Environmental Disclosures in Global Supply Chains

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Abstract

Economies committed to environmental goals, such as mitigating global warming, face the challenge that pollution and emissions largely originate from activities in foreign countries. While governments may attempt to tax domestic firms' sourcing of inputs from brown international firms, such approaches often have to rely on disclosures from these foreign companies. Addressing this issue, we examine international supply chain partners' disclosure strategies and their interplay with a domestic government's optimal regulatory policies. Such disclosures are key to SCOPE-3 emissions calculations and meaningful ESG ratings. Optimal policies in our environment account for endogenous information asymmetries and the exercise of market power by domestic firms, leading to predictions that contrast with the notion of a common price for CO2 emissions, as is implied by carbon credit markets. Our analysis characterizes how domestic households' exposures to global externalities shape both a government's optimal regulations and the precision of foreign firms' disclosures.

Keywords: Carbon credit markets; ESG ratings; Global warming; Asymmetric information; Optimal regulation

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1 Introduction

Many countries view environmental goals such as tackling global warming as a first-order objective underlying a wide range of policies and initiatives (UNFCCC, 2015). Yet economies across the globe face differing trade-offs related to pollution and emissions and thus frequently disagree on the optimal stringency of environmental regulations. Activities in foreign countries are evidently first-order drivers of global emissions (see Peters et al., 2008; Climate Action Tracker, 2023, among others), raising the concern that domestic activities and associated local laws alone have limited impact on the problem at hand.

Yet, given that a large portion of pollutive activities arises from internationally traded production inputs, governments may increase their reach by affecting domestic firms' global supply chain interactions. Indeed, policy makers increasingly recognize the importance of SCOPE-3 emissions, that is, *indirect* emissions that occur in a company's value chain. These indirect emissions make up the majority of total emissions across most sectors (Huang et al., 2009; Downie and Stubbs, 2013; Bolton and Kacperczyk, 2021). Specifically, governments may attempt to use their regulatory authority pertaining to domestic firms to discourage the sourcing of inputs from brown international supply chain partners (see, e.g., Copeland and Taylor, 2003). Similarly, investors concerned with the environment may rely on domestic firms' ESG scores, which must incorporate supply chain partners' environmental practices to be meaningful. The efficacy of such approaches, however, is contingent on disclosures provided by foreign producers (Hartmann and Stafford, 2018).

Motivated by these observations, we study how regulatory policies optimally target domestic firms' global supply chain relations when foreign suppliers strategically disclose information about their environmental impact. Our analysis provides insights on the shortcomings of carbon credit markets and other common regulatory interventions in the presence of international information asymmetries. We present a model of a domestic firm sourcing inputs from a foreign firm that provides disclosures on its production-related environmental externalities. These externalities negatively affect domestic households and are insufficiently internalized by both the domestic and the foreign firm. Moreover, our analysis recognizes the fact that many large firms headquartered in developed countries most concerned with global warming exert substantial market power when sourcing international inputs (see, e.g., Antràs and Staiger, 2012).

We start our analysis by examining the global supply chain equilibrium absent government interventions. In this setting, environmental disclosures increase the global supply chain partners' joint private surplus, yet they may expand activities generating negative externalities. This result emerges as foreign disclosures reduce the rationing of international transactions due to the domestic firm's exercise of market power under asymmetric information. Foreign producers or equivalently their governments optimally choose coarse disclosure regimes whereby the domestic trade partner obtains imprecise but still useful information about environmental standards and the associated production costs. Disclosures balance a foreign trade partners' incentives to retain private information about its production costs during price negotiations with the fact that excessive information asymmetries increase the probability of inefficient trade breakdowns.

We then proceed to analyzing a domestic government's interventions with policies accounting for domestic firms' indirect externalities, such as SCOPE-3 emissions. In particular, we study the optimal mechanism from a domestic country's perspective and its implementation via taxes, or equivalently tariffs, that condition on foreign firms' disclosures. Optimal tax schedules in this environment are non-linear functions of the disclosed environmental externalities created *within* a given supply chain relation. Rather than effectuating a system with one tax rate or price per unit of emissions, a government optimally uses the endogenously coarse disclosures of foreign input producers and recognizes that, given the residual information asymmetry, the terms of trade affect both the expected quantity and the conditional expected greenness of supply chain production.

This prescription contrasts with prevalent existing environmental policies, such as carbon credit markets. Markets such as the European Union Emissions Trading Scheme (EU ETS) feature a common market price for carbon allowances traded within the system, which covers multiple sectors, including power generation, manufacturing, and aviation. In contrast to models suggesting the optimality of such markets, our a analysis recognizes the real-world complexities that foreign producers optimally retain private information about the brownness of their production processes and that large domestic firms often exercise significant market power when sourcing inputs. In the presence of these frictions, optimal carbon tariffs vary across sectors, as a function of the distributions characterizing information asymmetries that remain after conditioning on disclosures. These distributions determine how elastically both environmental externalities and trade quantities respond to changes in the terms of trade.

Government policies are naturally taken into account by foreign supply chain partners. Our analysis reveals when and how penalizing trade with pollutive suppliers interferes with the precision of foreign disclosures. Interestingly, government interventions can make voluntary disclosures more or less informative, with the direction primarily depending on the strength of a domestic country's exposure to externalities. When this exposure is relatively low, foreign disclosures potentially become more precise in the presence of interventions by the domestic government. This happens when the private bilateral surplus from trade among supply chain partners is reduced by optimal tariffs but still remains positive. In those cases, the foreign supply chain partners find it optimal to choose more precise disclosures to avoid jeopardizing post-tax gains from trade under asymmetric information.

