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Green Consumption and Corporate Environmental Responsibility in North-South Trade[*]

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Abstract

As consumers become more environment-conscious, firms enhance their corporate environmental responsibility (CER) practices, such as adopting greener technologies, producing environment-friendly goods (i.e., CER goods) and capturing the price premium associated with environmental quality. Existing studies on the CER goods market adopt a closed-economy framework because CER verification and certification have traditionally been conducted locally. However, as CER certification becomes globally accessible, it is crucial to examine how firms from different countries compete in the CER goods market. We apply a North-South trade model to analyze the effects of stricter CER standards, trade liberalization, and stronger environmental awareness on firms' CER adoption decisions under two scenarios: CER is recognized only in the North, and CER is recognized in both North and South. Our findings indicate that both stricter CER standards and greater environmental awareness encourage firms to adopt CER, regardless of the scope of CER recognition. In contrast, the impact of trade liberalization depends on whether CER is recognized in the South. When CER is recognized only in the North, trade liberalization promotes CER adoption. However, when it is recognized in both North and South, trade liberalization discourages CER adoption.

Keywords: Environmental quality, Heterogeneous consumers, Corporate environmental responsibility, Eco-labelling, Trade liberalization
JEL classification: F18; H23; Q58

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1 Introduction

Consumer behavior and purchasing habits have evolved with increasing environmental awareness. For example, since the concept was adopted at the G8 Summit in 2004, the 3Rs (Reduce, Reuse, Recycle) have been gaining recognition among consumers in many countries.[1] Choosing electric and hybrid vehicles reduces pollutants emissions during operation, helping mitigate global warming and air pollution. Similarly, bringing personal water bottles and cups and separating PET bottles, cans, glass, and paper for recycling decreases the wasteful use of resources and waste and lessens the environmental impact.

As consumers become more environment-conscious, they turn to environment-conscious firms and pay premiums for eco-friendly products. Thus, by appealing to consumers about corporate environmental responsibility (CER), firms seek to enhance their brand reputation and gain a competitive edge. For example, global firms such as Apple, Microsoft, Google and Hitachi have committed to achieving carbon neutrality throughout their supply chain and entire operations.[2] Starbucks has also committed to achieving carbon-neutral green coffee beans and reducing water consumption during processing by 50% by 2030.

Consumers often struggle to assess whether firms are genuinely committed to CER. Some firms engage in green-washing, that is, creating a misleading impression of environmental responsibility through deceptive labeling or advertising. To address this issue, firms need to obtain certifications from recognized organizations such as the International Organization for Standardization (ISO), Science Based Targets (SBT),[3] and B Lab.[4] These certifications serve as credible signals of firms' CER and help consumers purchase preferred products.

This theoretical study investigates firms' incentives for obtaining such certificates. Specifically, we consider the following two features. First, consumer environmental awareness varies. The environmental Kuznets curve suggests that wealthier individuals generally exhibit greater environmental concerns than those with lower incomes. Factors such as education and cultural values also shape environmental awareness. Consequently, while some consumers are willing to pay a premium for environment-friendly products, others prioritize cost-effectiveness over environmental issues.

Second, the recognition of CER standards and goods can be different across countries. Some

[1]In 2005, Japan officially launched the "3R Initiative" at the G8 Environment Ministers' Meeting, where countries confirmed their commitment to waste reduction and the promotion of resource circulation.

[2]In fact, Microsoft aims to become carbon negative by 2030, meaning it will remove more carbon than it emits (https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/).

[3]SBT "develop standards, tools and guidance which allow companies to set greenhouse gas (GHG) emissions reductions targets in line with what is needed to keep global heating below catastrophic levels and reach net-zero by 2050 at latest" (https://sciencebasedtargets.org/resources/files/SBTi-Glossary.pdf).

[4]B Lab is the US non-profit organization issuing "B Corp Certification" which is awarded to firms that are environmentally and socially conscious and highly public-benefit based on rigorous evaluation.

CER standards, such as ISO 2600 and Fairtrade, are widely acknowledged in many countries, whereas others are not. This discrepancy may arise because verifying a firm's CER practices becomes more challenging when the firm is outside its jurisdiction. Many eco-labels are country- or region-specific. For instance, B Corp Certification recently announced that it would suspend its support for certification in regions without global or country-partner representation after December 6, 2023. Consequently, a firm's CER efforts may not be recognized beyond its home country. Even if a CER certificate is recognized internationally, the cost of producing CER goods may be too high for some firms, particularly those in the South.

We extend the North-South oligopoly model, with a representative firm in the North and in the South, to incorporate consumer heterogeneity into environmental awareness and vertically differentiated goods with different levels of environmental friendliness. A nonprofit organization establishes and verifies CER standards. Firms that comply with these standards receive certification, and their products are labeled as CER goods. We analyzed two scenarios with differing scopes of CER recognition. In the first scenario, CER is recognized only in the North, which may occur when the South has limited access to CER verification and certification. The second scenario assumes CER recognition in both North and South, reflecting broader accessibility to CER certification.[5]

We find that tightening the CER standard can encourage CER adoption, regardless of recognition scope. This result appears counterintuitive because higher CER standards lead to higher CER adoption costs. However, they also generate higher premiums for environment-friendly goods. In our analysis, the positive effect of the price premium can dominate the negative effect of higher costs, thereby incentivizing firms to adopt CER to attract environment-conscious consumers. In such cases, greater environmental awareness always promotes CER adoption in both scenarios. Intuitively, as consumers become more environment-conscious, their demand for environment-friendly goods increases, prompting firms to embrace CER.

By contrast, the impact of trade liberalization (i.e., import tariff reductions) on firms' CER adoption depends on CER recognition. When CER is recognized only in the North, tariff reductions motivate the North firm to undertake CER. This result occurs because lower tariffs intensify competition from the South firm in the non-CER goods market, leading the South firm to increase its production of non-CER goods. Consequently, the North firm finds it more profitable to differentiate itself by producing CER goods.

However, when the CER is recognized in both North and South, tariff reductions have the opposite effect, which discourages the adoption of CER in both countries. In the presence of a

[5] Alternatively, we can assume that CER is always recognized in both countries, but the South does not have access to clean technology in the first scenario while its does in the second. This modification does not alter our analysis and results.

tariff, the South firm is more eager to gain a price premium for environment-friendly goods than the North firm. If the environmental standard is not very high, only the South firm undertakes CER. Tariff reductions weaken the South firm's incentive for CER, as they increase the profits of non-CER goods more sharply, thereby discouraging South firm's CER adoption. On the other hand, if the environmental standard is sufficiently high, the North firm has an incentive to adopt CER. In this case, tariff reductions enhance the competitiveness of the South firm in the CER goods market, prompting the North firm to shift its production to non-CER goods.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 develops the basic model by considering a single firm in each country. Section 4 examines the case in which only the North recognizes CER, meaning that only the North firm can choose whether to adopt CER. Section 5 then examines the case in which CER is recognized in both North and South, allowing both firms to decide on CER adoption. Section 6 analyzes the greenhouse gas emissions under these two scenarios. Section 7 extends the analysis to a multi-firm setting for each country. Section 8 concludes the paper.

2 Literature review

Our study builds upon two primary strands of the literature: eco-labeling and CER. While both topics have been extensively examined in a closed-economy environment, relatively few studies address their implications in open economies. Our study contributes to the literature by integrating both eco-labeling and CER within the framework of North-South trade, offering novel insights into their combined effects. In particular, we are the first to explore how trade liberalization affects firms' CER adoption in the presence of heterogeneous consumers with different preferences towards environmental friendliness of goods.

2.1 Eco-labeling in international trade

Many studies have studied eco-labeling in a closed economy.[6] However, only a few papers have considered eco-labeling with international trade (e.g. Nimon and Beghin, 1999; Abe et al., 2002; Tian, 2003; and Greaker, 2006; Podhorsky, 2013).[7]

[6]Such studies include Mattoo and Singh (1994), Dosi and Moretto (2001), Bagnoli and Watts (2003), Amacher et al. (2004), Hamilton and Zilberman (2006), Ben Youssef and Lahmandi-Ayed (2008), Ibanez and Grolleau (2008), André et al. (2009), Ben Youssef and Abderrazak (2009), Harbaugh et al. (2011), Konishi (2011), Fischer and Lyon (2014, 2019), Li and van't Veld (2015), Walter and Chang (2017), Poret (2019), and Forlin (2021). See van't Veld (2020) for a literature review on eco-labeling in the framework of a closed economy.

[7]Broadly speaking, our analysis is also related to the literature on the international trade of different environmental quality goods (e.g., Toshimitsu, 2008; Ishikawa and Okubo, 2011; Ceccantoni et al., 2018). For instance, Ceccantoni et al. (2018) considered two asymmetric countries, a green country and a brown country, each hosting a firm, a

Tian (2003) extended the international duopoly model to study firms' competition for environmental quality and policy implications of the minimum standard of environmental quality. Tian (2003) assumed that consumers are homogeneous and are always environment-conscious. By contrast, we consider heterogeneous consumers with different preferences towards the environmental friendliness of goods. This heterogeneity allows for variable market sizes for different goods, enabling a deeper analysis of firms' strategic choices regarding CER.

Greaker (2006) applied a two-country, two-firm model to investigate a domestic country's choice between an environmental standard and an eco-labeling scheme. In Greaker (2006), the environmental standard applied only to domestic firms, whereas both domestic and foreign firms could adopt eco-labeling under the eco-labeling scheme. This difference between the two policies leads to different effects on the production costs of the two firms, which in turn results in different effects on consumer surplus, firm profits and welfare. Greaker (2006) examined which policy is optimal from the domestic country's perspective and whether the eco-labeling scheme serves protectionist purposes.

Our study is closely related to Nimon and Beghin (1999) and Abe et al. (2002). Nimon and Beghin (1999) employed a two-country model with vertical quality differentiation to analyze the effects of eco-labeling on the international trade of textile goods. They also assumed that only the North consumes goods and imposes a tariff on the imports from the South. However, our study differs from that of Nimon and Beghin (1999) in several ways. First, their analysis relied on numerical simulations without rigorous theoretical demonstrations. Therefore, it is difficult to determine the extent to which these findings hold in a general setting. Second, although tariffs were included in their model, they did not explicitly examine how tariff changes may alter the effects of eco-labeling on consumer and producer surpluses. Third, they did not consider producers' choices of eco-labeling. Instead, they assumed that the introduction of eco-labeling automatically creates an eco-labelled textile industry. This assumption precludes producers from adopting eco-labeling strategically to attract environmentally concerned consumers, which is a key feature of our analysis.

Abe et al. (2002) developed an international oligopoly model to examine the effects of eco-labeling on firms' profits and emissions. Similarly to our model, they assumed that the domestic country may or may not recognize foreign eco-labeling. They found that the introduction of domestic eco-labeling or the recognition of foreign eco-labeling could increase domestic emissions. Additionally, they showed that when foreign eco-labeling is not recognized, introducing domestic eco-labeling is not necessarily beneficial to domestic firms and may not harm foreign firms. Our

green firm and a brown firm, respectively. They assumed these firms produce two vertically differentiated goods with different environmental qualities. However, in contrast to our model, firm type is given exogenously in Ceccantoni et al. (2018).

study differs from that of Abe et al. (2002) in several respects. First, they assumed that when eco-labeling is introduced, the proportion of consumers who refuse to buy the non-labelled products is exogenously given and constant. However, we allow this fraction to be determined endogenously. Second, Abe et al. (2002) derived the fractions of firms adopting eco-labeling are derived numerically, whereas we obtain them in algebraic forms, which enables us to explore how these fractions respond to changes in other variables. Furthermore, Abe et al. (2002) did not consider the effects of trade liberalization on firms' adoption of eco-labeling, which is the focus of our study.

2.2 CER in international trade

Corporate environmental responsibility (CER) has been studied extensively in closed economies. Recent examples include Fukuda and Ouchida (2020), Hirose et al. (2020), Hirose and Matsumura (2022), Xu et al. (2022), Tomoda and Ouchida (2023) and Xing and Lee (2024). However, its impact on open economies remains underexplored. To the best of our knowledge, only a few studies have investigated CER within the framework of international trade (e.g., Jinji, 2013 and Bárcena-Ruiz and Sagasta, 2022, 2024).[8]

Jinji (2013) analyzed the impact of the CER on domestic welfare in the presence of emission taxes and export subsidies. He found that if these two policies are available, then the CER may decrease domestic welfare under transboundary pollution but does not affect it under local pollution. However, if only emissions taxes are available, then the CER may decrease domestic welfare under both types of pollution.

Bárcena-Ruiz and Sagasta (2022) employed an international duopoly model to investigate firms' incentives for CER when countries use emission taxes to regulate transboundary pollution, either non-cooperatively or cooperatively. They found that, in a non-cooperative setting, firms always adopt CER under local environmental damage; however, under global damage, firms adopt CER only if they are highly concerned about the environment. When taxes are determined cooperatively, both firms adopt CER in equilibrium under both local and global damage.

Bárcena-Ruiz and Sagasta (2024) studied countries' choices of emissions taxes for environment-friendly firms. They found that whether countries are motivated to impose carbon taxes depends on the extent of firms' CER and their disclosure of R&D knowledge. Under non-cooperative emission tax choices, if firms do not share their R&D knowledge, both countries impose taxes for low levels of CER, while neither does so for high levels of CER; however, if firms fully share their R&D

[8] In these studies, a firm is regarded as a CER firm if it considers how its production decisions affect the environment. A CER firm's objective function is usually given by $V = \pi - \gamma ED$, where π represents profits, ED denotes environmental damage (either local or global), and γ reflects the degree of CER commitment. In our study, a firm is regarded as a CER firm if it produces goods in a more environment-friendly manner, such as using a greener technology.

knowledge, only one country may impose emission taxes at intermediate levels of CER. Under cooperative choices of emission taxes, both countries have an incentive to impose taxes for a wider range of CER than in the non-cooperative case. In particular, with the full disclosure of R&D knowledge, both countries always implement positive taxes regardless of the degree of firms' CER.

Notably, Jinji (2013) and Bárcena-Ruiz and Sagasta (2024) did not allow for endogenous choices of the CER. Bárcena-Ruiz and Sagasta (2022) examined firms' adoption of CER in response to environmental taxes rather than tariff reductions. Moreover, these three studies did not consider heterogeneous consumers with different preferences toward the environmental friendliness of goods.

In the broader literature on corporate social responsibility (CSR) excluding environmental issues, endogenous CSR choices have not been widely examined in international trade. A few exceptions are Wang et al. (2012), Chang et al. (2014), Li et al. (2019) and Herkenhoff et al. (2024). Our study is closely related to that of Li et al. (2019), who considered heterogeneous consumers and tariffs. They employed an import-competing duopoly model with vertical product differentiation to examine the effects of consumer-oriented CSR when an importing country optimally imposes a tariff on foreign goods. In their model, firms compete in prices in the importing country's market, and a firm is regarded as a CSR firm if it aims to maximize the sum of its profits and a share of consumer surplus. The authors found that a foreign firm's CSR adoption decreases the equilibrium tariff rate, irrespective of the domestic firm's CSR status. In addition to considering environmental issues, our study differs from Li et al. (2019) in two significant ways. First, while they focused how tariffs respond to CSR adoption, our interest lies in how firms adjust their CER strategies in response to tariff reductions. Second, although Li et al. (2019) considered goods with different qualities and different preferences towards them, they did not emphasize the importance of this assumption. In their model, firms cannot choose the types of goods to produce. Therefore, there is no intrinsic connection between CSR firms and high-quality goods. In contrast, our analysis defines CER as the production of environment-friendly goods, where firms choose to undertake CER based on the price premium associated with CER goods.

3 The basic model

We construct an international duopoly model with environment-conscious consumers and firms. There are two countries, North and South, and each country has a single firm. Both North and South firms cause environmental pollution during production. Because we are primarily interested in environmental certifications and markets in the North, we assume that the goods being analyzed are consumed only in the North.[9] There are L consumers in the North who are heterogeneous regarding their preferences towards environmental friendliness of goods. This preference is indexed by a variable $\theta \in [0, \overline{\theta}]$. Assume that each consumer buys at most one unit of goods, which are considered durable goods (e.g., automobiles). A consumer of type θ obtains utility θe if they know that the good they buy is of environmental friendliness level e. However, consumers cannot directly observe e and rely on certifications issued by a credible organization.

The organization sets an environmental standard denoted by e_h. If a firm adopts CER and satisfies the standard, it is certified as a CER firm and its good as CER goods. If a firm does not adopt CER, it produces the non-CER good and is called a non-CER firm. As will be explained later, producing goods that are more environment-friendly costs more. Firms produce only one type of good. Consequently, two vertically differentiated goods with different levels of environmental friendliness exist. The environmental quality of the CER good is e_h, while that of the non-CER good is e_l, where $e_h > e_l$ holds and the subscripts h and l represent "high" and "low" qualities, respectively.[10]

Suppose that the price of the CER good is P_h and that of the non-CER good is P_l. The net utility for a consumer of type θ is given by

$$U(\theta) = \begin{cases} \theta e_h - P_h & \text{if} \quad \theta \in [\theta_h, \overline{\theta}], \\ \theta e_l - P_l & \text{if} \quad \theta \in [\theta_l, \theta_h), \\ 0 & \text{if} \quad \theta \in [0, \theta_l). \end{cases}$$

A consumer of type θ derives net utility of $\theta e_h - P_h$ if buying the CER good, $\theta e_l - P_l$ if buying the non-CER good, and zero utility if buying neither goods. Consumers with $\theta = \theta_l$ are indifferent between buying the non-CER good and neither goods, i.e., $\theta_l e_l - P_l = 0$, from which we obtain $\theta_l = \frac{P_l}{e_l}$. Similarly, consumers with $\theta = \theta_h$ are indifferent between buying the CER good and the non-CER good, i.e., $\theta_h e_h - P_h = \theta_h e_l - P_l$, implying that $\theta_h = \frac{P_h - P_l}{e_h - e_l}$. We assume $\frac{P_h}{e_h} > \frac{P_l}{e_l}$ so that $\theta_h > \theta_l$ holds.

Let $G(\theta)$ be the cumulative distribution of consumer types with $G(0) = 0$ and $G(\overline{\theta}) = 1$. Assume $G'(\theta) > 0$ for all $\theta \in [0, \overline{\theta}]$. Then the fraction of consumers who buy the CER good is $1 - G(\theta_h)$, the fraction who buy the non-CER good is $G(\theta_h) - G(\theta_l)$, and the fraction who buy neither goods is $G(\theta_l) > 0$.

[9] Our main results are valid even when there are consumers in the South. However, the presence of South consumers makes analysis involved without gaining useful insights.

[10] The CER firms may have an incentive to sell a portion of their CER goods as non-CER goods to consumers who are not environment-conscious by removing the CER label. This situation may arise if CER goods are overproduced or if the CER goods market is limited. However, we do not consider this case because our focus is on firms' decisions regarding CER adoption rather than their market strategies.

Given prices P_h and P_l, the per-capita demand for the CER good is

$$\frac{X_h}{L} = 1 - G(\theta_h) = 1 - G\left(\frac{P_h - P_l}{e_h - e_l}\right). \tag{1}$$

Here X_h is the endogenous number of consumers buying one unit of the CER good. The per-capita demand for the non-CER good is:

$$\frac{X_l}{L} = G(\theta_h) - G(\theta_l) = G\left(\frac{P_h - P_l}{e_h - e_l}\right) - G\left(\frac{P_l}{e_l}\right). \tag{2}$$

X_l is the endogenous number of consumers who buy one unit of the non-CER good. From these two demand functions, we obtain the following inverse demand functions. First, adding equation (1) to equation (2), we get

$$1 - G\left(\frac{P_l}{e_l}\right) = \frac{X_h + X_l}{L}.$$

Thus, P_l is a function of the sum $X_l + X_h$:

$$P_l = e_l G^{-1}\left(1 - \frac{X_h + X_l}{L}\right). \tag{3}$$

From equation (1), we have

$$\frac{P_h - P_l}{e_h - e_l} = G^{-1}\left(1 - \frac{X_h}{L}\right),$$

which yields

$$P_h - P_l = (e_h - e_l)G^{-1}\left(1 - \frac{X_h}{L}\right). \tag{4}$$

Using equations (3) and (4), we obtain P_h as a function of X_h/L and $(X_l + X_h)/L$:

$$P_h = (e_h - e_l)G^{-1}\left(1 - \frac{X_h}{L}\right) + e_l G^{-1}\left(1 - \frac{X_h + X_l}{L}\right).$$

For simplicity and tractability, we assume that $L = 1$ and $e_l = 1$ and that the density function $g(\theta) \equiv G'(\theta)$ is uniform over the compact support $[0, \overline{\theta}]$. Then, $G(\theta) = \theta/\overline{\theta}$ and $g(\theta) = 1/\overline{\theta}$ for all $\theta \in [0, \overline{\theta}]$. An increase in $\overline{\theta}$ implies that consumers in the North becomes more environment-conscious as a whole, which in turn can affect the market sizes of the non-CER and CER goods. Under these assumptions, the inverse demand functions for the non-CER and CER goods are respectively given by

$$P_l = \overline{\theta}(1 - X_h - X_l), \tag{5}$$

$$P_h = \overline{\theta}\left[e_h(1 - X_h) - X_l\right]. \tag{6}$$

$P_h > P_l$ implies that consumers who are more environment-conscious are willing to pay higher prices for CER goods. This price premium may encourage firms to undertake CER and produce CER goods.

