

# Domestic versus international emissions trading with capital mobility<sup>☆</sup>

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## ABSTRACT

We employ the footloose capital model to examine and compare how two countries decide on their emission permits non-cooperatively under domestic and international emissions trading in the presence of capital mobility. We find that even if two countries are symmetric and have the same carbon prices under domestic emissions trading, they can benefit from international emissions trading. This finding holds regardless of capital mobility. We also find that allowing footloose capital increases each country's and global emissions under domestic emissions trading; however, it does not affect emissions under international emissions trading. Additionally, we show that the cooperative choices of emission permits are the same regardless of international mobility of emission permits and capital and are always lower than the non-cooperative ones.

## 1. Introduction

Emissions trading is the general global trend for controlling carbon emissions. According to the Carbon Pricing Dashboard of the World Bank, 34 emissions trading systems (ETSs) are now implemented, including the EU ETS and China's national ETS, and they cover 17.55% of annual global greenhouse gas emissions in 2022. By contrast, the coverage share of carbon taxes is only 5.62%.<sup>1</sup> Emissions trading is also known as “cap and trade”. The cap of an ETS is set by the supply of emission permits, while the demand for emission permits depends on the output levels and emissions per unit of production of regulated producers. The permit price is determined by the interplay of the demand and supply of emission permits.

The permit prices are usually different between the ETSs because countries set different emission reduction targets. For instance, under the Paris Agreement, the EU is committed to a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990, whereas China plans to have its emissions peak before 2030. Different permit prices can lead to carbon leakage through two main channels. First, a higher carbon price in a country may induce the polluting firms in that country to produce less and those in other countries to produce more. Second, firms in the countries with higher permit prices may choose to relocate to

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<sup>1</sup> The equivalence between emissions trading and carbon taxes in an open economy has been extensively examined in the literature, e.g., Kiyono and Ishikawa (2013), Eichner and Pethig (2015, 2019), Ishikawa and Okubo (2017) and Lai (2022). Among others, Lai (2022) shows that international capital mobility can break the equivalence.

the countries with lower permit prices, which is known as the pollution haven effect (PHE).<sup>2</sup> Carbon leakage may undermine the global attempt to reduce carbon emissions.

To deal with carbon leakage and facilitate cooperation in emission reductions, international emissions trading has been proposed and implemented, which allows for the international mobility and trade of emission permits.<sup>3</sup> For instance, on January 1, 2020, the Swiss ETS and the EU ETS became linked, allowing covered entities in the EU ETS to be able to use the emission permits from the Swiss ETS for compliance, and vice versa. In addition, the UK is considering constructing its own ETS and linking it to the EU ETS.<sup>4</sup> Under international emissions trading, the permit prices are equalized between countries. Therefore, carbon leakage is avoided. However, it is not clear whether the emission reduction target is achieved. In fact, the superiority of international emissions trading over domestic emissions trading is not self-evident. Helm (2003) shows that the impact of international emissions trading on global pollution is ambiguous. This ambiguity arises from the absence of a central authority that determines the initial allocation of internationally tradable permits. Consequently, governments, acting in a non-cooperative manner, may issue a greater number of permits for strategic purposes such as rent-shifting.

To further understand how international emissions trading affects each country's and global emissions, we extend the footloose capital model in Martin and Rogers (1995) by taking into account production-generated emissions and tradable permits.<sup>5</sup> We mainly analyze and compare the non-cooperative choices of emission permits in four cases: (i) immobile capital and domestic emissions trading, (ii) immobile capital and international emissions trading, (iii) footloose capital and domestic emissions trading, and (iv) footloose capital and international emissions trading.

We find that when capital is immobile, international emissions trading decreases each country's and global emissions, compared with domestic emissions trading. This is because allowing international emissions trading decreases the marginal benefit of consumer surplus and eliminates countries' incentive to issue more permits to raise firms' capital rents. Comparing cases (i) and (iii), we find that allowing footloose capital increases each country's and global emissions. This finding confirms the PHE. That is, as capital becomes footloose, both countries are incentivized to attract more firms by loosening their environmental regulations, because doing so increases their consumer surplus and permit revenues. Although allowing footloose capital also eliminates countries' incentives to manipulate capital rents, the PHE is stronger. Therefore, countries issue more emission permits. In cases (iii) and (iv) with footloose capital, allowing international emissions trading eliminates the PHE because the permit price is always the same between countries and thus has no effect on firm locations. As a result, each country's and global emissions become lower under international emissions trading. By comparing cases (ii) and (iv), we show that under international emissions trading, allowing footloose capital does not affect each country's and global emissions because the choices of emission permits do not affect firm locations. The ranking of the levels of emissions in the four cases is: (iii) > (i) > (ii) = (iv).

We also investigate the cooperative choices of emission permits. The optimal levels of permits are always the same regardless of international mobility of emission permits and capital, and they are always lower than the non-cooperative levels of permits. According to Pfluger (2001), the situation where the non-cooperative choices of emission taxes are lower than the cooperative choices is called ecological dumping. Our finding confirms this phenomenon under emissions trading.

### 1.1. Relation to the literature

Our study follows the literature on environmental policies and international capital (or firm) mobility, e.g., Oates and Schwab (1988), Markusen et al. (1993, 1995), Rauscher (1995), Hoel (1997), Pfluger (2001), Mæstad (2006, 2007), Tsakiris et al. (2008), Hadjiyiannis et al. (2009, 2014), Ogawa and Wildasin (2009), Sanna-Randaccio and Sestini (2012), Ishikawa and Okubo (2011, 2016, 2017), Eichner and Pethig (2019), Richter et al. (2021), and Lai (2022). The basic setup in our paper is similar to that in Pfluger (2001) and Ishikawa and Okubo (2016, 2017). However, Pfluger (2001) considers local pollution and emission taxes, whereas we analyze global pollution and tradable permits. Ishikawa and Okubo (2016, 2017) focus on the comparison between emission taxes and permits rather than domestic and international emissions trading. Moreover, they do not analyze countries' choices of emission permits. Lai (2022) investigates how a country assigns emission permits to its two regions to maximize their joint welfare in the presence of capital mobility, which is similar to our analysis of cooperative emission permits with international emissions trading. The author also finds that capital mobility does not affect the cooperative issuance of emission permits. However, he does not analyze the non-cooperative permits and domestic emissions trading.

Our study also follows the literature on the comparison between domestic and international emissions trading. Examples include Copeland and Taylor (1995, 2005), Helm (2003), Holtsmark and Sommervoll (2012), Ishikawa et al. (2012, 2020),

<sup>2</sup> Empirical studies that support the PHE include Fredriksson et al. (2003), Kellenberg (2009), Chung (2014), Tanaka et al. (2022), among others.

<sup>3</sup> The idea of international emissions trading can be traced back to Article 17 of the Kyoto Protocol, which allows Annex B Parties to participate in emissions trading to fulfill their emission reduction commitments. In addition, the Kyoto Protocol also allows for the transfer of emission reductions between Annex B Parties through the joint implementation (Article 6) and between Annex B and non-Annex B Parties through the clean development mechanism (Article 12). The similar idea can also be found in the Paris Agreement. The provisions in Article 6 enable the use of internationally transferred mitigation outcomes to fulfill a country's nationally determined contributions.

<sup>4</sup> Source: Government of the United Kingdom, Legislation for a UK Emissions Trading System, March 11, 2020, <https://www.gov.uk/government/publications/legislation-for-a-uk-emissions-trading-system/legislation-for-a-uk-emissions-trading-system>.

<sup>5</sup> The footloose capital model is often employed to study environmental issues in an open economy. Examples include Zeng and Zhao (2009), Ishikawa and Okubo (2011, 2016, 2017). In this model, footloose capital means that firms can move freely across countries without incurring any cost. By contrast, immobile capital refers to the case where firms cannot move across countries. These two cases of capital mobility correspond to the two channels of carbon leakage mentioned above.

Marschinski et al. (2012), Antoniou et al. (2014), Grecker and Hagem (2014), Doda and Taschini (2017), Habla and Winkler (2018), Antoniou and Kyriakopoulou (2019), Doda et al. (2019), Lapan and Sikdar (2019), Queminn and de Perthuis (2019), Holtsmark and Midttømme (2021). Among others, Copeland and Taylor (1995) extend the Heckscher–Ohlin model to examine how national income and trade opportunities affect global emissions and welfare. They find that if factor prices are not equalized by the trade of goods, allowing international emissions trading decreases global emissions. The finding in Copeland and Taylor (1995) depends on the assumption of asymmetric countries with different factor endowments. However, we assume symmetric countries and thus provide new channels through which international emissions trading decreases emissions.

By contrast, Ishikawa et al. (2020), Copeland and Taylor (2005) and Holtsmark and Sommervoll (2012) find that international emissions trading can increase global emissions. In Ishikawa et al. (2020), emission permits are exogenously set at a cap. Under domestic emissions trading, the demand for emission permits is lower than the cap, which implies that emission permits are unbinding. However, international emissions trading increases the demand for emission permits, making them binding and increasing global emissions. Copeland and Taylor (2005) develop a three-country model with Heckscher–Ohlin features and assume international emissions trading among two countries. They assume that the permit levels are limited by an international environmental treaty and find that global emissions may increase through carbon leakage to the third country outside the treaty. Holtsmark and Sommervoll (2012) extend the climate policy game in Helm (2003) to consider asymmetric countries with different sizes, reflected by the number of firms. They show that international emissions trading decreases large countries' abatement but increases small countries' abatement; the former effect dominates the latter one, leading to more emissions.

In addition to the papers mentioned above, Antoniou and Kyriakopoulou (2019) extend the strategic trade policy model to investigate cap and trade schemes in the presence of both local and transboundary pollution. Countries can only control local pollution through an emission cap. Transboundary pollution, at a fixed level, is regulated by the international environmental agreement with domestic or international emissions trading. The authors find that international emissions trading on transboundary pollution may increase local pollution through a strategic effect, which is in turn welfare detrimental. Different from their finding, we show that international emissions trading is always environment and welfare beneficial.

We contribute to the literature by combining the aforementioned two strands of literature together. To our knowledge, only Tsakiris et al. (2017, 2018, 2023) consider international mobility of both emission permits and capital, as we do. However, their focuses and model settings are different from ours. Tsakiris et al. (2017, 2023) focus on the welfare ranking of different policy regimes, and different taxing rules of international capital rents, respectively. By contrast, our main interest is in the comparison between countries' choices of emission permits. Similar to ours, Tsakiris et al. (2018) also examine and compare the non-cooperative and cooperative levels of emissions permits. However, different from our finding, they show that the non-cooperative (decentralized) level of emission permits is efficient under international emissions trading, regardless of capital mobility.

Regarding model settings, Tsakiris et al. (2017, 2018, 2023) employ the international trade model with duality, which is perfectly competitive. By contrast, we adopt a new economic geography model, characterized by monopolistic competition. Our selection is underpinned by several considerations. Primarily, our model describes the features of the polluting industries. An example of the industry that is pollution-intensive and produces differentiated goods is the chemical industry. Additionally, as stated by Konishi and Tarui (2015), some seemingly homogeneous polluting industries, such as ceramics, ferrous and nonferrous metals, have also progressively evolved into differentiated-good industries with extensive evidence of intra-industry trade. Secondly, our choice of a monopolistically competitive model is motivated by the extensive exploration of capital mobility or endogenous firm location in the framework of new economic geography models. Given that our primary focus centers on studying how capital mobility affects countries' choices of emission permits under domestic and international emissions trading, the footloose capital model emerges as a natural and fitting choice for our analytical framework. Thirdly, our model adds new insights into understanding how diverse environmental policies affect welfare and how countries formulate their policy decisions strategically. For instance, we clearly explain why countries are motivated to attract polluting firms and how allowing international emissions trading affects consumer surplus through its effect on the prices of dirty goods. These specific aspects have not been thoroughly investigated in the three aforementioned papers.

The remainder of this paper is organized as follows. Section 2 introduces the basic setup of the model. Sections 3 and 4 examine and compare the non-cooperative choices of emission permits under domestic and international emissions trading, with immobile capital in Section 3 and footloose capital in Section 4. Section 5 discusses the assumptions and extensions of our model. Section 6 concludes this paper.