By contrast, when the domestic exposure to externalities exceeds a threshold, disclosures become very coarse, in fact generally binary, when the government intervenes. Fundamentally, this occurs because fine-tuning tariffs loses its potency when the domestic sector is highly exposed to externalities as trade is plagued by severe adverse selection. Generally, a marginal tax increase has two opposing effects for domestic surplus: on the one hand, a tax increase raises domestic surplus conditional on trade occurring, as it lowers the price the domestic firm offers. However, on the other hand, such a price decrease leads to the rationing of trade with higher-cost producers, which tend to be greener. This results in a compositional change whereby the remaining pool of suppliers with which trade occurs is on average browner. When the domestic sector is sufficiently strongly exposed to externalities, this second adverse selection effect is more potent and consistently dominates, implying that a marginal tax increase is counterproductive. As a result, given the information provided by a disclosure, the domestic government finds one of two tariffs optimal: either to impose punitive tariffs that eliminate trade altogether (if the expected net-surplus is negative) or to ensure trade occurs with all remaining types consistent with the provided disclosure (if the average net-surplus across these remaining supplier types is positive). In turn, anticipating such an extreme taxation policy, foreign disclosures optimally subsume the largest possible pool of relatively green producers under one disclosure (e.g., a "green" rating) with which trade occurs. The residual "brown" pool will be completely rationed. However, as we show, the "green pool" is excessively large, in the sense that it includes too many brown types and leads to the destruction of global surplus.

Related literature. Our paper contributes to the existing literature studying optimal government interventions in the context of environmental externalities. Weitzman (1974) is a seminal contribution to the debate on whether it's more efficient to regulate pollutants using prices (tariffs) or quantities (emission caps). Nordhaus (1991) examines the economic implications of global warming and provides one of the earliest assessments of the benefits and costs of slowing climate change and associated government policies. Poterba (1991) analyzes the practical challenges of designing a carbon tax, considering the interactions of policies with existing tax systems and the potential challenges in their political implementation. Pindyck (2013) surveys existing models on climate change policies, providing an examination of existing models and their limitations. Golosov et al. (2014) derive optimal carbon tax policies in a dynamic general equilibrium model with capital accumulation that recognizes the non-renewability of fossil-fuel inputs. Döttling and Rola-Janicka (2023) show that carbon tariffs may be dominated by a cap-and-trade system or abatement subsidies in a model with financial constraints and endogenous climate-related transition and physical risks.

Our paper is further related to the existing work examining how firms in supply chains possessing significant market power might strategically react to carbon tariffs. In particular, Fabra and Reguant (2014) examine how carbon costs are passed through to electricity prices in the presence of market power. Their findings suggest that strategic firms with market power might not fully pass through these costs to consumers, especially when demand is inelastic.

Our paper also contributes to the literature examining issues related to taxation and regulation in the context of international supply chains, where foreign firms cannot be regulated directly. Elliott et al. (2010) discusses how introducing carbon tariffs can affect international trade patterns and highlights carbon tariffs in one country might merely shift production and emissions elsewhere. Fowlie et al. (2016) explores the implications of market-based emissions regulations on industry dynamics, especially concerning firms' exit and entry decisions, and how this interacts with international supply chains.

Another strand of the literature touches on the problem of emissions underreporting when rules or regulations rely on firms' disclosures. Lyon and Kim (2011) empirically investigates the strategic disclosure of greenhouse gas emissions. It finds that firms often disclose emissions in a manner that serves their own interests, particularly when disclosure is voluntary. Our theoretical analysis recognizes that the reliance on voluntary foreign disclosure is particularly relevant in the context of efforts to curb global warming and pollution, since domestic policy makers cannot mandates specific disclosure standards in foreign jurisdictions.

Our paper further contributes to the theoretical literature specifically considering environmental disclosures, such as Lyon and Maxwell (2011); Chen and Schneemeier (2022); Aghamolla and An (2023); Chen (2023); Wu et al. (2023); Xue (2023) and Gupta and Starmans (2024). Relative to these paper, our analysis is concerned with the regulatory problems arising in an international supply chain context where domestic policy makers cannot directly mandate foreign disclosures, but can leverage domestic firms' market power.

Finally, our paper is related to the general theoretical literature examining voluntary disclosure, but that abstracts from externalities affecting third parties and the associated scope for government interventions. Grossman (1981b) and Milgrom (1981) find that when disclosures are ex post verifiable, it is optimal for an agent to fully reveal his private information to his counterparties. This result emerges since agents making the disclosure decision in these papers do not face counterparties with market power, implying that the agent who discloses information is only concerned with his counterparties' conditional beliefs about the mean asset payoff. "Unraveling" obtains then since any information that is withheld is interpreted to be unfavorable (see also Grossman and Hart (1980); Milgrom and Roberts (1986)).[1] In contrast, as in Glode et al. (2018), the disclosing entity in our setting is concerned with the full conditional distributions of payoffs resulting from disclosures, since the counterparty has market power and decides to screen the agent based on the shapes of these conditional distributions. As a result, our environment leads to optimal partial rather than full disclosure. Moreover, the presence of externalities and the differences in how they are affecting different parties implies that contrary to the efficiency results in Glode et al. (2018), disclo-

[1] Verrecchia (1983) modifies a setting akin to Grossman (1981b) and Milgrom (1981) by adding disclosure costs, whereas Fishman and Hagerty (1990) assume that a subset of private information cannot be disclosed. In both cases, maximal disclosure may not be optimal for the informed party. Admati and Pfleiderer (2000), however, show that a firm may pick a socially optimal disclosure plan despite disclosure costs if that firm is a monopolist that captures all gains to trade. Matthews and Postlewaite (1985), Okuno-Fujiwara et al. (1990), Fishman and Hagerty (2003), Shin (2003), Acharya et al. (2011), and Guttman et al. (2014) show, in different environments, that full disclosure becomes suboptimal once there is uncertainty about the existence of private information or its content.

sures generally do not ensure trade that maximizes total surplus, even when the domestic government employs an optimal mechanism.[2] More broadly, our focus on market power also relates our paper to Gal-Or (1985) who models oligopolistic firms that can commit ex ante to sharing noisy signals of their private information about the uncertain demand for their products, although in that setting, no information sharing arises as an equilibrium.

2 Model

Two firms from distinct countries interact in a global supply chain relationship. A domestic firm (D) sources an input from a foreign firm (F) and provides the final product to domestic households (H). The foreign firm's production of the input involves technologies that generate environmental externalities e. The foreign firm is privately informed about the value e, which captures the notion that in practice, a producer is best informed about the specific technologies and practices it is employing. In contrast, outside parties have imprecise prior information about the amount of negative externalities created by the foreign company's manufacturing activities. Outsiders' beliefs are characterized by the cumulative distribution function (CDF) $G(e)$. The function $G(e)$ is continuous and differentiable and the probability density function (PDF), denoted by $g(e)$, takes strictly positive values on the support $[\underline{e}, \overline{e}]$.

