are:

$$\frac{\partial \widehat{W}_i}{\partial \hat{e}_i}-\frac{3n+1}{(n+1)(2n+1)}\lambda_i \le 0,\ \hat{e}_i \ge 0,\ \hat{e}_i\left(\frac{\partial \widehat{W}_i}{\partial \hat{e}_i}-\frac{3n+1}{(n+1)(2n+1)}\lambda_i\right)=0,$$

$$\hat{x}_i^p-\hat{e}_i \ge 0,\ \lambda_i(\hat{x}_i^p-\hat{e}_i)=0,\ \lambda_i \ge 0, \tag{A.14}$$

where

$$\frac{\partial \widehat{W}_i}{\partial \hat{e}_i}=\frac{-4n(n^2+3n+1)}{(n+1)^2(2n+1)^2}\hat{e}_i+\frac{-2n^3-3n^2+2n+1}{(n+1)^2(2n+1)^2}\sum_{j=1,j\neq i}^{n}\hat{e}_j+\frac{n(2n^2+5n+1)(a-c)}{(2n+1)^2(n+1)}-\gamma. \tag{A.15}$$

The second-order condition $\frac{\partial \widehat{W}_i}{\partial \hat{e}_i}=-\frac{4n(n^2+3n+1)}{(n+1)^2(2n+1)^2}<0$, the solution to the optimization problem (A.13) exists. The equilibrium emissions caps of all countries will be the same under the symmetric assumption. Denote the equilibrium emissions caps in business-as-usual $\hat{e}^u$, when the parameter space $\frac{(a-c)}{(n+1)(2n+1)}<\gamma\le\frac{2(n+1)(a-c)}{(2n+1)^2}$, then:

$$\hat{e}^u=\frac{n(a-c)}{n+1}, \tag{A.16}$$

by the Eq.(A.16), we get the $\hat{x}_{ik}=\frac{(a-c)}{(n+1)}$, $\hat{x}_i^p=\frac{(a-c)n}{(n+1)}$, $\hat{x}_i^c=\frac{(a-c)n}{(n+1)}$.

Recall the $t^u=0$ under the uniform carbon tax, then $x_{ik}=\frac{(a-c)}{(n+1)}$, $e_i=\frac{n(a-c)}{(n+1)}$, $x_i^p=\frac{(a-c)n}{(n+1)}$, $x_i^c=\frac{(a-c)n}{(n+1)}$. We have $x_{ik}=\hat{x}_{ik}$, $e_i=\hat{e}_i$, $w_i=\widehat{w}_i$, therefore, the uniform carbon tax instrument and the emissions caps instrument result in the same levels of output, emissions, and welfare.

A.4.2.2 Social optimum

All countries choose the emissions caps $\hat{e}_i$ to maximize social welfare $\sum_{i=1}^{n}W_i$. The optimization problem is:

$$max\sum_{i=1}^{n}\widehat{W}_i=n\left(\frac{1}{2}(\hat{x}_i^c)^2+\sum_{k=1}^{n}\hat{x}_{ik}\,(a-\hat{x}_k^c-c)-\frac{(\hat{x}_i^p-\hat{e}_i)^2}{2}-\gamma\hat{E}\right)$$

$$\text{s.t.}\ \ 0\le\ \hat{e}_i\le\hat{x}_i^p. \tag{A.17}$$

The Kuhn-Tucker conditions of the optimization problem (A.17) are:

$$\frac{\partial\sum_{i=1}^{n}\widehat{W}_i}{\partial \hat{e}_i}-\frac{3n+1}{(n+1)(2n+1)}\lambda_i\le 0,\ \hat{e}_i\ge 0,\ \hat{e}_i\left(\frac{\partial\sum_{i=1}^{n}\widehat{W}_i}{\partial \hat{e}_i}-\frac{3n+1}{(n+1)(2n+1)}\lambda_i\right)=0,$$

$$\hat{x}_i^p-\hat{e}_i\ge 0,\ \lambda_i(\hat{x}_i^p-\hat{e}_i)=0,\ \lambda_i\ge 0, \tag{A.18}$$

where

$$\frac{\partial \sum_{i=1}^{n} \widehat{W}_i}{\partial \hat{e}_i} = \frac{-(2n^3+10n^2+7n+1)}{(n+1)^2(2n+1)^2}\hat{e}_i - \frac{n(2n^2+6n+3)}{(n+1)^2(2n+1)^2}\sum_{j=1,j\neq i}^{n}\hat{e}_j + \frac{2n(n+1)^2(a-c)}{(2n+1)^2(n+1)} - n\gamma. \quad \text{(A.19)}$$

