Free Trade Agreements with Environmental Provisions Between Asymmetric Countries: Transfer of Clean Technology and Enforcement

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Abstract

This paper investigates the effects of a free trade agreement (FTA) with environmental provisions between northern and southern countries. We explicitly consider clean technology transfers from the North to the South and the enforcement levels of adopting clean technology in the South, which have not been discussed so far. Southern producers benefit greatly from having unimpeded access to a northern market, but they are reluctant to use new high-cost, clean technology provided by the North. We investigate how environmentally conscious northern countries could design an FTA in which southern countries are provided with sufficient membership benefits but follow tighter enforcement requirements. We provide a quantitative evaluation of FTA policies using a numerical example.

Keywords: Free trade agreements; Deep integration; Technology transfer; Monetary transfer; Environmental provisions; Enforcement

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1 Introduction

Free trade agreements (FTAs) have been negotiated not only for reducing trade barriers, but also for coping with non-trade issues such as environmental standards, labor standards, and intellectual property rights (Limão 2007). Maggi and Ossa (2020) reported that all the agreements signed by the US since the North American Free Trade Agreement (NAFTA) in 1994 contain provisions on environmental and labor standards.[1] Additionally, there is an increasing number of FTAs between developed and developing countries. According to the World Trade Organization Database (WTO 2021), as of June 15, 2021, 349 trade agreements are in effect, and around 10% of these agreements are between developed countries, while close to 30% are between developed and developing countries (Behar and Cirera-i-Crivillé 2013). Brandi et al. (2020) report that environmental provisions in FTAs between asymmetric countries are now more prevalent. Nevertheless, very few studies have investigated the impacts of such agreements. The purpose of this paper is to provide a theoretical framework to investigate how FTAs between developed and developing countries have an impact on the environment.

Forming an FTA expands the pie for its member countries—for developing countries, access to markets in developed countries is a lucrative reward. Thus, it makes sense to utilize an FTA with environmental provisions as an alternative framework to address transboundary environmental problems. By participating in the North American Free Trade Agreement (NAFTA), Mexico gained access to the US and Canadian markets, and simultaneously, they also ratified the North American Agreement on Environmental Cooperation (NAAEC) and the North American Agreement on Labor Cooperation (NAALC) as side treaties of NAFTA.

In FTAs between developed and developing countries with environmental provisions, there is a technology gap between countries; thus, the transfer of clean technologies from developed to developing countries is essential for developing countries to satisfy environmental provisions. However, the existence of clean technologies might not be sufficient for developing

[1] See for example https://ustr.gov/issue-areas/environment/bilateral-and-regional-trade-agreements

countries to employ them because these technologies tend to be too costly to be implemented for developing countries despite the recent dramatic improvements in the cost-effectiveness of clean technologies. The Technology and Innovation Report 2021 at the United Nations Conference on Trade and Development reported several challenges of adapting new technologies by developing countries: digital divides, inadequate infrastructure, and skill shortages make using new clean technologies more expensive than dirty technologies.[2] Even if developed countries successfully transfer clean technologies to developing countries, it does not necessarily follow that developing countries would employ them. Firms in a developing country may still employ low-cost dirty technologies if the government's enforcement level of its environmental policies is low. In such a case, developed countries must also help southern governments monitor and enforce the environmental policies.[3]

In this paper, we develop a new theoretical model for a free trade agreement (FTA) with environmental provisions between developed (northern) and developing (southern) countries, taking the issues listed above. Unlike most existing papers that deal with stable multinational environmental agreements (MEAs) among symmetric countries, we assume that there is one northern country and multiple southern countries and that the northern country can sign an FTA with any number of southern countries. We consider high-marginal-cost clean and cheap dirty technologies that produce manufacturing goods to be traded; the northern country has clean technology, and the southern countries have only dirty technology without free trade agreements with the northern country. If a southern country establishes an FTA with the northern country, the clean technology becomes available. However, without being sufficiently

[2] See pages 77-90 https://unctad.org/system/files/official-document/tir2020_en.pdf

[3] **There are some examples of FTA addressing financial assistance to enhance the ability of member states to enforce environmental regulations. For instance, according to EU (2014), because the governmental effectiveness of new EU member states such as Estonia, Latvia, and Lithuania ranks below the average of existing members, the European Commission began to support a capacity building program for improving environmental enforcement (WB 2007). In the case of NAFTA, the US had several programs to support Mexico in ensuring compliance with environmental laws and increasing enforcement capacity along their borders (EPA 1991). The FTA between EU and Chile, signed in 2001, specifies the forms of technical and financial assistance (OECD 2007). We explicitly introduce a subsidy to encourage member states to implement cleaner technology as a way of supporting schemes.**

enforced, the southern firms have an incentive to use the cheaper dirty technology as a result of their optimization. Thus, southern countries may not want to participate in an FTA with the northern country if its environmental provision requires a strict enforcement of clean technology unless access to the northern market is sufficiently lucrative or participating in the FTA comes with monetary support from the northern country.

We first show that for any given level of enforcement and monetary support, there is a stable free trade agreement for southern countries, in the sense that (i) no southern insider wants to quit the FTA unilaterally, and (ii) no southern outsider wants to participate in the FTA unilaterally (Proposition 1). This stability notion was first introduced by d'Aspremont et al. (1983) to analyze cartels and is widely used by environmental economists (see Barrett 1994). Note that Proposition 1 assures neither that the stable FTA is nontrivial (at least one southern country participates in the FTA), nor that the northern country wants to have an FTA. This is because Proposition 1 is for any arbitrary combination of enforcement and monetary support policies. Thus, we try to characterize the optimal FTA policy for the northern country, then find the conditions for a nontrivial optimal FTA.

Unfortunately, it is generally difficult to characterize the optimal FTA for the northern country, so we specify functional forms. Using linear demand functions, we first characterize the optimal policies for each number of southern countries in the FTA and find that the enforcement level of the clean technology use (the fraction of production that uses the clean technology) goes down as the size of the FTA increases. Second, we characterize the optimal number of southern countries in the FTA by maximizing the northern country's payoff (Proposition 2). Proposition 3 provides sufficient conditions for the optimal FTA being nontrivial. This implies that the northern country has an incentive to form an FTA with environmental provisions with southern countries when (a) the clean technology is significantly superior to the dirty technology for reducing emissions, and (b) the northern country values reductions in emissions sufficiently.

With Proposition 2, we can easily see that there is a trade-off between having more southern countries in the FTA and the level of enforcement. If the number of southern countries in the FTA is small, these countries receive great benefits from being included in the FTA (i.e., by having exclusive accesses to a lucrative northern market), and thus they are willing to enforce the high-cost clean technology while demanding fewer transfers. Including more southern countries in the FTA, the enforcement level will decrease, and they may demand more transfers. Additionally, with more southern members, the northern country's consumer surplus increases while its domestic firm's profit and its tariff revenue decrease. Analyzing the optimal size of an FTA requires more specifications. Moreover, we do not know how the total level of emissions would be affected by an increase in the number of southern countries in the FTA, because the enforcement level for the FTA members decreases while the number of southern countries increases. Additionally, as the southern membership increases, the total transfers become increasingly costly for the northern country. As all of these factors are important and it is difficult to obtain qualitative results, we will present an example with reasonable parameter values and observe the optimal FTA policy for the northern country and its environmental implications.

With a numerical example, we confirm that these considerations play important roles in evaluating FTA policies. **Setting the tariff rate at the optimal level (without environmental considerations), we first demonstrate that for the northern country transfer of clean technology to a southern country without an FTA is dominated by coupling clean technology transfer with an FTA. This is because in order for a southern country to agree to use the costly clean technology the northern country must transfer sufficient money to the southern country. In contrast, if technology transfer comes with an FTA, the southern country can penetrate the tariff-protected northern market, and it would be willing to enforce clean technology despite its high cost. Then, we show that limiting southern memberships of an FTA with an environmental provision** is desirable for northern countries, but this results in sizable inequality between the FTA members and nonmembers among southern countries. Comparative static analyses of the numerical example demonstrate that if the number of member countries is kept constant, an increase in emissions from southern countries (as their dirty technology worsens) raises the aggregate emissions. However, this also shows that once the number of member countries is endogenized, its overall effect on the aggregate emissions can be negative, due to the subsequent increase in the number of southern participants that adopt clean technologies.

The rest of the paper is organized as follows. The following subsection provides a brief literature review. Section 2 presents the model and preliminary analysis, and Section 3 analyzes stable FTAs in the general model. Section 4 further analyzes the optimal stable FTAs using linear demand, and Section 5 is devoted to a numerical analysis. Section 6 concludes.

1.1 A Brief Literature Review

In this subsection, we first review four important issues related to our study: FTA formation between developed and developing countries, FTAs with environmental provisions between northern and southern countries, clean technology transfers, and their enforcement. Then, we also review several industrial organization papers that are directly related to our modeling strategy.