The foreign firm can be a cost-efficient producer, which motivates the domestic firm to potentially source its inputs from this firm. However, the foreign firm's production costs are not only affected by its efficiency, but also negatively related to the brownness of its production process: Pollutive production is cheaper from a private perspective. For instance, a brown production process may be cheaper as it economizes on abatement efforts. Formally,

[2] Ali et al. (2023) echo the results of Glode et al. (2018) in the context of voluntary disclosures in interactions with a monopolist. Monopoly pricing is also studied by Bergemann et al. (2015) who analyze how exogenously providing monopolists with additional information for price discrimination affects total surplus and its allocation. Inostroza and Tsoy (2022) investigate optimal security design with information design, and the main result shows that trade always occurs in equilibrium.

the foreign firm's production costs are given by $(c-e)$, where c represents production costs unrelated to externalities.

Two key features of the global supply chain we model are (1) the foreign firm's private information about its environmental standards, and (2) the domestic firm's market power. Specifically, the domestic firm chooses a price p that it will offer to the foreign firm in a take-it-or-leave-it offer. If the offer is rejected by the foreign firm, it is not used to source inputs and all parties obtain a payoff that is normalized to 0.[3] In contrast, if the foreign firm accepts the offer, it produces and delivers the input to the domestic firm, yielding it a payoff:

$$u_F = p \; - \underbrace{(c-e)}_{\text{costs}}, \tag{1}$$

where the first term represents the proceeds from the transaction and the terms in brackets capture the production costs accounting for the cost savings associated with brown technologies that generate high environmental externalities.

Absent government interventions, the domestic firm is not directly impacted by the negative externalities e. This assumption captures the more general notion that the domestic firm does not fully internalize the externalities associated with its sourcing of inputs. In contrast, the domestic household sector is negatively affected by the environmental externalities. In particular, given that production occurs and generates externalities e, domestic households suffer a disutility of $-\lambda e$, where $\lambda > 0$ captures the household's exposures to environmental damages.

Production is beneficial to the domestic section. We let v represent the total value the domestic sector obtains. Among them, δ is the fraction that the domestic firm internalizes, and $(1-\delta)$ is the domestic households' share. Overall, conditional on production and trade

[3]This normalized payoff could reflect in reduced form the possibility that the domestic firm instead relies on an outside option, such as a domestic supplier with known environmental standards.

occurring, the domestic firm's payoff is given by:

$$u_D = \delta v - p, \tag{2}$$

and the domestic households' payoff is given by:

$$u_H = (1-\delta)v - \lambda e. \tag{3}$$

The domestic surplus conditional on trade occurring is then given by:

$$u_D + u_H = v - \lambda e - p, \tag{4}$$

and the global surplus conditional on trade occurring takes the form:

$$u_D + u_H + u_F = v - c + (1-\lambda)e. \tag{5}$$

Environmental Disclosures. Central to our analysis is the possibility of environmental disclosures by the foreign firm. We suppose that the disclosure policy is chosen by the foreign government. The foreign regulator maximizes the foreign surplus knowing that the cross-section of foreign firms is described by the distribution $G(e)$. So the disclosure policy is chosen based on the distribution of e, without knowing the specific realization e. This increases the tractability of our baseline analysis, as it eliminates the signaling concerns. In Section 4.3, we also consider the case where a disclosure plan is instead chosen by the foreign firm after it has learnt its type e (so called "interim" disclosure), and we show that our results are robust to this type of interim disclosure under reasonable equilibrium refinements.

Regarding the disclosure technology, we consider ex post verifiable disclosures. This assumption is motivated by the fact that it is in principle *technologically feasible* that a foreign firm or country would subject itself to environmental certification processes administered by international rating agencies. In the context of CO2 emissions, it is for example possible to allow foreign agencies to monitor such emissions. However, this technological feasibility still leaves the question whether a foreign firm or foreign country finds it privately optimal to commit to such verification. Under ex post verifiability, choosing *not* to commit to providing incremental information is always an option. Ex post verifiability is also a common assumption in the disclosure literature (see Verrecchia (2001); Milgrom (2008a); Beyer et al. (2010) for related surveys). We formally define ex post verifiability as follows.

Definition 1. *A signal whose realization s belongs to a set S is called "ex post verifiable" if it can be represented by a function $D : [\underline{e}, \overline{e}] \to S$ such that $D^{-1}(s) \equiv \{v : D(v) = s\} \in \mathscr{B}([\underline{e}, \overline{e}])$ $\forall s \in S$, where $\mathscr{B}([\underline{e}, \overline{e}])$ denotes the Borel algebra on $[\underline{e}, \overline{e}]$.*

This definition implies that for any signal realization $s \in S$, $D^{-1}(s)$ is a Borel set in $[\underline{e}, \overline{e}]$. Since a Borel set in $[\underline{e}, \overline{e}]$ must be characterized by unions of intervals, designing a disclosure plan implies combining partitions to inform the trade partner about possible realizations of e. In the literature, it is common to impose monotonicity restrictions with regards to the disclosure functions agents choose, since doing so significantly increases analytical tractability (see Orlov, Zryumov, and Skrzypacz, 2023).[4] We follow this approach as stated in the following assumption.

Assumption 1. *Disclosure plans $D(e)$ are restricted to be monotone in e.*

[4]Monotonicity is also imposed in the context of the security design literature, where it has similar justifications. See, e.g., Innes (1990), Nachman and Noe (1994), and DeMarzo and Duffie (1999).

In particular, a disclosure plan $D(e)$ can be represented as follows:

$$D(e) = \begin{cases} \underline{e}, & \text{for } e \in [\underline{e}, e_1), \\ e_1, & \text{for } e \in [e_1, e_2), \\ e_2, & \text{for } e \in [e_2, e_3), \\ \ldots & \\ e_n, & \text{for } e \in [e_n, \overline{e}], \end{cases} \tag{6}$$

where the partition cutoffs $e_1, ..., e_n$, with $\underline{e} < e_1 < e_2 < ... < e_n < \overline{e}$, separate the domain of types $[\underline{e}, \overline{e}]$ into disjoint subsets. Disclosure plans of this type resemble commonly used discrete ratings systems in practice, which typically pool ranges of types under a given ratings category. It is, however, worth noting that full revelation is also feasible under ex post verifiability, in which case the number of possible ratings goes to infinity.