Both firms have the same production technologies. For simplicity, the fixed and marginal costs of the non-CER goods are normalized to zero. Adopting CER and obtaining certifications from a reputable organization requires a firm to employ an environment-friendly technology for production and incur a fixed cost of F and a marginal cost of $c(e_h)$, where $c'(e_h) > 0$ and $c(e_l) = 0$. For simplicity and tractability, we assume $F = 0$ and $c(e_h) = \delta(e_h - e_l)$. If δ is sufficiently small, then both firms adopt CER; however, if δ is sufficiently large, then no firm adopts CER. In the following analysis, we assume that δ is not too large or too small. Additionally, the South firm must pay a specific tariff to export goods to the North. We assume for simplicity that the tariff rate is identical between the CER and the non-CER goods and is denoted by τ.

Firms have two stages of decision-making. In the first stage, given the environmental quality standard e_h, firms decide whether to adopt CER. In the second stage, they engage in the Cournot competition in the North market.[11] The game is solved via backward induction.

We examine two scenarios. In the first scenario, the certification organization operates exclusively in the North and can only verify whether the North firm meets the CER standard. Consequently, only the North firm chooses whether to undertake CER, whereas the South firm has no incentive to adopt CER. In the second scenario, the certification organization operates in both countries, allowing both firms to decide on CER adoption.

4 CER only in the North

In this section, we analyze the first scenario, in which only the North firm can choose whether to undertake CER. Specifically, we first study the two cases without and with the North firm's CER adoption. For clarity, we denote these cases as (l, l) and (h, l), respectively. In this notation, the first letter represents the North firm's CER adoption status, and the second letter represents the South firm's status, where "l"and "h" respectively indicate no CER adoption and CER adoption. We then investigate how the North firm decides on its CER adoption endogenously and how the factors such as environmental awareness and tariff reductions affect its decisions.

[11] Under Bertrand competition, given any level of e_h, the South firm would have an incentive to produce a different type of good from the North firm; otherwise, it would earn zero profit because of its higher effective marginal cost. Consequently, at most two potential equilibria can emerge as e_h increases. However, because our primary interest is in how firms' CER adoption decisions evolve, we consider Cournot competition rather than Bertrand competition in our analysis.

4.1 Case (l, l)

The profits of each firm without the North firm's CER adoption are, respectively, given by[12]

$$\pi_{ll} = P_l x_{ll},$$
$$\pi_{ll}^* = P_l x_{ll}^* - \tau x_{ll}^*.$$

Neither firm produces a CER good under (l, l) and thus $X_h = 0$. The inverse demand function for the non-CER good in Equation (5) becomes: $P_l = \overline{\theta}(1 - X_l)$ where $X_l = x_{ll} + x_{ll}^*$. In particular, given any level of P_l, an increase in $\overline{\theta}$, interpreted as increased environmental awareness in the North, increases the market size of the non-CER good, even though consumers do not purchase the CER good in this case.

The first-order conditions (FOCs) for profit maximization are[13]

$$1 - X_l - x_{ll} = 0,$$
$$1 - X_l - x_{ll}^* = \tau/\overline{\theta},$$

implying $x_{ll} = x_{ll}^* + \tau/\overline{\theta}$. For convenience, we define $\tilde{\tau} \equiv \tau/\overline{\theta}$. Solving these conditions yields the output and profit of each firm.

$$x_{ll} = \frac{1 + \tilde{\tau}}{3}, \quad \pi_l = (x_{ll})^2,$$
$$x_{ll}^* = \frac{1 - 2\tilde{\tau}}{3}, \quad \pi_l^* = (x_{ll}^*)^2.$$

We assume $\tilde{\tau} < \frac{1}{2}$ to ensure $x_{ll}^* > 0$.

As is well known in the Cournot international oligopolistic competition, a tariff reduction decreases the output and profits of the North firm but increases those of the South firm. Interestingly, an increase in $\overline{\theta}$ also generates the same effect.[14] Intuitively, given the North firm's output, the South firm expands its production in response to a larger market size for the non-CER good as $\overline{\theta}$ increases. However, the North firm's best response does not explicitly depend on $\overline{\theta}$, since its marginal production cost is zero. Because the non-CER goods are perfect substitutes, the North firm reduces its output and thus makes less profits, whereas the South firm produces more and gains higher profits.

[12] Asterisks in this paper refer to South-related variables throughout the paper.

[13] We confirm that the corresponding second-order conditions for the firms' profit maximization are satisfied throughout this paper. Therefore, we only present only FOCs in the following analysis.

[14] This result is valid even with production-related costs, as long as the North firm's effective marginal costs are lower than those of the South firm.

4.2 Case (h, l)

When the North firm adopts CER, the profits of each firm are, respectively, given by

$$\pi_{hl} = P_h x_{hl} - c(e_h)x_{hl},$$
$$\pi^*_{hl} = P_l x^*_{hl} - \tau x^*_{hl}.$$

Here, the North firm produces the CER good, while the South firm produces the non-CER good, that is, $X_h = x_{hl}$ and $X_l = x^*_{hl}$. The FOCs for profit maximization are

$$e_h(1 - X_h - x_{hl}) - X_l = \tilde{\delta}(e_h - 1),$$
$$1 - X_h - X_l - x^*_{hl} = \tilde{\tau},$$

where $\tilde{\delta} \equiv \delta/\overline{\theta}$. Using these conditions, we derive the output and profit of each firm:

$$x_{hl} = \frac{1 + \tilde{\tau} + 2(1 - \tilde{\delta})(e_h - 1)}{4e_h - 1}, \quad \pi_{hl} = e_h \left(x_{hl}\right)^2,$$
$$x^*_{hl} = \frac{e_h(1 - 2\tilde{\tau}) + \tilde{\delta}(e_h - 1)}{4e_h - 1}, \quad \pi^*_{hl} = \left(x^*_{hl}\right)^2.$$

We assume $\tilde{\delta} < 1$ so that $x_{hl} > 0$ always holds for $e_h > 1$.

The effects of a tariff decrease are conventional. A tariff reduction induces the South firm to produce more and decreases the price of the non-CER good. Consequently, consumers substitute away from the CER good and toward the non-CER good, i.e., $\partial x_{hl}/\partial\tau > 0$ and $\partial x^*_{hl}/\partial\tau < 0$. This raises the South firm's profits while reducing the North firm's profits: $\partial \pi_{hl}/\partial\tau > 0$ and $\partial \pi^*_{hl}/\partial\tau < 0$.

An increase in $\overline{\theta}$ increases the aggregate demand for both non-CER and CER goods. However, the effect on each type of good is ambiguous, as indicated by

$$\frac{\partial x_{hl}}{\partial \overline{\theta}} = \frac{1}{(4e_h - 1)\overline{\theta}^2}[2(e_h - 1)\delta - \tau], \tag{7}$$
$$\frac{\partial x^*_{hl}}{\partial \overline{\theta}} = \frac{1}{(4e_h - 1)\overline{\theta}^2}[2e_h\tau - (e_h - 1)\delta]. \tag{8}$$

This is because the best response functions of both firms are now affected by $\overline{\theta}$, which is different in the case without the North firm adopting CER. Specifically, as $\overline{\theta}$ increases, each firm has an incentive to produce more given its rival's output decisions. Therefore, the effects of $\overline{\theta}$ on the two firms' outputs and profits depend on their effective marginal costs. If $\frac{\tau}{2} < (e_h - 1)\delta < 2e_h\tau$, an increase in $\overline{\theta}$ raises both firms' outputs and profits. If $(e_h - 1)\delta > 2e_h\tau$, the North firm's output and profits increase while the South firm's output and profits decrease. Conversely, if $(e_h - 1)\delta < \frac{\tau}{2}$, the South firm's output and profits increase, whereas the North firm's output and profits decrease.

Next, we examine the effects of increasing e_h on each firm's output and profits:

$$\begin{aligned}
\frac{\partial x_{hl}}{\partial e_h} &= -\frac{2}{(4e_h-1)^2}(2\tilde{\tau}+3\tilde{\delta}-1),\\
\frac{\partial \pi_{hl}}{\partial e_h} &= \frac{1}{2}x_{hl}\left[1-\tilde{\delta}-\frac{4e_h+1}{(4e_h-1)^2}(2\tilde{\tau}+3\tilde{\delta}-1)\right],\\
\frac{\partial x^*_{hl}}{\partial e_h} &= \frac{1}{(4e_h-1)^2}(2\tilde{\tau}+3\tilde{\delta}-1),\\
\frac{\partial \pi^*_{hl}}{\partial e_h} &= \frac{2x^*_{hl}}{(4e_h-1)^2}(2\tilde{\tau}+3\tilde{\delta}-1),
\end{aligned}$$

where $\partial\frac{4e_h+1}{(4e_h-1)^2}/\partial e_h < 0$ and $\frac{4e_h+1}{(4e_h-1)^2} \in \left(0, \frac{5}{9}\right)$ in the second equation. If the cost of CER adoption is sufficiently low, i.e., $2\tilde{\tau}+3\tilde{\delta}-1 \leq 0$, an increase in e_h expands the North firm's production and contracts the South firm's production, leading to higher profits for the North firm and lower profits for the South firm. If the cost of CER adoption is sufficiently high, i.e., $2\tilde{\tau}+3\tilde{\delta}-1 > 0$, then as e_h increases, the South firm produces more and earns more profits, while the North firm produces less. However, the North firm's profits may still increase if the price premium effect outweighs the output reduction. Specifically, if $5\tilde{\tau}+12\tilde{\delta}-7 \leq 0$, then $\frac{\partial \pi_{hl}}{\partial e_h} \geq 0$ always holds. In this case, the North firm's profits monotonically increase with e_h. However, if $5\tilde{\tau}+12\tilde{\delta}-7 > 0$, then π_{hl} first decreases and then increases in e_h. In this case, the North firm benefits from CER adoption only when e_h is sufficiently large to generate a substantial price premium.

4.3 Endogenous choices of CER adoption

We now investigate how the North firm's CER adoption decisions evolve as e_h increases, by comparing $(\pi_{ll})^{\frac{1}{2}}$ and $(\pi_{hl})^{\frac{1}{2}}$:

$$(\pi_{hl})^{\frac{1}{2}} - (\pi_{ll})^{\frac{1}{2}} = \frac{2(e_h)^{\frac{1}{2}}(e_h-1)}{4e_h-1}\left\{1-\frac{4(e_h)^{\frac{1}{2}}+1}{6\left[e_h+(e_h)^{\frac{1}{2}}\right]}(1+\tilde{\tau})-\tilde{\delta}\right\}.$$

The second term in the braces increases with e_h and simplifies to $(7-5\tilde{\tau}-12\tilde{\delta})/12$ at $e_h = 1$. If $5\tilde{\tau}+12\tilde{\delta}-7 \leq 0$, the North firm always adopts CER. This finding is consistent with the earlier finding that an increase in e_h always boosts the North firm's profits within this coefficient range. However, if $5\tilde{\tau}+12\tilde{\delta}-7 > 0$, the North firm adopts CER only when $e_h > e_{h,1}$, where the threshold

$e_{h,1}$ is defined as

$$(e_{h,1})^{\frac{1}{2}} \equiv \frac{6\tilde{\delta} + 4\tilde{\tau} - 2 + \sqrt{(6\tilde{\delta} + 4\tilde{\tau} - 2)^2 + 24(1-\tilde{\delta})(1+\tilde{\tau})}}{12(1-\tilde{\delta})}. \tag{9}$$

It implies that higher CER standards encourage the North firm to adopt CER.[15] By examining the effects of τ and $\overline{\theta}$ on the threshold of the North firm's CER adoption, we have $\partial e_{h,1}/\partial \tau > 0$ and $\partial e_{h,1}/\partial \overline{\theta} < 0$.[16]

Proposition 1 *Suppose that CER is recognized only in the North and that* $\frac{7-5\tilde{\tau}}{12} < \tilde{\delta} < 1$ *holds. The North firm adopts CER at the threshold* $e_{h,1}$*. The threshold* $e_{h,1}$ *decreases as the tariff decreases or North's environmental awareness increases.*

A tariff reduction decreases the North firm's profits regardless of whether it adopts the CER. However, by adopting CER, the North firm earns a price premium for the CER good and produces less, which mitigates the negative effect of tariff reductions on its profits, as indicated by $\frac{\partial \pi_{hl}}{\partial \tau} < \frac{\partial \pi_{ll}}{\partial \tau}$. Therefore, as tariffs decline, the North firm has more incentives to adopt CER.

Without CER adoption, an increase in the North's environmental awareness decreases the North firm's profits. With CER adoption, this effect becomes ambiguous, as indicated in Equation (7). Nevertheless, adopting CER mitigates the negative effect on the North firm, i.e., $\frac{\partial \pi_{hl}}{\partial \overline{\theta}} > \frac{\partial \pi_{ll}}{\partial \overline{\theta}}$. Consequently, higher $\overline{\theta}$ encourages the North firm to adopt CER at a smaller e_h.

5 CER in both North and South

In this section, we investigate the scenario in which the South firm's CER can also be certified. Therefore, the South firm may also have an incentive to adopt CER and produce the CER goods. As each firm has two choices— adopting or not adopting CER—this framework gives rise to four possible cases: (l,l), (h,l), (l,h), and (h,h). The first two cases are examined in the previous section. In what follows, we concentrate on the remaining two cases, first studying them, respectively, and then explore firms' endogenous choices regarding CER adoption.

[15] This result depends on the assumption of a linear marginal cost for the CER. By conjecture, if the marginal cost of the CER is convex with respect to e_h, the North firm may revert to non-CER as CER standards become sufficiently high. In the literature, the effects of quality standards on the firms' adoption of high quality are mixed. Similar to our result, Belleflamme and Forlin (2020) found that higher quality standards induce more firms to produce high-quality goods. By contrast, Forlin (2021) showed that higher eco-label standards discourage firms from adopting eco-labels.

[16] All proofs of propositions and lemmas are provided in the appendix.

5.1 Case of (l, h)

In this case, the South firm adopts CER while the North firm does not. The profits of each firm are given by

$$\pi_{lh} = P_l x_{lh},$$
$$\pi^*_{lh} = P_h x^*_{lh} - c(e_h)x^*_{lh} - \tau x^*_{lh}.$$

The FOCs for profit maximization are

$$1 - X_h - X_l - x_{lh} = 0,$$
$$e_h(1 - X_h - x^*_{lh}) - X_l = \tilde{\delta}(e_h - 1) + \tilde{\tau}.$$

With these conditions and $X_h = x^*_{lh}$ and $X_l = x_{lh}$, we can derive each firm's output and profits:

$$x_{lh} = \frac{e_h + \tilde{\tau} + \tilde{\delta}(e_h - 1)}{4e_h - 1}, \quad \pi_{lh} = (x_{lh})^2,$$
$$x^*_{lh} = \frac{1 - 2\tilde{\tau} + 2(1 - \tilde{\delta})(e_h - 1)}{4e_h - 1}, \quad \pi^*_{lh} = e_h\left(x^*_{lh}\right)^2.$$

A tariff reduction induces the South firm to increase its production of the CER good, which decreases the demand for the non-CER good produced by the North firm. This effect arises because the price of the CER good decreases relative to the non-CER good, as indicated by $\frac{\partial(p_h - p_l)}{\partial\tau} > 0$. Similarly, an increase in $\overline{\theta}$ expands consumers' demand for the CER good while diminishing the demand for the non-CER good. Consequently, the South firm increases its output, whereas the North firm decreases its output.

To examine the effects of an increase in the environmental quality standard on each firm's output and profits, we obtain:

$$\frac{\partial x_{lh}}{\partial e_h} = \frac{1}{(4e_h - 1)^2}\left(3\tilde{\delta} - 4\tilde{\tau} - 1\right),$$
$$\frac{\partial \pi_{lh}}{\partial e_h} = \frac{2x_{lh}}{(4e_h - 1)^2}\left(3\tilde{\delta} - 4\tilde{\tau} - 1\right),$$
$$\frac{\partial x^*_{lh}}{\partial e_h} = \frac{2}{(4e_h - 1)^2}\left(1 - 3\tilde{\delta} + 4\tilde{\tau}\right),$$
$$\frac{\partial \pi^*_{lh}}{\partial e_h} = \frac{1}{2}x^*_{lh}\left[1 - \tilde{\delta} + \frac{4e_h + 1}{(4e_h - 1)^2}\left(1 - 3\tilde{\delta} + 4\tilde{\tau}\right)\right],$$

where $\partial\frac{4e_h+1}{(4e_h-1)^2}/\partial e_h < 0$ and $\frac{4e_h+1}{(4e_h-1)^2} \in \left(0, \frac{5}{9}\right)$. The effects depend on the values of $\tilde{\delta}$ and $\tilde{\tau}$. If

$1 - 3\tilde{\delta} + 4\tilde{\tau} \geq 0$, an increase in e_h expands the South firm's production while decreasing the North firm's production, leading to higher profits for the South firm but lower profits for the North firm. If $1 - 3\tilde{\delta} + 4\tilde{\tau} < 0$, the North firm produces more and makes more profits as e_h becomes higher. However, the South firm's production decreases. The effect on its profits is ambiguous because of the price premium associated with the CER good. If $7 - 12\tilde{\delta} + 10\tilde{\tau} > 0$, the price premium outweighs lower output and the South firm still benefits from a higher e_h. If $7 - 12\tilde{\delta} + 10\tilde{\tau} < 0$, then the overall effect on the profits depends on the value of e_h. Specifically, π^*_{lh} first decreases and then increases as e_h rises.

5.2 Case of (h, h)

In this case, both firms adopt CER. The demand for the CER good, as given in Equation (6), simplifies to $P_h = \overline{\theta} e_h (1 - X_h)$. The profit functions are given by

$$\pi_{hh} = P_h x_{hh} - c(e_h) x_{hh},$$
$$\pi^*_{hh} = P_h x^*_{hh} - c(e_h) x^*_{hh} - \tau x^*_{hh}.$$

The FOCs of the profit maximization problems are

$$e_h(1 - X_h - x_{hh}) = \tilde{\delta}(e_h - 1),$$
$$e_h(1 - X_h - x^*_{hh}) = \tilde{\delta}(e_h - 1) + \tilde{\tau}.$$

Using these conditions along with the market-clearing condition $X_h = x_{hh} + x^*_{hh}$, we derive each firm's output and profits:

$$x_{hh} = \frac{e_h + \tilde{\tau} - \tilde{\delta}(e_h - 1)}{3e_h}, \quad \pi_{hh} = e_h \left(x_{hh}\right)^2,$$
$$x^*_{hh} = \frac{e_h - 2\tilde{\tau} - \tilde{\delta}(e_h - 1)}{3e_h}, \quad \pi^*_{hh} = e_h \left(x^*_{hh}\right)^2.$$

In the CER good market, a tariff reduction enhances the competitiveness of the South firm while reducing that of the North firm. Consequently, the South firm produces more and makes more profits, whereas the North firm produces less and obtains less profits.

The effects of an increase in $\overline{\theta}$ on the output levels of the two firms are derived as

$$\frac{\partial x_{hh}}{\partial \overline{\theta}} = \frac{(e_h - 1)\delta}{3e_h \overline{\theta}^2} - \frac{\tau}{3e_h \overline{\theta}^2}, \tag{10}$$

$$\frac{\partial x_{hh}^*}{\partial \overline{\theta}} = \frac{(e_h - 1)\delta}{3e_h\overline{\theta}^2} + \frac{2\tau}{3e_h\overline{\theta}^2}.$$

As consumers become more environment-conscious, they are more willing to pay a price premium for the CER good. Therefore, given its rival's output decisions, each firm tends to produce more. However, because the CER goods are perfect substitutes, the effect on each firm's output depends on its effective marginal costs, as discussed in the previous section. Because the South firm incurs a higher marginal cost due to the tariff, its output always increases as $\overline{\theta}$ rises. This in turn decreases the North firm's output, as indicated by the second term on the right-hand side of Equation (10). The net effect on the North firm's output depends on the relative magnitudes of the positive demand effect and the negative substitution effect. If $(e_h - 1)\delta > \tau$, the positive effect dominates, and the North firm's output also increases as $\overline{\theta}$ rises. However, if $(e_h - 1)\delta < \tau$, the negative substitution effect dominates, leading to a reduction in the North firm's output.