Until the beginning of the 21st century, FTAs were signed mostly between developed or developing countries and very few between developed and developing countries. In order to explain this fact, Das and Ghosh (2006) considered a world economy consisting of asymmetric countries, specifically, a world economy with two developed countries in the north and two developing countries in the south, and analyzed what kind of FTAs would be formed. Using a stylized Cournot oligopoly model, they showed that high-income northern countries are more willing to form an FTA between themselves. In contrast, a low-income southern country will want to be a partner with a high-income northern country,

but since the northern country will gain little benefits, the southern countries are likely to form an FTA between them as leftovers.[4] Thus, in such North-South type models, it has been theoretically shown that an FTA is more likely to be formed between the two northern or the two southern countries, and less likely to be formed between a northern and a southern countries.[5]

In reality, as noted in the introduction, North-South FTAs have increased in recent years. This fact, as Limão (2007) pointed out, seems to illustrate the importance of considering factors other than gains from trade when analyzing North-South FTAs. This perception is now shared by many researchers and is widely discussed as a matter of "deep integration," which is an FTA with various non-tariff issues such as the environment, labor, technology standard, and intellectual property rights. For example, Maggi and Ossa (2020,2021) discussed the political economy of deep integration and suggested that the welfare analysis of such deep integrations would be very complicated. Our research interests are in line with the literature on deep integration, but we are specifically interested in the effects of clean technology transfer and imperfect enforcement under FTAs. The importance of technology upgrades induced by an FTA in developing countries was empirically investigated by Gutierréz and Teshima (2018). Pointing out that the adoption of superior clean technology can be associated with a reduction in abatement expenditure, they analyzed Mexican data on NAFTA and found that these two phenomena occur simultaneously in Mexico.

Many theoretical and empirical studies have investigated how FTAs affect the trade barriers of member countries to nonmember countries as external trade barriers. On the empirical

[4] Many papers investigated whether or not subsequent formations of FTAs and customs unions will lead to the global free trade (for example, Yi 1996, Goyal and Joshi 2006, Furusawa and Konishi 2007, and Daisaka and Furusawa 2014). However, these papers mostly assume that countries are ex ante homogenous by employing symmetric oligopoly models, and the results are mixed depending on the formulation of the game and the solution concepts.

[5] See also Missios and Yildiz (2017) and Wang and Zhao (2022) for related analysis using a four-country North-South type model.

front, several authors such as Martinez-Zarzoso and Oueslati (2018), and Brandi et al. (2020) analyzed the impact of FTAs with environmental provisions on member countries' emissions and showed that such FTAs contribute to reducing emissions. Brandi et al. (2020) demonstrated that only developing countries with stricter enforcement of environmental policies can green their exports in response to the environmental provisions in trade agreements. This study provides a theoretical mechanism for how FTAs with environmental provisions can reduce emissions based on these empirical findings.[6] Maggi (2014) provided a comprehensive survey on this issue (see Yamamoto 2021 for recent developments).

Regarding our modeling strategy, our model has a closer relationship with the literature on licensing and cartel formation in the field of industrial organization. Katz and Shapiro (1986) considered the optimal licensing strategies by allowing the technology firm to license the same technology to multiple competing licensees. Building on Katz and Shapiro (1986), Creane et al. (2014) allowed for heterogeneous licensees. In our model, the southern countries' incentive to form an FTA with the northern country comes from lucrative access to the northern market, and we adopt this licensing model as a part of our model of FTAs with environmental provisions. We also adopt the solution concept (stable cartels) from the literature on cartel formation. d'Aspremont et al. (1983) introduced a cartel formation game among homogenous firms, and Donsimoni et al. (1986) allowed for heterogeneous firms. Their solution concept, stable cartel, was used by Barrett (1994) to define self-enforcing international environmental agreements.[7] While our theoretical model is new in the literature on FTAs with environmental provisions, it is based on these two modeling devices in the literature of industrial organization.

[6] We will come back to these papers when we interpret the findings from our numerical analysis in Section 5.

[7] In the literature on international agreements on climate change and international pollution, many researchers have studies self-enforcing environmental agreements (SIEAs) between symmetric countries. See, for example, Barrett (1994), Carraro and Siniscalco (1993), Eichner and Pethig (2013a, 2013b, 2015), and Kuhn et al (2015). For some exceptional studies on international environmental agreements among asymmetric countries, see Barrett (2001) and Takashima (2018).

2 The Model

2.1 The basic structure of the model

In this model, there are one northern country and m southern countries, each of which has a representative consumer who consume a numeraire good and an industrial good. The industrial good is produced competitively. The consumer is endowed with the numeraire good, which is used for production of the industrial good with a constant marginal cost. We assume that the numeraire good is freely tradable.

The set of southern countries is denoted by $S = \{1, ..., m\}$. The northern country (denoted by 0) has an inverse demand function for an industrial good $P(\bar{Q})$, whereas the southern countries have identical inverse demand functions for the industrial good $p(q_j)$, where $\bar{Q}$ and q_j are aggregated quantities in the northern and southern country j's markets, respectively. We assume that P and p are twice continuously differentiable.

There are two technologies that produce industrial goods: clean and dirty. Although these two technologies produce the same goods, the clean technology emits less environmental pollutants in production.[8] Northern country 0 always employs clean technology C, whereas southern countries have only dirty technology D initially. **Northern country's marginal cost of production using clean technology is denoted by c_0, and each southern country's marginal costs of productions using technologies C and D are denoted by c_C and c_D, respectively. We naturally assume:**

(A1) $c_0 > c_C > c_D > 0$.

To produce one unit of an industrial good, clean technology costs more than dirty technology for southern countries. This assumption reflects the challenges southern countries face in employing new clean technologies.

[8] One of the simplest examples that illustrate this is electricity. It can be generated from coal, natural gas, solar panels, and wind mills, but environmental pollutants in production vary greatly.

The emissions from producing one unit with clean and dirty technologies are denoted by e_C and e_D, respectively. By definition, we assume:

(A2) $e_D > e_C \geq 0$.

The northern country applies a common tariff rate $\tau > 0$ on imports from southern countries. Unless southern country j has a free trade agreement with the northern country, the tariff rate τ applies. We fix τ throughout this study (τ is not a policy variable).

(A3) $\tau > 0$ is unaffected by the formation of an FTA.

This is because the WTO prohibits increasing tariffs when countries form an FTA and a customs union.[9] The northern and southern countries have a single (monopoly) firm each. Southern country j's export quantity to the northern country 0 is denoted by Q_j and country 0's domestic supply is denoted by Q_0. We do not consider indirect exports via a third country.[10] Thus, the total supply in country 0 is $\bar{Q} = \sum_{j \in S} Q_j + Q_0$. For simplicity, we assume that the southern countries do not import industrial goods.[11]

2.2 Free trade agreement, environmental provisions, and law enforcement

We consider FTAs with environmental provisions between northern country 0 and some of the southern countries. We denote FTA partners with northern country 0 by set $A \subseteq S =$

[9] One of the key principles of the WTO is nondiscrimination (Obviously, an FTA is itself discriminatory, but the GATT's Article 24 allows for FTAs and customs unions as long as they do not provide negative externalities to outsiders.). Increasing τ appears to discriminate outsiders from FTA members, even though it is motivated by a northern country's intention to encourage southern countries to join. See Furusawa and Konishi (2007).

[10] Although an FTA does allow to export via a third country that is a member of the FTA, it is necessary to certify the origin of the goods to apply the adequate tariff rate in the importing country. Thus, in our simple model, we do not need to consider indirect export.

[11] As our main concern lies in environmental pollution from technologies used in production in developing countries, production activities in developed countries using clean technologies are not of great importance. Therefore, we assume away imports of the southern countries from the northern country. A similar assumption is imposed by Limão (2007), where small (developing) countries derive no utility from non-numeraire (industrial) goods to narrow the focus of the analysis.

$\{1, ..., m\}$. Country 0 levies no tariff on the imports from countries $j \in A$, following the WTO's requirements for forming FTAs. With the environmental provisions accompanied with FTAs, we assume that countries $j \in A$ must accept a clean technology C transferred from country 0 and need to use technology C that requires a higher marginal cost than dirty technology D to produce the industrial good. However, as $\alpha_C > \alpha_D$, country j's firm is tempted to use technology D without an enforcement mechanism, so law enforcement of country j needs to randomly audit firms to check if the clean technology is being used. Suppose that country j faces the level of enforcement of technology C, $\xi \in [0, 1]$. Then, firm j produces a fraction ξ of its output with technology C and the rest $1 - \xi$ is produced with technology D to save money. Enforcing the use of technology C is costly for the government of country j as it requires strong infrastructure, such as an audit system, and well-disciplined police. Let $F_j(\xi)$ be country j's cost of establishing law enforcement that achieves enforcement level $\xi \in [0, 1]$. We assume that $F_j(\xi) = F + f_j(\xi)$ with $F \geq 0$, $f_j(0) = 0$, $f_j'(\cdot) > 0$, and $f_j''(\cdot) > 0$, and that southern countries can differ in their enforcement costs and can be ordered (country 1 is the most efficient in law enforcement).

(A4) Ordered Enforcement Cost: for $\xi \in [0, 1]$, $f_1(\xi) \leq f_2(\xi) \leq ... \leq f_m(\xi)$ and $f_1'(\xi) \leq f_2'(\xi) \leq ... \leq f_m'(\xi)$.