Government interventions. Since the domestic firm do not internalize the negative externalities affecting domestic households, there is a potential role for interventions by the domestic government. In the presence of a tariff τ that is applied to the transaction between the domestic and the foreign firm, the domestic firm's payoff conditional on trade occurring is given by:

$$u_D = \delta v - p - \tau. \tag{7}$$

Timing and equilibrium. The timing of the game is as follows:

1. The foreign government chooses a disclosure policy represented by a function $D : [\underline{e}, \overline{e}] \to S$.

2. The domestic government chooses a tariff schedule that is a function of the possible disclosures S.

3. The foreign firm privately observes e.

4. A disclosure signal $D(e) \in S$ is made public according to the plan $D(e)$.

5. The domestic firm makes a take-it-or-leave-it offer to the foreign firm.

6. The foreign firm accepts or rejects the offer.

7. International production occurs conditional on an acceptance and payoffs are realized.

Figure 1 illustrates this timeline. It is worth highlighting that the domestic government determines its tax policy *after* the disclosure policy has been chosen. The same equilibrium analysis would apply if the domestic government moved first, but could not commit to a taxation policy, that is, if it optimally revised its taxation policy once the foreign disclosure regime is actually set. On the other hand, if the domestic government moved first and could perfectly commit to a taxation policy, the problem would become trivial and unrealistic: The domestic government could always obtain the disclosure plan it wants by threatening that any other disclosure plan would result in infinite tariffs on all transactions. That is, such a setting would effectively eliminate the foreign government's ability to choose disclosures. As a result, we instead consider a timing that implies that the foreign firm or its government can indeed choose their disclosure regime.

An equilibrium consists of the foreign government's disclosure policy, the domestic government's tariff scheme, the domestic firm's take-it-or-leave-it offer, and the foreign firm's acceptance decision. We analyze Perfect Bayesian Equilibria (PBE) of this game.

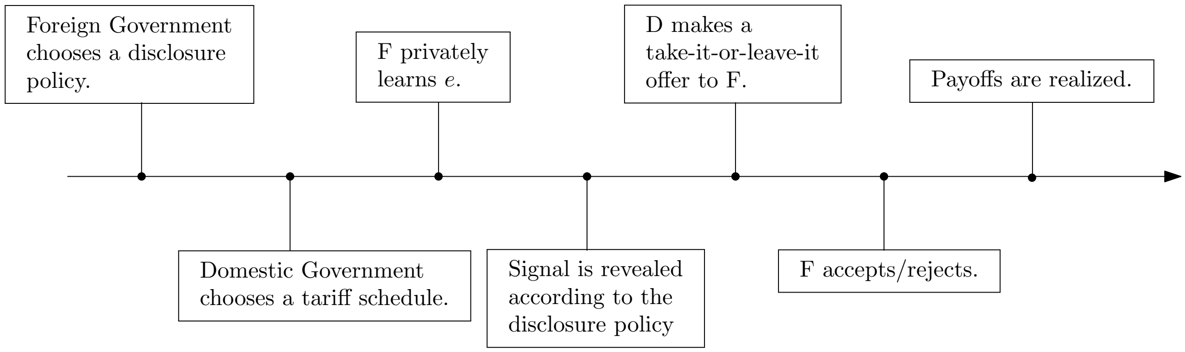


Figure 1: Timeline. The figure illustrates the timeline of the game.

Observability of ex post realizations absent disclosures. One might wonder to what extent it might be feasible for a domestic government to tax parties creating high emissions based on the ex post realizations of emissions (rather than using their voluntary disclosures). A typical feature of externalities such as carbon emissions is that they are not measurable at the level of an individual firm unless measurements are taken locally (at the foreign firm's plant), at the time of their creation.[5] Otherwise, it is not possible to trace emissions back to their source. Formally, this is consistent with an environment where each supply chain relation is atomistic in size, yet households are exposed to aggregate emissions which represent the integral across all individual supply chain interactions. In this case, observing global emissions does not reveal an individual foreign firm's production externalities and thus cannot be used to determine penalties for their domestic supply chain partners, consistent with the setting we study.

[5] See Barwick et al. (2024) and Cong et al. (2024) among others.

3 Model Analysis

3.1 Laissez-Faire Equilibrium

We first study equilibrium outcomes absent interventions by the domestic government. By backward induction, we start by analyzing the trading game with and without disclosures and then turn to the foreign government's optimal choice of disclosure standards.

Trade absent disclosure. To start, consider the case absent disclosures by the foreign government. The domestic firm's optimal pricing decision is characterized by the following program:

$$p^* = \arg\max_p \{(\delta v - p) \cdot (1 - G(c-p))\}, \tag{8}$$

where the first term represents the domestic firm's payoff conditional on trade occurring, and where the second term is the probability of trade; all foreign firm types satisfying $e \geq (c-p)$ accept a price offer p. This problem is equivalent to the domestic firm choosing the marginal foreign firm type $x = c - p$ that is just indifferent between accepting and rejecting the offer. The solution to the following problem yields the corresponding optimal marginal type:

$$e^* = \arg\max_{x \in [\underline{e}, \overline{e}]} \{(\delta v - c + x) \cdot (1 - G(x))\}. \tag{9}$$

If $e^* = \underline{e}$, trade occurs with probability one, that is, irrespective of the realization of e. In this case, not disclosing information is optimal for the foreign firm, since the equilibrium offer by the domestic firm is already the highest possible price. To focus our analysis on scenarios where disclosures may optimally occur in equilibrium absent government interventions, we make the following assumption going forward.

Assumption 2. *Absent disclosure, the probability of trade is less than one, $e^* > \underline{e}$.*

When Assumption 2 is satisfied, trade break downs occur with positive probability absent disclosures due to the presence of asymmetric information and the domestic firm's exercise of market power. In particular, trade breaks down for *low* levels of externalities $e < e^*$, since greener production is associated with relatively high production costs for the foreign firm.