## 2. Basic model

There are two countries, Home and Foreign, and two factors, labor and capital. We denote the mass of labor and capital in Home as  $L$  and  $K$ , and those in Foreign as  $L^*$  and  $K^*$ , respectively.<sup>6</sup> Labor is mobile nationally but immobile internationally. By contrast, capital can move freely across countries when there is no restriction on it. Capital is distributed uniformly across residents within each country, and capital rents are paid to local owners regardless of where it is used. In the new economic geography literature, it is often assumed that capital and labor are distributed across countries proportionately, so that international trade is not motivated by comparative advantage (e.g., Ottaviano and Thisse, 2004; Baldwin and Okubo, 2006; and Takahashi et al., 2013). However, we further assume that the production factors are distributed across countries *equally* to isolate our analysis from the home market

<sup>6</sup> Variables with asterisks are Foreign-related throughout the paper.

effect. Or in other words, firm location is only affected by the difference between permit prices in our analysis. Without loss of generality, the global levels of capital and labor are both normalized to unity, implying that  $K = K^* = L = L^* = 1/2$ .

Individuals in each country consume two kinds of goods: clean agricultural goods which are homogeneous, and dirty manufacturing goods with different varieties. We adopt a quasi-linear utility function for a representative individual in Home:

$$U = \mu \ln M + A - D(E + E^*) \quad (1)$$

where

$$M \equiv \left[ \int_0^n (x_i^{HH})^{1-\frac{1}{\sigma}} di + \int_0^{n^*} (x_j^{FH})^{1-\frac{1}{\sigma}} dj \right]^{\frac{\sigma}{\sigma-1}} \quad (2)$$

is the composite consumption of manufacturing varieties from the two countries.  $A$  is the consumption of agricultural goods.  $D(\cdot)$  is the environmental damage function that measures the disutility of global emissions.  $E$  and  $E^*$  are the emission permits issued by the two countries, each of which allows a firm to emit one unit of carbon.  $n$  and  $n^*$  are the masses of different varieties in Home and Foreign.  $x_i^{HH}$  and  $x_j^{FH}$  denote the consumption of Home variety  $i$  and Foreign variety  $j$ . In the superscripts, the first uppercase letter represents the production location, and the second represents the consumption location.  $\mu$  is a coefficient that measures the intensity of preference for manufacturing goods.  $\sigma > 1$  is the constant elasticity of substitution between different varieties.

The budget constraint of the representative individual in Home is

$$\int_0^n p_i^{HH} x_i^{HH} di + \int_0^{n^*} p_j^{FH} x_j^{FH} dj + p_A A = I/L. \quad (3)$$

$I$  denotes total income, which includes the total wages, capital rents and permit revenues from the government:  $I = wL + \int_0^K r_i di + tE$ , with  $w$  being the wage rate,  $r$  the capital rent and  $t$  the permit price.  $p_i^{HH}$  and  $p_j^{FH}$  are the prices of manufacturing goods.  $p_A$  is the price of agricultural goods. Similarly, the corresponding variables for Foreign can be obtained. For simplicity, we assume that  $\mu$  and  $\sigma$  are the same across countries.

Next, we describe the supply side. The clean goods are the numéraire. They are freely tradable, subject to constant returns to scale and perfect competition. Each unit of them requires only one unit of labor for production. Based on the assumptions, wage rates and the prices of clean goods are equalized across countries. For simplicity, we normalize them to be one:  $p_A = w = p_A^* = w^* = 1$ .

The dirty goods are traded with iceberg trade costs; that is,  $\tau$  units of them are traded for one unit consumed eventually. Each firm produces a variety of dirty goods at a fixed cost of one unit of capital. Therefore, the mass of firms is equal to the mass of varieties in each country. In addition, one unit of production requires one unit of labor. Carbon emissions are generated during production. Without abatement, one unit of production emits one unit of carbon. If the permit price is sufficiently high, a firm does abatement to reduce its emissions and its demand for emission permits. However, it has no incentive to do so if the permit price is sufficiently low, because the abatement cost is higher than the expenditure on emission permits. In the following, we assume that emission permits are always binding and the levels of them are sufficiently low so that firms always do abatement. Following Copeland and Taylor (1994), Konishi and Tarui (2015) and Forslid et al. (2017), we treat emissions as an input of the production of dirty goods and assume that the variable cost takes the form of Cobb–Douglas function:<sup>7</sup>

$$X_i = e_i^\beta t^{1-\beta}. \quad (4)$$

$X_i$  is the total production of a firm in Home, given by  $X_i = Lx_i^{HH} + L^* \tau x_i^{HF}$ .  $Lx_i^{HH}$  and  $L^* \tau x_i^{HF}$  are the total demand for variety  $i$  in Home and Foreign, respectively. Because of trade costs, a firm in Home has to produce  $L^* \tau x_i^{HF}$  units of goods to satisfy Foreign's demand.  $\beta$  is a technological parameter measuring the abatement efficiency ( $0 < \beta < 1$ ). A firm's cost function can be derived as  $c_i = r_i + \phi t^\beta X_i$  where  $\phi = \beta^{-\beta} (1 - \beta)^{-(1-\beta)}$ . Its demand for emission permits can be obtained by applying Sheppard's lemma:  $e_i = \partial c_i / \partial t = \beta \phi t^{\beta-1} X_i$ . Correspondingly, its emission intensity is  $e_i / X_i = \beta \phi t^{\beta-1}$ .

Following the markup pricing rule of the Dixit–Stiglitz monopolistic competition model, we derive the prices of the dirty goods:

$$p_i^{HH} = \frac{\sigma}{\sigma-1} \phi t^\beta; \quad p_i^{HF} = \tau p_i^{HH}; \quad p_j^{FF} = \frac{\sigma}{\sigma-1} \phi t^{*\beta}; \quad p_j^{FH} = \tau p_j^{FF}. \quad (5)$$

Because the firms and varieties are symmetric, we suppress the subscripts of  $i$  and  $j$  in what follows. With these prices, we can obtain the aggregate price indices,  $P$  and  $P^*$ , and the consumption of each variety in each country, which are shown in Appendix A. Note that  $MP = M^* P^* = \mu$  holds.

We now investigate the markets of capital and emission permits. In the capital markets, capital rents are the fixed cost of each firm's production, which are equal to each firm's selling profits in the two countries minus the variable cost, i.e.,

$$\text{Home capital rents: } r = Lp^{HH} x^{HH} + L^* p^{HF} x^{HF} - \phi t^\beta X = \frac{1}{\sigma-1} \phi t^\beta X; \quad (6)$$

$$\text{Foreign capital rents: } r^* = L^* p^{FF} x^{FF} + Lp^{FH} x^{FH} - \phi t^{*\beta} X^* = \frac{1}{\sigma-1} \phi t^{*\beta} X^*. \quad (7)$$

<sup>7</sup> See Appendix A for more details about the Cobb–Douglas production function and cost function.

If capital is immobile, capital rents can be different between Home and Foreign. However, if capital is footloose, capital rents are equalized between them.<sup>8</sup>

The permit markets are assumed to be perfectly competitive and all the permits are auctioned off to the manufacturing firms.<sup>9</sup> The permit price is determined by the interplay of the demand and supply of emission permits. Under domestic emissions trading, the market clearing conditions are

$$\text{Home permit market: } E = n\beta\phi t^{\beta-1}X; \quad (8)$$

$$\text{Foreign permit market: } E^* = n^*\beta\phi t^{*\beta-1}X^*. \quad (9)$$

Each country's supply of permits equals the demand for them from domestic firms. In this case, a firm's expenditure on emission permits is  $\frac{tE}{n} = \beta\phi t^\beta X = \beta(\sigma-1)r$  in Home and  $\frac{t^*E^*}{n^*} = \beta\phi t^{*\beta} X^* = \beta(\sigma-1)r^*$  in Foreign. Under international emissions trading, the total supply of permits by the two countries equals the total demand from all the firms in the two countries:

$$\text{International permit market: } E + E^* = n\beta\phi \tilde{t}^{\beta-1}X + n^*\beta\phi \tilde{t}^{*\beta-1}X^*. \quad (10)$$

$\tilde{t}$  is the corresponding permit price, which is the same in the two countries.<sup>10</sup> A firm's expenditure on emission permits is now given by  $\frac{\tilde{t}(E+E^*)}{n+n^*} = \frac{n}{n+n^*}\beta(\sigma-1)\tilde{r} + \frac{n^*}{n+n^*}\beta(\sigma-1)\tilde{r}^*$ . Although each country's permit revenues may be affected by its choices of emission permits, the sum of the two countries' permit revenues is always constant:

$$tE + t^*E^* = \tilde{t}(E + E^*) = \frac{\beta\mu(\sigma-1)}{\sigma}. \quad (11)$$

Each country's welfare is defined as the sum of its residents' indirect utilities. For simplicity, we assume a linear disutility function of global emissions, i.e.,  $D(E + E^*) = \delta(E + E^*)$ .<sup>11</sup> The marginal environmental damage is given by  $\delta$  and is constant. Home's welfare is

$$W = -\frac{1}{2}\mu \ln P + tE + \frac{1}{2}r - \frac{1}{2}\delta(E + E^*) + \left(\frac{1}{2}\mu \ln \mu + \frac{1}{2} - \frac{1}{2}\mu\right). \quad (12)$$

It is negatively related to the aggregate price index and the environmental damage and positively related to the permit revenues and capital rents. In the non-cooperative permit game, each country decides on its issuance of emission permits to maximize its own welfare, without considering how its decision affects the other country's welfare. In the following, we examine and compare optimal emission permits in four cases: domestic or international emissions trading with immobile or footloose capital.

In each case, given a country's choice of emission permits, the other country's best response is determined by the condition where the marginal benefits from emission permits are equal to the marginal damage from them. Since the two countries are symmetric, they have the same strategy and must choose the same levels of emission permits at the equilibrium:  $E_N = E_N^*$ .<sup>12</sup> Therefore, the optimal levels of emission permits at the Nash equilibrium can be obtained by substituting  $E_N = E_N^*$  into the best response function:

$$\left(\frac{dW}{dE}\right)_N = \underbrace{\left(-\frac{1}{2}\mu \frac{d \ln P}{dE}\right)_N + \left(\frac{dtE}{dE}\right)_N + \frac{1}{2}\left(\frac{dr}{dE}\right)_N}_{\text{marginal benefits}} - \frac{1}{2}\delta = 0. \quad (13)$$

To understand how the equilibrium permits are affected by the international mobility of emission permits and capital, we only need to examine and compare how the marginal benefits at the equilibrium are affected.

### 3. Emissions trading with immobile capital

In this section, capital is assumed to be immobile between countries. The mass of firms in each country is exogenously given by the initial capital stock, i.e.,  $n = n^* = K = K^* = 1/2$ .

<sup>8</sup> We do not take into account the full agglomeration of firms in one country because it does not happen at the equilibrium of countries' decisions in our analysis.

<sup>9</sup> Firms are subject to monopolistic competition in the goods markets but are price takers in the emission permit markets. The assumption of this inconsistent formulation is based on the fact that emission permits are commonly used by a large number of firms in many different sectors, and therefore no specific firm owns market power in the permit market. For instance, there are more than 12,000 plants regulated by the EU ETS (Makridou et al., 2019). In our model, we assume a continuum of firms, which coordinates with the price-taking behavior in the permit markets. Of course, it is also worthwhile to investigate the case where firms possess some market power in the permit market (e.g., Wirl, 2009; Lange, 2012; Antoniou et al., 2014; Haita, 2014). Among others, Wirl (2009) and Antoniou et al. (2014) study this issue with the notion of supply function equilibria defined by Klemperer and Meyer (1989). However, our model is not feasible and tractable to do so because we assume CES preference and Cobb–Douglas production technology for dirty goods, with emissions being an input of their production.

<sup>10</sup> Tildes denote the case of international emissions trading.

<sup>11</sup> The assumption of linear environmental damage function is often adopted in the literature on environmental policies and endogenous firm locations, e.g., Markusen et al. (1993, 1995) and Forslid et al. (2017). However, our results would not change even if we assume a convex function of environmental damage ( $D'' > 0$ ). See Section 5.3 for more details.

<sup>12</sup> The subscript "N" denotes the Nash equilibrium.