A special case of the above is that all southern countries have the same enforcement costs: $f(\xi) = f_j(\xi)$ for any $j = 1, ..., S$ and any $\xi \in [0, 1]$. Knowing the southern countries' enforcement costs, northern country 0 chooses southern FTA members and sets up an enforcement level standard $\xi \in [0, 1]$, offering them a sign-up subsidy $\sigma \geq 0$ for joining the FTAs.

2.3 Northern market

The industrial good market in northern country 0 is a Cournot oligopoly with an inverse demand function $P = P(\bar{Q})$. Firms in different countries have different effective marginal costs. Northern firm 0 has marginal cost c_0, firm $j \in A$ has

marginal cost $c_j = c_C$ or c_D, depending on the type of technology j uses. And firm $j \in S \backslash A$ has marginal cost $c_j = c_D + \tau$. When there are m southern countries that supply the product to country 0, and they have heterogeneous costs $(c_0, c_1..., c_m)$. Country j's best response is a solution of

$$\arg\max_{Q_j} P\left(Q_j + Q_{-j}\right) Q_j - c_j Q_j, \tag{1}$$

where $Q_{-j} = \sum_{i \neq j} Q_i$. Summing up the first order conditions over $j = 0, 1, ..., m$, we obtain

$$(m+1) P\left(\bar{Q}\right) - \sum_{i=0}^{m} c_i + P'\left(\bar{Q}\right) \bar{Q} = 0, \tag{2}$$

which determines equilibrium total output $\bar{Q}$. We assume:

(A5) Northern country's demand satisfies strategic substitute condition: $P'(\bar{Q}) + P''(\bar{Q}) Q_j \leq 0$ for all $\bar{Q}$ and $Q_j < \bar{Q}$.

With this condition, $\bar{Q}$ is uniquely determined (see, for example, Lemma 1 in Creane et al., 2014). Then, $\bar{Q}$ determines all other equilibrium allocations: for all $j = 0, ..., m$, firm j's supply to country 0 is

$$Q_j(\bar{Q}) = \frac{P(\bar{Q}) - c_j}{-P'(\bar{Q})}, \tag{3}$$

and firm j's equilibrium profit is written as

$$\Pi_j(\bar{Q}) = \frac{(P(\bar{Q}) - c_j)^2}{-P'(\bar{Q})}, \tag{4}$$

as long as $P(\bar{Q}) \geq c_j$ is satisfied (otherwise, $Q_j = 0$). The standard analysis of the Cournot market shows that $\bar{Q}$ is a decreasing function of $\sum_{i=0}^{m} c_i$, and firm j's profit, which is a decreasing function of $\bar{Q}$. Thus, keeping c_j constant, if $\sum_{i=0}^{m} c_i$ decreases, then Π_j goes down.

2.4 Southern markets

In contrast, we greatly simplify each southern country's market equilibrium. Let country j's domestic inverse demand function be $p(q_j)$. Firm j uses the dirty technology D:

$$\pi_j(q_j) = p(q_j)q_j - \bar{c}_j q_j. \tag{5}$$

If firm j uses dirty technology, firm j's monopoly output and profit with dirty technology D by q_D and $\pi_D = \frac{(p(q_D)-c_D)^2}{-p'(q_D)}$, where q_D is implicitly defined by $p(q_D) - c_D + p'(q_D)q_D = 0$. Similarly, with marginal cost c_C, southern countries' monopoly output and profit with clean technology C by q_C (defined in the same way as q_D) and $\pi_C = \frac{(p(q_C)-c_C)^2}{-p'(q_C)}$. As $c_D < c_C$, $q_C < q_D$ and $\pi_C < \pi_D$ hold.

If country j is a nonmember of an FTA ($j \in S \backslash A$), firm j uses surely technology D. If country j is a member of the FTA, we can have several different possible scenarios for the output of firm j as country j has a clean technology enforcement level ξ.

(A6) Southern FTA member j's industrial good production is capped with $Q_C + q_C$, and the average marginal cost under ξ is $\xi c_C + (1-\xi)c_D$.

This assumption that "j's industrial good production is capped with $Q_C + q_C$" is justified if the law enforcement enforces ξ and monitors firm j's output level.[12] **If firm j produces more than $Q_C + q_C$, law enforcement proves that firm j uses dirty technology D, since $c_C > c_D$.** Still, firm j has an incentive to use dirty technology D to produce $Q_C + q_C$ to earn the difference in the marginal costs. Based on enforcement level ξ, firm j produces $(1-\xi)q_C$ with dirty technology D, and the rest with clean technology C. This assumption implies that each country's equilibrium output level is solely determined by the number of southern countries participating in the FTA (independent of the enforcement level, ξ, and the sign-up subsidy for the FTA member, σ).

[12] Note that the northern country can also observe the monopolist's output level through the import amounts from country j. If southern country j exports more than Q_C, the northern country doubts that country j is enforcing the agreement.

Under this assumption, firm j earns exporting and domestic profits with the clean technology, and some additional profit with the dirty technology $(1-\xi)(c_C - c_D)(Q_C + q_C)$ due to limited enforcement.

2.5 Externalities from pollution

The total amount of pollutive emissions in the world is described as follows

$$E = e_C Q_0 + \sum_{j \in A} (\xi e_C + (1-\xi) e_D)(Q_j + q_j) + \sum_{j \in S \setminus A} e_D (Q_D + q_D), \tag{6}$$

where $\xi e_C + (1-\xi)e_D$ is the emission rate of country j for $j \in A$, and $Q \equiv (Q_0, ..., Q_m)$ and $q \equiv (q_1, ..., q_m)$ denote supply vectors in the northern and southern countries, respectively. Northern and southern countries receive negative externalities from pollutive emissions in an additive manner (global pollutive emissions) by $d_N E$ and $d_S E$, respectively. For simplicity, we assume that only the northern country cares about these negative externalities:

(A7) Marginal disutility from negative externalities E from pollutive emissions is $d_N > 0$ in northern country, where it is $d_S = 0$ in southern countries.

Even if $d_S > 0$, the qualitative results of this study will not be affected as long as $d_N > d_S$. However, positive d_S affects southern countries' incentives to join the FTA and significantly complicates the calculations.

3 Stable FTA

3.1 Global equilibrium allocation with FTA

Suppose that k southern countries are in the FTA ($|A| = k$). In northern country 0's market, the unique equilibrium allocation is described by $\bar{Q}(k)$ which is the solution of equation (2) for $c_0 = w_N \alpha_C$, $c_j = w_S \alpha_C$ for all $j \in A$, and $c_j = w_S \alpha_D + \tau$ for all $j \notin A$. The northern country's consumer surplus is described by $CS(k) = \int_0^{\bar{Q}(k)} \left(P(\tilde{Q}) - P(\bar{Q}(k)) \right) d\tilde{Q}$. Let $Q(k) \equiv (Q_0(k), Q_1(k), ..., Q_m(k))$ and $\Pi(k) \equiv (\Pi_0(k), \Pi_1(k), ..., \Pi_m(k))$ be such that $Q_j(k) \equiv Q_j(\bar{Q}(k))$ and $\Pi_j(k) \equiv \Pi_j(\bar{Q}(k))$ for the above $c = (c_0, c_1, ..., c_m)$. Countries' supply and profit vectors in the northern market are dependent on their technologies: $Q_j(k) = Q_C(k)$ and $\Pi_j(k) = \Pi_C(k)$ for $j \in A$, and $Q_j(k) = Q_D(k)$ and $\Pi_j(k) = \Pi_D(k)$ for $j \notin A$. The southern countries' domestic supply vector is simply determined as $q_j = q_C$ if $j \in A$, and $q_j = q_D$ otherwise.

The worldwide emission of pollutive substance under this free trade agreement is described by

$$\begin{aligned} E(k,\xi) &= e_C Q_0(k) + \sum_{j \in A} \left(\xi e_C + (1-\xi) e_D\right) \left(Q_j(k) + q_C\right) + \sum_{j \in S \setminus A} e_D (Q_j(k) + q_D) \\ &= e_C Q_0(k) + k \left(\xi e_C + (1-\xi) e_D\right) \left(Q_C(k) + q_C\right) + (m-k) e_D (Q_D(k) + q_D). \end{aligned} \tag{7}$$

The northern country sets a clean-technology enforcement level $\xi \in [0,1]$ and a sign-up subsidy $\sigma \geq 0$ for its FTA member (southern) countries, and the northern country agrees to form a free trade agreement with southern country j if country j is willing to adopt the clean technology by spending enforcement cost $F_j(\xi) \geq 0$ (open membership, or non-discrimination). The northern country's social welfare can be written as

$$SW(k,\xi,\sigma) = \overline{SW}(k) - k\sigma - d_N E(k,\xi), \tag{8}$$

where $\overline{SW}(k) = CS(k) + \Pi_0(k) + \tau\,(m-k)\,Q_D(k)$ is the northern country's gross social welfare—the sum of consumer surplus, producer surplus, and the tariff revenue.