In case an interior solution obtains, $e^* \in [\underline{e}, \overline{e}]$, the following first-order condition holds:

$$\Pi'(e^*) = 1 - G(e^*) - (\delta v - c + e^*) \cdot g(e^*) = 0. \tag{10}$$

We restrict attention to distributions $G(\cdot)$ where the marginal profit function, $\Pi'(\cdot)$, is decreasing, such that the first-order condition (10) holds at the optimum, unless there is a corner solution.

Trade with disclosure. Conditional on the foreign firm disclosing a signal $\tilde{s} \in S$ revealing that $e \in [a, b)$ and implying the associated conditional CDF:

$$G_{\tilde{s}}(e) \equiv \frac{G(e) - G(a)}{G(b) - G(a)}, \tag{11}$$

the domestic firm solves the program:

$$e^*_{\tilde{s}} = \arg \max_{x \in [a,b)} \{(\delta v - c + x) \cdot (1 - G_{\tilde{s}}(x))\}. \tag{12}$$

Conditional on an interior solution, this yields the first-order condition:

$$\Pi'_{\tilde{s}}(e^*_{\tilde{s}}) = 1 - G_{\tilde{s}}(e^*_{\tilde{s}}) - (\delta v - c + e^*_{\tilde{s}}) \cdot g_{\tilde{s}}(e^*_{\tilde{s}}) = 0. \tag{13}$$

A useful property that we will leverage in our analysis below is that the optimal marginal type is unaffected if a signal leads to the truncation of the unconditional distribution $G(e)$ from below, provided that the truncation is weakly below the unconditional optimum. That is, suppose that absent disclosures, the optimal marginal type is interior, $e^* \in [\underline{e}, \overline{e}]$, and solves equation (10). If the domestic firm now receives a signal $\tilde{s}$ that truncates the distribution $G(e)$ from below at $a \leq e^*$, revealing that $e \in [a, \overline{e}]$, we obtain the conditional CDF:

$$G_{\tilde{s}}(e) = \frac{G(e) - G(a)}{1 - G(a)}. \tag{14}$$

Substituting this expression into equation (12) yields

$$e^*_{\tilde{s}} = \arg\max_{x \in [a,b)} \left\{ (\delta v - c + x) \cdot \left(\frac{1 - G(x)}{1 - G(a)} \right) \right\}, \tag{15}$$

which has the same solution as the unconditional program (9), since scaling the objective by a constant factor $(1 - G(a))$ does not affect the optimum.

3.1.1 Bilateral Trade Efficiency Under Voluntary Disclosure

With the above observation, the following lemma characterizes a key property of disclosure plans that are privately optimal for foreign firms.

Lemma 1. *Suppose Assumptions 1 and 2 hold. Absent government interventions, the foreign government optimally designs a partial disclosure plan that ensures that trade occurs if and only if it generates positive joint surplus for the domestic and foreign firm, that is, for*

$$u_D + u_F \geq 0 \quad \Leftrightarrow \quad e \geq c - \delta v. \tag{16}$$

The proof of Lemma 1 is by contradiction.[6] Suppose that contrary to Lemma 1 the foreign government chose a disclosure plan that potentially generates a signal conditional on which trade does not occur with types e for which the bilateral surplus is positive, that is, where $e > c - \delta v$. Specifically, the plan includes a possible disclosure $\tilde{s} \in S$ revealing that

[6] A related result is derived in Glode, Opp, and Zhang (2018).

$e \in [a,b)$ and the optimally chosen marginal type conditional on this disclosure is $e^*_{\tilde{s}} > c - \delta v$. If there are excluded types e satisfying

$$c - \delta v < e < e^*_{\tilde{s}}, \tag{17}$$

the foreign firm can strictly improve its ex ante utility by adjusting its disclosure plan as follows: it can split the original disclosure interval $[a,b)$ into two new disclosure intervals, $[a, e^*_{\tilde{s}})$ and $[e^*_{\tilde{s}}, b)$, associated with the new signals $\hat{s}_1$ and $\hat{s}_2$, while keeping the rest of the disclosure plan unchanged. With this adjusted disclosure plan, conditional on a disclosure $\hat{s}_2$ indicating that $e \in [e^*_{\tilde{s}}, b)$, the price optimally charged by the domestic firm is still $p = c - e^*_{\tilde{s}}$, implying that all types in the interval $[e^*_{\tilde{s}}, b)$ are still trading at the same price under this revised disclosure plan (see the truncation property highlighted in the previous subsection).

Moreover, there will be trade with a positive measure of previously excluded types belonging to the interval $[a, e^*_{\tilde{s}})$ at a price exceeding $p = c - e^*_{\tilde{s}}$. Conditional on a signal $\hat{s}_1$ revealing that $e \in [a, e^*_{\tilde{s}})$, the optimal marginal type is a strictly interior element of the interval $[c - \delta v, e^*_{\tilde{s}})$. The marginal type will be interior for the following reasons: (1) Offering a price $p = c - e^*_{\tilde{s}}$ would yield the domestic firm a payoff of zero, since the acceptance probability would be zero. (2) Offering a price $p = \delta v$ would yield the domestic firm zero since this is its valuation for the good. (3) Offering a price in between these two prices (below δv and above $c - e^*_{\tilde{s}}$) yields a strictly positive probability of trade (since the PDF $g(\cdot)$ takes strictly positive values everywhere on the domain), while the price is also below δv, and thus will yield the foreign firm a positive surplus. At the same time, this (interior) price offer will yield the foreign firm an information rent, since all types above the marginal type (conditional on the disclosure $\hat{s}_1$) will obtain strictly positive surplus. As a result, the foreign firm obtains strictly higher ex ante utility under this revised disclosure plan, implying that the initial supposition is inconsistent with optimality and cannot be an equilibrium.

3.1.2 Optimal Disclosure Plans

Outsiders' beliefs are characterized by the cumulative distribution function (CDF) $G(e)$. The function $G(e)$ is continuous and differentiable and the probability density function (PDF), denoted by $g(e)$, takes strictly positive values on the support $[\underline{e}, \overline{e}]$. Going beyond the above-discussed general property, we now characterize optimal disclosure plans. To start, we define

$$\hat{e}^o \equiv \max(c - \delta v, \underline{e}), \tag{18}$$

that is, the lowest type of e such that there are positive bilateral gains from trade between the domestic and foreign firm (which excludes the damages to households). Given the result of Lemma 1, we can assume without loss of generality that all types in $[\underline{e}, \hat{e})$ are pooled together in one disclosure interval, since trade will not occur with those types in equilibrium.