### 3.1. Domestic emissions trading

We first investigate the case of domestic emissions trading. With the market clearing conditions of emission permits in Eqs. (8) and (9) and the global permit revenues in Eq. (11), we describe the relationship between relative permit prices ( $t^*/t$ ) and relative levels of emission permits ( $E^*/E$ ) as follows:

$$\frac{2}{1 + \frac{t^*}{t} \frac{E^*}{E}} = \frac{1}{1 + \tau^{1-\sigma} T} + \frac{\tau^{1-\sigma}}{T + \tau^{1-\sigma}}, \quad (14)$$

where  $T = \left(\frac{t^*}{t}\right)^{\beta(1-\sigma)}$ . We define  $\frac{t^*}{t} = f\left(\frac{E^*}{E}\right)$ . Appendix B shows that  $f' < 0$  holds.

Substituting  $t^* = tf$  into Eq. (11), we obtain  $t = \frac{\beta\mu(\sigma-1)}{\sigma(E+tfE^*)}$ . An increase in  $E$  decreases the permit prices in both countries, i.e.,  $dt/dE < 0$ ,  $dt^*/dE < 0$ . For Home, its permit price  $t$  decreases because of a higher supply of emission permits. As  $t$  decreases, the prices of Home varieties decrease, as shown in Eq. (5). Therefore, the demand for Home varieties increases in both countries, which in turn decreases the demand for Foreign varieties because dirty goods are substitutes. Foreign firms tend to produce less and thus demand less for emission permits. As a result, Foreign permit price  $t^*$  also decreases. Analogously, we can show that  $dt/dE^* < 0$  and  $dt^*/dE^* < 0$  hold. This finding is concluded in the following lemma.<sup>13</sup>

**Lemma 1.** *Under domestic emissions trading and internationally immobile capital, an increase in a country's emission permits decreases the permit prices in both countries.*

With the market clearing conditions of capital and emission permits in Eqs. (6), (7), (8) and (9), the relationship between capital rents and permit revenues is described as

$$r = \frac{2tE}{\beta(\sigma-1)}; \quad r^* = \frac{2t^*E^*}{\beta(\sigma-1)}. \quad (15)$$

An increase in a country's emission permits increases both permit revenues and capital rents of that country, i.e.,  $dtE/dE > 0$ ,  $dr/dE > 0$ .

At the symmetric equilibrium,  $E_N = E_N^*$  holds. The equilibrium prices of emission permits in the two countries are the same:  $t_N = t_N^* = \frac{\beta\mu(\sigma-1)}{2\sigma E_N}$ . Although the effect of emission permits on the permit price is generally different between the two countries, it is higher in Home than in Foreign at the equilibrium. That is,

$$-\left(\frac{dt}{dE}\right)_N = \frac{\beta\mu(\sigma-1)(1+\Phi)}{4\sigma E_N^2} > -\left(\frac{dt^*}{dE}\right)_N = \frac{\beta\mu(\sigma-1)(1-\Phi)}{4\sigma E_N^2}; \quad (16)$$

where  $\Phi \equiv -f'_N = \frac{(1+\tau^{1-\sigma})^2}{4\tau^{1-\sigma}\beta(\sigma-1)+(1+\tau^{1-\sigma})^2} < 1$ .

The effects of emission permits on the welfare components in Eq. (13) are now given by

$$\begin{aligned} \left(-\frac{1}{2}\mu\frac{d\ln P}{dE}\right)_N &= -\frac{\sigma E_N}{\sigma-1} \left[ \frac{1}{1+\tau^{1-\sigma}} \left(\frac{dt}{dE}\right)_N + \frac{\tau^{1-\sigma}}{1+\tau^{1-\sigma}} \left(\frac{dt^*}{dE}\right)_N \right] \\ &= \frac{\beta\mu}{4E_N} \left( 1 + \frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}} \Phi \right); \end{aligned} \quad (17)$$

$$\left(\frac{dtE}{dE}\right)_N = \frac{\beta\mu(\sigma-1)}{2\sigma E_N} + E_N \left(\frac{dt}{dE}\right)_N = \frac{\beta\mu(\sigma-1)}{4\sigma E_N} (1-\Phi); \quad (18)$$

$$\left(\frac{1}{2}\frac{dr}{dE}\right)_N = \frac{1}{\beta(\sigma-1)} \left(\frac{dtE}{dE}\right)_N = \frac{\mu}{4\sigma E_N} (1-\Phi). \quad (19)$$

More issuance of emission permits increases a country's consumer surplus, permit revenues and capital rents at the equilibrium. However, it decreases the marginal benefits. Since the marginal damage from emissions is constant, the equilibrium emission permits are unique, which are derived as follows:

$$E_N = E_N^* = \frac{\beta\mu}{2\delta} \left( 1 + \frac{\sigma-1}{\sigma} + \frac{1}{\sigma\beta} \right) - \frac{\beta\mu\Phi}{2\delta} \left( \frac{2\tau^{1-\sigma}}{1+\tau^{1-\sigma}} + \frac{1-\beta}{\sigma\beta} \right). \quad (20)$$

### 3.2. International emissions trading

When emission permits are traded internationally, the permit price is obtained from Eq. (11):

$$\tilde{t} = \frac{\beta\mu(\sigma-1)}{\sigma} \frac{1}{\tilde{E} + \tilde{E}^*}. \quad (21)$$

Different from domestic emissions trading, an increase in either country's emission permits decreases the permit price in both countries equally. That is,  $d\tilde{t}/d\tilde{E} = d\tilde{t}/d\tilde{E}^* < 0$ . This difference is one of the reasons that lead to different choices of emission permits under domestic and international emissions trading, as shown below.

<sup>13</sup> See Appendix B for the proof of Lemma 1.

Since the permit prices are the same in the two countries, the total production becomes the same across all firms, i.e.,  $\bar{X} = \bar{X}^* = \frac{\mu(\sigma-1)}{\sigma\phi} \bar{r}^{-\beta}$ . Substituting it into Eqs. (6) and (7) yields  $\bar{r} = \bar{r}^* = \mu/\sigma$ . Capital rents in Home and Foreign are equalized and constant under international emissions trading. As a result, countries' choices of emission permits have no effect on capital rents.<sup>14</sup> By contrast, under domestic emissions trading, a country's capital rents are not constant. They are affected not only by its own but also by the other country's permit prices.

At the equilibrium, the prices of emission permits are  $\bar{t}_N = \frac{\beta\mu(\sigma-1)}{2\sigma\bar{E}_N}$ . The effect of emission permits on the permit price at the equilibrium becomes

$$\left(\frac{d\bar{t}}{d\bar{E}}\right)_N = \left(\frac{d\bar{t}}{d\bar{E}^*}\right)_N = -\frac{\beta\mu(\sigma-1)}{4\sigma(\bar{E}_N)^2}. \quad (22)$$

The effects on the welfare components in Eq. (13) are now given by

$$\left(-\frac{1}{2}\mu\frac{d\ln\bar{P}}{d\bar{E}}\right)_N = -\frac{\sigma\bar{E}_N}{\sigma-1}\left(\frac{d\bar{t}}{d\bar{E}}\right)_N = \frac{\beta\mu}{4\bar{E}_N}; \quad (23)$$

$$\left(\frac{d\bar{t}\bar{E}}{d\bar{E}}\right)_N = \frac{\beta\mu(\sigma-1)}{2\sigma\bar{E}_N} + \bar{E}_N\left(\frac{d\bar{t}}{d\bar{E}}\right)_N = \frac{\beta\mu(\sigma-1)}{4\sigma\bar{E}_N}; \quad (24)$$

$$\left(\frac{1}{2}\frac{d\bar{r}}{d\bar{E}}\right)_N = 0. \quad (25)$$

The equilibrium emission permits are thus derived as

$$\bar{E}_N = \bar{E}_N^* = \frac{\beta\mu}{2\delta}\left(1 + \frac{\sigma-1}{\sigma}\right). \quad (26)$$

Because  $\bar{E}_N = \bar{E}_N^* < E_N = E_N^*$  always holds, we have the following proposition:<sup>15</sup>

**Proposition 1.** Suppose that capital is immobile between countries. Compared with domestic emissions trading, international emissions trading decreases each country's and global emissions.

To understand the intuitions behind this proposition, we investigate and compare how the issuance of emission permits affects the marginal benefits of consumer surplus, capital rents and permit revenues at the equilibrium under domestic and international emissions trading. A difference between these two cases lies in the different effects of emission permits on permit prices. Given a specific level of  $E_N = \bar{E}_N$ , the effect on permit price under international emissions trading is the average of the effects on Home and Foreign permit prices under domestic emissions trading, i.e.,  $\left(\frac{d\bar{t}}{d\bar{E}}\right)_N = \frac{1}{2}\left[\left(\frac{d\bar{t}}{d\bar{E}}\right)_N + \left(\frac{d\bar{t}^*}{d\bar{E}}\right)_N\right]$ . However, in the case of domestic emissions trading, these effects are further adjusted by the trade costs to affect consumer surplus in Eq. (17), with a higher weight of local effect and a lower weight of foreign effect. As a result, international emissions trading decreases the marginal benefit of consumer surplus from more emission permits, compared with domestic emissions trading. For permit revenues in Eqs. (18) and (24), international emissions trading increases the marginal benefit of them because  $\left(\frac{d\bar{t}\bar{E}}{d\bar{E}}\right)_N > \left(\frac{d\bar{t}\bar{E}}{d\bar{E}}\right)_N$ . Capital rents increase in the level of emission permits under domestic emissions trading; however, they are constant under international emissions trading. Or in other words, international emissions trading eliminates a country's attempt to issue more permits for higher capital rents. Because the two negative effects dominate the positive effect, the total marginal benefits decrease, leading to less issuance of emission permits at the equilibrium.

#### 4. Emissions trading with footloose capital

In this section, we assume that capital can move freely across countries. The mass of firms is now endogenously determined in each country. At the trade equilibrium, capital rents in Home and Foreign, given by Eqs. (6) and (7) respectively, are equalized. That is,

$$\text{International capital rents: } r = r^*; \implies t^\beta X = t^{*\beta} X^*. \quad (27)$$

The expenditure on emission permits also becomes the same across firms, i.e.,  $\frac{tE}{n} = \frac{t^*E^*}{n^*} = \beta(\sigma-1)r$  under domestic emissions trading, and  $\frac{\bar{t}(E+E^*)}{n+n^*} = \beta(\sigma-1)\bar{r}$  under international emissions trading. With Eq. (11), we can show that  $r = r^* = \bar{r} = \mu/\sigma$  always holds. Therefore, countries' choices of emission permits do not affect capital rents when capital is footloose.

<sup>14</sup> If the two countries differ in their factor endowments, international emissions trading may not equalize capital rents. However, capital rents are still constant and countries' choices of emission permits have no effect on them. See Appendix D for more details.

<sup>15</sup> See Appendix B for the proof of Proposition 1.

#### 4.1. Domestic emissions trading

To make sure that firms always disperse across countries ( $0 < n < 1$ ) at the equilibrium in Eq. (27), we assume  $\frac{2\tau^{1-\sigma}}{1+(\tau^{1-\sigma})^2} < T < \frac{1+(\tau^{1-\sigma})^2}{2\tau^{1-\sigma}}$ , which implies that the difference of permit prices in the two countries is modest. With the conditions in Eqs. (8), (9), (27) and  $r = r^* = \mu/\sigma$ , we have

$$n = \frac{\sigma t E}{\beta \mu (\sigma - 1)}; \quad n^* = \frac{\sigma t^* E^*}{\beta \mu (\sigma - 1)}. \quad (28)$$

Note that a country's permit price is affected by the permit levels in both countries. Therefore, the mass of firms in each country is affected not only by its own choice of emission permits directly but also by the other country's choice of permits indirectly through the effect on the permit price.

Taking the mass of firms into Eq. (27) gives

$$\frac{t^* E^*}{t E} T = \frac{[1 + (\tau^{1-\sigma})^2] T - 2\tau^{1-\sigma}}{1 + (\tau^{1-\sigma})^2 - 2\tau^{1-\sigma} T}. \quad (29)$$

Similar to that under internationally immobile capital, Eq. (29) describes the relationship between relative permit prices ( $t^*/t$ ) and relative levels of emission permits ( $E^*/E$ ). We define  $\frac{t^*}{t} = g(\frac{E^*}{E})$ . Appendix C shows that  $g' < 0$  holds.

With  $n + n^* = 1$ ,  $t^* = g t$  and Eq. (28), we obtain  $t = \frac{\beta \mu (\sigma - 1)}{\sigma} \frac{1}{E + g E^*}$ . Investigating the effects of  $E$  and  $E^*$  on the permit prices and firm locations, we have the following lemma:<sup>16</sup>

**Lemma 2.** : Under domestic emissions trading and footloose capital, an increase in a country's emission permits increases the mass of firms in that country and decreases the permit prices in both countries.