We next examine the effects of e_h on each firm's output and profits:

$$\begin{aligned}
\frac{\partial x_{hh}}{\partial e_h} &= -\frac{\tilde{\delta}}{3e_h^2} - \frac{\tilde{\tau}}{3e_h^2}, \\
\frac{\partial \pi_{hh}}{\partial e_h} &= \frac{(1-\tilde{\delta})e_h - (\tilde{\delta} + \tilde{\tau})}{3e_h} x_{hh}, \\
\frac{\partial x_{hh}^*}{\partial e_h} &= -\frac{\tilde{\delta}}{3e_h^2} + \frac{2\tilde{\tau}}{3e_h^2}, \\
\frac{\partial \pi_{hh}^*}{\partial e_h} &= \frac{(1-\tilde{\delta})e_h + 2\tilde{\tau} - \tilde{\delta}}{3e_h} x_{hh}^*.
\end{aligned}$$

Similar to the effects of $\overline{\theta}$, an increase in e_h can also have asymmetric effects on the two firms due to their asymmetric effective marginal costs. On the one hand, an increase in e_h raises the cost of CER adoption for both firms, which tends to reduce their outputs, as reflected in the negative term $-\frac{\tilde{\delta}}{3e_h^2}$. However, as environmental quality standards become stricter, consumers who are more environment-conscious exhibit reduced sensitivity to tariffs on the imported CER good. This mitigates the negative impact of tariffs on the South firm's production, allowing it to increase its output while simultaneously reducing the North firm's market share. Since both of these effects are negative for the North firm, it produces less as e_h increases. However, the overall effect on the South firm is ambiguous because these two effects work in opposite directions. If the tariff-mitigation effect outweighs, that is, $\tilde{\delta} < 2\tilde{\tau}$, then the South firm produces more as e_h increases. The effects on the firms' profits still depend on the tension between changes in output and the price premiums. Both firms tend to benefit from a higher e_h when e_h is sufficiently large, indicating that the price premium dominates the cost increase. Moreover, the South firm tends to benefit more than the North firm, as the effect of e_h on its output is stronger than that on the North firm's output.

5.3 Endogenous choices of CER adoption

We now investigate the two firms' choice of CER adoption as e_h increases. As demonstrated earlier, if $\tilde{\delta}$ is sufficiently small, then each firm has an incentive to adopt CER regardless of its rival's decisions. Consequently, (h, h) represents the equilibrium. However, if $\tilde{\delta}$ is sufficiently large, no firm adopts CER because the effect of CER cost always dominates the price premium. Our interest is particularly in the intermediate range of $\tilde{\delta}$, specifically $\frac{7}{12} + \frac{5}{6}\tilde{\tau} < \tilde{\delta} < 1$. Within this range, an equilibrium in which only one firm adopts CER can emerge as e_h increases.

First, we need to examine which firm adopts CER first as e_h increases. Given any e_h, we have

$$\left[(\pi_{lh}^*)^{\frac{1}{2}} - (\pi_{ll}^*)^{\frac{1}{2}}\right] - \left[(\pi_{hl})^{\frac{1}{2}} - (\pi_{ll})^{\frac{1}{2}}\right] = \frac{\left[4\,(e_h)^{\frac{1}{2}} + 1\right]\left[(e_h)^{\frac{1}{2}} - 1\right]}{4e_h - 1}\tilde{\tau} > 0.$$

This implies that the South firm always benefits more from CER than the North firm. Therefore, as e_h increases, the South firm has a greater incentive to adopt CER. To confirm this result, we obtain the difference of the South firm's profits with and without CER adoption:

$$(\pi_{lh}^*)^{\frac{1}{2}} - (\pi_{ll}^*)^{\frac{1}{2}} = \frac{2(e_h)^{\frac{1}{2}}(e_h - 1)}{4e_h - 1}\left\{1 - \frac{4(e_h)^{\frac{1}{2}} + 1}{6\left[e_h + (e_h)^{\frac{1}{2}}\right]}(1 - 2\tilde{\tau}) - \tilde{\delta}\right\},$$

which is positive for $e_h > e_{h,2}$, where the threshold $e_{h,2}$ is defined as

$$(e_{h,2})^{\frac{1}{2}} \equiv \frac{6\tilde{\delta} - 8\tilde{\tau} - 2 + \sqrt{(6\tilde{\delta} - 8\tilde{\tau} - 2)^2 + 24(1 - \tilde{\delta})(1 - 2\tilde{\tau})}}{12(1 - \tilde{\delta})} < (e_{h,1})^{\frac{1}{2}}.$$

Thus, the South firm adopts CER at the threshold $e_{h,2}$. By examining the effects of τ and $\overline{\theta}$ on the threshold of the South firm's CER adoption, we have $\partial e_{h,2}/\partial \tau < 0$ and $\partial e_{h,2}/\partial \overline{\theta} < 0$.

Different from Proposition 1 where tariff reductions incentivize CER adoption, in this case, tariff reductions discourage the South firm from adopting CER. The South firm produces more and benefits from tariff reductions regardless of whether it adopts the CER. However, the South firm has a stronger incentive to adopt CER than the North firm because it has to pay tariffs, and adopting the CER mitigates the negative effect of these tariffs through the price premium of CER goods. As tariffs decline, this mitigation effect is weakened. In other words, the South firm benefits more from tariff reductions when it does not adopt CER, as indicated by $\frac{\partial \pi_{lh}^*}{\partial \tau} > \frac{\partial \pi_{ll}^*}{\partial \tau}$. Consequently, the South firm delays its CER adoption, thus requiring a higher value of e_h to make CER adoption profitable.

Higher environmental awareness in the North increases the South firm's output and profits, irrespective of its CER adoption status. Nevertheless, the South firm benefits consistently from adopting CER, as doing so not only expands its production to a greater extent but also yields a price premiums as reflected by $\frac{\partial x_{lh}^*}{\partial \overline{\theta}} > \frac{\partial x_{ll}^*}{\partial \overline{\theta}}$ and $\frac{\partial \pi_{lh}^*}{\partial \overline{\theta}} > \frac{\partial \pi_{ll}^*}{\partial \overline{\theta}}$. Consequently, an increase in $\overline{\theta}$ encourages the South firm to adopt CER at a lower level of e_h.

As e_h increases, the North firm also has an incentive to adopt CER. The difference between the North firm's profits with and without CER can be expressed as

$$(\pi_{hh})^{\frac{1}{2}} - (\pi_{lh})^{\frac{1}{2}} = \frac{(e_h - 1)\left[4(e_h)^{\frac{1}{2}} - 1\right]\left[e_h + (e_h)^{\frac{1}{2}}\right]}{3e_h(4e_h - 1)} \left\{ \frac{4(e_h)^{\frac{1}{2}} + 1}{4(e_h)^{\frac{1}{2}} - 1} \frac{e_h + \tilde{\tau}}{\left[(e_h)^{\frac{1}{2}} + 1\right]^2} - \tilde{\delta} \right\}.$$

We define $e_{h,3}$ as the threshold at which $(\pi_{hh})^{\frac{1}{2}} = (\pi_{lh})^{\frac{1}{2}}$. Thus, the North firm adopts CER at the threshold $e_{h,3}$. Although it is challenging to derive a closed-form solution for $e_{h,3}$, Appendix B shows that $e_{h,3}$ is decreasing in τ and decreasing in $\overline{\theta}$, i.e., $\partial e_{h,3}/\partial \tau < 0$ and $\partial e_{h,3}/\partial \overline{\theta} < 0$.[17]

Similarly to the South firm case, tariff reductions also discourage the North firm from adopting CER. Intuitively, lower tariffs enable the South firm to supply more CER goods to the North, thus increasing competition and making the CER good market less profitable for the North firm. In response, the North firm has an incentive to serve a market different from that of the South firm by producing the non-CER good. Although tariff reductions also decrease the profits of the non-CER good, this negative effect is smaller than that in the CER market, that is, $\frac{\partial \pi_{hh}}{\partial \tau} > \frac{\partial \pi_{lh}}{\partial \tau}$. As a result, as tariffs decline, the North firm postpones its CER adoption to mitigate potential losses.

The intuition behind the effect of $\overline{\theta}$ on the North firm's CER adoption is similar to that in Proposition 1. In the absence of CER adoption, an increase in environmental awareness in the North reduces the North firm's profits. However, when the North firm adopts CER, the effect becomes ambiguous. Nonetheless, adopting CER helps to mitigate the negative impact on the North firm, as indicated by $\frac{\partial \pi_{hh}}{\partial \overline{\theta}} > \frac{\partial \pi_{lh}}{\partial \overline{\theta}}$. Therefore, an increase in $\overline{\theta}$ encourages the North firm to adopt CER at a lower level of e_h, even when the South firm has already adopted CER.

We summarize the above findings in the following proposition.

Proposition 2 *Suppose that CER is recognized in both North and South and that* $\frac{7}{12} + \frac{5}{6}\tilde{\tau} < \tilde{\delta} < 1$ *holds. The South and the North firms, respectively, adopt CER at the thresholds* $e_{h,2}$ *and* $e_{h,3}$*, where* $e_{h,2} < e_{h,3}$ *holds. Both* $e_{h,2}$ *and* $e_{h,3}$ *increase as tariffs decrease. However, both* $e_{h,2}$ *and* $e_{h,3}$

[17] In Appendix B, we demonstrate that in the equilibrium of (h,h), the South firm has no incentive to revert to non-CER. In other words, as e_h increases, the equilibrium transitions are $(l,l) \to (l,h) \to (h,h)$. The configuration of (h,l) cannot be an equilibrium.

decrease as North's environmental awareness increases.

6 Greenhouse gas emissions

In our framework, CER adoption represents investment in environmental R&D or the usage of environment-friendly technologies for production. In this section, we specifically focus on greenhouse gas emissions, an environmental issue that has recently attracted considerable attention. For this, we assume that a firm that does not adopt CER emits one unit of greenhouse gases per unit of production, whereas CER adoption reduces its emissions per unit to $\gamma(e_h) < 1$. We further assume $\gamma'(e_h) < 0$ which indicates that stricter CER standards lead to lower emissions per unit of output.

We examine how an increase in the environmental quality standard e_h affects global emissions.[18] Our main finding in this subsection is that the effect of stricter CER standards on global emissions can be non-monotonic. In particular, a higher e_h can increase global emissions instead of mitigating them.

6.1 CER only in the North

When $1 < e_h < e_{h,1}$, the North firm does not adopt CER, and an increase in e_h has no impact on either the firm's or global emissions. However, when $e_h \geq e_{h,1}$, the North firm adopts CER, and global emissions become

$$E_{hl}^{global} = \gamma(e_h)x_{hl} + x_{hl}^*.$$

It follows from $E_{hl}^{global} < x_{hl} + x_{hl}^*$ and $\frac{\partial(x_{hl}+x_{hl}^*)}{\partial e_h} < 0$ that $E_{hl}^{global} < \frac{2-\tilde{\tau}}{3}$ for $e_h > 1$. Therefore, global emissions drop at $e_h = e_{h,1}$. Taking the derivative of E_{hl}^{global} with respect to e_h yields

$$\frac{\partial E_{hl}^{global}}{\partial e_h} = \gamma(e_h)\frac{\partial x_{hl}}{\partial e_h} + \gamma'(e_h)x_{hl} + \frac{\partial x_{hl}^*}{\partial e_h} = \frac{2\tilde{\tau} + 3\tilde{\delta} - 1}{(4e_h - 1)^2}[1 - 2\gamma(e_h)] + \gamma'(e_h)x_{hl}.$$

Once the North firm adopts CER, both its emissions per unit of production $\gamma(e_h)$ and its total output x_{hl} decrease as e_h increases, leading to lower emissions from its production. By contrast, the South firm expands its production and thus emits more. If the reduction in the North firm's emissions outweighs the increase in the South firm's emissions, global emissions decrease as the CER standards become more stringent. This scenario occurs if γ remains relatively high even after

[18] Similarly, one can analyze how an increase in e_h affects consumer surplus in the North which is given by $CS = \frac{1}{2}\overline{\theta}^2(X_l + X_h)^2 + \frac{1}{2}\overline{\theta}^2(e_h - 1)X_h^2$, where the first term represents the total consumer surplus from goods consumption and the second term captures additional gains from environmental awareness. However, these effects are generally ambiguous and hence we do not provide the details here.

CER adoption (e.g., $\gamma(e_h) \simeq 1$). Conversely, if the increase in the South firm's emissions dominates, global emissions increase with e_h. The latter scenario arises when γ is sufficiently low after CER adoption (e.g., $\gamma(e_h) \simeq 0$).

Thus, we obtain the following proposition.

Proposition 3 *Suppose that CER is recognized only in the North and* $\frac{7-5\tilde{\tau}}{12} < \tilde{\delta} < 1$ *holds. As* e_h *increases, the global emissions initially remain constant, then drop discretely at* $e_h = e_{h,1}$*, and then increase if* γ *is close to 0 but decrease if* γ *is close to 1.*

6.2 CER in the North and South

When $1 < e_h < e_{h,2}$ holds, neither firm adopts CER, and changes in e_h do not affect either the firm's or global emissions. However, when $e_h > e_{h,3}$ holds, both firms adopt CER, and global emissions are given by $E_{hh}^{global} = \gamma(e_h)(x_{hh} + x_{hh}^*)$. In this case, an increase in e_h decreases the firms' per-unit emissions and their output levels, thereby lowering the emissions of the two firms and, consequently, global emissions.

For the intermediate range $e_{h,2} < e_h < e_{h,3}$, only the South firm adopts CER, and the global emissions are

$$E_{lh}^{global} = x_{lh} + \gamma(e_h)x_{lh}^*.$$

Since $E_{lh}^{global} < x_{lh} + x_{lh}^*$ and $\frac{\partial(x_{lh}+x_{lh}^*)}{\partial e_h} < 0$, it follows that $E_{lh}^{global} < \frac{2-\tilde{\tau}}{3}$ for $e_h > 1$. Thus, global emissions decrease at $e_h = e_{h,2}$. Moreover, because $E_{lh}^{global} > \gamma(e_h)(x_{lh} + x_{lh}^*)$ and

$$(x_{lh} + x_{lh}^*) - (x_{hh} + x_{hh}^*) = \frac{e_h - 1}{3e_h(4e_h - 1)}[(5e_h - 2)\tilde{\delta} + \tilde{\tau} + e_h] > 0,$$

global emissions decline at $e_h = e_{h,3}$. Taking the derivative of E_{lh}^{global} with respect to e_h yields

$$\frac{\partial E_{lh}^{global}}{\partial e_h} = \frac{\partial x_{lh}}{\partial e_h} + \gamma(e_h)\frac{\partial x_{lh}^*}{\partial e_h} + \gamma'(e_h)x_{lh}^* = \frac{3\tilde{\delta} - 4\tilde{\tau} - 1}{(4e_h - 1)^2}[1 - 2\gamma(e_h)] + \gamma'(e_h)x_{lh}^*.$$

As e_h increases, the South firm's per-unit emissions $\gamma(e_h)$ and its total output x_{lh}^* both decline, reducing the overall emissions. Conversely, the North firm produces more and thus generates more emissions. If the reduction in the South firm's emissions outweighs the increase in the North firm's emissions, global emissions decrease as the CER standards become stricter. This scenario occurs if γ remains relatively high even after CER adoption (e.g., $\gamma(e_h) \simeq 1$). In contrast, if the increase in the North firm's emissions dominates, global emissions increase with e_h. Hence, the second scenario arises when γ is sufficiently low after CER adoption (e.g., $\gamma(e_h) \simeq 0$). Thus, we obtain the following proposition.

Proposition 4 *Suppose that CER is recognized in both North and South and that* $\frac{7}{12} + \frac{5}{6}\tilde{\tau} < \tilde{\delta} < 1$ *holds. As* e_h *increases, global emissions initially remain constant, but they then decrease discretely at* $e_h = e_{h,2}$*, and increase if* γ *is close to 0 but decrease if* γ *is close to 1, then decrease again discretely at* $e_h = e_{h,3}$*, and then decrease.*

6.3 Effects of CER recognition in the South

We have examined two scenarios in which CER is recognized only in the North and where CER is recognized in both countries, respectively. The CER adoption choices among the two firms are summarized in Figure 1. We now compare these two scenarios to understand how expanding the scope of CER recognition affects firms' outputs, profits and emissions.[19] We focus on the case with $\frac{7}{12} + \frac{5}{6}\tilde{\tau} < \tilde{\delta} < 1$.

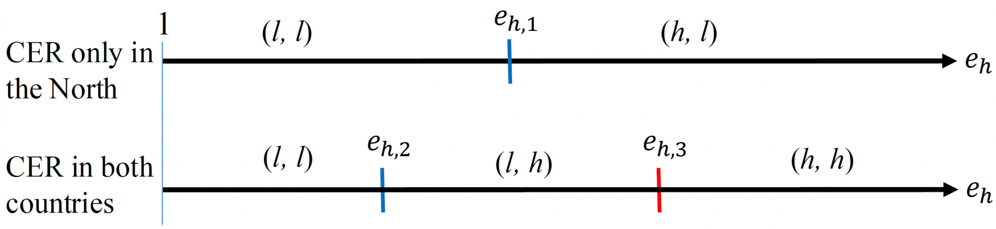

Figure 1: CER only in the North versus CER in both countries

When $1 < e_h < e_{e,2}$, neither firm adopts CER. In this interval, allowing CER recognition in the South has no effect on the firms' outputs, as both firms continue to produce the non-CER good. When $e_{e,2} < e_h < e_{e,1}$, a wider scope of CER recognition motivates the South firm to adopt CER, which subsequently reduces its own output and global production but increases the North firm's production. As a result, both firms benefit from the CER recognition in the South. Meanwhile, the North firm's emissions increase and the South firm's emissions decrease, leading to an overall reduction in global emissions.

When $e_{e,1} < e_h < e_{e,3}$, the CER recognition in the South induces the North firm to switch to non-CER production while the South firm adopts the CER. Consequently, the North firm's output and emissions both increase, whereas the South firm's output and emissions both fall. As the effects on the North firm strengthen, global production and emissions increase. The effect on profits is ambiguous. Although the North firm produces more of the non-CER good and avoids the extra

[19]See Appendix C for detailed calculations and the proof of $e_{h,1} < e_{h,3}$.

cost of the CER, it also forgoes the potential price premium; the South firm produces less but reaps the CER price premium.

When $e_h > e_{e,3}$, the South firm is again incentivized to adopt CER, reducing both its own and global production. Consequently, both the South firm's and global emissions decline. The impact on the North firm's output, and thus its profits, is ambiguous. The South firm's profit outcome is likewise uncertain, as it faces a trade-off between lower output and a higher price premium associated with the CER.

Thus, regarding global emissions, we obtain the following proposition.

Proposition 5 *Suppose that* $\frac{7}{12} + \frac{5}{6}\tilde{\tau} < \tilde{\delta} < 1$ *holds and* e_h *is given. Compared to the case of CER recognition only in the North, a wider scope of CER recognition in both countries does not affect the global emissions if* $1 < e_h < e_{e,2}$*, decreases them if* $e_{e,2} < e_h < e_{e,1}$*, increases them if* $e_{e,1} < e_h < e_{e,3}$*, and decreases them if* $e_h > e_{e,3}$*.*

7 Extension: Many firms in each country

In the previous sections, we have analyzed the impact of tariff reductions and higher environmental awareness on CER adoption assuming that there is a single firm in each country. In this section, we extend the model to consider a continuum of identical firms within a unit interval in each country. This framework provides deeper insight into how CER standards e_h affect the share of CER firms in each country.

7.1 CER only in the North

We study the first scenario in which only North firms can choose whether to undertake CER. Denote by β the share or the mass of the CER firms in the North. Then, the share or the mass of the non-CER firms is $1-\beta$ in the North and 1 in the South. A non-CER firm's profit in the North and the South and a CER firm's profit in the North are respectively given by

$$\pi_{i,l} = P_l x_{i,l},$$
$$\pi^*_{i,l} = P_l x^*_{i,l} - \tau x^*_{i,l},$$
$$\pi_{j,h} = P_h x_{j,h} - c(e_h) x_{j,h},$$

where i and j denote the representative non-CER and CER firms, respectively.

The first-order conditions (FOCs) of the profit maximization problems are

$$1 - X_h - X_l - x_{i,l} = 0,$$

$$1 - X_h - X_l - x^*_{i,l} = \tilde{\tau},$$
$$e_h(1 - X_h - x_{j,h}) - X_l = \tilde{\delta}(e_h - 1).$$

The first and second equations imply that $x^*_{i,l} = x_{i,l} - \tilde{\tau}$ holds. Because the firms are symmetric for each type, we have $X_h = \beta x_{j,h}$ and $X_l = (1-\beta)x_{i,l} + x^*_{i,l} = (2-\beta)x_{i,l} - \tilde{\tau}$. Under these conditions, we obtain the production levels of these three types of firms:

$$x_{i,l} = \frac{[e_h(1+\beta) - \beta](1+\tilde{\tau}) - \beta(1-\tilde{\delta})(e_h - 1)}{\beta + (3-\beta)[e_h(1+\beta) - \beta]}, \tag{11}$$

$$x_{j,h} = \frac{1 + \tilde{\tau} + (3-\beta)(1-\tilde{\delta})(e_h - 1)}{\beta + (3-\beta)[e_h(1+\beta) - \beta]}, \tag{12}$$

$$x^*_{i,l} = x_{i,l} - \tilde{\tau} = \frac{(e_h - 1)\beta\tilde{\delta} + e_h - [(e_h - 1)\beta(1-\beta) + 2e_h]\,\tilde{\tau}}{\beta + (3-\beta)[e_h(1+\beta) - \beta]}. \tag{13}$$

We assume that $\tilde{\tau}$ is sufficiently small so that $x^*_{i,l} > 0$ always holds. Noting $\frac{(e_h-1)\beta\tilde{\delta}+e_h}{(e_h-1)\beta(1-\beta)+2e_h} > \frac{e_h}{(e_h-1)\beta(1-\beta)+2e_h} > \frac{e_h}{\frac{1}{4}(e_h-1)+2e_h} > \frac{4}{9}$, we assume $\tilde{\tau} < \frac{4}{9}$. The profits of the three types of firms are respectively given by $\pi_{i,l} = (x_{i,l})^2$, $\pi_{j,h} = e_h(x_{j,h})^2$, and $\pi^*_{i,l} = (x^*_{i,l})^2$.