Southern country j' consumer surplus is described by $cs_j = cs_D \equiv \int_0^{q_D} \left(p(q) - p(q_D)\right) dq$ if $j \notin A$, and $cs_j = cs_C \equiv \int_0^{q_C} \left(p(q) - p(q_C)\right) dq$ if $j \in A$. As we assume $d_S = 0$, the southern countries' gross social welfare excluding the enforcement cost and the sign-up subsidy for the

FTA can be written as

$$sw^{OUT}(k,\xi) \equiv cs_D(k) + \Pi_D(k) + \pi_D \tag{9}$$

if $j \notin A$, and

$$sw^{IN}(k,\xi) \equiv cs_C(k) + \Pi_C(k) + \pi_C + (1-\xi)(\alpha_C - \alpha_D)\, w_S\,(Q_C(k) + q_C) \tag{10}$$

if $j \in A$. When k southern countries participate in the FTA, they spend the enforcement cost and receive the sign-up subsidy, and thus their net social welfare is given by

$$sw^{IN}(k,\xi) - F - f_j(\xi) + \sigma. \tag{11}$$

3.2 Participation decision in an FTA

Here, we consider an FTA between northern country 0 and some southern countries and analyze the set of equilibrium participants in the free trade agreements with northern country 0. Let $A \subset S$ be the set of southern countries that participate in free trade agreements, and let its cardinality be $k = |A|$. Note that all countries j in A have **(official)** marginal costs $c_j = c_C$ and countries j in $S \backslash A$ have marginal costs $c_j = c_D + \tau$. Following d'Aspremont et al. (1983) and Donsimoni et al. (1986), we define a stable FTA. A *stable FTA* $A \subseteq S$ is the set of southern FTA member countries that is described by the following two inequalities:

$$sw^{IN}(k,\xi) - F - f_j(\xi) + \sigma \geq sw^{OUT}(k-1,\xi) \text{ for all } j \in A \text{ (internal stability)} \tag{12}$$

and

$$sw^{IN}(k+1,\xi) - F - f_j(\xi) + \sigma \leq sw^{OUT}(k,\xi) \text{ for all } j \notin A \text{ (external stability).} \tag{13}$$

If a set of southern country members satisfies both internal and external stability conditions, then it is called a *stable FTA for southern countries under* ξ *and* σ. Extending the proof by

Donsimoni et al. (1986), we can show that there always exists a stable FTA.

Proposition 1. For all $\xi \in [0,1]$ and all $\sigma \geq 0$, there exists a stable FTA for southern countries under (A1)-(A7).

With general functional forms, it is difficult to make general statements besides the existence of a stable FTA for southern countries, so we will adopt linear demand functions to describe the optimal FTA participation rule for the northern country in the next section.

4 Optimal Stable FTA Rules Under Linear Demand

Here, we allow the northern country to set the FTA rule (ξ, σ) and southern countries can passively decide whether they will participate ($A \subseteq S$ is a stable FTA for southern countries under ξ and σ). We assume that the northern country can choose a policy combination of the enforcement level ξ of the clean technology use and a sign-up subsidy σ for FTA participation. We strengthen condition (A5) to linear demand functions to discuss the optimal policy mix.

(A5') Demand functions are linear: $P(Q) = 1 - Q$ (northern market), and $p(q) = a - bq$ (southern markets).

Here, we assume that the northern country has the inverse demand function $P(Q) = 1 - Q$, and each southern country has $p(q) = a - bq$. Recall that we assume that southern countries do not suffer from negative externalities ($d_S = 0$), whereas the northern country does ($d_N > 0$). With (A6'), we can explicitly calculate the equilibrium allocation so that we can derive the formulas for equilibrium total emissions, and the aggregate social welfare of northern and southern countries as a function of enforcement level ξ by endogenizing FTA membership k.

With the equilibrium allocation derived and reported in Appendix 2, we can analyze the optimal FTA rule for the northern country. The northern country can choose a policy combination, an enforcement level $\xi \in [0,1]$, and a sign-up subsidy $\sigma \geq 0$ for the participants of the FTA from southern countries in order to maximize the social welfare (8). In order to find the optimal FTA policy for the northern country, we can use the following two-step procedure: first, for each $k = 1, ..., m$, find an optimal combination of policies (ξ^k, σ^k), then solve the optimal FTA size k.

The first step solves the following problem (see Appendix 2 for formulas of equilibrium allocations):

$$(\xi^{k*}, \sigma^{k*}) \in \arg\max_{\xi,\sigma} SW(k, \xi, \sigma) \quad s.t. \quad \begin{cases} sw^{IN}(k, \xi) - F - f_k(\xi) + \sigma \geq sw^{OUT}(k-1) \\ sw^{IN}(k+1, \xi) - F - f_{k+1}(\xi) + \sigma \leq sw^{OUT}(k) \end{cases}, \tag{14}$$

where $SW(k, \xi, \sigma)$, $sw^{IN}(k, \xi)$, and $sw^{OUT}(k)$ are given in equations (8), (9), and (10), respectively. Then, $\left(\xi^{k^*}, \sigma^{k^*}\right)$ is the optimal policy that implements a size k^* FTA. With linear demand, we can simplify the constrained optimization problem in the first step (14) to a simple unconstrained optimization problem. Let

$$\sigma(k, \xi) \equiv sw^{OUT}(k-1) - \left\{ sw^{IN}(k, \xi) - F - f_k(\xi) \right\}. \tag{15}$$

This $\sigma(k, \xi)$ turns out to be the optimal transfer from the northern country to the southern countries for each k and ξ when $\sigma(k, \xi) \geq 0$.

Lemma 1. Suppose that (A1)-(A4), (A5'), (A6), and (A7) hold. If $sw^{OUT}(k-1) - \left\{ sw^{IN}(k, \xi) - F - f_k(\xi) \right\} \geq 0$ holds, $\sigma(k, \xi)$ is increasing in k and ξ. Problem (14) can be rewritten as follows:

$$\xi_k^* \in \arg\max_{\xi} SW(k, \xi, \sigma(k, \xi)). \tag{16}$$

Under $\xi = \xi_k^*$, southern countries $\{1, ..., k\}$ forms a stable FTA with the northern countries.

Now, we are ready to characterize the optimal FTA with environmental provisions for the northern country.[13] By choosing k optimally, we obtain the optimal size of the FTA

[13] Recall that τ is an uncontrollable variable (see footnote 9). Otherwise, it is easy to see that a prohibitive tariff is optimal as long as there is at least one southern FTA member.

memberships for southern countries k^*:

$$k^* = \arg \max_{k=0,1,...,m} SW(k, \xi^{k*}, \sigma^{k*}). \tag{17}$$

Proposition 2. Suppose that (A1)-(A4), (A5'), (A6), and (A7) hold. Then, the optimal stable FTA for the northern country is $A = \{1, ..., k^*\}$, where k^* maximizes $SW(k, \xi_k^*, \sigma(k, \xi_k^*))$ over $k = 0, 1, ..., m$. We have $1 \geq \xi_1^* \geq \xi_2^* \geq ... \geq \xi_m^* \geq 0$ with strict inequalities $\xi_{k-1}^* > \xi_k^*$ for all ks with an interior solution $1 > \xi_k^* > 0$.

This proposition shows that there is a trade-off between the number of southern participants and the level of enforcement. Although it is difficult to analyze whether the equilibrium σ_k^* increases monotonically in k without specifying f_k functions (ξ_k^* decreases monotonically in k), it is quite natural to assume that the total subsidy payment increases monotonically in k, that is, $k\sigma_k^* < (k+1)\,\sigma_{k+1}^*$ holds for all k as long as the solutions are interior. Thus, the northern country cannot expand the membership of the FTA too much, because such an expansion means that the transfer program becomes more costly and the level of enforcement decreases.[14]

Finally, notice that although Proposition 1 assures the existence of a stable FTA for southern countries, the stable FTA might be no FTA between the northern and southern countries ($k = 0$). Thus, it is important to note the conditions for a nontrivial FTA. These depend on many parameters, but we can provide some intuitive sufficient conditions. We want to show that there is a positive k such that both northern and southern countries are better off. For this, it suffices to show that in the case of $k = 1$, both the southern member country and the northern country are better off by having an FTA with the most strict environmental provision $\xi = 1$ and compensation $\sigma(1, 1) = sw^{OUT}(0, 0) - \left\{sw^{IN}(1, 1) - F - f_1(1)\right\}$, which makes the southern country indifferent between joining or staying out of the FTA.

[14] See Furusawa and Konishi (2005). They analyzed free trade networks with transfers with bilateral transfers.

Proposition 3. Suppose that (A1)-(A4), (A5'), (A6), and (A7) hold. If (i) there are positive joint gains from forming an FTA between the northern country and southern country 1 ($\overline{SW}(1) - d_N E(1,1) + sw^{IN}(1,1) - (F + f_1(1)) > \overline{SW}(0) - d_N E(0,0) + sw^{OUT}(0,0)$), and (ii) the northern country's gains from the emission reduction from forming the FTA exceeds its loss in the gross total surplus ($\overline{SW}(1) - d_N E(1,1) \geq \overline{SW}(0) - d_N E(0,0)$), then the optimal FTA for the northern country is nontrivial.