Intuitively, an increase in a country's emission permits decreases its permit price, which makes this country more attractive. Therefore, more firms locate themselves in this country and fewer firms in the other country. Fewer firms in the other country lead to less demand for emission permits there, which in turn decreases the permit price in that country.

At the equilibrium, the permit prices and the masses of firms are the same in the two countries:  $t_N^{fl} = t_N^{*fl} = \frac{\beta \mu (\sigma - 1)}{2\sigma E_N^{fl}}$ ,  $n_N^{fl} = n_N^{*fl} = \frac{1}{2}$ .<sup>17</sup> The effects of emission permits on the permit prices and firm locations become

$$\left( \frac{dt^{fl}}{dE^{fl}} \right)_N = -\frac{\beta \mu (\sigma - 1)}{4\sigma (E_N^{fl})^2} (1 + \Psi); \quad \left( \frac{dn^{fl}}{dE^{fl}} \right)_N = \frac{1 - \Psi}{4E_N^{fl}}; \quad (30)$$

$$\left( \frac{dn^{*fl}}{dE^{fl}} \right)_N = -\frac{1 - \Psi}{4E_N^{fl}}; \quad \left( \frac{dt^{*fl}}{dE^{fl}} \right)_N = -\frac{\beta \mu (\sigma - 1)}{4\sigma (E_N^{fl})^2} (1 - \Psi). \quad (31)$$

where  $\Psi \equiv -g'_N = \frac{(1-\tau^{1-\sigma})^2}{4\tau^{1-\sigma}\beta(\sigma-1)+(1-\tau^{1-\sigma})^2} < 1$ . Note that  $\Psi < \Phi$  holds. Compared with the case of immobile capital, allowing footloose capital mitigates the effect of emission permits on the local permit price but deteriorates the effect on the foreign permit price, i.e.,  $\left( \frac{dt^{fl}}{dE^{fl}} \right)_N > \left( \frac{dt}{dE} \right)_N$ ,  $\left( \frac{dt^{*fl}}{dE^{fl}} \right)_N < \left( \frac{dt^*}{dE} \right)_N$ . Intuitively, if capital is immobile, as  $E$  increases, the permit price decreases more in Home than in Foreign, as shown in Eq. (16). As capital becomes footloose, firms relocate from Foreign to Home, leading to more demand for permits in Home and less demand for permits in Foreign. Therefore, the permit price rebounds in Home but decreases further in Foreign. Because of the rebound effect of footloose capital on Home's permit price, allowing footloose capital increases the marginal benefit of permit revenues:

$$\left( \frac{dt^{fl} E^{fl}}{dE^{fl}} \right)_N = \frac{\beta \mu (\sigma - 1)}{2\sigma E_N^{fl}} + E_N^{fl} \left( \frac{dt^{fl}}{dE^{fl}} \right)_N = \frac{\beta \mu (\sigma - 1)}{4\sigma E_N^{fl}} (1 - \Psi) > \left( \frac{dt E}{dE} \right)_N. \quad (32)$$

The effect of emission permits on the consumer surplus is now given by

$$\begin{aligned} \left( -\frac{1}{2} \mu \frac{d \ln P^{fl}}{dE^{fl}} \right)_N &= -\frac{\sigma E_N^{fl}}{\sigma - 1} \left[ \frac{1}{1 + \tau^{1-\sigma}} \left( \frac{dt^{fl}}{dE^{fl}} \right)_N + \frac{\tau^{1-\sigma}}{1 + \tau^{1-\sigma}} \left( \frac{dt^{*fl}}{dE^{fl}} \right)_N \right] \\ &\quad + \frac{\mu}{\sigma - 1} \frac{1 - \tau^{1-\sigma}}{1 + \tau^{1-\sigma}} \left( \frac{dn^{fl}}{dE^{fl}} \right)_N. \end{aligned} \quad (33)$$

On the right-hand side, the first term captures the effects of emission permits on permit prices in Home and Foreign, as mentioned above. The second term represents the effect on firm locations or the pollution haven effect, which is positive as more emission permits attract more firms. Compared with the case of immobile capital, the first term is smaller than Eq. (17) because of the rebound effect in Home. However, since the second term is dominant, allowing footloose capital increases the marginal benefit of consumer surplus, i.e.,  $\left( -\frac{1}{2} \mu \frac{d \ln P^{fl}}{dE^{fl}} \right)_N = \frac{\beta \mu}{4E_N^{fl}} \left( 1 + \frac{1+\tau^{1-\sigma}}{1-\tau^{1-\sigma}} \Psi \right) > \left( -\frac{1}{2} \mu \frac{d \ln P}{dE} \right)_N$ .

<sup>16</sup> See Appendix C for the proof of Lemma 2.

<sup>17</sup> “fl” in the superscripts denotes the case of footloose capital.

Although allowing footloose capital eliminates countries' incentive to issue more emission permits to raise firms' capital rents, i.e.,  $\left(\frac{1}{2} \frac{dr^{fl}}{dE^{fl}}\right)_N = 0$ , it increases the marginal benefits of consumer surplus and permit revenues. Because the latter positive effects dominate the former negative effect, total marginal benefits increase. As a result, allowing footloose capital increases each country's and global emissions, i.e.,

$$E_N^{fl} = E_N^{*fl} = \frac{\beta\mu}{2\delta} \left[ 1 + \frac{\sigma-1}{\sigma} + \left( \frac{2\tau^{1-\sigma}}{1-\tau^{1-\sigma}} + \frac{1}{\sigma} \right) \Psi \right] > E_N. \quad (34)$$

When capital becomes footloose, each country has an incentive to attract more firms because doing so improves its consumer surplus and permit revenues. Therefore, both countries increase their emission permits to loosen their environmental regulations. Since the countries are symmetric, they choose the same level of emission permits eventually, which does not change firm locations.

We conclude our finding in the following proposition:<sup>18</sup>

**Proposition 2.** *Under domestic emissions trading, allowing footloose capital increases each country's and global emissions.*

#### 4.2. International emissions trading

With international emissions trading, the permit price is always the same in the two countries, leading to  $T = 1$ . The equilibrium condition in Eq. (27) implies that  $\tilde{n}^{fl} = \tilde{n}^{*fl} = 1/2$  holds at the trade equilibrium. Although capital is footloose, the mass of firms is not affected by countries' choices of emission permits. Intuitively, firms can directly purchase the emission permits issued by either country in the international permit market without changing their locations. Therefore, the analysis of the optimal emission permits becomes the same as that of internationally immobile capital. The equilibrium permit levels are also the same in the two cases.

**Proposition 3.** *Under international emissions trading, allowing footloose capital does not change each country's and global emissions.*

Proposition 3 does not depend on our assumption of symmetric countries. If countries are different in their factor endowments, allowing footloose capital would change the mass of firms and thus the welfare of each country. However, such changes in firm locations are motivated by the difference in market sizes (i.e., the home market effect) rather than the levels of permits, because the permit price is always the same across countries under international emissions trading. Consequently, the equilibrium permit levels with footloose capital are the same as that with immobile capital.<sup>19</sup>

With footloose capital, how allowing international emissions trading affects the choices of emission permits depends on its effects on the consumer surplus and permit revenues, given that capital rents are always constant. On the one hand, international emissions trading decreases the marginal benefit of consumer surplus because it eliminates countries' incentives to attract firms, or the pollution haven effect. On the other hand, it increases the marginal benefit of permit revenues because the equalization of permit prices across countries leads to a smaller effect of emission permits on the local permit price, i.e.,  $\left(\frac{dr^{fl}}{dE^{fl}}\right)_N > \left(\frac{dr^{fl}}{dE^{fl}}\right)_N$ . The former effect is dominant. Therefore, the total marginal benefits decrease, which leads to less issuance of emission permits under international emissions trading. This finding is concluded in the following proposition:

**Proposition 4.** *Suppose that capital is footloose between countries. Compared with domestic emissions trading, international emissions trading decreases each country's and global emissions.*

Until now, we have investigated and compared how countries issue their emission permits non-cooperatively when the permits are traded domestically and internationally in the presence of capital mobility. According to the findings above, we can rank the equilibrium levels of emissions as:  $E_N^{fl} > E_N > \tilde{E}_N = \tilde{E}_N^{fl}$ . Because the permit prices take the same form in the four cases, i.e.,  $t_N = t_N^* = \frac{\beta\mu(\sigma-1)}{2\sigma E_N}$ , we rank the equilibrium permit prices as:  $t_N^{fl} < t_N < \tilde{t}_N = \tilde{t}_N^{fl}$ . In addition to pollution emissions, the goods market is distorted by the monopolistic competition. Therefore, each country has an incentive to adjust its permit price below its marginal environmental damage. That is,  $t_N^{fl} < t_N < \tilde{t}_N = \tilde{t}_N^{fl} < \frac{1}{2}\delta$ .<sup>20</sup>

## 5. Discussions

### 5.1. Cooperative choices of emission permits

In this section, we discuss the cooperative choices of emission permits, in which each country maximizes the joint welfare by considering the spillover effect of its decision on the other country. The joint welfare, denoted by  $W^{coop}$ , is defined as the sum of

<sup>18</sup> See Appendix C for the proof of Proposition 2. It is not surprising that under domestic emission taxes, allowing footloose capital also increases each country's and global emissions. However, we find that the equilibrium emissions are lower under emission permits than under emission taxes and emission permits are welfare superior to emission taxes. Our finding is consistent with Proposition 6 in Eichner and Pethig (2019). Detailed analysis is available upon request.

<sup>19</sup> Appendix D provides the proof of Proposition 3 under the random distribution of capital and labor across countries. More generally, Proposition 3 holds even if countries are also different in their evaluations of environmental damage. See Appendix D for more details.

<sup>20</sup> This relation holds because  $\tilde{t}_N = \frac{\sigma-1}{2\sigma-1}\delta < \frac{1}{2}\delta$ .

the two countries' welfare:

$$W^{coop} = \underbrace{-\frac{1}{2}\mu(\ln P + \ln P^*)}_{CS} + \frac{1}{2}(r + r^*) + (tE + t^*E^*) - \delta(E + E^*) + (\mu \ln \mu + 1 - \mu). \quad (35)$$

The sums of capital rents and permit revenues are respectively given by  $\mu/\sigma$  and  $\beta\mu(\sigma - 1)/\sigma$ , which are constant. Each country's issuance of emission permits only redistributes the capital rents and permit revenues between countries but has no effect on the total value of them. Therefore, the cooperative choices of permits are only determined by the consumer surplus and environmental damage in the two countries. Furthermore, we find that the effects of emission permits on the consumer surplus are the same at the equilibria in the four cases. Specifically, when capital is immobile, the effects under domestic and international emissions trading are respectively given by

$$\left(\frac{dCS}{dE}\right)_N = -\frac{\sigma E_N}{\sigma - 1} \left[ \left(\frac{dt}{dE}\right)_N + \left(\frac{dt^*}{dE}\right)_N \right] = \frac{\beta\mu}{2E_N}; \quad (36)$$

$$\left(\frac{d\widetilde{CS}}{d\tilde{E}}\right)_N = -\frac{2\sigma \tilde{E}_N}{\sigma - 1} \left(\frac{d\tilde{t}}{d\tilde{E}}\right)_N = \frac{\beta\mu}{2\tilde{E}_N}; \quad (37)$$

which are the same because the effect on permit prices under international emissions trading is the average of the effects on Home's and Foreign's permit prices under domestic emissions trading. On the other hand, under footloose capital, each country has no incentive to manipulate permit prices and firm locations because it aims to maximize the joint rather than its own welfare. Therefore, allowing footloose capital does not affect the cooperative choices of permits.

Solving the first-order condition of the joint welfare maximization yields

$$\frac{dW^{coop}}{dE} = 0; \implies E_N^{coop} = \frac{\beta\mu}{2\delta}. \quad (38)$$

When emission permits are determined non-cooperatively in the four cases, the optimal level of permits is the lowest under international emissions trading:  $\tilde{E}_N = \tilde{E}_N^{fl} = \frac{\beta\mu}{2\delta} \left(1 + \frac{\sigma-1}{\sigma}\right)$ . Because  $E_N^{coop} < \tilde{E}_N$  holds, we conclude that the cooperative levels of permits are always lower than the non-cooperative levels of permits. Correspondingly, the cooperative permit prices are always higher than the non-cooperative permit prices.