Before deriving the equilibrium of CER adoption among firms, we first investigate how firms adjust their outputs in response to changes in e_h, τ, $\overline{\theta}$, and β. The results are summarized in the following lemma.

Lemma 1 *(i)* $\frac{\partial x_{i,l}}{\partial e_h} > 0$, $\frac{\partial x^*_{i,l}}{\partial e_h} > 0$, $\frac{\partial x_{j,h}}{\partial e_h} < 0$; *(ii)* $\frac{\partial x_{i,l}}{\partial \tau} > 0$, $\frac{\partial x_{j,h}}{\partial \tau} > 0$, $\frac{\partial x^*_{i,l}}{\partial \tau} < 0$; *(iii)* $\frac{\partial x_{i,l}}{\partial \overline{\theta}} < 0$; *(iv)* $\frac{\partial x_{i,l}}{\partial \beta} > 0$, $\frac{\partial x^*_{i,l}}{\partial \beta} > 0$, $\frac{\partial x_{j,h}}{\partial \beta} < 0$.

First, stricter CER standards e_h increase the production cost of the CER goods, making them more expensive. As a result, only highly environment-conscious consumers are willing to pay for them. This reduces the demand for the CER good while increasing the demand for the non-CER good, thereby encouraging non-CER firms in both North and South to expand their production. Consequently, a higher e_h increases the profits of non-CER firms in both countries, that is, $\partial \pi_{i,l}/\partial e_h > 0$ and $\partial \pi^*_{i,l}/\partial e_h > 0$. The profits of CER firms in the North increase only when the positive effect of e_h on the price premium outweighs the negative effect on their outputs.

Second, a reduction in tariff τ lowers the cost of imports while making domestic goods, both CER and non-CER, relatively more expensive. This leads to a decrease in the demand for both types of goods in the North and an increase in the demand for the non-CER goods from the South. Consequently, a tariff reduction decreases the profits of both CER and non-CER firms in the North, while increasing the profits of non-CER firms in the South, that is, $\partial \pi_{i,l}/\partial \tau > 0$, $\partial \pi_{j,h}/\partial \tau > 0$ and $\partial \pi^*_{i,l}/\partial \tau < 0$.

Third, an increase in $\overline{\theta}$ decreases the output and profits of non-CER firms in the North, i.e., $\partial\pi_{i,l}/\partial\overline{\theta} < 0$. However, the impacts on CER firms in the North and non-CER firms in the South are ambiguous and depend on their effective marginal costs, as illustrated in the two-firm case.

Finally, given e_h, τ and $\overline{\theta}$, an increase in β, the share of CER firms in the North, makes the CER good market more competitive, reducing the output of each CER firm. Conversely, the reduced competition in the non-CER good market allows non-CER firms in both North and South to increase production. As a result, an increase in β raises the profits of non-CER firms in both countries, i.e., $\partial\pi_{i,l}/\partial\beta > 0$ and $\partial\pi^*_{i,l}/\partial\beta > 0$, while reducing the profits of the CER firms in the North, i.e., $\partial\pi_{j,h}/\partial\beta < 0$.

We now derive the equilibrium of CER adoption among firms in the North. In equilibrium with $0 < \beta < 1$, the non-CER and the CER firms in the North make the same profits. That is, $\pi_{i,l} = (x_{i,l})^2 = \pi_{j,h} = e_h(x_{j,h})^2$ holds, from which we can derive the share of the CER firms in the North as

$$\hat{\beta} = \frac{(e_h)^{\frac{1}{2}}}{1+(e_h)^{\frac{1}{2}}} \frac{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta}) - (1+\tilde{\tau})}{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})}. \tag{14}$$

To ensure $0 < \hat{\beta} < 1$, we assume e_h satisfies the following condition:

$$\frac{1+\tilde{\tau}}{3(1-\tilde{\delta})} - 1 < (e_h)^{\frac{1}{2}} < \frac{1+\tilde{\tau}}{1-\tilde{\delta}} - 1,$$

or equivalently,

$$\left[\frac{1+\tilde{\tau}}{3(1-\tilde{\delta})} - 1\right]^2 < e_h < \left(\frac{1+\tilde{\tau}}{1-\tilde{\delta}} - 1\right)^2.$$

We also assume $\frac{5-\tilde{\tau}}{6} < \tilde{\delta} < 1$, so that $\frac{1+\tilde{\tau}}{3(1-\tilde{\delta})} - 1 > 1$.

Recall that the effect of an increase in e_h on the CER firms' profits is ambiguous and depends on the CER standards of e_h and the values of the coefficients τ, δ, and $\overline{\theta}$. However, if an equilibrium exists, then this effect must be positive and greater than its effect on the non-CER firms' profits in the North. That is, $\partial\pi_{j,h}/\partial e_h > \partial\pi_{i,l}/\partial e_h$ must hold in equilibrium. For subsequent analyses, we assume that this condition holds.[20]

By examining the effects of e_h, τ and $\overline{\theta}$ on CER adoption in equilibrium, we have the following proposition.

[20]To ensure the existence of the equilibrium, we need to impose stricter assumptions on τ, δ and $\overline{\theta}$, which are not available due to the complexity of the model. However, our results hold under the loose assumptions described in this section, implying that they are valid under stricter conditions.

Proposition 6 *Suppose that there are many firms in each country and that the CER is recognized only in the North. An increase in the CER standard e_h, an increase in environmental awareness $\overline{\theta}$, and a tariff reduction each lead more North firms to adopt CER.*

In equilibrium, an increase in e_h increases the profits of both non-CER and CER firms in the North. However, the profits of CER firms increase more, as indicated by the assumption of $\partial\pi_{j,h}/\partial e_h > \partial\pi_{i,l}/\partial e_h$. This makes the production and sales of CER goods more profitable and encourages more firms in the North to adopt CER. As shown in Lemma 1, an increase in the share of CER firms decreases their profits while increasing those of non-CER firms. This adjustment continues until a new equilibrium is reached where both types of firms earn equal profits again.

In contrast, a tariff reduction increases the competitiveness of South firms, allowing them to produce and export more non-CER goods to the North. This intensified competition reduces the production and profits of both CER and non-CER firms in the North, with non-CER firms being more adversely affected in the equilibrium. That is, $\partial\pi_{i,l}/\partial\tau > \partial\pi_{j,h}/\partial\tau > 0$ holds under $\beta = \hat{\beta}$. To mitigate these losses, firms in the North have an incentive to adopt CER practices and produce the CER good.

An increase in $\overline{\theta}$ reduces the profits of the non-CER firms in the North. Although the effect on the CER firms in the North is ambiguous, it consistently exceeds the impact on the non-CER firms there, i.e., $\partial\pi_{j,h}/\partial\overline{\theta} > \partial\pi_{i,l}/\partial\overline{\theta}$. Thus, as the North becomes more environment-conscious, more firms in the North are incentivized to adopt CER to mitigate the negative effect on the non-CER firms.

7.2 CER in both North and South

We now investigate the scenario in which South firms' CER is also certified by the organization. Therefore, South firms may also have an incentive to adopt CER and produce the CER good. However, the four types of firms, North non-CER firms, North CER firms, South non-CER firms, and South CER firms, cannot co-exist in the equilibrium.

If any, the profit of a South CER firm is given by

$$\pi^*_{j,h} = P_h x^*_{j,h} - c(e_h)x^*_{j,h} - \tau x^*_{j,h}.$$

Solving the profit maximization problem yields $\pi^*_{j,h} = e_h(x^*_{j,h})^2$. Recall that the profits of a North non-CER firm, a North CER firm, and a South non-CER firm are respectively given by

$$\pi_{i,l} = (x_{i,l})^2, \quad \pi_{j,h} = e_h(x_{j,h})^2, \quad \pi^*_{i,l} = (x^*_{i,l})^2.$$

Suppose that both non-CER and CER firms exist in the North, then $\pi_{i,l} = (x_{i,l})^2 = \pi_{j,h} = e_h(x_{j,h})^2$ holds. The profit of a South firm is $\pi^*_{i,l} = (x_{i,l} - \tilde{\tau})^2$ if it does not adopt CER, and is $\pi^*_{j,h} = e_h(x_{j,h} - \frac{\tilde{\tau}}{e_h})^2$ if it adopts CER. As $\pi^*_{j,h} > \pi^*_{i,l}$ holds, all firms in the South have an incentive to adopt CER while the share of the North firms adopting CER is $\beta \in (0,1)$.

Similarly, suppose that both non-CER and CER firms exist in the South, then $\pi^*_{i,l} = (x^*_{i,l})^2 = \pi^*_{j,h} = e_h(x^*_{j,h})^2$ holds. The profit of a North firm is $\pi_{i,l} = (x^*_{i,l} + \tilde{\tau})^2$ if it does not undertake CER, and is $\pi_{j,h} = e_h(x^*_{j,h} + \frac{\tilde{\tau}}{e_h})^2$ if it undertakes CER. In this case, we obtain $\pi_{i,l} > \pi_{j,h}$, implying that no firm in the North has an incentive to adopt CER while the share of the South firms adopting CER is $\beta^* \in (0,1)$.

These two cases also indicate that South firms have more incentives to adopt CER than North firms. This is because South firms have to pay the tariff for their exports to the North. A higher marginal cost induces South firms to adopt CER at a lower level of e_h to attract environment-conscious consumers.

Thus, as e_h increases from $e_l(= 1)$, the equilibrium shifts as follows: $(0,0) \to (0,\beta^*) \to (0,1) \to (\beta,1) \to (1,1)$, where in the parentheses, the first and second numbers denote the share of CER firms in the North and South, respectively. Notably, the cases of $(0,0)$, $(0,1)$ and $(1,1)$ mirror the equilibria of (l,l), (l,h) and (h,h) in the case of two firms. In what follows, we focus on the cases of $(0,\beta^*)$ and $(\beta,1)$.

7.2.1 Case $(0,\beta^*)$

In this case, no firm adopts CER in the North while $1-\beta^*$ proportion of firms do not adopt CER and β^* proportion of firms adopt CER in the South. The corresponding profit functions for these three types of firms are

$$\pi_{i,l} = P_l x_{i,l},$$
$$\pi^*_{i,l} = P_l x^*_{i,l} - \tau x^*_{i,l},$$
$$\pi^*_{j,h} = P_h x^*_{j,h} - c(e_h)x^*_{j,h} - \tau x^*_{j,h}.$$

The FOCs are

$$1 - X_h - X_l - x_{i,l} = 0,$$
$$1 - X_h - X_l - x^*_{i,l} = \tilde{\tau},$$
$$e_h(1 - X_h - x^*_{j,h}) - X_l = \tilde{\delta}(e_h - 1) + \tilde{\tau}.$$

The first and second equations imply that $x_{i,l} = x^*_{i,l} + \tilde{\tau}$ holds. Because the firms are symmetric for each type, we have $X_h = \beta^* x^*_{j,h}$ and $X_l = x_{i,l} + (1-\beta^*)x^*_{i,l} = (2-\beta^*)x^*_{i,l} + \tilde{\tau}$. Considering these factors, the FOCs yield

$$x^*_{i,l} = \frac{[e_h(1+\beta^*) - \beta^*](1-2\tilde{\tau}) - \beta^*(1-\tilde{\delta})(e_h - 1)}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]}, \tag{15}$$

$$x^*_{j,h} = \frac{1 - 2\tilde{\tau} + (3-\beta^*)(1-\tilde{\delta})(e_h - 1)}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]}, \tag{16}$$

$$x_{i,l} = x^*_{i,l} + \tilde{\tau} = \frac{(e_h - 1)\beta^*\tilde{\delta} + e_h + [(e_h-1)(1+\beta^*)(1-\beta^*) + 1]\,\tilde{\tau}}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]}. \tag{17}$$

The profits of the three types of firms are respectively given by $\pi^*_{i,l} = (x^*_{i,l})^2$, $\pi^*_{j,h} = e_h(x^*_{j,h})^2$, and $\pi_{i,l} = (x_{i,l})^2$.

Before deriving the equilibrium of CER adoption among firms in the South, we first investigate how firms respond to changes in e_h, τ, $\overline{\theta}$, and β^* by adjusting their outputs. The results are summarized in the following lemma.

Lemma 2 *(i)* $\frac{\partial x^*_{i,l}}{\partial e_h} > 0$, $\frac{\partial x_{i,l}}{\partial e_h} > 0$, $\frac{\partial x^*_{j,h}}{\partial e_h} < 0$*; (ii)* $\frac{\partial x^*_{i,l}}{\partial \tau} < 0$, $\frac{\partial x^*_{j,h}}{\partial \tau} < 0$, $\frac{\partial x_{i,l}}{\partial \tau} > 0$*; (iii)* $\frac{\partial x^*_{j,h}}{\partial \overline{\theta}} > 0$, $\frac{\partial x_{i,l}}{\partial \overline{\theta}} < 0$*; (iv)* $\frac{\partial x^*_{i,l}}{\partial \beta^*} > 0$, $\frac{\partial x_{i,l}}{\partial \beta^*} > 0$, $\frac{\partial x^*_{j,h}}{\partial \beta^*} < 0$.

The intuition behind Lemma 2 is similar to that behind Lemma 1. First, an increase in e_h raises the production cost of the CER good in the South, making them more expensive. This reduces the demand for the CER good and CER firms' outputs in the South, while increasing the demand for the non-CER good, thereby encouraging non-CER firms in both North and South to produce more. As a result, a higher e_h increases the profits of non-CER firms in both countries, i.e., $\partial\pi_{i,l}/\partial e_h > 0$ and $\partial\pi^*_{i,l}/\partial e_h > 0$. For CER firms in the South, their profits increase only when the positive effect of e_h on the price premium outweighs the negative effect on outputs.

Second, tariff reductions lower the cost of importing both CER and non-CER goods from the South, while making the non-CER good in the North relatively more expensive. This in turn decreases the demand for the non-CER good in the North and increases demand for both types of goods from the South. Consequently, a tariff reduction decreases the profits of non-CER firms in the North, while increasing the profits of both CER and non-CER firms in the South, i.e., $\partial\pi_{i,l}/\partial\tau > 0$, $\partial\pi^*_{i,l}/\partial\tau < 0$ and $\partial\pi^*_{j,h}/\partial\tau < 0$.

Third, an increase in $\overline{\theta}$ raises the output and profits of the CER firms in the South, while reducing those of the non-CER firms in the North, i.e., $\partial\pi^*_{j,h}/\partial\overline{\theta} > 0$ and $\partial\pi_{i,l}/\partial\overline{\theta} < 0$. However, the impact on the non-CER firms in the South is ambiguous, depending on their effective marginal costs, as illustrated in the case of two firms.

Finally, given e_h, τ, and $\overline{\theta}$, an increase in β^*, the share of CER firms in the South, makes the CER good market more competitive, reducing the output of each CER firm. Conversely, the reduced competition in the non-CER good market allows non-CER firms in both North and South to expand production. As a result, an increase in β^* raises the profits of non-CER firms in both countries, i.e., $\partial \pi_{i,l}/\partial \beta^* > 0$ and $\partial \pi_{i,l}^*/\partial \beta^* > 0$, while reducing the profits of the CER firms in the South, i.e., $\partial \pi_{j,h}^*/\partial \beta^* < 0$.

Next, we derive the equilibrium with CER adoption among firms in the South. In an equilibrium with $0 < \beta^* < 1$, the non-CER and the CER firms in the South make the same profits. That is, $\pi_{i,l}^* = (x_{i,l}^*)^2 = \pi_{j,h}^* = e_h (x_{j,h}^*)^2$ holds, from which we can derive the share of the CER firms in the South as

$$\hat{\beta}^* = \frac{(e_h)^{\frac{1}{2}}}{1 + (e_h)^{\frac{1}{2}}} \frac{3\left[1 + (e_h)^{\frac{1}{2}}\right](1 - \tilde{\delta}) - (1 - 2\tilde{\tau})}{1 - 2\tilde{\tau} + \left[(e_h)^{\frac{1}{2}} - 1\right](1 - \tilde{\delta})}. \tag{18}$$

To ensure $0 < \hat{\beta}^* < 1$, e_h needs to satisfy

$$\frac{1 - 2\tilde{\tau}}{3(1 - \tilde{\delta})} - 1 < (e_h)^{\frac{1}{2}} < \frac{1 - 2\tilde{\tau}}{1 - \tilde{\delta}} - 1,$$

or equivalently,

$$\left[\frac{1 - 2\tilde{\tau}}{3(1 - \tilde{\delta})} - 1\right]^2 < e_h < \left(\frac{1 - 2\tilde{\tau}}{1 - \tilde{\delta}} - 1\right)^2.$$

We assume $\frac{5+2\tilde{\tau}}{6} < \tilde{\delta} < 1$, so that $\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1 > 1$. Again, to ensure the existence of the equilibrium, we assume that $\partial \pi_{j,h}^*/\partial e_h > \partial \pi_{i,l}^*/\partial e_h$ holds in equilibrium. Notably, the threshold at which South firms begin adopting CER is lower than the corresponding threshold for North firms in the previous section, i.e., $\left[\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1\right]^2 < \left[\frac{1+\tilde{\tau}}{3(1-\tilde{\delta})} - 1\right]^2$. This result arises due to the existence of tariffs. It indicates that, compared with North firms, South firms have more incentive to adopt CER, as doing so mitigates the negative effects of tariffs on their profits.

By investigating the effects of stricter CER standards, tariff reductions and higher environmental awareness on CER adoption among South firms, we have the following proposition.

Proposition 7 *Suppose that there are many firms in each country and that the CER is recognized in both North and South. An increase in e_h or $\overline{\theta}$ encourages more South firms to undertake CER. However, a tariff reduction discourages CER among South firms.*

Similar to the case in which CER is recognized only in the North, an increase in e_h encourages CER among South firms. Again, this is because although an increase in e_h raises the profits of both non-CER and CER firms in the South, the profits of CER firms increase more, as indicated by assuming $\partial\pi^*_{j,h}/\partial e_h > \partial\pi^*_{i,l}/\partial e_h$. Consequently, more firms in the South adopt CER to produce and supply CER goods. As Lemma 2 indicates, an increase in the share of CER firms decreases their profits while increasing those of non-CER firms. This adjustment continues until a new equilibrium is reached where both types of firms earn equal profits.

In contrast, a tariff decrease induces the South firms to produce more, regardless of whether they adopt CER or not, as indicated by $\partial x^*_{i,l}/\partial\tau < 0$ and $\partial x^*_{j,h}/\partial\tau < 0$. However, at equilibrium, non-CER firms in the South benefit more because they are more affected by the tariffs, i.e., $\partial\pi^*_{i,l}/\partial\tau - \partial\pi^*_{j,h}/\partial\tau < 0$ holds under $\beta^* = \hat{\beta}^*$. Consequently, a tariff reduction discourages South firms from adopting CER until a new equilibrium is established.

An increase in $\overline{\theta}$ raises the profits of the CER firms in the South. Although its effect on the non-CER firms in the South is ambiguous, it is always dominated by the positive effects on the CER firms, as reflected in $\partial\pi^*_{j,h}/\partial\overline{\theta} > \partial\pi^*_{i,l}/\partial\overline{\theta}$. Hence, as $\overline{\theta}$ increases, more firms in the South adopt CER to capture these additional benefits.

7.2.2 Case $(\beta, 1)$

In this case, all the firms in the South and a mass of β firms in the North undertake CER and produce the CER good, while the remaining $1-\beta$ proportion of firms in the North produce the non-CER good. The profit functions for these three types of firms are

$$\begin{aligned}
\pi_{i,l} &= P_l x_{i,l}, \\
\pi_{j,h} &= P_l x_{j,h} - c(e_h)x_{j,h}, \\
\pi^*_{j,h} &= P_h x^*_{j,h} - c(e_h)x^*_{j,h} - \tau x^*_{j,h}.
\end{aligned}$$

The FOCs are

$$\begin{aligned}
1 - X_h - X_l - x_{i,l} &= 0, \\
e_h(1 - X_h - x_{j,h}) - X_l &= \tilde{\delta}(e_h - 1), \\
e_h(1 - X_h - x^*_{j,h}) - X_l &= \tilde{\delta}(e_h - 1) + \tilde{\tau}.
\end{aligned}$$

The second and third conditions imply that $x^*_{j,h} = x_{j,h} - \frac{\tilde{\tau}}{e_h}$. Because the firms are symmetric for each type, we have $X_l = (1-\beta)x_{i,l}$ and $X_h = \beta x_{j,h} + x^*_{j,h} = (1+\beta)x_{j,h} - \frac{\tilde{\tau}}{e_h}$. Taking them into account, the FOCs yield

$$x_{i,l} = \frac{(2+\beta)(e_h+\tilde{\tau}) - (1+\beta)(1-\tilde{\delta})(e_h-1) - (1+\beta)(1+\tilde{\tau})}{e_h(2+\beta)(2-\beta) - (1+\beta)(1-\beta)},$$

$$x_{j,h} = \frac{(2-\beta)(1-\tilde{\delta})(e_h-1) + (2-\beta)(1+\tilde{\tau}) - (1-\beta)(e_h+\tilde{\tau})(e_h)^{-1}}{e_h(2+\beta)(2-\beta) - (1+\beta)(1-\beta)},$$

$$x^*_{j,h} = \frac{(2-\beta)(1-\tilde{\delta})(e_h-1) + 1 - (1+\beta)(2-\beta)\tilde{\tau} + \beta(1-\beta)\tilde{\tau}(e_h)^{-1}}{e_h(2+\beta)(2-\beta) - (1+\beta)(1-\beta)}.$$

The profits of the three types of firms are respectively given by $\pi_{i,l} = (x_{i,l})^2$, $\pi_{j,h} = e_h(x_{j,h})^2$ and $\pi^*_{j,h} = e_h(x^*_{j,h})^2$.