Condition (ii) may seem restrictive since it is likely that $\overline{SW}(1) < \overline{SW}(0)$ holds especially if τ is close to the optimal tariff rate for no FTA case. However, it is not difficult to show that condition (ii) holds, if (a) e_C is significantly smaller than e_D, and (b) the northern country has a sufficiently high concern about environmental damages (d_N is significantly high). This can be seen by rewriting the reduction in the emissions by the above FTA:

$$\begin{aligned} |\Delta E| &= E(0,0) - E(1,1) \\ &= e_C \left[Q_0(0) - Q_0(1)\right] + \{e_D(Q_D(0) + q_D) - e_C \left(Q_C(1) + q_C\right)\} \\ &+ (m-1)\, e_D \left[Q_D(0) - Q_D(1)\right]. \end{aligned} \tag{18}$$

Under the FTA, Q_0 is crowded out by Q_C by the southern member, but production using clean technology increases and production using a dirty technology decreases. Thus, if e_C is significantly smaller than e_D, introducing an FTA has a positive and large impact on the reduction of emissions. If d_N is large, it is clear that condition (ii) is easily satisfied.

5 A Numerical Example

The three propositions derived above provide a qualitative characterization of FTAs in our model. They do not directly answer, for example, how much an FTA impacts total environmental pollutant emissions. Therefore, in this section, using a simple numerical example, we demonstrate the quantitative properties of our model. In particular, we are interested in how the law enforcement level ξ, the sign-up transfer σ to the southern member countries, and total emissions of environmental pollutants E are affected by the number of southern member countries in an FTA. We specify the f_k function as follows:

$$f_k(\xi) = f(\xi) = \frac{1}{2}\beta\xi^2, \tag{19}$$

for all $k = 1, ..., m$. This formulation satisfies $f'(0) = 0$ while $f(1) = \beta < \infty$. Then, ξ_k^* is written as

$$\begin{aligned}\xi_k^* = \frac{(e_D - e_C)}{\beta} &\left[(d_N + d_S)\left\{\frac{1 + c_0 + kc_C + (m-k)(c_D + \tau) - (m+2)c_C}{m+2} + \frac{a - c_C}{2b}\right\}\right. \\ &\left.- (k-1)\, d_S \left(\frac{-c_C + (c_D + \tau)}{m+2}\right)\right] \end{aligned}\tag{20}$$

if the RHS is less than 1, and $\xi_k^* = 1$ otherwise.

We set the parameter values as $m = 10$, $c_0 = 0.1$, $c_C = 0.08$, $c_D = 0.05$, $\tau = 0.1333$, $a = 0.3$, $b = 1$, $d_N = 0.5$, $d_S = 0$, $e_D = 0.3$, and $e_C = 0.1$. This tariff rate τ is set at the optimal tariff level when the government maximizes the gross social welfare without environmental consideration. We also assume that $\beta_k = \beta = 0.02$ for all k and $F = 0$.

We set the tariff rate at the level that maximizes the northern country's gross social welfare $\overline{SW}$. Under the optimal tariff, having an FTA does not improve $\overline{SW}$ (Table 1). This means that without environmental consideration, FTA between North and South is not attractive for the north. We can also compare the cases of FTAs with environmental provisions and simple technology transfers (Tables 1 and 2). For the same tariff rate τ, if a southern country signs an FTA with the northern country, it receives not only clean technology but also access to a big northern market, and it is quite beneficial for the southern country. Since the southern country is eager to sign an FTA, the northern country can set a

Table 1: Basic Optimal Tariff and FTA

k	0	1	2	3	4	5	6	7	8	9	10
Q	0.75556	0.76417	0.77278	0.78139	0.79000	0.79861	0.80722	0.81583	0.82444	0.83306	0.84167
P	0.24444	0.23583	0.22722	0.21861	0.21000	0.20139	0.19278	0.18417	0.17556	0.16694	0.15833
Q_0	0.14444	0.13583	0.12722	0.11861	0.11000	0.10139	0.09278	0.08417	0.07556	0.06694	0.05833
Q_C	0.16444	0.15583	0.14722	0.13861	0.13000	0.12139	0.11278	0.10417	0.09556	0.08694	0.07833
Q_D	0.06111	0.05250	0.04389	0.03528	0.02667	0.01806	0.00944	0.00083	0	0	0
Π_0	0.02086	0.01845	0.01619	0.01407	0.0121	0.01028	0.00861	0.00708	0.00571	0.00448	0.00340
Π_C	0.02704	0.02428	0.02167	0.01921	0.0169	0.01474	0.01272	0.01085	0.00913	0.00756	0.00614
Π_D	0.00373	0.00276	0.00193	0.00124	0.00071	0.00033	0.00009	0.00000	0	0	0
CS	0.28543	0.29198	0.29859	0.30528	0.31205	0.31889	0.32580	0.33279	0.33985	0.34699	0.35420
ξ	0	1	1	1	1	1	1	1	1	0.98472	0.94167
E	0.57278	0.51942	0.4695	0.42302	0.38	0.34042	0.30428	0.27158	0.247	0.22686	0.21614
σ	0	0.00474	0.00637	0.00800	0.00963	0.01126	0.01289	0.01453	0.01616	0.01708	0.01675
TR	0.08148	0.063	0.04681	0.03293	0.02133	0.01204	0.00504	0.00033	0	0	0
SW	0.10139	0.10898	0.11410	0.11676	0.11696	0.11468	0.10994	0.10274	0.09280	0.08431	0.08204
$\overline{SW}$	0.38778	0.37343	0.36159	0.35228	0.34548	0.34121	0.33945	0.34021	0.34556	0.35147	0.35760

Q: Equilibrium total output in the N(orth), P: the price, Q_0: N's domestic supply, Q_C: S(outh)'s supply to N with clean technology, Q_D: S(outh)'s supply to N with dirty technology, Π_0: profit of N's firm, Π_C: profit of S's firm with clean technology, Π_D: profit of S's firm with dirty technology, CS: N's consumer surplus, ξ: enforcement level, E: aggregate emissions, σ: subsidy for joining the FTAs, TR: tariff revenues, SW: N's social welfare, $\overline{SW}$: N's gross social welfare without environmental consideration

Table 2: Optimal Tariff With Tech Transfers Only

k	0	1	2	3	4	5	6	7	8	9	10
τ	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333	0.1333
Q	0.75556	0.75306	0.75056	0.74806	0.74556	0.74306	0.74056	0.73806	0.73556	0.73306	0.73056
P	0.24444	0.24694	0.24944	0.25194	0.25444	0.25694	0.25944	0.26194	0.26444	0.26694	0.26944
Q_0	0.14444	0.14694	0.14944	0.15194	0.15444	0.15694	0.15944	0.16194	0.16444	0.16694	0.16944
$Q_{\lvert c\rvert}$	0.03111	0.03361	0.03611	0.03861	0.04111	0.04361	0.04611	0.04861	0.05111	0.05361	0.05611
Q_D	0.06111	0.06361	0.06611	0.06861	0.07111	0.07361	0.07611	0.07861	0.08111	0.08361	0.08611
Π_0	0.02086	0.02159	0.02233	0.02309	0.02385	0.02463	0.02542	0.02623	0.02704	0.02787	0.02871
$\Pi_{\lvert c\rvert}$	0.00097	0.00113	0.00130	0.00149	0.00169	0.00190	0.00213	0.00236	0.00261	0.00287	0.00315
Π_D	0.00373	0.00405	0.00437	0.00471	0.00506	0.00542	0.00579	0.00618	0.00658	0.00699	0.00742
CS	0.28543	0.28355	0.28167	0.27979	0.27793	0.27607	0.27421	0.27236	0.27052	0.26869	0.26686
ξ	0	0.71806	0.73056	0.74306	0.75556	0.76806	0.78056	0.79306	0.80556	0.81806	0.83056
E	0.57278	0.53831	0.50283	0.46636	0.42889	0.39042	0.35094	0.31047	0.26900	0.22653	0.18306
σ	0	0.01720	0.01840	0.01890	0.01941	0.01992	0.02044	0.02098	0.02152	0.02206	0.02262
TR	0.08148	0.07633	0.07052	0.06404	0.05689	0.04907	0.04059	0.03144	0.02163	0.01115	0
SW	0.10139	0.09512	0.08630	0.07704	0.06660	0.05496	0.04209	0.02796	0.01257	-0.004	-0.022
$\overline{SW}$	0.38778	0.38147	0.37452	0.36692	0.35867	0.34977	0.34023	0.33003	0.31919	0.30770	0.29557

high enforcement level ξ without supporting the southern country with subsidy σ much. In contrast, if a southern country receives clean technology only and still faces the same tariff rate τ, then it is not beneficial to the southern country at all. It needs to suffer from a higher marginal cost and a smaller output whereas it must follow the enforcement guideline. Since the Northern country must subsidize the difference, it also relaxes the enforcement level ξ in an effort to reduce the high subsidy σ. As a result, an FTA with an environmental provision achieves a higher social welfare and less emissions than a simple clean technology transfer.

This numerical example is not the most realistic, but it provides a good understanding of the model. Our main findings are as follows.