**Proposition 5.** *The cooperative choices of emission permits are always the same regardless of international mobility of emission permits and capital and are always lower than the non-cooperative choices of emission permits.*

## 5.2. Welfare ranking

In the main part, we mainly focused on how emission permits and thus emissions are affected by international mobility of emission permits and capital. In this part, we further examine how welfare is affected. At the equilibria in all four cases, a country's welfare can be expressed as<sup>21</sup>

$$W_N = \frac{1}{2}\beta\mu \ln E_N - \delta E_N. \quad (39)$$

For  $E_N > \frac{\beta\mu}{2\delta}$ , the equilibrium welfare is decreasing in the levels of emission permits; or in other words, more issuance of emission permits at the equilibrium is welfare detrimental. Based on the propositions above, we can rank welfare as follows:

**Proposition 6.** *Compared with domestic emissions trading, international emissions trading increases each country's and global welfare regardless of capital mobility. Allowing footloose capital decreases each country's and global welfare under domestic emissions trading; however, it does not change these welfare under international emissions trading. Welfare under cooperative permits is always higher than that under non-cooperative permits, regardless of international mobility of permits and capital.*

Tsakiris et al. (2017) also investigate welfare ranking of domestic and international emissions trading in the presence of capital mobility. However, they find that when capital is footloose and pollution is global, welfare is the same at the equilibrium under domestic and international emissions trading, which is different from our finding. Besides, they do not consider immobile capital.

It is possible to extend our analysis to a regime choice game by the countries. Each country can non-cooperatively choose domestic or international emissions trading and immobile or footloose capital. Although international emissions trading improves the welfare of each country, such an outcome may not arise as a Nash equilibrium in the regime choice game. This extension is beyond the scope of our study and is left for future work.<sup>22</sup>

<sup>21</sup> The constant terms are suppressed. See Appendix E for the derivation of the welfare function.

<sup>22</sup> Please refer to Helm (2003) for an analysis of regime choice between domestic and international emissions trading.

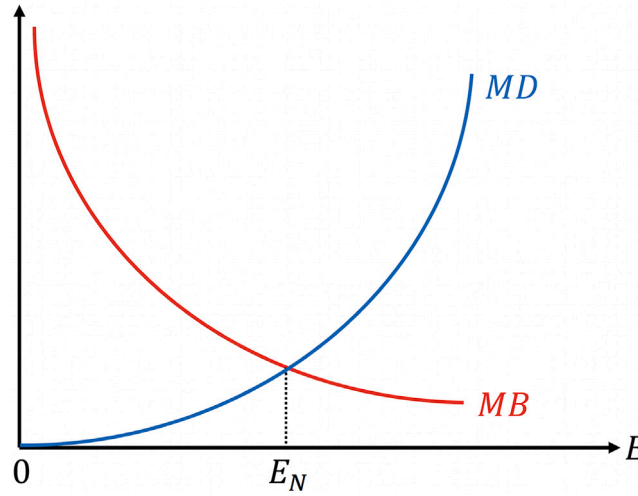


Fig. 1. Equilibrium emission permits under immobile capital and domestic emissions trading.

### 5.3. Convex environmental damage

In the main part, we considered a linear environmental damage function for simplicity. However, our results would not change even if we assume a convex environmental damage function, i.e.,  $D'' > 0$ . With convex environmental damage, Home's best response function in Eq. (13) can be written as

$$\left(\frac{dW}{dE}\right)_N = \underbrace{\left(-\frac{1}{2}\mu\frac{d\ln P}{dE}\right)_N + \left(\frac{drE}{dE}\right)_N + \frac{1}{2}\left(\frac{dr}{dE}\right)_N}_{\text{marginal benefits}} - \frac{1}{2}D' = 0. \quad (40)$$

Home's marginal damage ( $MD$ ) is now  $D'/2$  instead of  $\delta/2$ . Note that considering convex environmental damage does not affect the marginal benefits ( $MB$ ). Therefore, the analysis of the marginal benefits in the main part remains valid in this section.

In the case of immobile capital and domestic emissions trading, the equilibrium emission permits are described by Fig. 1. The  $MB$  curve is decreasing in the level of emission permits, while the  $MD$  curve is now increasing in it.<sup>23</sup> The equilibrium level of emission permits is determined at the intersection of the  $MB$  and  $MD$  curves. Allowing international emissions trading or footloose capital may affect the  $MB$  curve but would not affect the  $MD$  curve. According to the results in the main part, allowing international emissions trading decreases the marginal benefits of emission permits regardless of capital mobility. Therefore, the  $MB$  curve shifts down, and the equilibrium level of emission permits becomes lower. Propositions 1 and 4 hold. Similarly, under domestic emissions trading, allowing footloose capital increases the marginal benefits of emission permits. Therefore, the  $MB$  curve shifts up, and the equilibrium level of emission permits becomes higher. Proposition 2 holds. Under international emissions trading, allowing footloose capital does not affect the marginal benefits. Hence, the  $MB$  curve and the equilibrium level of emission permits remain the same. Proposition 3 holds.

When countries choose their emission permits cooperatively, in contrast to Eq. (38), the equilibrium is determined by

$$\frac{\beta\mu}{2E_N^{coop}} = D'; \implies \frac{\beta\mu}{4E_N^{coop}} = \frac{1}{2}D'. \quad (41)$$

Because  $\beta\mu/4E_N^{coop}$  is smaller than the marginal benefits in the non-cooperative games, the cooperative choices of emission permits are always lower than the non-cooperative choices of emission permits. Proposition 5 holds.

At the equilibria in all four cases, a country's welfare, in contrast to Eq. (39), can be expressed as

$$W_N = \frac{1}{2}\beta\mu \ln E_N - \frac{1}{2}D(2E_N). \quad (42)$$

For  $E_N > E_N^{coop}$ , the equilibrium welfare is decreasing in the levels of emission permits; or in other words, more issuance of emission permits at the equilibrium is welfare detrimental. Therefore, the welfare ranking of the four regimes in Proposition 6 still holds here.

<sup>23</sup> The  $MD$  curve is not necessary to be convex.

#### 5.4. Capital taxation

In the main part, we only focused on one policy instrument of emission permits. However, in the presence of capital, a legitimate question is how our results would change if capital is taxed by the local governments.<sup>24</sup> We denote the capital tax rate as  $\rho$  in Home and  $\rho^*$  in Foreign. For simplicity, we assume that the capital taxes and emission permits are determined non-cooperatively and simultaneously by the countries. The disposal of capital tax revenues does not matter because there is no income effect in our model. Countries may distribute them across their residents or just keep them as government income. When capital is immobile between countries, the total after-tax capital rents are  $(1 - \rho)r/2$  in Home and  $(1 - \rho^*)r^*/2$  in Foreign. Correspondingly, the capital tax revenues are  $\rho r/2$  and  $\rho^* r^*/2$ . The sums of them are  $r/2$  and  $r^*/2$ , which are the same as the total capital rents in the main part without capital taxation. Imposing capital taxation does not affect the demand and supply of dirty goods and the welfare function of each country. Therefore, countries' decisions on emission permits remain the same and the findings in Section 3 still hold.

When capital is footloose, imposing capital taxation affects firm locations and thus may affect firms' production and their demand for emission permits. We provide a detailed analysis of emission permit and capital tax competition in Appendix F. The key findings are concluded as follows. Under international emissions trading, capital taxes only affect firm locations while emission permits only affect permit prices. Therefore, adding capital tax competition to emission permit competition does not affect countries' decisions on emissions permits in Section 4.2. However, countries subsidize capital at the equilibrium, i.e.,  $\rho_N = \rho_N^* < 0$ . Under domestic emissions trading, both capital tax rates and emission permits can affect firm locations and permit prices. Countries still have an incentive to subsidize capital to attract firms. However, this in turn discourages countries to attract firms with emission permits. As a result, adding capital tax competition to emission permit competition decreases countries' choices of emissions permits, compared with the results in Section 4.1. In addition, we surprisingly find that in the presence of both emission permit and capital tax competition, allowing footloose capital does not affect each country's and global emissions. Intuitively, this is because countries' incentive to subsidize capital eliminates all the marginal benefits of consumer surplus and permit revenues in Section 4.1. Note that the findings may depend on our assumption of symmetric countries. It is worthwhile to investigate how these findings would be modified in the presence of asymmetric countries. We leave this issue for future research.

In a perfectly competitive context of large symmetric countries with mobile capital, Eichner and Pethig (2019) find that adding capital tax competition to permit competition under domestic emissions trading does not affect the outcome of the game. That is, countries refrain from taxing capital ( $\rho_N = \rho_N^* = 0$ ) and choose the same levels of emission permits as without capital taxation. We verify that their finding may not hold in a monopolistically competitive model as ours.

**Proposition 7.** *Suppose countries compete in both emission permits and capital tax rates. Allowing international emissions trading decreases each country's and global emissions under both immobile and footloose capital. However, allowing footloose capital does not affect each country's and global emissions under both domestic and international emissions trading.*

#### 6. Conclusion

In this study, we extended the footloose capital model to examine and compare how countries issue their emission permits under domestic and international emissions trading in the presence of capital mobility. We found that compared with domestic emissions trading, international emissions trading decreases each country's emission permits and leads to fewer global emissions, regardless of capital mobility. This finding suggests that international emissions trading or linking different emissions trading systems can be effective in inducing the governments to choose more stringent emission permits and thus can help them achieve their emission reduction targets. We also found that under domestic emissions trading, allowing footloose capital increases each country's and global emissions; however, under international emissions trading, it does not change these emissions. This finding indicates the significance of considering capital mobility in policy analysis because it can affect how emissions trading works.

We make a final remark to conclude. To keep our model simple and tractable, we considered two symmetric countries. However, asymmetric features of countries are crucial to their decisions on environmental policies. In this part, we analyze how our results would change if market sizes are different across countries.<sup>25</sup> Considering different market sizes means that we need to incorporate the home market effect (HME) into our analysis, which states that firms have an incentive to locate themselves in the larger country. According to the literature on new economic geography and the environment (e.g., Forslid et al., 2017), the larger country usually imposes more stringent environmental regulations because it has the advantage of a larger market, while the smaller country usually imposes laxer environmental regulations to compensate for its smaller market. In Appendix D, we also show that under international emissions trading, the larger country issues fewer emission permits than the smaller country. However, countries' choices of emission permits are not motivated by the HME because emission permits do not affect firm locations under international emissions trading. As a result, allowing footloose capital would not affect each country's and global emissions. Proposition 3 still holds. Under domestic emissions trading, we cannot obtain analytical results because the model becomes intractable. Intuitively, allowing footloose capital would increase the smaller country's emissions because both the PHE and the HME work in the same direction to increase its emissions. However, how the larger country's emissions change would depend on the tension between the two effects. It is likely

<sup>24</sup> For the joint study of environmental policy and capital tax competition, please refer to Habla (2018), Eichner and Pethig (2018, 2019), Yamagishi (2019), Madiès et al. (2022), and Tsakiris et al. (2023), among others.

<sup>25</sup> Although we only provide a discussion about different market sizes here, other asymmetric features, such as different evaluations of environmental damage from emissions, can be analyzed similarly.

that allowing footloose capital still increases the larger country's emissions if the PHE dominates the HME. In addition, we expect that allowing international emission trading would still decrease each country's and global emissions regardless of capital mobility, because it could still eliminate the effects of emission permits on capital rents under immobile capital and the PHE under footloose capital. The detailed analysis of emissions trading in the presence of different market sizes goes beyond the scope of our study and is left for future research.

### CRedit authorship contribution statement

**Haitao Cheng:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

### Declaration of competing interest

The author declares that there is no conflict of interest.

### Data availability

No data was used for the research described in the article.

### Appendix A. Production and consumption of dirty goods

In this part, we show how to derive the Cobb–Douglas production function and the cost function of dirty goods in the main part. We assume that a firm invests a fraction  $\theta$  of labor into abatement to decrease emissions and the rest of labor into production:<sup>26</sup>

$$X = (1 - \theta)l; \quad e = \varphi(\theta)l. \quad (43)$$

Note that the labor input coefficient is 1. The abatement function  $\varphi(\theta)$  should satisfy the following three conditions: (i)  $\varphi'(\theta) < 0$ ; (ii)  $\varphi(0) = 1$ ; and (iii)  $\varphi(1) = 0$ . These conditions imply that more investment in abatement leads to less production and fewer emissions, and that the total emissions are equal to the production level without abatement and tend to be zero as the fraction of labor for abatement increases to one. For simplicity, we assume:

$$\varphi(\theta) = (1 - \theta)^{\frac{1}{\beta}}. \quad (44)$$

$1/\beta$  measures the effectiveness of the abatement technology.