The second-order condition $\frac{\partial \sum_{i=1}^{n} \widehat{W}_i}{\partial \hat{e}_i} = \frac{-(2n^3+10n^2+7n+1)}{(n+1)^2(2n+1)^2} < 0$, the solution to the optimization problem (A.17) exists. The equilibrium emissions caps of all countries will be the same under the symmetric assumption. Denote the equilibrium emissions caps in social optima $\hat{e}^c$, when the parameter space $\frac{(a-c)}{(n+1)(2n+1)} < \gamma \leq \frac{2(n+1)(a-c)}{(2n+1)^2}$, then:

$$\hat{e}^c = \frac{2n(n+1)(a-c) - n(2n+1)^2\gamma}{2n^2+2n+1}, \quad \text{(A.20)}$$

by Eq.(A.20), we get the $\hat{x}_{ik} = \frac{(2n+1)(a-c)-n(2n+1)\gamma}{2n^2+2n+1}$, $\hat{x}_i^p = \frac{n(2n+1)(a-c)-n^2(2n+1)\gamma}{2n^2+2n+1}$, $\hat{x}_i^c = \frac{n(2n+1)(a-c)-n^2(2n+1)\gamma}{2n^2+2n+1}$.

Recall the $t^c = \frac{-n(a-c)+n(2n+1)(n+1)\gamma}{2n^2+2n+1}$ under the uniform carbon tax, then $x_{ik} = \frac{(2n+1)(a-c)-n(2n+1)\gamma}{2n^2+2n+1}$, $e_i = \frac{2n(n+1)(a-c)-n(2n+1)^2\gamma}{2n^2+2n+1}$, $x_i^p = \frac{n(2n+1)(a-c)-n^2(2n+1)\gamma}{2n^2+2n+1}$, $x_i^c = \frac{n(2n+1)(a-c)-n^2(2n+1)\gamma}{2n^2+2n+1}$. We have $x_{ik} = \hat{x}_{ik}$, $e_i = \hat{e}_i$, $w_i = \widehat{w}_i$, therefore, the uniform carbon tax instrument and the emissions caps instrument result in the same levels of output, emissions, and welfare.

A.4.2.3 Climate coalition

The signatories choose the emissions caps $\hat{e}_s$ to maximize the welfare of the coalition $\sum_{s=1}^{m} \widehat{W}_{s\in S}$, and the non-signatories $f \in NS$ choose the individual emissions caps $\hat{e}_f$ to maximize own welfare $\widehat{W}_{f\notin S}$. The optimization problem of signatories is:

$$max \sum_{s=1}^{m} \widehat{W}_s = \sum_{s=1}^{m}\Big[\frac{1}{2}(\hat{x}_s^c)^2 + \sum_{k=1}^{n}\hat{x}_{sk}(a - \hat{x}_k^c - c) - \frac{(\hat{x}_s^p - \hat{e}_s)^2}{2} - \gamma\hat{E}\Big]$$

$$\text{s.t. } 0 \leq \hat{e}_s \leq \hat{x}_s^p. \quad \text{(A.21)}$$

The Kuhn-Tucker conditions of the optimization problem (A.21) are:

$$\frac{\partial \sum_{s=1}^{m}\widehat{W}_s}{\partial \hat{e}_s} - \frac{3n+1}{(n+1)(2n+1)}\lambda_s \leq 0,\ \hat{e}_s \geq 0,\ \hat{e}_s\left(\frac{\partial \sum_{s=1}^{m}\widehat{W}_s}{\partial \hat{e}_s} - \frac{3n+1}{(n+1)(2n+1)}\lambda_s\right) = 0,$$

$$\hat{x}_s^p - \hat{e}_s \geq 0,\ \lambda_s(\hat{x}_s^p - \hat{e}_s) = 0,\ \lambda_s \geq 0, \quad \text{(A.22)}$$

where

$$\frac{\partial \sum_{s=1}^{m} \widehat{W}_s}{\partial \hat{e}_s} = \frac{(2n^2+4n+1)m-(4n^3+14n^2+8n+1)}{(n+1)^2(2n+1)^2}\hat{e}_s + \frac{(2n^2+4n+1)m-(4n^3+10n^2+4n)}{(n+1)^2(2n+1)^2}\sum_{i\in S, i\neq s}\hat{e}_i$$
$$+\frac{(2n^2+4n+1)m-(2n^3+5n^2+2n)}{(n+1)^2(2n+1)^2}\sum_{f\notin S}\hat{e}_f$$
$$+\frac{-nm+n(2n^2+5n+2)}{(2n+1)^2(n+1)}(a-c)-m\gamma. \tag{A.23}$$