Before deriving the equilibrium of CER adoption among firms in the North, we first investigate how firms respond to changes in e_h, τ, $\overline{\theta}$ and β by adjusting their outputs. The results are summarized in the following lemma.

Lemma 3 *(i)* $\frac{\partial x_{i,l}}{\partial e_h} > 0$, $\frac{\partial x_{j,h}}{\partial e_h} < 0$; *(ii)* $\frac{\partial x_{i,l}}{\partial \tau} > 0$, $\frac{\partial x_{j,h}}{\partial \tau} > 0$, $\frac{\partial x^*_{j,h}}{\partial \tau} < 0$; *(iii)* $\frac{\partial x_{i,l}}{\partial \overline{\theta}} < 0$, $\frac{\partial x_{j,h}}{\partial \overline{\theta}} > 0$, $\frac{\partial x^*_{j,h}}{\partial \overline{\theta}} > 0$; *(iv)* $\frac{\partial x_{i,l}}{\partial \beta} > 0$, $\frac{\partial x_{j,h}}{\partial \beta} < 0$, $\frac{\partial x^*_{j,h}}{\partial \beta} < 0$.

Similarly to Lemmas 1 and 2, an increase in e_h raises the production cost of the CER good in the North, making them more expensive. This reduces the demand for the CER good and CER firms' outputs in the North, while increasing the demand for the non-CER good in the North, thereby encouraging non-CER firms in the North to produce more.[21] As a result, higher e_h increases the profits of non-CER firms in the North, i.e., $\partial\pi_{i,l}/\partial e_h > 0$. For CER firms in the North, their profits increase only when the positive effect of e_h on the price premium outweighs the negative effect on outputs.

Second, a tariff reduction lowers the cost of importing the CER good from the South, while making both non-CER and CER goods in the North relatively more expensive. This in turn decreases the demand for both types of goods in the North and increases the demand for the CER good from the South. Consequently, a tariff reduction decreases the profits of both non-CER and CER firms in the North, while increasing the profits of CER firms in the South, i.e., $\partial\pi_{i,l}/\partial\tau > 0$, $\partial\pi_{j,h}/\partial\tau > 0$ and $\partial\pi^*_{j,h}/\partial\tau < 0$.

Third, an increase in $\overline{\theta}$ heightens the demand for the CER good. Therefore, the CER firms in both North and South produce more, whereas the non-CER firms in the North produce less. As a result, a higher $\overline{\theta}$ raises the profits of the CER firms in both countries and lowers the profits of the non-CER firms in the North, i.e., $\partial\pi_{i,l}/\partial\overline{\theta} < 0$, $\partial\pi_{j,h}/\partial\overline{\theta} > 0$, $\partial\pi^*_{j,h}/\partial\overline{\theta} > 0$.

[21] We demonstrate in Appendix H that $\frac{\partial x^*_{j,h}}{\partial e_h} < 0$ holds under $\tilde{\tau} < \frac{1}{3}$.

Finally, given e_h, τ and $\overline{\theta}$, an increase in β, the share of CER firms in the North, makes the CER good market more competitive, thereby reducing the output of each CER firm. Conversely, the reduced competition in the non-CER good market allows non-CER firms in the North to produce more. As a result, an increase in β raises the profits of non-CER firms in the North, i.e., $\partial\pi_{i,l}/\partial\beta > 0$, while reducing the profits of the CER firms in both countries, i.e., $\partial\pi_{j,h}/\partial\beta < 0$, $\partial\pi^*_{j,h}/\partial\beta < 0$.

We now derive the equilibrium of CER adoption among firms in the North, given that all the South firms have adopted CER. In equilibrium with $0 < \beta < 1$, the non-CER and the CER firms in the North make the same profits. That is, $\pi_{i,l} = (x_{i,l})^2 = \pi_{j,h} = e_h(x_{j,h})^2$ holds, from which we can derive the share of the CER firms in the North as

$$\hat{\beta}' = \frac{1 + 2(e_h)^{\frac{1}{2}}}{1 + (e_h)^{\frac{1}{2}}} \frac{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}}{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}}. \tag{19}$$

To ensure $0 < \hat{\beta}' < 1$, e_h needs to satisfy

$$\frac{\tilde{\delta} + \sqrt{\tilde{\delta}^2 - 4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} < (e_h)^{\frac{1}{2}} < \frac{3\tilde{\delta} + \sqrt{9\tilde{\delta}^2 + 4(1-\tilde{\delta})(2\tilde{\delta} - \tilde{\tau})}}{2(1-\tilde{\delta})},$$

or equivalently,

$$\left[\frac{\tilde{\delta} + \sqrt{\tilde{\delta}^2 - 4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}\right]^2 < e_h < \left[\frac{3\tilde{\delta} + \sqrt{9\tilde{\delta}^2 + 4(1-\tilde{\delta})(2\tilde{\delta} - \tilde{\tau})}}{2(1-\tilde{\delta})}\right]^2.$$

Note that $9\tilde{\delta}^2 + 4(1-\tilde{\delta})(2\tilde{\delta} - \tilde{\tau}) > \tilde{\delta}^2 - 4(1-\tilde{\delta})\tilde{\tau} > 0$, because $\tilde{\delta} > \frac{5+2\tilde{\tau}}{6}$.[22] Again, to ensure the existence of the equilibrium, we assume that $\partial\pi_{j,h}/\partial e_h > \partial\pi_{i,l}/\partial e_h$ holds in equilibrium.

By investigating the effects of stricter CER standards, tariff reductions, and higher environmental awareness of CER adoption among North firms, we have the following proposition.

Proposition 8 *Suppose that there are many firms in each country and that the CER is recognized in both North and South. An increase in e_h or $\overline{\theta}$ encourages more North firms to undertake CER. However, a tariff reduction discourages the CER among North firms.*

Similar to Proposition 6, an increase in e_h or $\overline{\theta}$ encourages CER among North firms. Notably, stronger environmental awareness induces more firms in the North to adopt CER, as doing so not only expands their output but also generates a price premium in this case. However, unlike

[22]See Appendix J for the proof of $\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} > \frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1$.

Proposition 6, a decrease in tariffs discourages CER among North firms. As shown in Lemma 3, a tariff reduction decreases the profits of both the CER and non-CER firms in the North because they produce less. However, in equilibrium, non-CER firms in the North experience fewer losses because they are less affected by the tariffs, i.e., $\partial\pi_{i,l}/\partial\tau - \partial\pi_{j,h}/\partial\tau < 0$ holds under $\beta = \hat{\beta}'$. Consequently, a tariff reduction induces more firms in the North to produce the non-CER good and discourages them from adopting CER until a new equilibrium is reached.

8 Conclusion

We employed a North-South trade model to investigate firms' decisions regarding corporate environmental responsibility (CER) practices when consumers are environment-conscious and willing to pay more for environment-friendly goods. We found that higher CER standards and environmental awareness can promote CER among firms, irrespective of whether CER is recognized only in the North or in both countries. However, the impact of trade liberalization on CER adoption depends on the scope of CER recognition. When CER is recognized only in North, a tariff reduction encourages CER among North firms. Conversely, when CER is recognized in both North and South, a tariff reduction discourages its adoption.

In the main part, we assumed a uniform distribution of consumers across $[0, \overline{\theta}]$, which implies that the mass of consumers with different environmental awareness is the same. However, it is possible to extend the analysis to incorporate non-uniform consumer distributions. For instance, the distribution could be skewed towards low or high values of θ, indicating that consumers are disproportionately less or more environmentally concerned, respectively. Incorporating different consumer distributions alters the relative market sizes for both non-CER and CER goods, thereby affecting the threshold values of e_h at which firms begin to embrace CER and the specific shares of CER firms given any value of e_h. For instance, if a disproportionately large mass of consumers care about the environmental friendliness of goods, then firms would have a greater incentive to adopt CER to capture a larger environment-conscious market. Despite these effects, introducing different distributions of consumers would not affect the sequence of firms' CER adoption, because it does not provide any new incentive for the firms to change their strategy. As a result, when the South firms' CER is also certified and recognized, the South firms would still have a stronger incentive for CER than the North firms due to tariffs, which is consistent with the findings under the uniform distribution.

Appendix

Appendix A: Proof of Proposition 1

In this appendix, we first demonstrate $\frac{\partial e_{h,1}}{\partial \tau} > 0$ and $\frac{\partial e_{h,1}}{\partial \overline{\theta}} < 0$. For convenience, we restate the difference between the North firm's profits with and without CER adoption:

$$(\pi_{hl})^{\frac{1}{2}} - (\pi_{ll})^{\frac{1}{2}} = \frac{2(e_h)^{\frac{1}{2}}(e_h - 1)}{(4e_h - 1)\overline{\theta}} \left\{ \overline{\theta} - \frac{4(e_h)^{\frac{1}{2}} + 1}{6\left[e_h + (e_h)^{\frac{1}{2}}\right]}(\overline{\theta} + \tau) - \delta \right\}.$$

Define the function $f((e_h)^{\frac{1}{2}}) \equiv \overline{\theta} - \frac{4(e_h)^{\frac{1}{2}}+1}{6\left[e_h+(e_h)^{\frac{1}{2}}\right]}(\overline{\theta} + \tau)$. Assuming that $\frac{7-5\tilde{\tau}}{12} < \tilde{\delta} < 1$ holds, we can verify that $f(1) = \frac{7\overline{\theta}-5\tau}{12} < \delta$ and $f(+\infty) = \overline{\theta} > \delta$. Moreover, we have

$$\frac{\partial f((e_h)^{\frac{1}{2}})}{\partial (e_h)^{\frac{1}{2}}} = \frac{(\overline{\theta} + \tau)\left[4e_h + 2(e_h)^{\frac{1}{2}} + 1\right]}{6\left[e_h + (e_h)^{\frac{1}{2}}\right]^2} > 0,$$

implying that $f((e_h)^{\frac{1}{2}})$ is increasing in $(e_h)^{\frac{1}{2}}$ and hence in e_h. Therefore, $e_{h,1}$ is the unique solution to the equation $f((e_h)^{\frac{1}{2}}) = \delta$. Furthermore, we obtain that

$$\frac{\partial f((e_h)^{\frac{1}{2}})}{\partial \tau} < 0, \quad \frac{\partial f((e_h)^{\frac{1}{2}})}{\partial \overline{\theta}} > 0,$$

which indicate that, for any given level of e_h, a decrease in τ increases $f((e_h)^{\frac{1}{2}})$, and an increase in $\overline{\theta}$ also increases $f((e_h)^{\frac{1}{2}})$. Consequently, both a lower τ and a higher $\overline{\theta}$ lead to a lower threshold value of e_h at which $f((e_h)^{\frac{1}{2}}) = \delta$. That is, $\frac{\partial e_{h,1}}{\partial \tau} > 0$ and $\frac{\partial e_{h,1}}{\partial \overline{\theta}} < 0$ hold.

Then, we demonstrate that adopting CER mitigates the negative effect of tariff reductions on the North firm's profits. That is, $\frac{\partial \pi_{hl}}{\partial \tau} < \frac{\partial \pi_{ll}}{\partial \tau}$ holds. The effects of tariffs on the North firm's profits without and with CER adoption and the difference between them are given by

$$\begin{aligned} \frac{\partial \pi_{ll}}{\partial \tau} &= 2x_{ll}\frac{\partial x_{ll}}{\partial \tau} = \frac{2}{3\overline{\theta}}x_{ll} > 0, \\ \frac{\partial \pi_{hl}}{\partial \tau} &= 2e_h x_{hl}\frac{\partial x_{hl}}{\partial \tau} = \frac{2e_h}{(4e_h - 1)\overline{\theta}}x_{hl} > 0, \\ \frac{\partial \pi_{hl}}{\partial \tau} - \frac{\partial \pi_{ll}}{\partial \tau} &= \frac{2}{3\overline{\theta}}\left(\frac{3e_h}{4e_h - 1}x_{hl} - x_{ll}\right). \end{aligned}$$

In the third equation, since $\frac{3e_h}{4e_h-1} < 1$ and $x_{hl} < x_{ll}$ under the condition of $\frac{7-5\tilde{\tau}}{12} < \tilde{\delta} < 1$, we have $\frac{\partial \pi_{hl}}{\partial \tau} < \frac{\partial \pi_{ll}}{\partial \tau}$.

Last, we demonstrate that adopting CER mitigates the negative effect of a higher $\overline{\theta}$ on the North firm's profits. That is, $\frac{\partial \pi_{hl}}{\partial \overline{\theta}} > \frac{\partial \pi_{ll}}{\partial \overline{\theta}}$ holds. The effects of $\overline{\theta}$ on the North firm's profits without and with CER adoption and the difference between them are given by

$$\frac{\partial \pi_{ll}}{\partial \overline{\theta}} = 2x_{ll}\frac{\partial x_{ll}}{\partial \overline{\theta}} = -\frac{2\tilde{\tau}}{3\overline{\theta}}x_{ll} < 0,$$
$$\frac{\partial \pi_{hl}}{\partial \overline{\theta}} = 2e_h x_{hl}\frac{\partial x_{hl}}{\partial \overline{\theta}} = \frac{2e_h x_{hl}}{(4e_h-1)\overline{\theta}}\left[2(e_h-1)\tilde{\delta} - \tilde{\tau}\right],$$
$$\frac{\partial \pi_{hl}}{\partial \overline{\theta}} - \frac{\partial \pi_{ll}}{\partial \overline{\theta}} = \frac{4e_h(e_h-1)\tilde{\delta}}{(4e_h-1)\overline{\theta}}x_{hl} + \frac{2\tilde{\tau}}{3\overline{\theta}}\left(x_{ll} - \frac{3e_h}{4e_h-1}x_{hl}\right).$$

In the third equation, since $\frac{3e_h}{4e_h-1} < 1$ and $x_{hl} < x_{ll}$ under the condition of $\frac{7-5\tilde{\tau}}{12} < \tilde{\delta} < 1$, the second term of this equation is positive and hence we have $\frac{\partial \pi_{hl}}{\partial \overline{\theta}} > \frac{\partial \pi_{ll}}{\partial \overline{\theta}}$.

Appendix B: Proof of Proposition 2

Appendix B.1: Effects of τ and $\overline{\theta}$ on $e_{h,2}$

In this appendix, we first demonstrate $\frac{\partial e_{h,2}}{\partial \tau} < 0$ and $\frac{\partial e_{h,2}}{\partial \overline{\theta}} < 0$. For convenience, we restate the difference between the South firm's profits with and without CER adoption:

$$(\pi_{lh}^*)^{\frac{1}{2}} - (\pi_{ll}^*)^{\frac{1}{2}} = \frac{2(e_h)^{\frac{1}{2}}(e_h-1)}{(4e_h-1)\overline{\theta}}\left\{\overline{\theta} - \frac{4(e_h)^{\frac{1}{2}}+1}{6\left[e_h+(e_h)^{\frac{1}{2}}\right]}(\overline{\theta}-2\tau) - \delta\right\}.$$

Define the function $g((e_h)^{\frac{1}{2}}) \equiv \overline{\theta} - \frac{4(e_h)^{\frac{1}{2}}+1}{6\left[e_h+(e_h)^{\frac{1}{2}}\right]}(\overline{\theta}-2\tau)$.Asuming $\frac{7+10\tilde{\tau}}{12} < \tilde{\delta} < 1$, we can verify that $g(1) = \frac{7\overline{\theta}+10\tau}{12} < \delta$ and $g(+\infty) = \overline{\theta} > \delta$. Moreover, with $\tilde{\tau} = \frac{\tau}{\overline{\theta}} < \frac{1}{2}$, we also have

$$\frac{\partial g((e_h)^{\frac{1}{2}})}{\partial (e_h)^{\frac{1}{2}}} = \frac{(\overline{\theta}-2\tau)\left[4e_h+2(e_h)^{\frac{1}{2}}+1\right]}{6\left[e_h+(e_h)^{\frac{1}{2}}\right]^2} > 0,$$

implying that $g((e_h)^{\frac{1}{2}})$ is increasing in $(e_h)^{\frac{1}{2}}$ and hence in e_h. Therefore, $e_{h,2}$ is the unique solution to the equation $g((e_h)^{\frac{1}{2}}) = \delta$. Furthermore, we obtain that

$$\frac{\partial g((e_h)^{\frac{1}{2}})}{\partial \tau} > 0, \quad \frac{\partial g((e_h)^{\frac{1}{2}})}{\partial \overline{\theta}} > 0,$$

which indicate that, for any given level of e_h, a decrease in τ decreases $g((e_h)^{\frac{1}{2}})$, and an increase in $\overline{\theta}$ increases it. Consequently, a lower τ leads to a higher threshold value of e_h, and a higher $\overline{\theta}$ leads to a lower threshold value of e_h at which $g((e_h)^{\frac{1}{2}}) = \delta$. Hence, we conclude $\frac{\partial e_{h,2}}{\partial \tau} < 0$ and $\frac{\partial e_{h,2}}{\partial \overline{\theta}} < 0$.

Then, we demonstrate that at the threshold of $e_{h,2}$, as tariffs decline, the South firm benefits more if it does not adopt CER. That is, $\frac{\partial \pi^*_{lh}}{\partial \tau} > \frac{\partial \pi^*_{ll}}{\partial \tau}$ holds under $e_h = e_{h,2}$. Given that the North firm does not adopt CER, the effects of tariffs on the South firm's profits without and with CER adoption are given by

$$\begin{aligned}
\frac{\partial \pi^*_{ll}}{\partial \tau} &= 2x^*_{ll}\frac{\partial x^*_{ll}}{\partial \tau} = -\frac{4}{3\overline{\theta}}x^*_{ll} < 0, \\
\frac{\partial \pi^*_{lh}}{\partial \tau} &= 2e_h x^*_{lh}\frac{\partial x^*_{lh}}{\partial \tau} = -\frac{4e_h}{(4e_h-1)\overline{\theta}}x^*_{lh} < 0.
\end{aligned}$$

At the threshold of $e_{h,2}$, $\pi^*_{ll} = (x^*_{ll})^2 = \pi^*_{lh} = e_{h,2}(x^*_{lh})^2$ holds, implying $x^*_{ll} = (e_{h,2})^{\frac{1}{2}}x^*_{lh}$. Therefore, under $e_h = e_{h,2}$, we have

$$\frac{\partial \pi^*_{lh}}{\partial \tau} - \frac{\partial \pi^*_{ll}}{\partial \tau} = \frac{4x^*_{ll}}{3(4e_{h,2}-1)\overline{\theta}}\left[4(e_{h,2})^{\frac{1}{2}}+1\right]\left[(e_{h,2})^{\frac{1}{2}}-1\right] > 0.$$

Last, we demonstrate that at the threshold of $e_{h,2}$, an increase in $\overline{\theta}$ yields a greater rise in the South firm's output and profits if it adopts CER, compared to not adopting CER. That is, $\frac{\partial x^*_{lh}}{\partial \overline{\theta}} > \frac{\partial x^*_{ll}}{\partial \overline{\theta}}$ and $\frac{\partial \pi^*_{lh}}{\partial \overline{\theta}} > \frac{\partial \pi^*_{ll}}{\partial \overline{\theta}}$ hold. Given that the North firm does not adopt CER, the effects of $\overline{\theta}$ on the South firm's output and profits without and with CER adoption are given by

$$\begin{aligned}
\frac{\partial x^*_{ll}}{\partial \overline{\theta}} &= \frac{2\tilde{\tau}}{3\overline{\theta}} > 0, \\
\frac{\partial x^*_{lh}}{\partial \overline{\theta}} &= \frac{2}{(4e_h-1)\overline{\theta}}\left[\tilde{\tau}+(e_h-1)\tilde{\delta}\right] > 0, \\
\frac{\partial \pi^*_{ll}}{\partial \overline{\theta}} &= 2x^*_{ll}\frac{\partial x^*_{ll}}{\partial \overline{\theta}} = \frac{4\tilde{\tau}}{3\overline{\theta}}x^*_{ll} > 0, \\
\frac{\partial \pi^*_{lh}}{\partial \overline{\theta}} &= 2e_h x^*_{lh}\frac{\partial x^*_{lh}}{\partial \overline{\theta}} = \frac{4e_h x^*_{lh}}{(4e_h-1)\overline{\theta}}\left[\tilde{\tau}+(e_h-1)\tilde{\delta}\right] > 0.
\end{aligned}$$

The difference in output effects is

$$\frac{\partial x^*_{lh}}{\partial \overline{\theta}} - \frac{\partial x^*_{ll}}{\partial \overline{\theta}} = \frac{2(e_h-1)}{3(4e_h-1)\overline{\theta}}(3\tilde{\delta}-4\tilde{\tau}) > 0,$$

which holds because $3\tilde{\delta} - 4\tilde{\tau} > \frac{7-6\tilde{\tau}}{4} > 0$.