A firm's cost function consists of capital rents, wages and the purchase of emission permits:

$$c = r + l + te = r + X \left[ (1 - \theta)^{-1} + t(1 - \theta)^{\frac{1-\beta}{\beta}} \right]. \quad (45)$$

Given any production level  $X$ , a firm minimizes its cost by deciding on how much to invest in abatement. Taking the first derivative of  $c$  with respect to  $\theta$  gives

$$\frac{\partial c}{\partial \theta} = X(1 - \theta)^{-2} \left[ 1 - \frac{1 - \beta}{\beta} t(1 - \theta)^{\frac{1}{\beta}} \right]. \quad (46)$$

Note that  $(1 - \theta)^{\frac{1}{\beta}} \in [0, 1]$ . If  $\frac{1 - \beta}{\beta} t \leq 1$ , then  $\frac{\partial c}{\partial \theta} \geq 0$  always holds. The optimal value of  $\theta$  is 0, which implies no abatement. In this case,  $e = X = l$  and  $c = r + (1 + t)X$ .

If  $\frac{1 - \beta}{\beta} t > 1$ , then

$$\frac{\partial c}{\partial \theta} = 0; \implies \theta = 1 - \left( \frac{\beta}{1 - \beta} \frac{1}{t} \right)^{\beta}. \quad (47)$$

As the permit price increases, a firm invests more in abatement to decrease its demand for emission permits. Substituting  $1 - \theta = X/l$  into  $e = (1 - \theta)^{\frac{1}{\beta}} l$  yields Eq. (4):  $X = e^{\beta} l^{1-\beta}$ . Taking the value of  $\theta$  into Eq. (45), we can derive a firm's cost function as  $c = r + \phi t^{\beta} X$ . In the main part, we assume that  $\frac{1 - \beta}{\beta} t > 1$  always holds.

With the prices of dirty goods in Eq. (5), we can obtain the aggregate price indices,  $P$  and  $P^*$ , and the consumption of each variety in each country as follows:

$$P = \frac{\sigma \phi}{\sigma - 1} \left[ n t^{\beta(1-\sigma)} + n^* \tau^{1-\sigma} t^{*\beta(1-\sigma)} \right]^{\frac{1}{1-\sigma}}; \quad (48)$$

$$P^* = \frac{\sigma \phi}{\sigma - 1} \left[ n^* t^{*\beta(1-\sigma)} + n \tau^{1-\sigma} t^{\beta(1-\sigma)} \right]^{\frac{1}{1-\sigma}}; \quad (49)$$

$$x^{HH} = \frac{\mu(\sigma - 1)}{\sigma \phi} \frac{t^{-\beta\sigma}}{n t^{\beta(1-\sigma)} + n^* \tau^{1-\sigma} t^{*\beta(1-\sigma)}}; \quad (50)$$

<sup>26</sup> In this section, the subscripts are suppressed for conciseness.

$$x^{FH} = \frac{\mu(\sigma-1)}{\sigma\phi} \frac{\tau^{-\sigma} t^{*\beta-\beta\sigma}}{n t^{\beta(1-\sigma)} + n^* \tau^{1-\sigma} t^{*\beta(1-\sigma)}}; \quad (51)$$

$$x^{FF} = \frac{\mu(\sigma-1)}{\sigma\phi} \frac{t^{*\beta-\beta\sigma}}{n^* t^{*\beta(1-\sigma)} + n \tau^{1-\sigma} t^{\beta(1-\sigma)}}; \quad (52)$$

$$x^{HF} = \frac{\mu(\sigma-1)}{\sigma\phi} \frac{\tau^{-\sigma} t^{*\beta-\beta\sigma}}{n^* t^{*\beta(1-\sigma)} + n \tau^{1-\sigma} t^{\beta(1-\sigma)}}. \quad (53)$$

## Appendix B. Emissions trading with immobile capital

First, we show that in Eq. (14),  $t^*/t$  is decreasing in  $E^*/E$ , i.e.,  $f' < 0$  holds. For reference, we write Eq. (14) again here:

$$\frac{2}{1 + \frac{t^*}{t} \frac{E^*}{E}} = \underbrace{\frac{1}{1 + \tau^{1-\sigma} T} + \frac{\tau^{1-\sigma}}{T + \tau^{1-\sigma}}}_{RHS}.$$

Taking partial derivative of the right hand side (*RHS*) of Eq. (14) with respect to  $t^*/t$ , we have

$$\begin{aligned} RHS' &= \frac{\partial RHS}{\partial \frac{t^*}{t}} = \frac{\partial RHS}{\partial T} \frac{\partial T}{\partial \frac{t^*}{t}} \\ &= \left[ \frac{\tau^{1-\sigma}}{(1 + \tau^{1-\sigma} T)^2} + \frac{\tau^{1-\sigma}}{(T + \tau^{1-\sigma})^2} \right] \beta(\sigma-1) \left( \frac{t^*}{t} \right)^{\beta(1-\sigma)-1} \\ &> 0. \end{aligned} \quad (54)$$

Taking total derivative of both sides of Eq. (14) gives

$$-\frac{2}{\left(1 + \frac{t^*}{t} \frac{E^*}{E}\right)^2} \left( \frac{t^*}{t} d \frac{E^*}{E} + \frac{E^*}{E} d \frac{t^*}{t} \right) = RHS' d \frac{t^*}{t}. \quad (55)$$

Therefore,

$$\frac{d(t^*/t)}{d(E^*/E)} = -\frac{t^*}{t} \left[ \frac{1}{2} RHS' \left( 1 + \frac{t^*}{t} \frac{E^*}{E} \right)^2 + \frac{E^*}{E} \right]^{-1} < 0. \quad (56)$$

**Proof of Lemma 1.** The effect of Home's issuance of emission permits on the permit price in Home is given by

$$\frac{dt}{dE} = -\frac{\beta\mu(\sigma-1)}{\sigma(E + fE^*)^2} \left( 1 - \frac{E^{*2}}{E^2} f' \right) < 0. \quad (57)$$

The inequality holds because  $1 - \frac{E^{*2}}{E^2} f' > 0$ .

The effect of Home's issuance of emission permits on the permit price in Foreign is given by

$$\begin{aligned} \frac{dt^*}{dE} &= -\frac{\beta\mu(\sigma-1)}{\sigma(E + fE^*)^2} \left( f + \frac{E^*}{E} f' \right) \\ &= -\frac{\beta\mu(\sigma-1)}{\sigma(E + fE^*)^2} \frac{t^*}{t} \left[ 1 - \frac{\frac{E^*}{E}}{\frac{1}{2} RHS' \left( 1 + \frac{t^*}{t} \frac{E^*}{E} \right)^2 + \frac{E^*}{E}} \right] \\ &= -\frac{\beta\mu(\sigma-1)}{\sigma(E + fE^*)^2} \frac{t^*}{t} \frac{\frac{1}{2} RHS' \left( 1 + \frac{t^*}{t} \frac{E^*}{E} \right)^2}{\frac{1}{2} RHS' \left( 1 + \frac{t^*}{t} \frac{E^*}{E} \right)^2 + \frac{E^*}{E}} \\ &< 0. \end{aligned} \quad (58)$$

Since the two countries are symmetric, we can show analogously that  $\frac{dt^*}{dE^*} < 0$  and  $\frac{dt}{dE^*} < 0$  hold.

**Proof of Proposition 1.** Proposition 1 holds because with immobile capital, each country's optimal choices of emission permits are higher under domestic emissions trading than under international emissions trading:

$$\begin{aligned} E_N - \tilde{E}_N &= \frac{\beta\mu}{2\delta} \left[ \frac{1}{\sigma\beta} - \left( \frac{2\tau^{1-\sigma}}{1 + \tau^{1-\sigma}} + \frac{1-\beta}{\sigma\beta} \right) \Phi \right] \\ &= \frac{\beta\mu}{2\delta\sigma} \frac{(1 - \tau^{1-\sigma}) [(2\sigma-1)\tau^{1-\sigma} + 1]}{4\tau^{1-\sigma}\beta(\sigma-1) + (1 + \tau^{1-\sigma})^2} \\ &> 0. \end{aligned} \quad (59)$$

### Appendix C. Emissions trading with footloose capital

First, we show that in Eq. (29),  $t^*/t$  is decreasing in  $E^*/E$ , i.e.,  $g' < 0$  holds. Taking total derivatives of both sides of Eq. (29) gives

$$[\beta(1-\sigma)+1]\frac{t}{t^*}d\frac{t^*}{t}+\frac{E}{E^*}d\frac{E^*}{E}=\Omega\beta(1-\sigma)\frac{t}{t^*}d\frac{t^*}{t}; \quad (60)$$

where

$$\Omega=\left\{\frac{1+(\tau^{1-\sigma})^2}{[1+(\tau^{1-\sigma})^2]T-2\tau^{1-\sigma}}+\frac{2\tau^{1-\sigma}}{1+(\tau^{1-\sigma})^2-2\tau^{1-\sigma}T}\right\}T. \quad (61)$$

Note that  $\Omega > 1$  holds because

$$\Omega-1=2\tau^{1-\sigma}\left\{\frac{1}{[1+(\tau^{1-\sigma})^2]T-2\tau^{1-\sigma}}+\frac{T}{1+(\tau^{1-\sigma})^2-2\tau^{1-\sigma}T}\right\}>0. \quad (62)$$

The effect of a change in relative emission permits on relative permit prices is given by

$$\frac{d(t^*/t)}{d(E^*/E)}=-\frac{t^*}{t}\frac{E}{E^*}\frac{1}{(\Omega-1)\beta(\sigma-1)+1}<0. \quad (63)$$

**Proof of Lemma 2.** An increase in Home's emission permits decreases its permit price:

$$\frac{dt}{dE}=-\frac{\beta\mu(\sigma-1)}{\sigma(E+gE^*)^2}\left(1-\frac{E^*{}^2}{E^2}g'\right)<0, \quad (64)$$

which makes Home more attractive. Therefore, more firms locate themselves in Home and fewer firms in Foreign. This pollution haven effect can be verified by

$$\frac{dn}{dE}=\frac{n}{t}\frac{dt}{dE}+\frac{n}{E}=\frac{nn^*}{E}\frac{(\Omega-1)\beta(\sigma-1)}{(\Omega-1)\beta(\sigma-1)+1}>0; \quad \frac{dn^*}{dE}=-\frac{dn}{dE}<0. \quad (65)$$

Fewer firms in Foreign lead to less demand for emission permits, which in turn decreases the permit price there:

$$\frac{dt^*}{dE}=\frac{t^*}{n^*}\frac{dn^*}{dE}<0. \quad (66)$$

Analogously, we can demonstrate that  $\frac{dt^*}{dE^*}<0$ ,  $\frac{dn^*}{dE^*}>0$ ,  $\frac{dn}{dE^*}<0$  and  $\frac{dt}{dE^*}<0$  hold.