Next, we define functions that formalize the maximum range of types that can be pooled under one signal without inducing inefficient screening by the domestic firm. In particular, we define the left efficiency bound function $lb : (\hat{e}; \overline{e}] \to \mathbb{R}$ and the right efficiency bound function $rb : (\hat{e}^o; \overline{e}] \to \mathbb{R}$ as follows:

$$lb(e) \equiv \begin{cases} x \in [\hat{e}^o, e) : \Pi'(x) = 0, & \text{for } \Pi'(\hat{e}^o) > 0, \\ \hat{e}, & \text{for } \Pi'(\hat{e}^o) \leq 0, \end{cases} \tag{19}$$

$$rb(e) \equiv \begin{cases} G^{-1}(1 - \Pi'(e)), & \text{for } \Pi'(e) > 0, \\ \overline{e}, & \text{for } \Pi'(e) \leq 0. \end{cases} \tag{20}$$

If e represents the upper bound of a disclosure interval, then the smallest feasible lower bound of this interval is given by $lb(e)$. Conversely, if we start with e as a lower bound of such a pooling interval, then $rb(e)$ yields the highest associated feasible upper bound.

Lemma 2. *Given any two partition cutoffs e_{s-1} and e_{s+1} with $s \geq 2$ that satisfy the efficiency constraint $e_{s-1} \geq lb(lb(e_{s+1}))$, the interior cutoff e_s that maximizes the foreign firm's expected payoff is either equal to $rb(e_{s-1})$ or equal to $lb(e_{s+1})$.*

Lemma 2 dramatically reduces the set of partition cutoffs that can be optimal. Given any two neighboring partition cutoffs e_{s-1} and e_{s+1} that do not immediately violate the efficiency constraints, the optimal interior cutoff e_s takes one of two possible candidate values: $rb(e_{s-1})$ or $lb(e_{s+1})$.

We now derive a condition that ensures that one of these two candidates consistently dominates. To do so, we specify the function $\Phi : \Omega \to \mathbb{R}$ as:

$$\Phi(u,w) \equiv u[G(lb(w)) - G(rb(w))] + lb(w)[G(w) - G(lb(w)] - rb(w)[G(w) - G(rb(w))], \tag{21}$$

where the domain of the function Φ is defined as follows:

$$\Omega \equiv \{(u,w) : u \in (lb(lb(w)), lb(w)] \text{ and } w \in (rb(\hat{e}^o), \overline{e}]\}. \tag{22}$$

The Φ-function represents the foreign firm's expected net benefit of choosing, given some generic neighboring partition cutoffs u and w, an interior cutoff $\tilde{v}$ that is equal to $lb(w)$ rather than equal to $rb(u)$. The Φ-function encodes non-local properties of the function $G(\cdot)$ affecting the optimal disclosure plan. We can show that the sign of Φ is not uniquely determined. However, under a large range of specifications for $G(\cdot)$, the Φ-function takes weakly positive values everywhere on it domain — we present below several examples involving uniform distributions or truncated Normal distributions where this is the case. In cases like these, the characterization of an optimal disclosure plan is highly tractable. Correspondingly, we specify the following technical condition.

Assumption 3. $\Phi(u,w) \geq 0, \forall (u,w) \in \Omega$.

The following proposition characterizes optimal disclosure plans absent government interventions.

Proposition 1. *Suppose Assumptions 1–3 hold. Absent government interventions, the partition cutoffs of an optimal disclosure plan function are given by a descending sequence starting with* $e_{n+1} = \overline{e}$ *and where:*

$$e_s = lb(e_{s+1}), \quad \textit{for} \quad s = n, (n-1), ..., 3, 2. \tag{23}$$

When $c - \delta v < \underline{e}$*, this sequence* $\{e_n, e_{n-1}, e_{n-2}, ..., e_2\}$ *is finite. Otherwise, this sequence is infinite (that is,* $n \to \infty$*) and converges to* $\hat{e}^o$ *from above.*

While we will discuss examples with concrete distributions below, it is worth highlighting a general property of disclosure plans based on Lemma 1 and Proposition 1: The foreign firm benefits from maximizing the size of the disclosure intervals subject to the constraint that the disclosure does not induce trade breakdowns that are bilaterally inefficient. As such, for values of e where the bilateral gains from trade $(\delta v - c + e)$ become small, the disclosure intervals and the associated information asymmetries also need to shrink to prevent such trade breakdowns. Naturally, the smaller the disclosure interval, the less information asymmetry remains between the supply chain partners. If bilateral gains from trade approach zero (for $e \downarrow \hat{e}^o$), the disclosure intervals in fact become locally arbitrarily small in the vicinity of $\hat{e}^o$. We illustrate Proposition 1 using an example of uniform distributions.

Example 1. Suppose $e \in U[\underline{e}, \overline{e}]$. We can verify that Assumption 3 holds. Applying Proposition 1, absent government interventions, the partition cutoffs of an optimal disclosure plan function are given by a descending sequence starting with $e_{n+1} = \overline{e}$ and where:

$$e_s = lb(e_{s+1}) = \frac{\delta v - c + e_{s+1}}{2}, \qquad \text{for} \quad s = n, (n-1), ..., 3, 2. \tag{24}$$

Here, n is chosen so that $lb(e_2) \leq \underline{e}$, equivalently $\frac{\delta v - c + e_2}{2} \leq \underline{e}$. This disclosure plan states that the cutoffs in the optimal disclosure are achieved by sequentially applying the left-bound function, staring from the right end of the support of the distribution.

3.2 Government Interventions

In this subsection, we consider government interventions. While government interventions can take various forms, we focus on the optimal interventions from the perspective of the domestic country. In the appendix we consider the case where the government imposes an unconditional transaction tax τ that does not vary with either the foreign firm's disclosures or the domestic firm's price offers (naturally τ is a subsidy when it takes negative values).

We make the following assumption.