(1) Starting from no free trade agreement, if one southern country joins the FTA, it gets a high market share in the northern market. Thus, if only one country joins the agreement, a high enforcement rate can be imposed with only a small sign-up subsidy (Depending on the parameter values, $\xi = 1$ and $\sigma = 0$ can occur very easily).

(2) In this set of parameter values **with the optimal tariff rate**, tariff revenue plays a strong role in the northern country's social welfare; as a result, it cares less about the FTA.

(3) With this set of parameter values, the total emission in the world, E_k^*, is monotonically decreasing in k but the level of enforcement ξ_k^* is also monotonically decreasing. **In our model the lucrativeness of getting access to the northern market by joining an FTA with environmental provisions declines as the southern membership expands. This implies that it becomes more costly for the northern country to support the southern members' enforcement costs, thus ξ_k^* declines as k increases. The total emission E_k^* does not necessarily go down with k exactly because of this reason, but it still tends to decrease as k increases.**

(4) The northern country needs to evaluate the benefits and costs of changing its policies

(ξ and σ) to increase southern countries' membership by evaluating CS, Π_0, and TR (tariff revenues), in addition to emissions E. Here, $k = 4$ is the optimal number of southern countries in the FTA **(Table 1)**.

(5) Under some parameter values, nonmember southern countries can be effectively excluded from the northern market (if $P(k) < c_C + \tau$).

Moreover, we can easily see how changes in enforcement cost β, tariff rate τ, cost of the clean technology c_C, and emissions from the dirty technology e_D, affect the optimal number of southern countries participating in the FTA. In Appendix 3, we show the results of the changes in these values ($\beta_k = \beta$ from 0.02 to 0.03, τ from 0.1333 to 0.1, c_C from 0.08 to 0.06, and e_D from 0.3 to 0.5), from which we can observe the following.

(1) If the enforcement efficiency is lower (higher β), enforcement of clean technology implementation is more difficult and FTA membership declines. **This is because to support the southern FTA members becomes more costly. (Table 3)**

(2) A **lower** tariff rate (τ) decreases the number of member countries. Southern countries have **less** incentive to become a member **with lower** tariff rate, **since they can still have access to the northern market even if they are outsiders. (Table 4)**

(3) If clean technology is less costly (lower c_C), more states will join the FTA. Additionally, the total emission declines because such a reduction will be easier. **As c_C goes down, it becomes easier to enforce clean technology, which in turn gives the northern country stronger incentives to accept more southern countries. As a result, both effects bring down the total emissions. (Table 5)**

(4) An increase in the emission rate (higher e_D) in southern countries raises the aggregate emissions if the number of member countries is kept constant. **However, these higher emissions induce the northern country to include more southern countries to the FTA. Thus, the number of member countries adopting the clean technology increases and eventually the aggregate level of emissions can decline. Indeed, the**

total emissions under the stable FTA in Table 1 is 0.38 whereas the ones under the stable FTA in Table 6 is 0.3762 due to expanded southern membership. (Tables 1 and 6)

The above numerical example implies that the optimal size of the FTA for the northern country cannot be large so that the southern member countries are sufficiently motivated to introduce strict environmental regulations. Brandi et al. (2020) investigated the effects of environmental provisions on exports from developing countries based on the newly created dataset on a broad range of environmental provisions across 680 FTAs. Their analysis shows that only developing countries with stricter enforcement of environmental policies can green their exports in response to environmental provisions in trade agreements. Thus, if many participating countries have a low level of enforcement of environmental regulations, they may not necessarily contribute to emission reductions even under trade agreements with environmental provisions.

6 Conclusion

In this paper, we analyzed the stable free trade agreements with environmental provisions between northern and southern countries, explicitly considering clean technology transfers and the enforcement of tighter environmental regulation. We characterized the optimal stable FTA for the northern country, and provided sufficient conditions for the optimal stable FTA to be nontrivial. Our numerical results indicated that the optimal size of the FTA for the northern country could be rather small to assure the southern member countries sufficient benefits of getting access to the lucrative northern market so that they are willing to implement strict environmental measures. It should be noted that behind this result is Proposition 2: there is a trade-off between the size of the FTA and the enforcement level of environmental regulations in southern member countries, that is, an increase in the number of southern members in the FTA will lead to the participation of countries with weaker enforcement. In analyzing FTAs with environmental provisions, we should consider the enforcement level of environmental regulations in southern countries. As several empirical studies examine the effects of environmental provisions on exports from developing countries, developing countries may not necessarily green their exports in response to environmental provisions in trade agreements. Consequently, if many participating countries have a low level of enforcement of environmental regulations, they may not necessarily contribute to emission reductions even under trade agreements with environmental provisions.

Although we demonstrated that bundling a free trade agreement with an environmental agreement between northern and southern countries would be beneficial in the presence of technology transfers and enforcement issues, our model has some limitations. We assumed that there is a unique northern country in order to make the optimal FTA for the northern country to be characterized easily. With multiple and heterogeneous northern countries, there might be conflicts of interest among them, and there may be trade between the northern countries.[15] In addition, northern countries may have different positions on clean technology transfer to southern countries. For example, suppose that one northern country has a patent for clean technology, whereas the other does not. Then, there are conflicts of interest in the FTA's clean technology transfer policies to the south. These realistic considerations may make the analysis more complicated. The future direction of this study will be one that explores the case of multiple northern countries taking these considerations into account.

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[15] The main difference between FTAs and CUs is that the members of an FTA do not need to coordinate their tariff rates, while the members of a CU must set the same tariff rates on their imports. Although an FTA or a CU does not make a difference in our model with a single Northern country, there might be some implications of having an FTA or a CU when there are multiple northern countries.

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Appendix 1: Proofs

Proof of Proposition 1. First, note $f_1(\xi) \leq f_2(\xi) \leq ... \leq f_m(\xi)$ for all $\xi \in [0,1]$ by (A4).

We will prove that there is a stable FTA by an induction argument.

1. Start with $k = 0$. If $sw^{IN}(1,\xi) - F - f_1(\xi) + \sigma \leq sw^{OUT}(0,\xi)$, then, $k = 0$ is a stable FTA, and we are done. Otherwise, we have $sw^{IN}(1,\xi) - F - f_1(\xi) + \sigma > sw^{OUT}(0,\xi)$.

2. For an FTA size $k \geq 1$, suppose that $sw^{IN}(k,\xi) - F - f_k(\xi) + \sigma > sw^{OUT}(k-1,\xi)$ holds. This implies $sw^{IN}(k,\xi) - F - f_j(\xi) + \sigma > sw^{OUT}(k-1,\xi)$ for all $j \in A$. If $sw^{IN}(k+1,\xi) - F - f_{k+1}(\xi) + \sigma \leq sw^{OUT}(k,\xi)$, then $sw^{IN}(k+1,\xi) - F - f_j(\xi) + \sigma \leq sw^{OUT}(k,\xi)$ holds for all $j \notin A$, and $A = \{1,...,k\}$ is a stable FTA. Otherwise, we have $sw^{IN}(k+1,\xi) - F - f_{k+1}(\xi) + \sigma > sw^{OUT}(k,\xi)$, and the induction hypothesis holds for an FTA size $k+1$.

3. By induction, $sw^{IN}(m,\xi) - F - f_m(\xi) + \sigma > sw^{OUT}(m-1,\xi)$ holds. This implies that $A = S$ is internally stable. As there are no more southern countries, we conclude that $A = S$ is a stable FTA.

We completed the proof. *Q.E.D.*

Proof of Lemma 1. First, note that given k and ξ, the northern country's social welfare $SW(k,\xi,\sigma)$ is monotonically decreasing in σ. Thus, as long as the constraints in (14) are satisfied, σ should be minimized. In the following, we show that if the first constraint is satisfied with equality then the second condition is also satisfied. From the above calculations, we know

$$
\begin{aligned}
sw^{IN}(k) &= \Pi_C(k) + cs_C + \pi_C + (1-\xi)\left(q_C + Q_C(k)\right)(c_C - c_D) \\
&= \left(\frac{1}{m+2}\right)^2 \left[1 + c_0 - (m+2)\,c_C + m\,(c_D + \tau) - k\,(c_D + \tau - c_C)\right]^2 + \frac{3\,(a - c_C)^2}{8b} \\
&+ (1-\xi)\left(\frac{a - c_C}{2b} + \frac{1 + c_0 - (m+2)\,c_C + m\,(c_D + \tau) - k\,(c_D + \tau - c_C)}{m+2}\right)(c_C - c_D),
\end{aligned} \tag{21}
$$

and

$$
Q_C(k) = \frac{1 + c_0 - (m - k + 2)\,c_C + (m - k)\,(c_D + \tau)}{m+2}, \tag{22}
$$

$$
\begin{aligned}
sw^{OUT}(k-1) &= \Pi_D(k) + cs_D + \pi_D \\
&= \left(\frac{1}{m+2}\right)^2 \left[1 + c_0 - 2\,(c_D + \tau) + (c_D + \tau - c_C) - k\,(c_D + \tau - c_C)\right]^2 \\
&+ \frac{3\,(a - c_D)^2}{8b} \left[1 + c_0 - 2c_C + m\,(c_D + \tau - c_C) - (c_D + \tau - c_C)\right]^2 \\
&- \left[1 + c_0 - 2\,(c_D + \tau) + (c_D + \tau - c_C)\right]^2.
\end{aligned} \tag{23}
$$