**Proof of Proposition 2.** First, we demonstrate that allowing footloose capital increases the marginal benefit of consumer surplus:

$$\begin{aligned} &\left(-\frac{1}{2}\mu\frac{d\ln P^{fl}}{dE^{fl}}\right)_N-\left(-\frac{1}{2}\mu\frac{d\ln P}{dE}\right)_N \\ &=\frac{\beta\mu}{4E_N}\left(\frac{1+\tau^{1-\sigma}}{1-\tau^{1-\sigma}}\Psi-\frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}}\Phi\right) \\ &=\frac{\beta\mu\tau^{1-\sigma}(1-\tau^{1-\sigma})(1+\tau^{1-\sigma})}{E_N[4\tau^{1-\sigma}\beta(\sigma-1)+(1-\tau^{1-\sigma})^2][4\tau^{1-\sigma}\beta(\sigma-1)+(1+\tau^{1-\sigma})^2]} \\ &>0. \end{aligned} \quad (67)$$

$\left(\frac{dt^{fl}E^{fl}}{dE^{fl}}\right)_N>\left(\frac{dtE}{dE}\right)_N$  holds because  $\Psi<\Phi$  holds. Total marginal benefits increase because

$$\begin{aligned} &\left(-\frac{1}{2}\mu\frac{d\ln P^{fl}}{dE^{fl}}\right)_N+\left(\frac{1}{2}\frac{dr^{fl}}{dE^{fl}}\right)_N+\left(\frac{dt^{fl}E^{fl}}{dE^{fl}}\right)_N-\left(-\frac{1}{2}\mu\frac{d\ln P}{dE}\right)_N-\left(\frac{1}{2}\frac{dr}{dE}\right)_N-\left(\frac{dtE}{dE}\right)_N \\ &=\frac{\beta\mu\tau^{1-\sigma}(1-\tau^{1-\sigma})[1+(2\sigma-1)\tau^{1-\sigma}]}{\sigma E_N[4\tau^{1-\sigma}\beta(\sigma-1)+(1-\tau^{1-\sigma})^2][4\tau^{1-\sigma}\beta(\sigma-1)+(1+\tau^{1-\sigma})^2]} \\ &>0. \end{aligned} \quad (68)$$

Allowing footloose capital increases each country's and global emissions because

$$\begin{aligned} &E_N^{fl}-E_N \\ &=\frac{\beta\mu}{2\delta}\left[\left(\frac{2\tau^{1-\sigma}}{1-\tau^{1-\sigma}}+\frac{1}{\sigma}\right)\Psi+\left(\frac{2\tau^{1-\sigma}}{1+\tau^{1-\sigma}}+\frac{1-\beta}{\sigma\beta}\right)\Phi-\frac{1}{\sigma\beta}\right] \\ &=\frac{2\beta\mu\tau^{1-\sigma}(1-\tau^{1-\sigma})[1+(2\sigma-1)\tau^{1-\sigma}]}{\delta\sigma[4\tau^{1-\sigma}\beta(\sigma-1)+(1-\tau^{1-\sigma})^2][4\tau^{1-\sigma}\beta(\sigma-1)+(1+\tau^{1-\sigma})^2]} \\ &>0. \end{aligned} \quad (69)$$

## Appendix D. Asymmetric countries

*Proof of Proposition 3 under the random distribution of capital and labor*

In this part, we analyze and compare how allowing footloose capital affects the non-cooperative choices of emission permits under international emissions trading. To understand our results in a more general case, we assume that capital and labor are distributed across countries randomly rather than equally. However, global levels of capital and labor are still fixed. For simplicity, we assume that firms always disperse across countries under footloose capital. That is,  $0 < \bar{n} < 1$  always holds.

Because the total production of each firm is related to both market clearing conditions of emission permits and capital, we derive it here:

$$\tilde{X} = L\tilde{x}^{HH} + L^*\tau\tilde{x}^{HF} = \frac{\mu(\sigma-1)}{\sigma\phi} \left( \frac{L}{\bar{n} + \bar{n}^*\tau^{1-\sigma}} + \frac{L^*\tau^{1-\sigma}}{\bar{n}^* + \bar{n}\tau^{1-\sigma}} \right) \tilde{t}^{-\beta}; \quad (70)$$

$$\tilde{X}^* = L^*\tilde{x}^{FF} + L\tau\tilde{x}^{FH} = \frac{\mu(\sigma-1)}{\sigma\phi} \left( \frac{L^*}{\bar{n}^* + \bar{n}\tau^{1-\sigma}} + \frac{L\tau^{1-\sigma}}{\bar{n} + \bar{n}^*\tau^{1-\sigma}} \right) \tilde{t}^{-\beta}. \quad (71)$$

Substituting the total production of each firm in Home and Foreign into the market clearing condition of emission permits under international emissions trading in Eq. (10), we have

$$\tilde{t} = \frac{\beta\mu(\sigma-1)}{\sigma} \frac{L + L^*}{\tilde{E} + \tilde{E}^*}. \quad (72)$$

This result holds regardless of capital mobility.

Capital rents in Home and Foreign are respectively given by

$$\tilde{r} = \frac{1}{\sigma-1} \phi \tilde{t}^\beta \tilde{X} = \frac{\mu}{\sigma} \left( \frac{L}{\bar{n} + \bar{n}^*\tau^{1-\sigma}} + \frac{L^*\tau^{1-\sigma}}{\bar{n}^* + \bar{n}\tau^{1-\sigma}} \right); \quad (73)$$

$$\tilde{r}^* = \frac{1}{\sigma-1} \phi \tilde{t}^\beta \tilde{X}^* = \frac{\mu}{\sigma} \left( \frac{L^*}{\bar{n}^* + \bar{n}\tau^{1-\sigma}} + \frac{L\tau^{1-\sigma}}{\bar{n} + \bar{n}^*\tau^{1-\sigma}} \right). \quad (74)$$

If capital is immobile internationally, then  $\bar{n} = K$  and  $\bar{n}^* = K^*$ . Allowing footloose capital may change the mass of firms in each country. However, since firm relocation is only motivated by different factor endowment in the two countries, the mass of firms is irrelevant to the permit price, i.e.,  $\bar{n} = \frac{L-L^*\tau^{1-\sigma}}{1-\tau^{1-\sigma}} \frac{K+K^*}{L+L^*}$ . Therefore, capital rents are constant under both immobile and footloose capital. Countries' choices of emission permits are not driven by capital rents.

In contrast to Eq. (12), Home's welfare is now given by

$$\tilde{W} = -L\mu \ln \tilde{P} + \tilde{t}\tilde{E} + K\tilde{r} - L\delta(\tilde{E} + \tilde{E}^*) + (L\mu \ln \mu + L - L\mu). \quad (75)$$

To understand how consumer surplus is affected by capital mobility, we first derive the natural logarithm of the aggregate price index in Home:

$$\ln \tilde{P} = \ln \frac{\sigma\phi}{\sigma-1} (\bar{n} + \bar{n}^*\tau^{1-\sigma})^{\frac{1}{1-\sigma}} + \beta \ln \tilde{t}. \quad (76)$$

Although the first term is affected by capital mobility, it is irrelevant to the permit prices in both cases. Therefore, countries' choices of emission permits only affect consumer surplus through the second term. Specifically,

$$-L\mu \frac{d \ln \tilde{P}}{d \tilde{E}} = -\frac{L\beta\mu}{\tilde{t}} \frac{d \tilde{t}}{d \tilde{E}}. \quad (77)$$

The first-order conditions of Home and Foreign welfare with respect to their choices of emission permits are respectively given by

$$\text{F.O.C for Home: } \frac{L\beta\mu}{\tilde{E} + \tilde{E}^*} + \frac{\beta\mu(\sigma-1)}{\sigma} \frac{L + L^*}{\tilde{E} + \tilde{E}^*} - \tilde{E} \frac{\beta\mu(\sigma-1)}{\sigma} \frac{L + L^*}{(\tilde{E} + \tilde{E}^*)^2} = L\delta; \quad (78)$$

$$\text{F.O.C for Foreign: } \frac{L^*\beta\mu}{\tilde{E} + \tilde{E}^*} + \frac{\beta\mu(\sigma-1)}{\sigma} \frac{L + L^*}{\tilde{E} + \tilde{E}^*} - \tilde{E}^* \frac{\beta\mu(\sigma-1)}{\sigma} \frac{L + L^*}{(\tilde{E} + \tilde{E}^*)^2} = L^*\delta. \quad (79)$$

Summing up the two equations, we have  $\tilde{E} + \tilde{E}^* = \frac{\beta\mu}{\delta} \left( 1 + \frac{\sigma-1}{\sigma} \right)$ , which is the same as that in the main part with symmetric countries. Substituting it into the F.O.Cs for Home and Foreign yields

$$\tilde{E}_N = \frac{\beta\mu}{\delta} \left( 1 + \frac{\sigma-1}{\sigma} \right) \frac{L^*}{L + L^*}; \quad \tilde{E}_N^* = \frac{\beta\mu}{\delta} \left( 1 + \frac{\sigma-1}{\sigma} \right) \frac{L}{L + L^*}. \quad (80)$$

The above analysis holds regardless of capital mobility. Therefore, allowing footloose capital does not affect countries' choices of emission permits under international emissions trading. Since the global level of labor is assumed to be fixed, and each country's choice of emission permits is negatively related to its labor level (or market size), we conclude that the larger country issues fewer emission permits than the smaller country does at the equilibrium.

### Different evaluations of environmental damage

Even if countries have different evaluations of environmental damage from emissions, the mass of firms are still constant under both immobile and footloose capital. Denote the marginal environmental damage in Foreign as  $\delta^*$ . Then, in contrast to Eq. (79), the first-order condition of Foreign welfare with respect to its choice of emission permits is now given by

$$\text{F.O.C for Foreign: } \frac{L^* \beta \mu}{\tilde{E} + \tilde{E}^*} + \frac{\beta \mu (\sigma - 1)}{\sigma} \frac{L + L^*}{\tilde{E} + \tilde{E}^*} - \tilde{E}^* \frac{\beta \mu (\sigma - 1)}{\sigma} \frac{L + L^*}{(\tilde{E} + \tilde{E}^*)^2} = L^* \delta^*. \quad (81)$$

Similarly, we can derive the equilibrium emission permits:

$$\tilde{E}_N = \frac{\beta \mu}{(L\delta + L^* \delta^*)^2} \frac{2\sigma - 1}{\sigma - 1} \left[ LL^* (\delta^* - \delta) + \frac{\sigma - 1}{\sigma} (L + L^*) L^* \delta^* \right]; \quad (82)$$

$$\tilde{E}_N^* = \frac{\beta \mu}{(L\delta + L^* \delta^*)^2} \frac{2\sigma - 1}{\sigma - 1} \left[ LL^* (\delta - \delta^*) + \frac{\sigma - 1}{\sigma} (L + L^*) L \delta \right]. \quad (83)$$

Again, the above analysis holds regardless of capital mobility. Therefore, allowing footloose capital does not affect countries' choices of emission permits under international emissions trading, even if countries are different in their factor endowments and evaluations of environmental damage. Proposition 3 holds.

Although we could not derive analytical results about other propositions, it is likely that allowing international emissions trading still decreases each country's and global emissions because it could still eliminate the effects of emission permits on capital rents under immobile capital and the PHE under footloose capital. Under domestic emissions trading, it is expected that allowing footloose capital still increases each country's and global emissions because of the PHE. However, since countries are asymmetric in their evaluations of environmental damage, the country with a larger environmental damage coefficient should have a smaller incentive to attract firms than the country with a smaller environmental damage coefficient. Consequently, emissions may increase more in the country with a smaller damage coefficient.

### Appendix E. Welfare ranking

At the equilibrium, we have

$$\ln P_N = \frac{1}{1 - \sigma} \ln \frac{1}{2} (1 + \tau^{1 - \sigma}) + \ln \left( \frac{\sigma \phi}{\sigma - 1} \right) + \beta \ln \frac{\beta \mu (\sigma - 1)}{2\sigma} - \beta \ln E_N; \quad (84)$$

$$\frac{1}{2} r_N + t_N E_N = \frac{\mu [\beta (\sigma - 1) + 1]}{2\sigma}. \quad (85)$$

Taking these results into Eq. (12) and suppressing the same constant terms in the four cases, we can express welfare at the equilibrium as Eq. (39).

### Appendix F. Capital taxation

We have discussed capital taxation under immobile capital in Section 5.4. In this appendix, we focus on the case of footloose capital. Specifically, we first study how countries non-cooperatively decide on their capital tax rates and emission permits simultaneously and then investigate how adding capital tax competition to emission permit competition affects our results in the main part.

We first investigate the case of international emissions trading. The equilibrium condition of firm locations now becomes<sup>27</sup>

$$(1 - \rho)r = (1 - \rho^*)r^*; \quad (86)$$

$$\Rightarrow \frac{1 - \rho}{n + n^* \tau^{1 - \sigma}} + \frac{(1 - \rho)\tau^{1 - \sigma}}{n^* + n\tau^{1 - \sigma}} = \frac{(1 - \rho^*)\tau^{1 - \sigma}}{n + n^* \tau^{1 - \sigma}} + \frac{1 - \rho^*}{n^* + n\tau^{1 - \sigma}}. \quad (87)$$

The effect of capital tax on firm locations is

$$\frac{dn}{d\rho} = -\frac{1}{1 - \rho^*} \frac{(1 + \tau^{1 - \sigma})^2}{(\frac{1 - \rho}{1 - \rho^*} + 1)^2 (1 - \tau^{1 - \sigma})^2} < 0; \quad \frac{dn^*}{d\rho} = -\frac{dn}{d\rho} > 0. \quad (88)$$

As a country's capital tax rate increases, firms relocate from this country to the other country. The permit price is still  $t = \frac{\beta \mu (\sigma - 1)}{\sigma (E + E^*)}$ , which is irrelevant to capital tax rates. Therefore, capital tax rates only affect firm locations but do not affect permit prices; by contrast, the choices of emission permits only affect permit prices but do not affect firm locations.