Under $e_h = e_{h,2}$, the difference in profit effects is

$$\frac{\partial \pi^*_{lh}}{\partial \overline{\theta}} - \frac{\partial \pi^*_{ll}}{\partial \overline{\theta}} = 2x^*_{ll}\left[(e_{h,2})^{\frac{1}{2}}\frac{\partial x^*_{lh}}{\partial \overline{\theta}} - \frac{\partial x^*_{ll}}{\partial \overline{\theta}}\right].$$

Because $(e_{h,2})^{\frac{1}{2}} > 1$ and $\frac{\partial x^*_{lh}}{\partial \overline{\theta}} > \frac{\partial x^*_{ll}}{\partial \overline{\theta}} > 0$ hold, it follows that $\frac{\partial \pi^*_{lh}}{\partial \overline{\theta}} > \frac{\partial \pi^*_{ll}}{\partial \overline{\theta}}$.

Appendix B.2: Effects of τ and $\overline{\theta}$ on $e_{h,3}$

In this part, we first demonstrate $\frac{\partial e_{h,3}}{\partial \tau} < 0$ and $\frac{\partial e_{h,3}}{\partial \overline{\theta}} < 0$. For convenience, we restate the difference between the North firm's profits with and without CER adoption:

$$(\pi_{hh})^{\frac{1}{2}} - (\pi_{lh})^{\frac{1}{2}} = \frac{(e_h - 1)\left[4\,(e_h)^{\frac{1}{2}} - 1\right]\left[e_h + (e_h)^{\frac{1}{2}}\right]}{3e_h(4e_h - 1)\overline{\theta}} \left\{ \frac{4\,(e_h)^{\frac{1}{2}} + 1}{4\,(e_h)^{\frac{1}{2}} - 1} \frac{\overline{\theta} e_h + \tau}{\left[(e_h)^{\frac{1}{2}} + 1\right]^2} - \delta \right\}.$$

Define $m \equiv (e_h)^{\frac{1}{2}}$ and $h(m) \equiv \frac{4m+1}{4m-1} \frac{\overline{\theta} m^2 + \tau}{(m+1)^2}$. Assuming that $\frac{7+10\tilde{\tau}}{12} < \tilde{\delta} < 1$ holds, we can verify that $h(1) = \frac{5}{12}(\overline{\theta} + \tau) < \frac{7}{12}\overline{\theta} + \frac{5}{6}\tau < \delta$ and $h(+\infty) = \overline{\theta} > \delta$.

We show that $e_{h,3}$ is unique. Taking the derivative of $h(m)$ with respective to m gives

$$\frac{\partial h(m)}{\partial m} = \frac{2\overline{\theta}}{(4m-1)^2(m+1)^3} \underbrace{\left[12m^3 - 4m^2 - m - (16m^2 + 4m + 3)\tilde{\tau}\right]}_{\equiv k(m)}.$$

$k(m)$ is increasing in m because $\partial k(m)/\partial m = 36m^2 - 8m - 1 - (32m+4)\tilde{\tau} > 36m^2 - 8m - 1 - (32m+4)\frac{1}{2} = 36m^2 - 24m - 3 > 0$. $k(1) = 7 - 23\tilde{\tau}$ could be positive or negative. If $k(1) > 0$, then $k(m) > 0$, and thus $\partial h(m)/\partial m > 0$ always holds. In this case, $h(m)$ always increases in m and there is an unique solution to $h(m) = \delta$. If $k(1) < 0$, then as m increases, $k(m)$ is negative at first and then positive. In this case, $h(m)$ first decreases with m and then increases in it. However, since $h(1) < \delta$, there is still an unique solution to $h(m) = \delta$. Therefore, $e_{h,3}$ is unique.

Furthermore, we obtain that

$$\frac{\partial h(m)}{\partial \tau} > 0, \quad \frac{\partial h(m)}{\partial \overline{\theta}} > 0,$$

which indicate that, for any given level of e_h, a decrease in τ decreases $h(m)$, and an increase in $\overline{\theta}$ increases it. Consequently, a lower τ leads to a higher threshold value of e_h, and a higher $\overline{\theta}$ leads to a lower threshold value of e_h at which $h(m) = \delta$. Hence, we conclude $\frac{\partial e_{h,3}}{\partial \tau} < 0$ and $\frac{\partial e_{h,3}}{\partial \overline{\theta}} < 0$.

We now demonstrate that in the equilibrium of (h,h), the South firm has no incentive to revert to non-CER. Given that the North firm adopts CER, the difference between the South firm's profits with and without CER adoption is

$$(\pi^*_{hh})^{\frac{1}{2}} - (\pi^*_{hl})^{\frac{1}{2}} = \frac{(m-1)(4m-1)(m+1)^2}{3m(4m^2-1)\overline{\theta}} \left[\frac{\overline{\theta}(4m+1)m^2 + 2(3m^2 - m - 1)\tau}{(4m-1)(m+1)^2} - \delta\right].$$

As long as this difference is positive for $m > (e_{h,3})^{\frac{1}{2}}$, the South firm does not benefit from deviating from (h, h).

Since $h(2) - \delta = \frac{4\overline{\theta}+\tau}{7} - \delta < \frac{4\overline{\theta}+\tau}{7} - \frac{7}{12}\overline{\theta} - \frac{5}{6}\tau = -\frac{\overline{\theta}+58\tau}{84} < 0$, we infer $(e_{h,3})^{\frac{1}{2}} > 2$. Note that for $m > (e_{h,3})^{\frac{1}{2}}$, we have

$$\begin{aligned}&\left[(\pi^*_{hh})^{\frac{1}{2}} - (\pi^*_{hl})^{\frac{1}{2}}\right] - \left[(\pi_{hh})^{\frac{1}{2}} - (\pi_{lh})^{\frac{1}{2}}\right] \\ =& \frac{(m-1)(4m-1)(m+1)^2}{3m(4m^2-1)\overline{\theta}} \frac{3(2m^2-2m-1)\tau}{(4m-1)(m+1)^2} \\ >& \ 0.\end{aligned}$$

The inequality holds because $2m^2 - 2m - 1 > 0$ for $m > (e_{h,3})^{\frac{1}{2}} > 2$. Therefore, for $m > (e_{h,3})^{\frac{1}{2}}$,

$$(\pi^*_{hh})^{\frac{1}{2}} - (\pi^*_{hl})^{\frac{1}{2}} > (\pi_{hh})^{\frac{1}{2}} - (\pi_{lh})^{\frac{1}{2}} > 0.$$

Hence, at (h, h), the South firm has no incentive to revert to non-CER.

Then, we demonstrate that at the threshold of $e_{h,3}$, as tariffs decline, the North firm suffers less if it does not adopt the CER. That is, $\frac{\partial \pi_{hh}}{\partial \tau} > \frac{\partial \pi_{lh}}{\partial \tau}$ holds. Given that the South firm adopts CER, the effects of tariffs on the North firm's profits without and with CER adoption are given by

$$\begin{aligned}\frac{\partial \pi_{lh}}{\partial \tau} &= 2x_{lh}\frac{\partial x_{lh}}{\partial \tau} = \frac{2}{(4e_h - 1)\overline{\theta}} x_{lh} > 0, \\ \frac{\partial \pi_{hh}}{\partial \tau} &= 2e_h x_{hh}\frac{\partial x_{hh}}{\partial \tau} = \frac{2}{3\overline{\theta}} x_{hh} > 0.\end{aligned}$$

At the threshold of $e_{h,3}$, $\pi_{lh} = (x_{lh})^2 = \pi_{hh} = e_{h,3}(x_{hh})^2$ holds, implying $x_{lh} = (e_{h,3})^{\frac{1}{2}} x_{hh}$. Therefore, under the condition $e_h = e_{h,3}$, we have

$$\frac{\partial \pi_{hh}}{\partial \tau} - \frac{\partial \pi_{lh}}{\partial \tau} = \frac{2x_{lh}}{3(e_{h,3})^{\frac{1}{2}}(4e_{h,3} - 1)\overline{\theta}} \left[4(e_{h,3})^{\frac{1}{2}} + 1\right]\left[(e_{h,3})^{\frac{1}{2}} - 1\right] > 0.$$

Last, we demonstrate that adopting CER mitigates the negative effect of a higher $\overline{\theta}$ on the North firm's profits. That is, $\frac{\partial \pi_{hh}}{\partial \overline{\theta}} > \frac{\partial \pi_{lh}}{\partial \overline{\theta}}$ holds. Given that the South firm adopts CER, the effects of $\overline{\theta}$ on the North firm's profits without and with CER adoption are given by

$$\begin{aligned}\frac{\partial \pi_{lh}}{\partial \overline{\theta}} &= 2x_{lh}\frac{\partial x_{lh}}{\partial \overline{\theta}} = -\frac{2x_{lh}}{(4e_h - 1)\overline{\theta}}\left[\tilde{\tau} + (e_h - 1)\tilde{\delta}\right] < 0, \\ \frac{\partial \pi_{hh}}{\partial \overline{\theta}} &= 2e_h x_{hh}\frac{\partial x_{hh}}{\partial \overline{\theta}} = \frac{2x_{hh}}{3\overline{\theta}}\left[(e_h - 1)\tilde{\delta} - \tilde{\tau}\right].\end{aligned}$$

Under $e_h = e_{h,3}$, we have

$$\frac{\partial \pi_{hh}}{\partial \overline{\theta}} - \frac{\partial \pi_{lh}}{\partial \overline{\theta}} = \frac{2\left[(e_{h,3})^{\frac{1}{2}} - 1\right] x_{lh}}{3(e_{h,3})^{\frac{1}{2}}(4e_{h,3}-1)\overline{\theta}} \left\{ \left[(e_{h,3})^{\frac{1}{2}} + 1\right]^2 \left[4(e_{h,3})^{\frac{1}{2}} - 1\right] \tilde{\delta} - \left[4(e_{h,3})^{\frac{1}{2}} + 1\right] \tilde{\tau} \right\}.$$

Since $\left[(e_{h,3})^{\frac{1}{2}} + 1\right]^2 \left[4(e_{h,3})^{\frac{1}{2}} - 1\right] - \left[4(e_{h,3})^{\frac{1}{2}} + 1\right] > 4\left[4(e_{h,3})^{\frac{1}{2}} - 1\right] - \left[4(e_{h,3})^{\frac{1}{2}} + 1\right] > 0$ and $\tilde{\delta} > \tilde{\tau}$ under the conditions of $e_{h,3} > 1$ and $\frac{7+10\tilde{\tau}}{12} < \tilde{\delta} < 1$, the second term of this equation is positive and hence we have $\frac{\partial \pi_{hh}}{\partial \overline{\theta}} > \frac{\partial \pi_{lh}}{\partial \overline{\theta}}$.

Appendix C: Effects of CER recognition in the South

We first demonstrate $e_{h,1} < e_{h,3}$. Equivalently, we only need to show $h((e_{h,1})^{\frac{1}{2}}) < \delta$. Note that $(e_{h,1})^{\frac{1}{2}} < \frac{3\tilde{\delta}+2\tilde{\tau}-1}{3(1-\tilde{\delta})} \equiv \overline{m}$. We investigate $h(m)$ and observe that

$$h(m) = \frac{4m+1}{4m-1} \frac{\overline{\theta}m^2 + \tau}{(m+1)^2} < \frac{m+1}{m} \frac{\overline{\theta}m^2 + \tau}{(m+1)^2} = \frac{\overline{\theta}m^2 + \tau}{m(m+1)},$$

and

$$\frac{\overline{\theta}m^2 + \tau}{m(m+1)} - \delta = \frac{\overline{\theta}}{m(m+1)} \left[(1-\tilde{\delta})m^2 - \tilde{\delta}m + \tilde{\tau}\right].$$

We now demonstrate $h(\overline{m}) < \delta$. Recall that $\tilde{\delta} > \frac{7}{12} + \frac{5}{6}\tilde{\tau}$, which implies $1 - \tilde{\delta} < \frac{5}{12} - \frac{5}{6}\tilde{\tau}$. Then, we have

$$\begin{aligned} & (1-\tilde{\delta})\overline{m}^2 - \tilde{\delta}\overline{m} + \tilde{\tau} \\ = & \frac{1}{9(1-\tilde{\delta})}\left[3(1+\tilde{\tau})(1-\tilde{\delta}) - 2(1-2\tilde{\tau})(1+\tilde{\tau})\right] \\ < & \frac{1}{9(1-\tilde{\delta})}\left[3(1+\tilde{\tau})\left(\frac{5}{12} - \frac{5}{6}\tilde{\tau}\right) - 2(1-2\tilde{\tau})(1+\tilde{\tau})\right] \\ = & -\frac{(1+\tilde{\tau})(1-2\tilde{\tau})}{12(1-\tilde{\delta})} \\ < & 0. \end{aligned}$$

Thus, $\frac{\overline{\theta}\overline{m}^2+\tau}{\overline{m}(\overline{m}+1)} - \delta < 0$ holds, which implies $h(\overline{m}) < \delta$. Because $(e_{h,1})^{\frac{1}{2}} < \overline{m}$, we have $h((e_{h,1})^{\frac{1}{2}}) < \delta$. Therefore, $e_{h,1} < e_{h,3}$ must hold.[23]

[23] Note that the result does not depend on whether $h((e_{h,1})^{\frac{1}{2}}) < h(\overline{m})$ or $h((e_{h,1})^{\frac{1}{2}}) > h(\overline{m})$. As long as $h(\overline{m}) < \delta$, it follows that $h(m) < \delta$ for any $m < \overline{m}$, because $h(m)$ either increases monotonically in m or first decreases and then increases in m.

When $e_{e,2} < e_h < e_{e,1}$, the differences in the firms' outputs are given by

$$\begin{aligned} x_{lh} - x_{ll} &= \frac{e_h - 1}{3(4e_h - 1)}(3\tilde{\delta} - 4\tilde{\tau} - 1) > 0, \\ x^*_{lh} - x^*_{ll} &= -\frac{2(e_h - 1)}{3(4e_h - 1)}(3\tilde{\delta} - 4\tilde{\tau} - 1) < 0, \\ (x_{lh} + x^*_{lh}) - (x_{ll} + x^*_{ll}) &= -\frac{e_h - 1}{3(4e_h - 1)}(3\tilde{\delta} - 4\tilde{\tau} - 1) < 0. \end{aligned}$$

Global emissions decrease because $(x_{lh} + \gamma x^*_{lh}) - (x_{ll} + x^*_{ll}) < (x_{lh} + x^*_{lh}) - (x_{ll} + x^*_{ll}) < 0$.

When $e_{e,1} < e_h < e_{e,3}$, the differences in the firms' outputs are given by

$$\begin{aligned} x_{lh} - x_{hl} &= \frac{e_h - 1}{4e_h - 1}(3\tilde{\delta} - 1) > 0, \\ x^*_{lh} - x^*_{hl} &= -\frac{e_h - 1}{4e_h - 1}(3\tilde{\delta} - 2\tilde{\tau} - 1) < 0, \\ (x_{lh} + x^*_{lh}) - (x_{hl} + x^*_{hl}) &= \frac{2\tilde{\tau}(e_h - 1)}{4e_h - 1} > 0. \end{aligned}$$

Global emissions increase because

$$(x_{lh} + \gamma x^*_{lh}) - (\gamma x_{hl} + x^*_{hl}) = \frac{\tilde{\tau}}{4e_h - 1}(1 + 2e_h - 3\gamma) > 0.$$

When $e_h > e_{e,3}$, the differences of the firms' outputs are given by

$$\begin{aligned} x_{hh} - x_{hl} &= \frac{e_h - 1}{3e_h(4e_h - 1)}\left[\tilde{\delta} + \tilde{\tau} - 2(1 - \tilde{\delta})e_h\right], \\ x^*_{hh} - x^*_{hl} &= \frac{e_h - 1}{3e_h(4e_h - 1)}\left[(1 + 6\tilde{\tau} - 7\tilde{\delta})e_h + \tilde{\delta} - 2\tilde{\tau}\right] < 0, \\ (x_{hh} + x^*_{hh}) - (x_{hl} + x^*_{hl}) &= \frac{e_h - 1}{3e_h(4e_h - 1)}\left[(-1 + 6\tilde{\tau} - 5\tilde{\delta})e_h + 2\tilde{\delta} - \tilde{\tau}\right] < 0. \end{aligned}$$

In the second equation, observe that $1 + 6\tilde{\tau} - 7\tilde{\delta} < 1 + 6\tilde{\tau} - 7(\frac{7}{12} + \frac{5}{6}\tilde{\tau}) = -\frac{37}{12} + \frac{1}{6}\tilde{\tau} < 0$, implying $(1+6\tilde{\tau}-7\tilde{\delta})e_h+\tilde{\delta}-2\tilde{\tau} < (1+6\tilde{\tau}-7\tilde{\delta})+\tilde{\delta}-2\tilde{\tau} = -6\tilde{\delta}+4\tilde{\tau}+1 < -6(\frac{7}{12}+\frac{5}{6}\tilde{\tau})+4\tilde{\tau}+1 = -\frac{5}{2}-\tilde{\tau} < 0$. Therefore, $x^*_{hh} - x^*_{hl} < 0$ holds. In the third equation, since $-1 + 6\tilde{\tau} - 5\tilde{\delta} < 0$, it follows that $(-1+6\tilde{\tau}-5\tilde{\delta})e_h+2\tilde{\delta}-\tilde{\tau} < (-1+6\tilde{\tau}-5\tilde{\delta})+2\tilde{\delta}-\tilde{\tau} = -1+5\tilde{\tau}-3\tilde{\delta} < -1+5\tilde{\tau}-3(\frac{7}{12}+\frac{5}{6}\tilde{\tau}) = -\frac{11}{4}+\frac{5}{2}\tilde{\tau} < 0$. Therefore, $(x_{hh} + x^*_{hh}) - (x_{hl} + x^*_{hl}) < 0$.

The difference of global emissions in these two scenarios is

$$(\gamma x_{hh} + \gamma x^*_{hh}) - (\gamma x_{hl} + x^*_{hl}) = \gamma\left(x_{hh} + x^*_{hh} - x_{hl}\right) - x^*_{hl},$$

which is increasing in γ because

$$
\begin{aligned}
x_{hh} + x^*_{hh} - x_{hl} &= \frac{1}{3e_h(4e_h-1)}\left[(2e_h+1)e_h - (7e_h-1)\tilde{\tau} - 2(e_h-1)^2\tilde{\delta}\right] \\
&> \frac{1}{3e_h(4e_h-1)}\left[(2e_h+1)e_h - \frac{1}{2}(7e_h-1) - 2(e_h-1)^2\right] \\
&> \frac{e_h-1}{2e_h(4e_h-1)} \\
&> 0.
\end{aligned}
$$

Therefore, $(\gamma x_{hh} + \gamma x^*_{hh}) - (\gamma x_{hl} + x^*_{hl}) < (x_{hh} + x^*_{hh}) - (x_{hl} + x^*_{hl}) < 0$, implying that global emissions decrease because of the recognition of CER in the South.

Appendix D: Proof of Lemma 1

The effects of e_h on firms' outputs are derived as follows:

$$
\begin{aligned}
\frac{\partial x_{i,l}}{\partial e_h} &= \frac{\beta[(1+\beta)(1+\tilde{\tau}) - 3(1-\tilde{\delta})]}{\{\beta + (3-\beta)[e_h(1+\beta)-\beta]\}^2} > 0, \\
\frac{\partial x_{j,h}}{\partial e_h} &= \frac{(3-\beta)[3(1-\tilde{\delta}) - (1+\beta)(1+\tilde{\tau})]}{\{\beta + (3-\beta)[e_h(1+\beta)-\beta]\}^2} < 0, \\
\frac{\partial x^*_{i,l}}{\partial e_h} &= \frac{\partial(x_{i,l} - \tilde{\tau})}{\partial e_h} = \frac{\partial x_{i,l}}{\partial e_h} > 0.
\end{aligned}
$$

The inequalities hold because we have $\frac{1+\tilde{\tau}}{3(1-\tilde{\delta})} - 1 > 1$ which implies that $(1+\beta)(1+\tilde{\tau}) - 3(1-\tilde{\delta}) > 0$.