Assumption 4. *$v - c + (1 - \lambda)\underline{e} > 0$ and $v - c + (1 - \lambda)\overline{e} < 0$.*

This assumption implies that $\lambda > 1$, since $\overline{e} > \underline{e}$. Assumption 4 states that global surplus is positive at the minimum level of externalities $e = \underline{e}$ and negative at the maximum level of externalities $e = \overline{e}$. As a result, there is a unique interior threshold level $\hat{e} \in (\underline{e}, \overline{e})$ at which the global surplus conditional on trade occurring is exactly zero. This threshold level is given by:

$$\hat{e} = \frac{v - c}{\lambda - 1}. \tag{25}$$

Proposition 2. *Suppose Assumptions 1–4 are satisfied and that the hazard rate* $\frac{g(e)}{1-G(e)}$ *is an increasing function. Then, if the domestic government implements the optimal regulatory policy, there exists a threshold level* $\underline{\lambda}$*, such that if the domestic sector's exposure satisfies* $\lambda \leq \underline{\lambda}$*, the foreign government's optimal disclosure policy implies that total global surplus is maximized, that is, trade occurs if and only if*

$$u_H + u_D + u_F > 0. \tag{26}$$

As shown in Section 3.1, absent government interventions, voluntary disclosure plans generally ensure that trade occurs if and only if it generates positive private bilateral surplus for the two firms in the supply chain. However, one may be naturally interested in total global surplus, which additionally accounts for the disutility households experience due to production externalities. Proposition 2 shows that when households are not highly exposed to externalities, the optimal disclosure plans also ensure that total global surplus is maximized, provided that the domestic government intervenes optimally.

However, if domestic households' exposure to externalities is sufficiently large, this result no longer holds. The exposure parameter λ modulates the extent to which the domestic sector's view on the desirability of high-externality transactions differs from that of the foreign trade partner: for higher values of λ, the domestic sector benefits from trade under high-externality production are decreased, whereas the foreign firm's benefits remain unchanged. For sufficiently high values of λ any marginal increase in border tariffs is associated with such a potent negative selection effect (as only the higher-externality suppliers continue to trade) that it is never improving domestic surplus. As a result, the domestic planner solution is an extreme bang-bang solution: the domestic sector either optimally trades with the whole pool of foreign firm types conditional on a given disclosure or with none of them. Put differently, technical conditions that were satisfied absent government interventions and ensured that marginal optimality conditions held are now violated. Facing such an extreme domestic policy, the foreign government optimally designs a disclosure policy that leads to excessive pooling, in the sense that trade occurs when it destroys total global surplus.

Proposition 3. *Suppose Assumptions 1–4 hold and that $e \cdot g(e)$ is an increasing function, which is for example satisfied when e is uniformly distributed. Then, if the domestic government implements the optimal regulatory policy, there exists a threshold level $\hat{\lambda}$, such that when $\lambda \geq \hat{\lambda}$, the foreign firm's optimal disclosure plan induces excessive trade from a global perspective, that is, trades occurs for a range of externalities e such that*

$$u_H + u_D + u_F < 0. \tag{27}$$

Proof. See Appendix. □

When the domestic households are sufficiently strongly exposed to environmental damages, which is the case for high enough values of the parameter λ, the foreign government chooses a disclosure policy that pools types above the threshold level $\hat{e}$ with those below that level. As a result, when the disclosure indicates that externalities are in that region, trade occurs even though it may destroy global surplus. We will discuss this issue further in Section 5, where we examine disclosure plans under specific distributions.

3.2.1 Tariff Implementation of the Domestic Planner Solution

In the previous section, we solved the domestic planner's solution by assuming that the government uses a tariff scheme that ensures that the domestic firm acts as if it maximizes total domestic surplus. We now examine how this can be implemented by taxing the domestic firm's supply chain interaction with the foreign firm. We assume that government charges the lowest-absolute-value tax whenever government is indifferent among several different tariffs. This ensures that no tariff is charged if doing so achieves the optimum.

Suppose the foreign firm does not possess private information about e, the domestic households' expected payoff would be $(1-\delta)v - \lambda \cdot \mathbb{E}[e|\mathscr{F}]$. By charging the following Pigouvian tax

$$\tilde{\tau} = \lambda \cdot \mathbb{E}[e|\mathscr{F}] - (1-\delta)v, \tag{28}$$

the domestic firm internalizes the households' payoff when quoting a price to the foreign firm, and the domestic planner solution is implemented.

Turning to the case where the foreign firm has private information, we examine the domestic government's optimal tariff scheme as a function of the foreign firm's disclosure. Suppose the foreign firm discloses a signal $\tilde{s}$ revealing that $e \in [a,b)$ and that the optimal marginal type $e^{**}_{\tilde{s}}$ for the domestic planner is an interior solution $e^{**}_{\tilde{s}} \in [a,b)$, which satisfies the first-order condition (13):

$$1 - G_{\tilde{s}}(e^{**}_{\tilde{s}}) = (v - c + (1-\lambda) \cdot e^{**}_{\tilde{s}}) \cdot g_{\tilde{s}}(e^{**}_{\tilde{s}}). \tag{29}$$

The following proposition characterizes how the optimal tax depends on this marginal type $e^{**}_{\tilde{s}}$.

Proposition 4. *Suppose that $H(e) \equiv \frac{1-G(e)}{g(e)} - e$ is a decreasing function of e. Suppose the foreign firm's discloses a signal $\tilde{s}$ revealing that $e \in [a,b)$, and the domestic planner solution induces trade for $e \geq e^{**}_{\tilde{s}}$, where $e^{**}_{\tilde{s}} \in (a,b)$. Then the government can implement this solution by imposing a tariff*

$$\tau = \lambda e^{**}_{\tilde{s}} - (1-\delta)v. \tag{30}$$

Comparing the optimal tax under asymmetric information (30) to the optimal tax under symmetric information (28) reveals that both tariffs have a similar structure. However, whereas the tax under symmetric information leads the domestic firm to internalize the *ex-*

pected externality if trade were to occur (potentially off equilibrium), the optimal tax under asymmetric information causes the domestic firm to internalize the externality caused by the *marginal* type $e^{**}_{\tilde{s}}$ with which trade occurs under the domestic planner solution. This marginal type depends on the equilibrium disclosure choices of the foreign firm and the residual information asymmetry characterized by the conditional distribution $G_{\tilde{s}}(e)$.