In contrast to Eq. (12), Home's welfare is now given by

$$W = -\frac{1}{2} \mu \ln P + tE + \frac{1}{2} (1 - \rho)r + n\rho r - \frac{1}{2} \delta (E + E^*) + \left( \frac{1}{2} \mu \ln \mu + \frac{1}{2} - \frac{1}{2} \mu \right). \quad (89)$$

<sup>27</sup> The superscripts of “ $f$ ” and the tildes in the notations are suppressed for conciseness in this section.

$\frac{1}{2}(1-\rho)r$  is the total after-tax capital rents and  $n\rho r$  is the capital tax revenue. At the symmetric equilibrium, countries choose the same capital tax rates and emission permits, i.e.,  $\rho_N = \rho_N^*$ ,  $E_N = E_N^*$ . Similar to the main part, we investigate the marginal benefits of consumer surplus, permit revenues, after-tax capital rents and capital tax revenues at the equilibrium:

$$\left(-\frac{1}{2}\mu \frac{d \ln P}{d\rho}\right)_N = \frac{\mu}{\sigma-1} \frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}} \left(\frac{dn}{d\rho}\right)_N; \quad (90)$$

$$\left(\frac{dE}{d\rho}\right)_N = 0; \quad (91)$$

$$\left(\frac{1}{2} \frac{d(1-\rho)r}{d\rho}\right)_N = -\frac{\mu}{2\sigma} - \frac{\mu(1-\rho)}{\sigma} \frac{(1-\tau^{1-\sigma})^2}{(1+\tau^{1-\sigma})^2} \left(\frac{dn}{d\rho}\right)_N; \quad (92)$$

$$\left(\frac{dn\rho r}{d\rho}\right)_N = \frac{\mu}{2\sigma} + \frac{\mu\rho}{\sigma} \frac{4\tau^{1-\sigma}}{(1+\tau^{1-\sigma})^2} \left(\frac{dn}{d\rho}\right)_N. \quad (93)$$

Therefore, taking derivative of Home's welfare with respect to its capital tax rate gives

$$\begin{aligned} \left(\frac{dW}{d\rho}\right)_N &= \left(-\frac{1}{2}\mu \frac{d \ln P}{d\rho}\right)_N + \left(\frac{dE}{d\rho}\right)_N + \left(\frac{1}{2} \frac{d(1-\rho)r}{d\rho}\right)_N + \left(\frac{dn\rho r}{d\rho}\right)_N \\ &= \left[\frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}} \left(\frac{\sigma}{\sigma-1} - \frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}}\right) + \rho_N\right] \frac{\mu}{\sigma} \left(\frac{dn}{d\rho}\right)_N, \end{aligned} \quad (94)$$

which yields

$$\rho_N = \rho_N^* = -\frac{(1-\tau^{1-\sigma})^2}{(1+\tau^{1-\sigma})^2} \left(\frac{\sigma}{\sigma-1} \frac{1+\tau^{1-\sigma}}{1-\tau^{1-\sigma}} - 1\right). \quad (95)$$

Each country has an incentive to lower its capital tax rate to attract more firms. Eventually, countries subsidize capital at the equilibrium.

Taking derivative of Home's welfare with respect to its emission permits gives

$$\left(\frac{dW}{dE}\right)_N = \left(-\frac{1}{2}\mu \frac{d \ln P}{dE}\right)_N + \left(\frac{dE}{dE}\right)_N + \left(\frac{1}{2} \frac{d(1-\rho)r}{dE}\right)_N + \left(\frac{dn\rho r}{dE}\right)_N - \frac{1}{2}\delta. \quad (96)$$

Note that emission permits do not affect firm locations. The first and second terms are the same as Eqs. (23) and (24). The sum of the third and fourth terms is

$$\left(\frac{1}{2} \frac{d(1-\rho)r}{dE}\right)_N + \left(\frac{dn\rho r}{dE}\right)_N = \left(\frac{1}{2} \frac{dr}{dE}\right)_N = 0. \quad (97)$$

Therefore, countries' choices of emission permits are the same as that in Section 4.2.

We now turn to the case of domestic emissions trading. The equilibrium condition of firm locations is given by

$$\begin{aligned} (1-\rho)r &= (1-\rho^*)r^*; \\ \Rightarrow \frac{1-\rho}{n+n^*\tau^{1-\sigma}T} + \frac{(1-\rho)\tau^{1-\sigma}}{n^*T+n\tau^{1-\sigma}} &= \frac{(1-\rho^*)\tau^{1-\sigma}T}{n+n^*\tau^{1-\sigma}T} + \frac{(1-\rho^*)T}{n^*T+n\tau^{1-\sigma}}. \end{aligned} \quad (98)$$

Together with  $r = \frac{tE}{\beta(\sigma-1)n}$ ,  $r^* = \frac{t^*E^*}{\beta(\sigma-1)n^*}$ , we have  $\frac{r^*}{r} = \frac{n^*}{n} \frac{1-\rho}{1-\rho^*} \frac{E}{E^*}$ , which is used to eliminate  $T$  in the above equation. Similar to the analysis in the main part, we take total derivatives of both sides of Eq. (98) and obtain the relationship between  $\frac{n^*}{n}$  and  $\frac{1-\rho}{1-\rho^*}$ . At the symmetric equilibrium where  $\rho_N = \rho_N^*$  and  $E_N = E_N^*$ , this relationship is

$$\left(\frac{dn^*/n}{d(1-\rho)/(1-\rho^*)}\right)_N = -\frac{4\tau^{1-\sigma}\beta(\sigma-1)+(1+\tau^{1-\sigma})^2}{4\tau^{1-\sigma}\beta(\sigma-1)+(1-\tau^{1-\sigma})^2}. \quad (99)$$

With this equation, we can investigate how a country's capital tax affects firm locations and permit prices:

$$\left(\frac{dn}{d\rho}\right)_N = \frac{1}{4(1-\rho_N^*)} \left(\frac{dn^*/n}{d(1-\rho)/(1-\rho^*)}\right)_N < 0; \quad (100)$$

$$\left(\frac{dn^*}{d\rho}\right)_N = -\left(\frac{dn}{d\rho}\right)_N > 0; \quad (101)$$

$$\left(\frac{dt}{d\rho}\right)_N = \frac{t_N}{2(1-\rho_N^*)} \left[\left(\frac{dn^*/n}{d(1-\rho)/(1-\rho^*)}\right)_N + 1\right] < 0; \quad (102)$$

$$\left(\frac{dt^*}{d\rho}\right)_N = -\left(\frac{dt}{d\rho}\right)_N > 0. \quad (103)$$

Under domestic emissions trading, capital taxation affects not only firm locations but also permit prices, which is different from the case of international emissions trading. For instance, a higher capital tax rate in Home induces firms to relocate from Home to Foreign. This leads to less demand for emission permits in Home and more demand for emission permits in Foreign. As a result, permit price decreases in Home and increases in Foreign.

We investigate the marginal benefits of consumer surplus, permit revenues, after-tax capital rents and capital tax revenues at the equilibrium:

$$\left(-\frac{1}{2}\mu \frac{d \ln P}{d \rho}\right)_N = \frac{\mu}{\sigma-1} \frac{1-\tau^{1-\sigma}}{1+\tau^{1-\sigma}} \left[\left(\frac{dn}{d \rho}\right)_N - \frac{\beta(\sigma-1)}{2t_N} \left(\frac{dt}{d \rho}\right)_N\right]; \quad (104)$$

$$\left(\frac{dE}{d \rho}\right)_N = E_N \left(\frac{dt}{d \rho}\right)_N; \quad (105)$$

$$\left(\frac{1}{2} \frac{d(1-\rho)r}{d \rho}\right)_N = -\frac{\mu}{2\sigma} - \frac{\mu(1-\rho_N)}{\sigma} \left[\left(\frac{dn}{d \rho}\right)_N - \frac{1}{2t_N} \left(\frac{dt}{d \rho}\right)_N\right]; \quad (106)$$

$$\left(\frac{dnpr}{d \rho}\right)_N = \frac{\mu}{2\sigma} + \frac{\mu\rho_N}{2\sigma t_N} \left(\frac{dt}{d \rho}\right)_N. \quad (107)$$

Therefore, taking derivative of Home's welfare with respect to its capital tax rate gives

$$\begin{aligned} \left(\frac{dW}{d \rho}\right)_N &= \left(-\frac{1}{2}\mu \frac{d \ln P}{d \rho}\right)_N + \left(\frac{dE}{d \rho}\right)_N + \left(\frac{1}{2} \frac{d(1-\rho)r}{d \rho}\right)_N + \left(\frac{dnpr}{d \rho}\right)_N \\ &= -\frac{\mu}{4\sigma(1-\rho_N^*)} \frac{(1-\tau^{1-\sigma})^2}{4\tau^{1-\sigma}\beta(\sigma-1) + (1-\tau^{1-\sigma})^2} \left(\frac{\sigma}{\sigma-1} \frac{1+\tau^{1-\sigma}}{1-\tau^{1-\sigma}} - 1\right) + \frac{\mu\rho_N}{\sigma} \left(\frac{dn}{d \rho}\right)_N, \end{aligned} \quad (108)$$

which yields

$$\rho_N = \rho_N^* = -\frac{(1-\tau^{1-\sigma})^2}{4\tau^{1-\sigma}\beta(\sigma-1) + (1-\tau^{1-\sigma})^2} \left(\frac{\sigma}{\sigma-1} \frac{1+\tau^{1-\sigma}}{1-\tau^{1-\sigma}} - 1\right). \quad (109)$$

Each country has an incentive to lower its capital tax rate to attract more firms. Eventually, countries subsidize capital at the equilibrium. The subsidy rate under domestic emissions trading is smaller than that under international emissions trading.

The effect of Home's choices of emission permits on its welfare is still given by

$$\left(\frac{dW}{dE}\right)_N = \left(-\frac{1}{2}\mu \frac{d \ln P}{dE}\right)_N + \left(\frac{dE}{dE}\right)_N + \left(\frac{1}{2} \frac{d(1-\rho)r}{dE}\right)_N + \left(\frac{dnpr}{dE}\right)_N - \frac{1}{2}\delta. \quad (110)$$

At the symmetric equilibrium,  $\frac{1-\rho_N}{1-\rho_N^*} = 1$  holds. Therefore, the effects of emission permits on firm locations and permit prices at the equilibrium are the same as that in Eqs. (30) and (31). Then, the marginal benefits of consumer surplus and permit revenues, described by the first and second terms in the above equation, are also the same as that in Section 4.1. However, the difference lies in the sum of the third and fourth terms:

$$\left(\frac{1}{2} \frac{d(1-\rho)r}{dE}\right)_N + \left(\frac{dnpr}{dE}\right)_N = \left(\frac{1}{2} \frac{dr}{dE}\right)_N + \frac{\mu\rho_N}{\sigma} \left(\frac{dn}{dE}\right)_N = \frac{\mu\rho_N}{\sigma} \left(\frac{dn}{dE}\right)_N < 0, \quad (111)$$

which implies that subsidizing capital discourages countries to issue more permits to attract more firms. This effect does not exist under international emissions trading, as shown in Eq. (97), because the choices of emission permits do not affect firm locations in that case. The equilibrium level of emission permits is obtained as

$$\hat{E}_N = \hat{E}_N^* = E_N^{fl} + \frac{\mu(1-\Psi)}{2\delta\sigma} \rho_N < E_N^{fl}. \quad (112)$$

Recall that  $E_N^{fl}$  is the equilibrium level of emission permits in Section 4.1. In Section 5.4, we have shown that capital taxation does not affect countries' choices of emission permits under domestic emissions trading and immobile capital. We then compare  $\hat{E}_N$  with the permit level in Eq. (20) and find that they are the same. That is, under capital tax competition and emission permit competition, allowing footloose capital does not affect each country's and global emissions. Intuitively, allowing footloose capital encourages countries to subsidize capital, which in turn eliminates all the marginal benefits of consumer surplus and permit revenues in Section 4.1.

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