The effects of τ on firms' outputs are given by

$$
\begin{aligned}
\frac{\partial x_{i,l}}{\partial \tau} &= \frac{1}{\overline{\theta}}\frac{e_h(1+\beta)-\beta}{\beta + (3-\beta)[e_h(1+\beta)-\beta]} > 0, \\
\frac{\partial x_{j,h}}{\partial \tau} &= \frac{1}{\overline{\theta}}\frac{1}{\beta + (3-\beta)[e_h(1+\beta)-\beta]} > 0, \\
\frac{\partial x^*_{i,l}}{\partial \tau} &= -\frac{1}{\overline{\theta}}\frac{(e_h-1)\beta(1-\beta) + 2e_h}{\beta + (3-\beta)[e_h(1+\beta)-\beta]} < 0.
\end{aligned}
$$

The effects of $\overline{\theta}$ on firms' outputs are given by

$$
\begin{aligned}
\frac{\partial x_{i,l}}{\partial \overline{\theta}} &= -\frac{1}{\overline{\theta}}\frac{[e_h(1+\beta)-\beta]\tilde{\tau} + \beta(e_h-1)\tilde{\delta}}{\beta + (3-\beta)[e_h(1+\beta)-\beta]} < 0, \\
\frac{\partial x_{j,h}}{\partial \overline{\theta}} &= \frac{1}{\overline{\theta}}\frac{(3-\beta)(e_h-1)\tilde{\delta} - \tilde{\tau}}{\beta + (3-\beta)[e_h(1+\beta)-\beta]}, \\
\frac{\partial x^*_{i,l}}{\partial \overline{\theta}} &= \frac{1}{\overline{\theta}}\frac{[(e_h-1)\beta(1-\beta) + 2e_h]\tilde{\tau} - \beta(e_h-1)\tilde{\delta}}{\beta + (3-\beta)[e_h(1+\beta)-\beta]}.
\end{aligned}
$$

The effects of β on firms' outputs are derived as

$$\frac{\partial x_{i,l}}{\partial \beta} = \frac{(e_h-1)\left\{[e_h(1+\beta)^2-\beta^2]\tilde{\tau}+\tilde{\delta}\beta+2(1-\beta)\beta(1-\tilde{\delta})(e_h-1)+[3\tilde{\delta}-2+(2-\tilde{\delta})\beta][e_h(1+\beta)-\beta]\right\}}{\{\beta+(3-\beta)[e_h(1+\beta)-\beta]\}^2}$$
$$> 0,$$
$$\frac{\partial x_{j,h}}{\partial \beta} = -x_{j,h}\left(\frac{(1-\tilde{\delta})(e_h-1)}{1+\tilde{\tau}+(3-\beta)(1-\tilde{\delta})(e_h-1)}+\frac{2(1-\beta)(e_h-1)}{\beta+(3-\beta)[e_h(1+\beta)-\beta]}\right)<0,$$
$$\frac{\partial x^*_{i,l}}{\partial \beta} = \frac{\partial(x_{i,l}-\tilde{\tau})}{\partial \beta} = \frac{\partial x_{i,l}}{\partial \beta} > 0.$$

Note that we assume $\frac{5-\tilde{\tau}}{6} < \tilde{\delta} < 1$ and $\tilde{\tau} < \frac{4}{9}$, implying $\tilde{\delta} > \frac{41}{54} > \frac{2}{3}$. Therefore, $3\tilde{\delta}-2>0$ holds in the numerator of $\frac{\partial x_{i,l}}{\partial \beta}$, leading to $\frac{\partial x_{i,l}}{\partial \beta} > 0$.

Appendix E: Proof of Proposition 6

First, we demonstrate that when the CER is only recognized in the North, an increase in CER standard e_h encourages more firms in the North to adopt CER. Taking the logarithm of $\hat{\beta}$ in Equation (14) yields

$$\ln\hat{\beta} = \ln(e_h)^{\frac{1}{2}} - \ln\left[1+(e_h)^{\frac{1}{2}}\right] + \ln\left\{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1+\tilde{\tau})\right\}$$
$$- \ln\left\{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})\right\}.$$

Taking the derivative of $\ln\hat{\beta}$ with respective to $(e_h)^{\frac{1}{2}}$ gives

$$\frac{\partial \ln\hat{\beta}}{\partial (e_h)^{\frac{1}{2}}} = \frac{1}{(e_h)^{\frac{1}{2}}} - \frac{1}{1+(e_h)^{\frac{1}{2}}} + \frac{3(1-\tilde{\delta})}{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1+\tilde{\tau})} - \frac{1-\tilde{\delta}}{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})}$$
$$= \frac{1}{(e_h)^{\frac{1}{2}}\left[1+(e_h)^{\frac{1}{2}}\right]} + \frac{2(1-\tilde{\delta})[2(1+\tilde{\tau})-3(1-\tilde{\delta})]}{\left\{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1+\tilde{\tau})\right\}\left\{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})\right\}}$$
$$> 0.$$

The inequality holds because we have $e_h < \left(\frac{1+\tilde{\tau}}{1-\tilde{\delta}}-1\right)^2$, which implies that $2(1+\tilde{\tau}) > 2(1-\tilde{\delta})\left[1+(e_h)^{\frac{1}{2}}\right] > 4(1-\tilde{\delta}) > 3(1-\tilde{\delta})$. Therefore, $\frac{\partial\hat{\beta}}{\partial e_h} = \frac{\hat{\beta}}{2}(e_h)^{-\frac{1}{2}}\frac{\partial\ln\hat{\beta}}{\partial(e_h)^{\frac{1}{2}}} > 0$.

Second, we demonstrate that when the CER is recognized only in the North, a decrease in tariffs also encourages more firms in the North to undertake CER. Taking the derivative of $\ln\hat{\beta}$

with respective to $\tilde{\tau}$ gives

$$\frac{\partial \ln \hat{\beta}}{\partial \tilde{\tau}} = -\frac{1}{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1+\tilde{\tau})} - \frac{1}{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})} < 0.$$

Therefore, $\frac{\partial \hat{\beta}}{\partial \tau} = \frac{\hat{\beta}}{\overline{\theta}}\frac{\partial \ln \hat{\beta}}{\partial \tilde{\tau}} > 0$. Notably, a decrease in τ decreases the threshold at which firms begin to adopt CER and all firms choose to adopt it. This also implies that a tariff reduction encourages CER in the North, as illustrated in the two-firm analysis.

Third, we demonstrate that when CER is only recognized in the North, an increase in $\overline{\theta}$ encourages more firms in the North to undertake CER. Taking the derivative of $\ln \hat{\beta}$ with respective to $\overline{\theta}$ gives

$$\frac{\partial \ln \hat{\beta}}{\partial \overline{\theta}} = \frac{(\tilde{\delta}+\tilde{\tau})\left[4(e_h)^{\frac{1}{2}}+2\right]}{\overline{\theta}\left\{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1+\tilde{\tau})\right\}\left\{1+\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})\right\}} > 0.$$

Therefore, $\frac{\partial \hat{\beta}}{\partial \overline{\theta}} = \hat{\beta}\frac{\partial \ln \hat{\beta}}{\partial \overline{\theta}} > 0$. Notably, an increase in $\overline{\theta}$ decreases the thresholds at which firms begin to adopt CER, and all firms choose to so. This also implies that higher environmental awareness encourages CER in the North, as illustrated by the two-firm analysis.

We now demonstrate that, in equilibrium, non-CER firms in the North are more affected by the tariffs than CER firms in the North. That is, $\frac{\partial \pi_{i,l}}{\partial \tau} > \frac{\partial \pi_{j,h}}{\partial \tau} > 0$ holds under $\beta = \hat{\beta}$. The effects of tariffs on the North firms' profits are given by

$$\frac{\partial \pi_{i,l}}{\partial \tau} = 2x_{i,l}\frac{\partial x_{i,l}}{\partial \tau} > 0,$$
$$\frac{\partial \pi_{j,h}}{\partial \tau} = 2e_h x_{j,h}\frac{\partial x_{j,h}}{\partial \tau} > 0,$$

where $\frac{\partial x_{i,l}}{\partial \tau}$ and $\frac{\partial x_{j,h}}{\partial \tau}$ are obtained in Appendix D. In equilibrium, $\pi_{i,l} = (x_{i,l})^2 = \pi_{j,h} = e_h(x_{j,h})^2$ holds, implying $x_{i,l} = (e_h)^{\frac{1}{2}}x_{j,h}$. Therefore, under $\beta = \hat{\beta}$, we have

$$\frac{\partial \pi_{i,l}}{\partial \tau} - \frac{\partial \pi_{j,h}}{\partial \tau} = \frac{2x_{i,l}}{\overline{\theta}}\frac{(e_h-1)\hat{\beta}+e_h-(e_h)^{\frac{1}{2}}}{\hat{\beta}+(3-\hat{\beta})[e_h(1+\hat{\beta})-\hat{\beta}]} > 0.$$

This inequality confirms that non-CER firms in the North experience greater loss from tariff reduction than to CER firms in the North.

Finally, we show that in equilibrium, CER firms in the North benefit more or suffer less from a higher $\overline{\theta}$ than non-CER firms in the North. That is, $\partial \pi_{j,h}/\partial \overline{\theta} > \partial \pi_{i,l}/\partial \overline{\theta}$ holds under $\beta = \hat{\beta}$. In equilibrium, with $x_{i,l} = (e_h)^{\frac{1}{2}} x_{j,h}$, it follows that

$$\frac{\partial \pi_{j,h}}{\partial \overline{\theta}} - \frac{\partial \pi_{i,l}}{\partial \overline{\theta}} = \frac{2x_{i,l}}{\overline{\theta}} \frac{\left[e_h - (e_h)^{\frac{1}{2}} + \hat{\beta}(e_h - 1)\right] \tilde{\tau} + \left[(3-\hat{\beta})(e_h - 1)(e_h)^{\frac{1}{2}} + \hat{\beta}(e_h - 1)\right] \tilde{\delta}}{\hat{\beta} + (3-\hat{\beta})[e_h(1+\hat{\beta}) - \hat{\beta}]} > 0.$$

Appendix F: Proof of Lemma 2

The effects of e_h on firms' outputs are derived as follows:

$$\frac{\partial x^*_{i,l}}{\partial e_h} = \frac{\beta^*[(1+\beta^*)(1-2\tilde{\tau}) - 3(1-\tilde{\delta})]}{\{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]\}^2} > 0,$$
$$\frac{\partial x^*_{j,h}}{\partial e_h} = \frac{(3-\beta^*)[3(1-\tilde{\delta}) - (1+\beta^*)(1-2\tilde{\tau})]}{\{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]\}^2} < 0,$$
$$\frac{\partial x_{i,l}}{\partial e_h} = \frac{\partial(x^*_{i,l} + \tilde{\tau})}{\partial e_h} = \frac{\partial x^*_{i,l}}{\partial e_h} > 0.$$

The inequalities hold because we have $\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1 > 1$ which implies that $(1+\beta^*)(1-2\tilde{\tau}) - 3(1-\tilde{\delta}) > 0$.

The effects of τ on firms' outputs are given by

$$\frac{\partial x^*_{i,l}}{\partial \tau} = \frac{1}{\overline{\theta}} \frac{-2[e_h(1+\beta^*) - \beta^*]}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]} < 0,$$
$$\frac{\partial x^*_{j,h}}{\partial \tau} = \frac{1}{\overline{\theta}} \frac{-2}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]} < 0,$$
$$\frac{\partial x_{i,l}}{\partial \tau} = \frac{1}{\overline{\theta}} \frac{(e_h - 1)(1+\beta^*)(1-\beta^*) + 1}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]} > 0.$$

The effects of $\overline{\theta}$ on firms' outputs are given by

$$\frac{\partial x^*_{i,l}}{\partial \overline{\theta}} = \frac{1}{\overline{\theta}} \frac{2[e_h(1+\beta^*) - \beta^*]\tilde{\tau} - \beta^*(e_h - 1)\tilde{\delta}}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]},$$
$$\frac{\partial x^*_{j,h}}{\partial \overline{\theta}} = \frac{1}{\overline{\theta}} \frac{(3-\beta^*)(e_h - 1)\tilde{\delta} + 2\tilde{\tau}}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]} > 0,$$
$$\frac{\partial x_{i,l}}{\partial \overline{\theta}} = -\frac{1}{\overline{\theta}} \frac{[(e_h - 1)(1+\beta^*)(1-\beta^*) + 1]\tilde{\tau} + \beta^*(e_h - 1)\tilde{\delta}}{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]} < 0.$$

The effects of β^* on firms' outputs are derived as

$$\frac{\partial x^*_{i,l}}{\partial \beta^*} = \frac{e_h - 1}{\{\beta^* + (3-\beta^*)[e_h(1+\beta^*) - \beta^*]\}^2} \left\{ \begin{array}{l} (\tilde{\delta} - 2\tilde{\tau})\beta^* + 2(1-\beta^*)\beta^*(1-\tilde{\delta})(e_h - 1) + \\ [e_h(1+\beta^*) - \beta^*][(3-\beta^*)\tilde{\delta} - 2\tilde{\tau} - 2\tilde{\tau}\beta^* - 2 + 2\beta^*] \end{array} \right\}$$
$$>0,$$

$$\frac{\partial x^*_{j,h}}{\partial \beta^*} = -\, x^*_{j,h}\left(\frac{(1-\tilde{\delta})(e_h-1)}{1-2\tilde{\tau}+(3-\beta^*)(1-\tilde{\delta})(e_h-1)} + \frac{2(1-\beta^*)(e_h-1)}{\beta^*+(3-\beta^*)[e_h(1+\beta^*)-\beta^*]}\right) < 0,$$
$$\frac{\partial x_{i,l}}{\partial \beta^*} = \frac{\partial (x^*_{i,l}+\tilde{\tau})}{\partial \beta^*} = \frac{\partial x^*_{i,l}}{\partial \beta^*} > 0.$$

Note that we assume $\frac{5+2\tilde{\tau}}{6} < \tilde{\delta} < 1$ and $\tilde{\tau} < \frac{4}{9}$, implying that $(3-\beta^*)\tilde{\delta} - 2\tilde{\tau} - 2\tilde{\tau}\beta^* - 2 + 2\beta^* > (3-\beta^*)\frac{5+2\tilde{\tau}}{6} - 2\tilde{\tau} - 2\tilde{\tau}\beta^* - 2 + 2\beta^* = (\frac{1}{2}-\tilde{\tau})(1+\frac{7}{3}\beta^*) > 0$ holds in the numerator of $\frac{\partial x^*_{i,l}}{\partial \beta^*}$. Therefore, $\frac{\partial x^*_{i,l}}{\partial \beta^*} > 0$ holds.

Appendix G: Proof of Proposition 7

First, we demonstrate that when CER is recognized in both North and South, an increase in CER standard e_h encourages more firms in the South to adopt CER. Taking the logarithm of $\hat{\beta}^*$ in Equation (18) yields

$$\begin{aligned}\ln \hat{\beta}^* =& \ln(e_h)^{\frac{1}{2}} - \ln\left[1+(e_h)^{\frac{1}{2}}\right] + \ln\left\{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta}) - (1-2\tilde{\tau})\right\} \\ &- \ln\left\{1-2\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})\right\}.\end{aligned}$$

Taking the derivative of $\ln\hat{\beta}^*$ with respective to $(e_h)^{\frac{1}{2}}$ gives

$$\begin{aligned}\frac{\partial \ln\hat{\beta}^*}{\partial (e_h)^{\frac{1}{2}}} =& \frac{1}{(e_h)^{\frac{1}{2}}} - \frac{1}{1+(e_h)^{\frac{1}{2}}} + \frac{3(1-\tilde{\delta})}{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1-2\tilde{\tau})} - \frac{1-\tilde{\delta}}{1-2\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})} \\ =& \frac{1}{(e_h)^{\frac{1}{2}}\left[1+(e_h)^{\frac{1}{2}}\right]} + \frac{2(1-\tilde{\delta})[2(1-2\tilde{\tau})-3(1-\tilde{\delta})]}{\left\{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1-2\tilde{\tau})\right\}\left\{1-2\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})\right\}} \\ &> 0.\end{aligned}$$

The inequality holds because we have $e_h < \left(\frac{1-2\tilde{\tau}}{1-\tilde{\delta}}-1\right)^2$, which implies that $2(1-2\tilde{\tau}) > 2(1-\tilde{\delta})\left[1+(e_h)^{\frac{1}{2}}\right] > 4(1-\tilde{\delta})$. Therefore, $\frac{\partial\hat{\beta}^*}{\partial e_h} = \frac{\hat{\beta}^*}{2}(e_h)^{-\frac{1}{2}}\frac{\partial \ln\hat{\beta}^*}{\partial (e_h)^{\frac{1}{2}}} > 0$.

Second, we demonstrate that when the CER is recognized in both North and South, a decrease in tariffs discourages the CER among South firms. Taking the derivative of $\ln\hat{\beta}^*$ with respective to $\tilde{\tau}$ gives

$$\frac{\partial \ln\hat{\beta}^*}{\partial\tilde{\tau}} = -\frac{2}{3\left[1+(e_h)^{\frac{1}{2}}\right](1-\tilde{\delta})-(1-2\tilde{\tau})} + \frac{2}{1-2\tilde{\tau}+\left[(e_h)^{\frac{1}{2}}-1\right](1-\tilde{\delta})} > 0.$$

Therefore, $\frac{\partial\hat{\beta}^*}{\partial\tau} = \frac{\hat{\beta}^*}{\theta}\frac{\partial\ln\hat{\beta}^*}{\partial\tilde{\tau}} > 0$. Notably, a decrease in τ increases the thresholds at which firms begin to undertake CER and all firms choose to undertake it in the South. This also implies that a tariff reduction discourages the CER in the South, as illustrated in the two-firm analysis.

Third, we demonstrate that when CER is recognized in both North and South, an increase in $\overline{\theta}$ encourages more firms in the South to undertake CER. Taking the derivative of $\ln \hat{\beta}^*$ with respective to $\overline{\theta}$ gives

$$\frac{\partial \ln \hat{\beta}^*}{\partial \overline{\theta}} = \frac{(\tilde{\delta} - 2\tilde{\tau}) \left[4(e_h)^{\frac{1}{2}} + 2\right]}{\overline{\theta} \left\{3 \left[1 + (e_h)^{\frac{1}{2}}\right] (1 - \tilde{\delta}) - (1 - 2\tilde{\tau})\right\} \left\{1 - 2\tilde{\tau} + \left[(e_h)^{\frac{1}{2}} - 1\right] (1 - \tilde{\delta})\right\}} > 0.$$

Therefore, $\frac{\partial \hat{\beta}^*}{\partial \overline{\theta}} = \hat{\beta}^* \frac{\partial \ln \hat{\beta}^*}{\partial \overline{\theta}} > 0$. Notably, an increase in $\overline{\theta}$ decreases the thresholds at which firms begin to adopt CER and all firms choose to adopt CER in the South, as demonstrated in Appendix J. This also implies that higher environmental awareness encourages CER in the South, as illustrated by the two-firm analysis.

We now demonstrate that in equilibrium, non-CER firms in the South are affected to a larger extent by the tariffs than CER firms in the South. The effects of tariffs on South firms' profits are given by

$$\frac{\partial \pi_{i,l}^*}{\partial \tau} = 2x_{i,l}^* \frac{\partial x_{i,l}^*}{\partial \tau} < 0,$$
$$\frac{\partial \pi_{j,h}^*}{\partial \tau} = 2e_h x_{j,h}^* \frac{\partial x_{j,h}^*}{\partial \tau} < 0.$$

Tariff reduction induces the firms in the South to produce more, thereby increasing their profits, regardless of whether or not they adopt CER. Recall that in equilibrium, $\pi_{i,l}^* = (x_{i,l}^*)^2 = \pi_{j,h}^* = e_h(x_{j,h}^*)^2$ holds, implying $x_{i,l}^* = (e_h)^{\frac{1}{2}} x_{j,h}^*$. Therefore, under $\beta^* = \hat{\beta}^*$, we have

$$\frac{\partial \pi_{i,l}^*}{\partial \tau} - \frac{\partial \pi_{j,h}^*}{\partial \tau} = -\frac{4x_{i,l}^*}{\overline{\theta}} \frac{(e_h - 1)\hat{\beta}^* + e_h - (e_h)^{\frac{1}{2}}}{\hat{\beta}^* + (3 - \hat{\beta}^*)[e_h(1 + \hat{\beta}^*) - \hat{\beta}^*]} < 0.$$

This inequality implies that non-CER firms in the South benefit more from tariff reduction than CER firms in the South.

Finally, we show that in equilibrium, CER firms in the South benefit more from a higher $\overline{\theta}$ than non-CER firms in the South. That is, $\partial \pi_{j,h}^* / \partial \overline{\theta} > \partial \pi_{i,l}^* / \partial \overline{\theta}$ holds under $\beta = \hat{\beta}^*$. In equilibrium, with $x_{i,l}^* = (e_h)^{\frac{1}{2}} x_{j,h}^*$, it follows that

$$\frac{\partial \pi_{j,h}^*}{\partial \overline{\theta}} - \frac{\partial \pi_{i,l}^*}{\partial \overline{\theta}} = \frac{2x_{i,l}^*}{\overline{\theta}} \frac{\left[(3 - \hat{\beta}^*)(e_h - 1)(e_h)^{\frac{1}{2}} + \hat{\beta}^*(e_h - 1)\right] \tilde{\delta} - 2 \left[e_h - (e_h)^{\frac{1}{2}} + \hat{\beta}^*(e_h - 1)\right] \tilde{\tau}}{\hat{\beta}^* + (3 - \hat{\beta}^*)[e_h(1 + \hat{\beta}^*) - \hat{\beta}^*]} > 0,$$

which holds because $\tilde{\delta} > 2\tilde{\tau}$ and $\left[(3-\hat{\beta}^*)(e_h-1)(e_h)^{\frac{1}{2}} + \hat{\beta}^*(e_h-1)\right] > \left[e_h - (e_h)^{\frac{1}{2}} + \hat{\beta}^*(e_h-1)\right] > 0$.