The equilibrium emissions caps of signatories will be the same, and the equilibrium emissions caps of non-signatories will be the same under the symmetric assumption, Eq.(A.23) can be rewritten as:

$$\frac{\partial \sum_{s=1}^{m} \widehat{W}_s}{\partial \hat{e}_s} = \frac{(2n^2+4n+1)m^2-(4n^3+10n^2+4n)m-(4n^2+4n+1)}{(n+1)^2(2n+1)^2}\hat{e}_s$$
$$-\frac{(2n^2+4n+1)m^2-(4n^3+9n^2+3n)m+(2n^4+5n^3+2n^2)}{(n+1)^2(2n+1)^2}\hat{e}_f$$
$$+\frac{-nm+n(2n^2+5n+2)}{(2n+1)^2(n+1)}(a-c)-m\gamma. \tag{A.24}$$

Second-order condition $\frac{\partial \sum_{s=1}^{m} \widehat{W}_s}{\partial \hat{e}_s} = \frac{(2n^2+4n+1)m^2-(4n^3+10n^2+4n)m-(4n^2+4n+1)}{(n+1)^2(2n+1)^2} < 0$ hold on $m \in (0, n)$, the solution to the optimization problem (A.21) exists.

The optimization problem of non-signatory f is:

$$max \ \ \widehat{W}_f = \frac{1}{2}\left(\hat{x}_f^c\right)^2 + \sum_{k=1}^{n}\hat{x}_{fk}\left(a-\hat{x}_k^c-c\right) - \frac{(\hat{x}_f^p-\hat{e}_f)^2}{2} - \gamma\hat{E}$$
$$\text{s.t.} \ \ 0 \leq \hat{e}_f \leq \hat{x}_f^p. \tag{A.25}$$

The Kuhn-Tucker conditions of the optimization problem (A.25) are:

$$\frac{\partial \widehat{W}_f}{\partial \hat{e}_f} - \frac{3n+1}{(n+1)(2n+1)}\lambda_f \leq 0，\ \hat{e}_f \geq 0，\ \hat{e}_f\left(\frac{\partial \widehat{W}_f}{\partial \hat{e}_f} - \frac{3n+1}{(n+1)(2n+1)}\lambda_f\right) = 0，$$
$$\hat{x}_f^p - \hat{e}_f \geq 0，\ \lambda_f(\hat{x}_f^p - \hat{e}_f) = 0，\ \lambda_f \geq 0, \tag{A.26}$$

where

$$\frac{\partial \widehat{W}_i}{\partial \hat{e}_i} = \frac{-4n(n^2+3n+1)}{(n+1)^2(2n+1)^2}\hat{e}_i + \frac{-2n^3-3n^2+2n+1}{(n+1)^2(2n+1)^2}\sum_{j=1, j\neq i}^{n}\hat{e}_j + \frac{n(2n^2+5n+1)(a-c)}{(2n+1)^2(n+1)} - \gamma. \tag{A.27}$$

Recall the equilibrium emissions caps of signatories will be the same, and the equilibrium emissions caps of non-signatories will be the same under the symmetric assumption, thus, Eq.(A.27) can be rewritten as:

$$\frac{\partial \widehat{W}_f}{\partial \hat{e}_f} = \frac{m(2n^3+3n^2-2n-1)-(2n^4+5n^3+7n^2+5n+1)}{(n+1)^2(2n+1)^2}\hat{e}_f + m\frac{-2n^3-3n^2+2n+1}{(n+1)^2(2n+1)^2}\hat{e}_s$$
$$+\frac{n(2n^2+5n+1)}{(2n+1)^2(n+1)}(a-c)-\gamma. \tag{A.28}$$

Second-order condition $\frac{\partial \widehat{W}_f}{\partial \hat{e}_f} = \frac{m(2n^3+3n^2-2n-1)-(2n^4+5n^3+7n^2+5n+1)}{(n+1)^2(2n+1)^2} < 0$ hold on $m \in (0, n)$, the solution to the optimization problem (A.25) exists. We determine the solutions to the emissions of signatories and non-signatories by joint Eq.(A.22), Eq.(A.24), Eq.(A.26), and Eq.(A.28).

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