Thus, subtracting the former from the latter, we have

$$
\begin{aligned}
& sw^{OUT}(k-1) - sw^{IN}(k) \\
&= \frac{-\,(m+1)\,(c_D + \tau - c_C)\left[2\,(1 + c_0) - (m+2)\,c_C + (m+2)\,(c_D + \tau) - 2k\,(c_D + \tau - c_C)\right]}{(m+2)^2} \\
&- (1-\xi)\left(\frac{a - c_C}{2b} + \frac{1 + c_0 - (m+2)\,c_C + m\,(c_D + \tau) - k\,(c_D + \tau - c_C)}{m+2}\right)(c_C - c_D) - D,
\end{aligned} \tag{24}
$$

where $D = \frac{3(a-c_C)^2}{8b} - \frac{3(a-c_D)^2}{8b}$. That is, $sw^{OUT}(k-1) - sw^{IN}(k)$ is increasing in k and ξ. Because $f_k(\xi) \leq f_{k+1}(\xi)$, we conclude that if the first condition holds with equality $sw^{IN}(k,\xi) - F - f_k(\xi) + \sigma = sw^{OUT}(k-1)$, then the second condition holds with slack $sw^{IN}(k+1,\xi) - F - f_{k+1}(\xi) + \sigma < sw^{OUT}(k)$. *Q.E.D.*

Proof of Proposition 2. The first statement follows from Lemma 1. Problem (14) can be written as

$$SW(k, \xi, \sigma(k, \xi)) = CS(k) + \Pi_0(k) + \tau\,(m-k)\,Q_D(k) - k\sigma(k, \xi) - d_N E(k, \xi). \qquad (25)$$

Thus, given k, the social optimum ξ_k^* is characterized by

$$k\frac{\partial \sigma}{\partial \xi} + d_N \frac{\partial E}{\partial \xi} = 0. \qquad (26)$$

Rewriting this, we obtain

$$f_k'(\xi_k^*) = d_N\,(e_D - e_C)\left[\frac{1 + c_0 + kc_C + (m-k)\,(c_D + \tau) - (m+2)\,c_C}{m+2} + \frac{a - c_C}{2b}\right]. \qquad (27)$$

Because $(c_D + \tau) > c_C$, the RHS is decreasing in k. As $f_k''(\xi) > 0$ and $f_k'(\xi) \geq f_{k-1}'(\xi)$ for all ξ, we conclude that $\xi_k^* < \xi_{k-1}^*$ holds for all k as long as they are interior solutions. *Q.E.D.*

Proof of Proposition 3. It is sufficient to show that an FTA with $\xi = 1$ between the northern country and southern country 1 is mutually beneficial for an appropriate σ. It is easy to see that condition (i) assures that the total pie of the two countries increases due to an FTA. Condition (ii) assures that the northern country benefits from the FTA if there is no transfer from the northern country to southern country 1. This condition, together with condition (i), assures that there is a nonnegative transfer from the northern country to southern country 1 that enables both countries to be better-off. We have completed the proof. *Q.E.D.*

Appendix 2: Linear demand

Here, we assume (A6'): the northern country has the following demand function: $P(Q) = 1 - Q$. Firm j's profit maximization problem is

$$\max_{q_j^0} \left(1 - \sum_{i=0}^{m} Q_i\right) Q_j - c_j Q_j. \tag{28}$$

The first-order condition is

$$1 - \sum_{i=0}^{m} Q_i - Q_j - c_j = 0. \tag{29}$$

Summing them up, we obtain

$$(m+1) - \left((m+2) \sum_{i=0}^{m} Q_i\right) - \sum_{i=0}^{m} c_i = 0 \tag{30}$$

and

$$\bar{Q} = \sum_{i=0}^{m} Q_i = \frac{m+1}{m+2} - \frac{1}{m+2} \sum_{i=0}^{m} c_i. \tag{31}$$

Let $\alpha_C w_N = c_0$, $\alpha_C w_S = c_C$, and $\alpha_D w_S = c_D$.

Suppose that there are k southern countries in the FTA. We assume that in the presence of a tariff charged by the northern country, the marginal cost of using the clean technology in the FTA is lower than the one using the dirty technology outside of the FTA if they export $c^{OUT} = c_D + \tau > c^{IN} = c_C$ naturally (although $c_C > c_D$ holds). The equilibrium output by country j when k southern countries participate in the FTA is

$$\begin{aligned} Q_j &= \frac{1}{m+2} + \frac{1}{m+2} \sum_{i=0}^{m} c_i - c_j \\ &= \frac{1}{m+2} \left\{1 + \left(c_0 + k c_C + (m-k)\left(c_D + \tau\right)\right) - (m+2)\, c_j\right\}. \end{aligned} \tag{32}$$

Thus, the northern country's output and FTA and non-FTA southern countries' exports are written as

$$Q_0(k) = \frac{1}{m+2} \left\{ 1 + \left(kc_C + (m-k)(c_D + \tau) \right) - (m+1) c_0 \right\}, \tag{33}$$

$$Q_C(k) = \frac{1}{m+2} \left[1 + c_0 - (m-k+2) c_C + (m-k)(c_D + \tau) \right], \tag{34}$$

$$Q_D(k) = \frac{1}{m+2} \left[1 + c_0 + kc_C - (k+2)(c_D + \tau) \right], \tag{35}$$

respectively. Thus, the equilibrium total output in the northern market is

$$\bar{Q}(k) = \sum_{i=0}^{m} Q_i(k) = \frac{(m+1) - (c_0 + kc_C + (m-k)(c_D + \tau))}{m+2}. \tag{36}$$

Since $\Pi_j = Q_j^2$, profits from the northern market earned by firms in the northern country, the southern FTA country (with the clean technology), and the southern non-FTA country (with the dirty technology) are

$$\Pi_0(k) = \left(\frac{1}{m+2} \right)^2 \left[1 - (m+1) c_0 + kc_C + (m-k)(c_D + \tau) \right]^2, \tag{37}$$

$$\Pi_C(k) = \left(\frac{1}{m+2} \right)^2 \left[1 + c_0 - (m-k+2) c_C + (m-k)(c_D + \tau) \right]^2, \tag{38}$$

$$\Pi_D(k) = \left(\frac{1}{m+2} \right)^2 \left[1 + c_0 + kc_C - (k+2)(c_D + \tau) \right]^2, \tag{39}$$

respectively. Thus, the northern country's equilibrium consumer surplus CS is calculated as

$$CS(k) = \frac{\left[(m+1) - (c_0 + kc_C + (m-k)(c_D + \tau)) \right]^2}{2(m+2)^2}. \tag{40}$$

The amount of equilibrium total emissions is written as

$$\begin{aligned}
E(k,\xi) &= (2e_D - e_C)\left(\frac{m+1}{m+2} - \frac{c_0 + kc_C + (m-k)(c_D+\tau)}{m+2}\right) \\
&\quad - (e_D - e_C)(1-c_C) + e_D\left\{k\frac{a-c_C}{2b} + (m-k)\frac{a-c_D}{2b}\right\} \\
&\quad - (e_D - e_C)\left[\frac{1 + c_0 + kc_C + (m-k)(c_D+\tau) - (m+2)c_0}{m+2}\right] \\
&\quad - (e_D - e_C)k\xi\left\{\frac{1 + c_0 + kc_C + (m-k)c_D - (m+2)c_C}{m+2} + \frac{a-c_C}{2b}\right\}. \qquad (41)
\end{aligned}$$

The Northern country's tariff revenue is

$$TR(k) = \tau \times (m-k) \times Q_D(k) = \frac{m-k}{m+2}\left[1 + c_0 + kc_C - (k+2)(c_D+\tau)\right]\tau, \qquad (42)$$

and its social welfare without environmental concerns is

$$\begin{aligned}
SW^G(k) &= CS(k) + \Pi_0(k) + TR(k) \qquad (43) \\
&= \frac{\left[(m+1) - (c_0 + kc_C + (m-k)(c_D+\tau))\right]^2}{2(m+2)^2} \\
&\quad + \left(\frac{1}{m+2}\right)^2\left[1 - (m+1)c_0 + kc_C + (m-k)(c_D+\tau)\right]^2 \\
&\quad + \frac{m-k}{m+2}\left[1 + c_0 + kc_C - (k+2)(c_D+\tau)\right]\tau.
\end{aligned}$$

With (A6') again, southern countries have linear demand $p(q) = a - bq$. We can easily calculate domestic outputs, profits, and consumer surpluses in FTA and non-FTA southern countries are solely determined by whether the country is in the FTA (independent of k): $q_C = \frac{a-c_C}{2b}$, $\pi_C = \frac{(a-c_C)^2}{4b}$, $cs_C = \frac{(a-c_C)^2}{8b}$, and $q_D = \frac{a-c_D}{2b}$, $\pi_D = \frac{(a-c_D)^2}{4b}$, $cs_D = \frac{(a-c_D)^2}{8b}$, respectively.