Appendix H: Proof of Lemma 3

The effect of e_h on $x_{i,l}$ is

$$\frac{\partial x_{i,l}}{\partial e_h} = \frac{2+3\beta+\beta^2-3(1+\beta)(1-\tilde{\delta})-\tilde{\tau}(4-\beta^2)}{\left[e_h(4-\beta^2)-(1-\beta^2)\right]^2}.$$

The numerator, $2+3\beta+\beta^2-3(1+\beta)(1-\tilde{\delta})-\tilde{\tau}(4-\beta^2)$, is increasing in β. Therefore, $2+3\beta+\beta^2-3(1+\beta)(1-\tilde{\delta})-\tilde{\tau}(4-\beta^2) > 3\tilde{\delta}-1-4\tilde{\tau} > 3(\frac{5+2\tilde{\tau}}{6})-1-4\tilde{\tau} = 3(\frac{1}{2}-\tilde{\tau}) > 0$, which implies that $\frac{\partial x_{i,l}}{\partial e_h} > 0$.

The effect of e_h on $x_{j,h}$ is

$$\frac{\partial x_{j,h}}{\partial e_h} = \frac{3(2-\beta)(1-\tilde{\delta})-(4-\beta^2)+\tilde{\tau}[2(1-\beta)(4-\beta^2)](e_h)^{-1}-(1-\beta)(1-\beta^2)](e_h)^{-2}-(2-\beta)(4-\beta^2)]}{\left[e_h(4-\beta^2)-(1-\beta^2)\right]^2}.$$

In the numerator, the term $3(2-\beta)(1-\tilde{\delta})-(4-\beta^2)$ decreases in β for $0 < \beta < \frac{3(1-\tilde{\delta})}{2}$ and increases in β for $\frac{3(1-\tilde{\delta})}{2} < \beta < 1$. Since this term is negative under both $\beta = 0$ and $\beta = 1$, we have $3(2-\beta)(1-\tilde{\delta})-(4-\beta^2) < 0$. Moreover, $2(1-\beta)(4-\beta^2)](e_h)^{-1}-(1-\beta)(1-\beta^2)](e_h)^{-2}-(2-\beta)(4-\beta^2) < 2(1-\beta)(4-\beta^2)](e_h)^{-1}-(2-\beta)(4-\beta^2) = (4-\beta^2)](e_h)^{-1}[(2-2\beta)-(2-\beta)e_h] < 0$ because $(2-2\beta) < (2-\beta)$ and $1 < e_h$. As a result, $\frac{\partial x_{j,h}}{\partial e_h} < 0$ holds.

The effect of e_h on $x^*_{j,h}$ is

$$\frac{\partial x^*_{j,h}}{\partial e_h} = \frac{\begin{pmatrix} 3(2-\beta)(1-\tilde{\delta})-(4-\beta^2)+\tilde{\tau}(1+\beta)(2-\beta)(4-\beta^2)+ \\ \tilde{\tau}\left[\beta(1-\beta)(1-\beta^2)(e_h)^{-2}-2\beta(1-\beta)(4-\beta^2)(e_h)^{-1}\right] \end{pmatrix}}{\left[e_h(4-\beta^2)-(1-\beta^2)\right]^2}.$$

Note that $\beta(1-\beta)(1-\beta^2)(e_h)^{-2}-2\beta(1-\beta)(4-\beta^2)(e_h)^{-1} < 0$ holds. Now, we demonstrate that $3(2-\beta)(1-\tilde{\delta})-(4-\beta^2)+\tilde{\tau}(1+\beta)(2-\beta)(4-\beta^2) < 0$ holds under $\tilde{\tau} < \frac{1}{3}$. With $\frac{5+2\tilde{\tau}}{6} < \tilde{\delta} < 1$, we have

$$\begin{aligned} &3(2-\beta)(1-\tilde{\delta})-(4-\beta^2)+\tilde{\tau}(1+\beta)(2-\beta)(4-\beta^2) \\ &< (2-\beta)\frac{1-2\tilde{\tau}}{2}-(4-\beta^2)+\tilde{\tau}(1+\beta)(2-\beta)(4-\beta^2) \\ &< (2-\beta)\frac{1-\frac{2}{3}}{2}-(4-\beta^2)+\frac{1}{3}(1+\beta)(2-\beta)(4-\beta^2) \end{aligned}$$

$$
\begin{aligned}
&= \frac{2-\beta}{6} - \frac{1}{3}(4-\beta^2)(\beta^2-\beta+1) \\
&< \frac{1}{3} - \frac{3}{4} \\
&< 0.
\end{aligned}
$$

The second inequality holds because the terms in the second line increase in $\tilde{\tau}$. The third inequality holds because $\frac{2-\beta}{6} < \frac{1}{3}$, $4-\beta^2 > 3$ and $\beta^2-\beta+1 > \frac{3}{4}$. As a result, the numerator of $\frac{\partial x^*_{j,h}}{\partial e_h}$ is negative, implying that $\frac{\partial x^*_{j,h}}{\partial e_h} < 0$ holds under $\tilde{\tau} < \frac{1}{3}$.

The effects of τ on firms' outputs are given by

$$
\begin{aligned}
\frac{\partial x_{i,l}}{\partial \tau} &= \frac{1}{\bar{\bar{\theta}}} \frac{1}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} > 0, \\
\frac{\partial x_{j,h}}{\partial \tau} &= \frac{1}{\bar{\bar{\theta}}} \frac{2-\beta-(1-\beta)(e_h)^{-1}}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} > 0, \\
\frac{\partial x^*_{j,h}}{\partial \tau} &= -\frac{1}{\bar{\bar{\theta}}} \frac{-(1+\beta)(2-\beta)+\beta(1-\beta)(e_h)^{-1}}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} < 0.
\end{aligned}
$$

The effect of β on $x_{i,l}$ is

$$
\frac{\partial x_{i,l}}{\partial \beta} = \frac{\tilde{\delta}(e_h-1)}{(2+\beta)(e_h+\tilde{\tau})-(1+\beta)(1-\tilde{\delta})(e_h-1)-(1+\beta)(1+\tilde{\tau})} + \frac{2\beta(e_h-1)}{e_h(4-\beta^2)-(1-\beta^2)} > 0.
$$

The effect of β on $x_{j,h}$ is

$$
\frac{\partial x_{j,h}}{\partial \beta} = \frac{(e_h-1)\left\{-(2-\beta)^2(1-\tilde{\delta})e_h+(1-\tilde{\delta})(1+\beta^2-4\beta)+2\beta-\left[(2-\beta)^2-(1-\beta)^2(e_h)^{-1}\right]\tilde{\tau}\right\}}{[e_h(4-\beta^2)-(1-\beta^2)]^2}
$$

In the numerator, $(2-\beta)^2-(1-\beta)^2(e_h)^{-1} > 0$ holds. Recall that we assume $e_h > \left[\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}\right]^2$ and $\frac{5+2\tilde{\tau}}{6} < \tilde{\delta} < 1$. We can demonstrate that $\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau} > \frac{1}{4}\tilde{\delta}^2$ and therefore $e_h > \frac{9\tilde{\delta}^2}{16(1-\tilde{\delta})^2}$. Then, we have

$$
\begin{aligned}
&-(2-\beta)^2(1-\tilde{\delta})e_h+(1-\tilde{\delta})(1+\beta^2-4\beta)+2\beta \\
&< \frac{1}{16(1-\tilde{\delta})}\left[-9(2-\beta)^2\tilde{\delta}^2+16(1-\tilde{\delta})^2(1+\beta^2-4\beta)+32\beta(1-\tilde{\delta})\right] \\
&< \frac{1}{16(1-\tilde{\delta})}\left[-9(2-\beta)^2\left(\frac{5}{6}\right)^2+16\left(1-\frac{5}{6}\right)^2(1+\beta^2-4\beta)+32\beta\left(1-\frac{5}{6}\right)\right] \\
&= \frac{1}{16(1-\tilde{\delta})}\left[-\frac{221}{9}-\frac{209}{36}\beta^2+\frac{257}{9}\beta\right]
\end{aligned}
$$

$$
\begin{aligned}
&< \frac{1}{16(1-\tilde{\delta})}\left(-\frac{65}{36}\right) \\
&< 0.
\end{aligned}
$$

The second inequality holds because $-9(2-\beta)^2\tilde{\delta}^2+16(1-\tilde{\delta})^2(1+\beta^2-4\beta)+32\beta(1-\tilde{\delta})$ is deceasing in $\tilde{\delta}$ and $\tilde{\delta} > \frac{5+2\tilde{\tau}}{6} > \frac{5}{6}$. The third inequality holds because $-\frac{221}{9} - \frac{209}{36}\beta^2 + \frac{257}{9}\beta$ is increasing in β and $\beta < 1$.

The effect of β on $x^*_{j,h}$ is

$$
\frac{\partial x^*_{j,h}}{\partial \beta} = \frac{\partial(x_{j,h} - \tilde{\tau}/e_h)}{\partial \beta} = \frac{\partial x_{j,h}}{\partial \beta} < 0.
$$

The effects of $\overline{\theta}$ on firms' outputs are given by

$$
\begin{aligned}
\frac{\partial x_{i,l}}{\partial \overline{\theta}} &= -\frac{1}{\overline{\theta}} \frac{\tilde{\tau} + (1+\beta)(e_h-1)\tilde{\delta}}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} < 0, \\
\frac{\partial x_{j,h}}{\partial \overline{\theta}} &= \frac{1}{\overline{\theta}} \frac{(2-\beta)(e_h-1)\tilde{\delta} - \left[(2-\beta)-(1-\beta)(e_h)^{-1}\right]\tilde{\tau}}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} > 0, \\
\frac{\partial x^*_{j,h}}{\partial \overline{\theta}} &= \frac{1}{\overline{\theta}} \frac{(2-\beta)(e_h-1)\tilde{\delta} + \left[(1+\beta)(2-\beta)-\beta(1-\beta)(e_h)^{-1}\right]\tilde{\tau}}{e_h(2+\beta)(2-\beta)-(1+\beta)(1-\beta)} > 0.
\end{aligned}
$$

Earlier, we established that $e_h > \frac{9\tilde{\delta}^2}{16(1-\tilde{\delta})^2}$. Given $\tilde{\delta} > \frac{5+2\tilde{\tau}}{6} > \frac{5}{6}$, it follows that $e_h > \frac{225}{16}$. In the numerator of $\frac{\partial x_{j,h}}{\partial \overline{\theta}}$, we observe that $\tilde{\delta} > \tilde{\tau}$ and $(2-\beta)(e_h-1) - \left[(2-\beta)-(1-\beta)(e_h)^{-1}\right] = (2-\beta)(e_h-2)+(1-\beta)(e_h)^{-1} > 0$ because $e_h > 2$. Hence, $\frac{\partial x_{j,h}}{\partial \overline{\theta}} > 0$ holds.

Appendix I: Proof of Proposition 8

First, we demonstrate that when CER is recognized in both North and South, an increase in CER standard e_h encourages more firms in the North to adopt CER. Taking the logarithm of $\hat{\beta}'$ in Equation (19) yields

$$
\begin{aligned}
\ln \hat{\beta}' = &\ln\left[1+2(e_h)^{\frac{1}{2}}\right] - \ln\left[1+(e_h)^{\frac{1}{2}}\right] + \ln\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\} \\
&- \ln\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\}.
\end{aligned}
$$

Taking the derivative of $\ln \hat{\beta}'$ with respective to $(e_h)^{\frac{1}{2}}$ gives

$$
\frac{\partial \ln \hat{\beta}'}{\partial (e_h)^{\frac{1}{2}}} = \frac{2}{1+2(e_h)^{\frac{1}{2}}} - \frac{1}{1+(e_h)^{\frac{1}{2}}} + \frac{2(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}}{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}} - \frac{2(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}}{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}}
$$

$$= \frac{1}{\left[1+2(e_h)^{\frac{1}{2}}\right]\left[1+(e_h)^{\frac{1}{2}}\right]} + \frac{2\tilde{\delta}\left[(1-\tilde{\delta})e_h - \tilde{\tau}\right]}{\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\}\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\}}.$$

Recall that $e_h > \left[\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}\right]^2$. Then,

$$(1-\tilde{\delta})e_h - \tilde{\tau} > \frac{\tilde{\delta}^2 - 4(1-\tilde{\delta})\tilde{\tau} + \tilde{\delta}\sqrt{\tilde{\delta}^2 - 4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} > 0.$$

Therefore, $\frac{\partial \ln \hat{\beta}'}{\partial (e_h)^{\frac{1}{2}}} > 0$, which implies that $\frac{\partial \hat{\beta}'}{\partial e_h} = \frac{\hat{\beta}'}{2}(e_h)^{-\frac{1}{2}} \frac{\partial \ln \hat{\beta}'}{\partial (e_h)^{\frac{1}{2}}} > 0$.

Second, we demonstrate that when CER is recognized in both North and South, a decrease in tariffs discourages CER among North firms. Taking the derivative of $\ln \hat{\beta}'$ with respective to $\tilde{\tau}$ gives

$$\frac{\partial \ln \hat{\beta}'}{\partial \tilde{\tau}} = \frac{1}{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}} - \frac{1}{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}} > 0.$$

Therefore, $\frac{\partial \hat{\beta}'}{\partial \tau} = \frac{\hat{\beta}'}{\overline{\theta}} \frac{\partial \ln \hat{\beta}'}{\partial \tilde{\tau}} > 0$. Notably, a decrease in τ increases the thresholds at which firms begin to undertake CER and all firms choose to undertake CER in the North. This also implies that a tariff reduction discourages CER in the North, as illustrated by the two-firm analysis.

Third, we demonstrate that when CER is recognized in both North and South, an increase in $\overline{\theta}$ encourages more firms in the North to undertake CER. Taking the derivative of $\ln \hat{\beta}'$ with respective to $\overline{\theta}$ gives

$$\frac{\partial \ln \hat{\beta}'}{\partial \overline{\theta}} = \frac{2(e_h)^{\frac{3}{2}}\tilde{\delta}}{\overline{\theta}\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} - \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\}\left\{\left[(1-\tilde{\delta})(e_h)^{\frac{1}{2}} + \tilde{\delta}\right](e_h)^{\frac{1}{2}} + \tilde{\tau}\right\}} > 0.$$

Therefore, $\frac{\partial \hat{\beta}'}{\partial \overline{\theta}} = \hat{\beta}' \frac{\partial \ln \hat{\beta}'}{\partial \overline{\theta}} > 0$. Notably, an increase in $\overline{\theta}$ lowers the thresholds at which firms begin to adopt CER, and all firms choose to adopt CER in the North, as demonstrated in Appendix J. This also implies that higher environmental awareness encourages CER in the North, as illustrated by the two-firm analysis.

Finally, we demonstrate that in equilibrium, non-CER firms in the North are less affected by the tariffs than CER firms in the North. That is, $\frac{\partial \pi_{i,l}}{\partial \tau} < \frac{\partial \pi_{j,h}}{\partial \tau}$ holds under $\beta = \hat{\beta}'$. The effects of tariffs on the North firms' profits are given by

$$\frac{\partial \pi_{i,l}}{\partial \tau} = 2x_{i,l}\frac{\partial x_{i,l}}{\partial \tau} > 0,$$

$$\frac{\partial \pi_{j,h}}{\partial \tau} = 2e_h x_{j,h} \frac{\partial x_{j,h}}{\partial \tau} > 0,$$

where $\frac{\partial x_{i,l}}{\partial \tau}$ and $\frac{\partial x_{j,h}}{\partial \tau}$ are obtained in Appendix H. In equilibrium, $\pi_{i,l} = (x_{i,l})^2 = \pi_{j,h} = e_h(x_{j,h})^2$ holds, implying $x_{i,l} = (e_h)^{\frac{1}{2}} x_{j,h}$. Therefore, under $\beta = \hat{\beta}'$, we have

$$\frac{\partial \pi_{i,l}}{\partial \tau} - \frac{\partial \pi_{j,h}}{\partial \tau} = -\frac{2x_{i,l}}{\overline{\theta}} \frac{(e_h)^{\frac{1}{2}} - 1 + (1-\hat{\beta}')\left[(e_h)^{\frac{1}{2}} - (e_h)^{-\frac{1}{2}}\right]}{e_h(2+\hat{\beta}')(2-\hat{\beta}') - (1+\hat{\beta}')(1-\hat{\beta}')} < 0.$$

This inequality confirms that non-CER firms in the North experience smaller loss from tariff reduction, than the CER firms in the North.

Appendix J: CER in both North and South with many firms

When the CER is recognized in both North and South, as e_h increases, the shares or the masses of CER firms in the two countries are

$$(\beta, \beta^*) = \begin{cases} (0,0) & \text{if} \quad 1 < e_h \leq \left[\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1\right]^2, \\ (0, \hat{\beta}^*) & \text{if} \quad \left[\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1\right]^2 < e_h \leq \left(\frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1\right)^2, \\ (0,1) & \text{if} \quad \left(\frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1\right)^2 < e_h \leq \left[\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}\right]^2, \\ (\hat{\beta}', 1) & \text{if} \quad \left[\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}\right]^2 < e_h \leq \left[\frac{3\tilde{\delta}+\sqrt{9\tilde{\delta}^2+4(1-\tilde{\delta})(2\tilde{\delta}-\tilde{\tau})}}{2(1-\tilde{\delta})}\right]^2, \\ 1 & \text{if} \quad e_h > \left[\frac{3\tilde{\delta}+\sqrt{9\tilde{\delta}^2+4(1-\tilde{\delta})(2\tilde{\delta}-\tilde{\tau})}}{2(1-\tilde{\delta})}\right]^2. \end{cases}$$

First, we demonstrate that $\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} > \frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1$ holds. Note that

$$\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} - \left(\frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1\right) = \frac{4\tilde{\tau} - \tilde{\delta} + \sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}. \tag{20}$$

If $4\tilde{\tau} \geq \tilde{\delta}$, the above equation is positive. If $4\tilde{\tau} < \tilde{\delta}$, then

$$\left(\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}\right)^2 - \left(\tilde{\delta} - 4\tilde{\tau}\right)^2 = 4\tilde{\tau}(2\tilde{\delta}-1) + 4\tilde{\tau}(\tilde{\delta}-4\tilde{\tau}) > 0,$$

where $2\tilde{\delta} - 1 > 0$ because $\tilde{\delta} > \frac{5+2\tilde{\tau}}{6} > \frac{1}{2}$. In this case, the expression in (20) is positive. Therefore, $\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})} > \frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1$ always holds.

Second, we demonstrate that the thresholds are decreasing with $\overline{\theta}$. For $\frac{1-2\tilde{\tau}}{3(1-\tilde{\delta})} - 1$ and $\frac{1-2\tilde{\tau}}{1-\tilde{\delta}} - 1$, they decrease with $\overline{\theta}$ because

$$\frac{\partial \frac{1-2\tilde{\tau}}{1-\tilde{\delta}}}{\partial \overline{\theta}} = -\frac{\tilde{\delta} - 2\tilde{\tau}}{(1-\tilde{\delta})^2 \overline{\theta}} < 0.$$

For $\frac{\tilde{\delta}+\sqrt{\tilde{\delta}^2-4(1-\tilde{\delta})\tilde{\tau}}}{2(1-\tilde{\delta})}$, it decreases with $\overline{\theta}$ because $\partial\tilde{\delta}/\partial\overline{\theta} < 0$, $\partial 1/(1-\tilde{\delta})/\partial\overline{\theta} < 0$ and

$$\frac{\partial - (1-\tilde{\delta})\tilde{\tau}}{\partial \overline{\theta}} = -\frac{(2\tilde{\delta}-1)\tilde{\tau}}{\overline{\theta}} < 0.$$

For $\frac{3\tilde{\delta}+\sqrt{9\tilde{\delta}^2+4(1-\tilde{\delta})(2\tilde{\delta}-\tilde{\tau})}}{2(1-\tilde{\delta})}$, it decreases with $\overline{\theta}$ because $\partial\tilde{\delta}/\partial\overline{\theta} < 0$, $\partial 1/(1-\tilde{\delta})/\partial\overline{\theta} < 0$ and

$$\frac{\partial 9\tilde{\delta}^2 + 4(1-\tilde{\delta})(2\tilde{\delta}-\tilde{\tau})}{\partial \overline{\theta}} = -\frac{2}{\overline{\theta}}(\tilde{\delta}^2 + 4\tilde{\delta}\tilde{\tau} + 4\tilde{\delta} - 2\tilde{\tau}) < 0.$$

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