Finally, we can also calculate the optimal tariff rates explicitly. If the Northern government maximizes the gross social welfare $\overline{SW}(k) = CS(k) + \Pi_0(k) + TR(k)$, the optimal tariff rate is

$$\tau^*(k) = \frac{3 + (1-m)\,c_0 + (5k+mk)\,c_C + (m-5k-km-4)\,c_D}{m+7k+2km+8}.$$

Appendix 3: More numerical examples

Table 3: Lower Efficiency of Enforcement: $\beta = \beta_k = 0.025$

k	0	1	2	3	4	5	6	7	8	9	10
Q	0.75558	0.76419	0.77280	0.78141	0.79002	0.79863	0.80723	0.81584	0.82445	0.83306	0.84167
P	0.24442	0.23581	0.22720	0.21859	0.20998	0.20138	0.19277	0.18416	0.17555	0.16694	0.15833
Q_0	0.14442	0.13581	0.12720	0.11859	0.10998	0.10138	0.09277	0.08416	0.07555	0.06694	0.05833
Q_C	0.16442	0.15581	0.14720	0.13859	0.12998	0.12138	0.11277	0.10416	0.09555	0.08694	0.07833
Q_D	0.06112	0.05251	0.04390	0.03529	0.02668	0.01808	0.00947	0.00086	0	0	0
Π_0	0.02086	0.01844	0.01618	0.01406	0.01210	0.01028	0.00861	0.00708	0.00571	0.00448	0.00340
Π_C	0.02703	0.02428	0.02167	0.01921	0.01690	0.01473	0.01272	0.01085	0.00913	0.00756	0.00614
Π_D	0.00374	0.00276	0.00193	0.00125	0.00071	0.00033	0.00009	0	0	0	0
CS	0.28545	0.29199	0.29861	0.30530	0.31206	0.31890	0.32581	0.33280	0.33986	0.34699	0.35420
ξ	0	1	1	0.99437	0.95993	0.92550	0.89107	0.85663	0.82220	0.78777	0.75333
E	0.57279	0.51943	0.46952	0.42389	0.38771	0.35767	0.33342	0.31458	0.30547	0.29668	0.28708
σ	0	0.00975	0.01138	0.01270	0.01252	0.01241	0.01238	0.01243	0.01255	0.01269	0.01276
TR	0.08147	0.06299	0.04681	0.03293	0.02134	0.01205	0.00505	0.00034	0	0	0
SW	0.10138	0.10397	0.10409	0.10224	0.10157	0.10034	0.09848	0.09595	0.09244	0.08893	0.08647
$\overline{SW}$	0.38778	0.37343	0.36160	0.35229	0.34550	0.34122	0.33947	0.34022	0.34557	0.35147	0.35760

Table 4: Lower Tariff Rate: $\tau = 0.1$

k	0	1	2	3	4	5	6	7	8	9	10
$\bar{Q}$	0.78333	0.78917	0.79500	0.80083	0.80667	0.81250	0.81833	0.82417	0.83000	0.83583	0.84167
P	0.21667	0.21083	0.20500	0.19917	0.19333	0.18750	0.18167	0.17583	0.17000	0.16417	0.15833
Q_0	0.11667	0.11083	0.10500	0.09917	0.09333	0.08750	0.08167	0.07583	0.07000	0.06417	0.05833
Q_C	0.13667	0.13083	0.12500	0.11917	0.11333	0.10750	0.10167	0.09583	0.09000	0.08417	0.07833
Q_D	0.06667	0.06083	0.05500	0.04917	0.04333	0.03750	0.03167	0.02583	0.02000	0.01417	0.00833
Π_0	0.01361	0.01228	0.01103	0.00983	0.00871	0.00766	0.00667	0.00575	0.00490	0.00412	0.00340
Π_C	0.01868	0.01712	0.01563	0.01420	0.01284	0.01156	0.01034	0.00918	0.00810	0.00708	0.00614
Π_D	0.00444	0.00370	0.00303	0.00242	0.00188	0.00141	0.00100	0.00067	0.00040	0.00020	0.00007
CS	0.30681	0.31139	0.31601	0.32067	0.32536	0.33008	0.33483	0.33963	0.34445	0.34931	0.35420
ξ	0	1	1	1	1	1	1	1	1	0.97083	0.94167
E	0.58667	0.53692	0.48950	0.44442	0.40167	0.36125	0.32317	0.28742	0.25400	0.23311	0.21614
σ	0	0.01261	0.01336	0.01411	0.01486	0.01561	0.01636	0.01711	0.01785	0.01738	0.01695
TR	0.06667	0.05475	0.04400	0.03442	0.02600	0.01875	0.01267	0.00775	0.00400	0.00142	0
SW	0.09375	0.09735	0.09956	0.10037	0.09979	0.09781	0.09444	0.08967	0.08351	0.08187	0.08004
$\overline{SW}$	0.38708	0.37843	0.37104	0.36492	0.36007	0.35648	0.35417	0.35313	0.35335	0.35484	0.35760

Table 5: Cheaper Clean Technology: $cC = 0.06$

k	0	1	2	3	4	5	6	7	8	9	10
$\bar{Q}$	0.75558	0.76586	0.77613	0.78641	0.79668	0.80696	0.81723	0.82751	0.83778	0.84806	0.85833
P	0.24442	0.23414	0.22387	0.21359	0.20332	0.19304	0.18277	0.17249	0.16222	0.15194	0.14167
Q_0	0.14442	0.13414	0.12387	0.11359	0.10332	0.09304	0.08277	0.07249	0.06222	0.05194	0.04167
Q_C	0.18442	0.17414	0.16387	0.15359	0.14332	0.13304	0.12277	0.11249	0.10222	0.09194	0.08167
Q_D	0.06112	0.05084	0.04057	0.03029	0.02002	0.00974	0	0	0	0	0
Π_0	0.02086	0.01799	0.01534	0.01290	0.01067	0.00866	0.00685	0.00526	0.00387	0.00270	0.00174
Π_C	0.03401	0.03033	0.02685	0.02359	0.02054	0.01770	0.01507	0.01265	0.01045	0.00845	0.00667
Π_D	0.00374	0.00258	0.00165	0.00092	0.00040	0.00009	0	0	0	0	0
CS	0.28545	0.29327	0.30119	0.30922	0.31735	0.32559	0.33394	0.34239	0.35094	0.35960	0.36837
ξ	0	1	1	1	1	1	1	1	1	1	1
E	0.57279	0.51760	0.46652	0.41955	0.37669	0.33794	0.30394	0.28249	0.25900	0.23344	0.20583
σ	0	0	0	0	0.00222	0.00454	0.00686	0.00918	0.01139	0.01338	0.01517
TR	0.08147	0.06099	0.04326	0.02827	0.01601	0.00649	0	0	0	0	0
SW	0.10138	0.11346	0.12653	0.14061	0.14683	0.14908	0.14765	0.14211	0.13420	0.12512	0.11551
$\overline{SW}$	0.38778	0.37226	0.35979	0.35039	0.34404	0.34074	0.34079	0.34764	0.35481	0.36230	0.37010

Table 6: Lower Emission With a Dirty Technology $e_D = 0.35$

k	0	1	2	3	4	5	6	7	8	9	10
Q	0.75558	0.76419	0.77280	0.78141	0.79002	0.79863	0.80723	0.81584	0.82445	0.83306	0.84167
P	0.24442	0.23581	0.22720	0.21859	0.20998	0.20138	0.19277	0.18416	0.17555	0.16694	0.15833
Q_0	0.14442	0.13581	0.12720	0.11859	0.10998	0.10138	0.09277	0.08416	0.07555	0.06694	0.05833
Q_C	0.16442	0.15581	0.14720	0.13859	0.12998	0.12138	0.11277	0.10416	0.09555	0.08694	0.07833
Q_D	0.06112	0.05251	0.04390	0.03529	0.02668	0.01808	0.00947	0.00086	0	0	0
Π_0	0.02086	0.01844	0.01618	0.01406	0.01210	0.01028	0.00861	0.00708	0.00571	0.00448	0.00340
Π_C	0.02703	0.02428	0.02167	0.01921	0.01690	0.01473	0.01272	0.01085	0.00913	0.00756	0.00614
Π_D	0.00374	0.00276	0.00193	0.00125	0.00071	0.00033	0.00009	0	0	0	0
CS	0.28545	0.29199	0.29861	0.30530	0.31206	0.31890	0.32581	0.33280	0.33986	0.34699	0.35420
ξ	0	1	1	1	1	1	1	1	1	1	1
E	0.66585	0.59931	0.53708	0.47915	0.42553	0.37621	0.33119	0.29048	0.25950	0.22769	0.19417
σ	0	0.00475	0.00638	0.00801	0.00964	0.01127	0.01290	0.01453	0.01616	0.01773	0.01915
TR	0.08147	0.06299	0.04681	0.03293	0.02134	0.01205	0.00505	0.00034	0	0	0
SW	0.05485	0.06903	0.08031	0.08870	0.09419	0.09678	0.09648	0.09329	0.08655	0.07807	0.06901
$\overline{SW}$	0.38778	0.37343	0.36160	0.35229	0.34550	0.34122	0.33947	0.34022	0.34557	0.35147	0.35760