3.2.2 Uniform Distributions

In this section, we provide a full characterization of optimal government policies and optimal disclosure plans when externalities are uniformly distributed, $e \sim U[\underline{e}, \overline{e}]$. As a first step, the following proposition characterizes the government's optimal planner solution conditional on any disclosure by the foreign firm. Moreover, it details how the planner solution can be implemented via tariffs.

Proposition 5 (Tax Implementation). *Suppose externalities are uniformly distributed, $e \sim U[\underline{e}, \overline{e}]$, and $\lambda > 1$.*

1. *Suppose $\lambda < 2$ and the foreign firm's disclosure reveals that $e \in [a, b)$. The domestic planner solution and its implementation via tariffs have the following properties:*

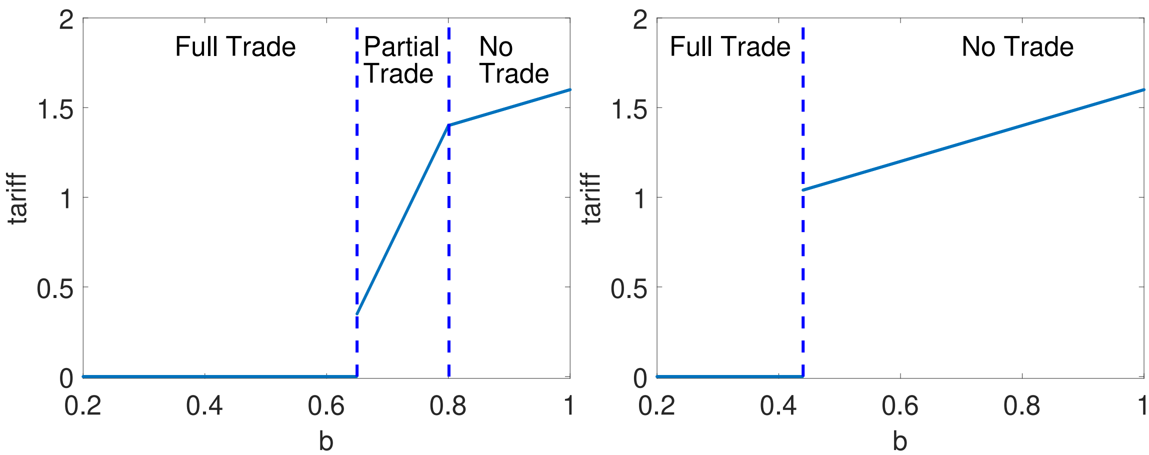
$$\tau \begin{cases} \leq 2a - b + \delta v - c & \text{if } a \geq \frac{b-(v-c)}{2-\lambda}, \\ = \frac{\lambda(b-\delta v+c)-2(1-\delta)v}{2-\lambda} & \text{if } a < \frac{b-(v-c)}{2-\lambda} < b, \\ \geq b + \delta v - c & \text{if } \frac{b-(v-c)}{2-\lambda} \geq b. \end{cases}$$

2. *Suppose $\lambda > 2$ and the foreign firm's disclosure reveals that $e \in [a, b)$. The domestic*

planner solution and its implementation via tariffs have the following properties:

$$\tau \begin{cases} \leq 2a - b + \delta v - c & \text{if } v - \lambda \frac{a+b}{2} - (c-a) \geq 0, \\ \geq b + \delta v - c & \text{otherwise.} \end{cases}$$

Proof. See Appendix. □



(a) $\lambda = 1.75$ **(b)** $\lambda = 2.5$

Figure 2: The figure considers a parameterization where $e \sim U[0,1]$, $\delta = 1$, and $(v-c) = 0.6$. It illustrates the tariff implementing the domestic planner solution for a generic disclosure revealing that $e \in [0.2, b)$ as a function of the upper bound b of the disclosure interval. The left-hand side panel considers the case where $\lambda = 1.75$, and the right-hand side panel the case where $\lambda = 2.5$.

Proposition 5 shows that outcomes differ dramatically between the cases of low and high environmental exposures, as represented by $\lambda < 2$ and $\lambda > 2$. The domestic planner's payoff is given by the probability of trade time the payoff conditional on trade, which is

$$v - c - \lambda E[e | e \geq e^{**}] + e^{**}, \tag{31}$$

where e^{**} is the cut-off-type firm that trades. Since a higher induced cut-off type leads to a lower trade probability, the probability of trade is a decreasing function of e^{**}. When e follows a uniform distribution with upper bound b, the domestic planner's expected payoff conditional on trade is $v-c-\lambda\frac{e^{**}+b}{2}+e^{**}$. It is evident that when $\lambda<2$, the payoff conditional on trade is an increasing function of e^{**} while when $\lambda>2$, it is a decreasing function. In the former case ($\lambda<2$), there is typically an interior e^{**} that maximizes the domestic planner's payoff. In the latter case ($\lambda>2$), the domestic planner optimally induces an equilibrium that features either trade with all types or none of them, depending on whether trade with all types leads to a positive expected payoff. Anticipating this policy by the domestic government, the foreign firm then optimally discloses at most two intervals where one of the them pools as many green types (low e) as possible subject to trade occurring and the other one containing all remaining browner (high e) types.

Figure 2 illustrates the results of Proposition 5 with comparative statics. It illustrates the tariff implementing the domestic planner solution for a generic disclosure revealing that $e\in[0.2,b)$ as a function of the upper bound b of the disclosure interval. The left-hand side panel considers the case where $\lambda=1.75$, and the right-hand side panel the case where $\lambda=2.5$. Throughout, absent government intervention, the marginal foreign firm type is equal to the lower bound of the disclosure interval, 0.2, that is, trade occurs with probability 1 for all values of the upper-bound parameter b between 0.2 and 1.

In contrast, under the domestic planner solution, the optimal marginal foreign firm type starts to exceed the value 0.2 for sufficiently high values of b, both in the case of $\lambda=1.75$ and the case where $\lambda=2.5$. Intuitively, once a disclosure indicates the possibility of sufficiently high environmental externalities, the government takes measures to reduce trade. First, consider the case where domestic households are strongly exposed to the externalities caused by the foreign firm's production, $\lambda=2.5$ (right-hand side panel). As we increase the upper-bound parameter b, the domestic planner solution discretely switches between choosing a marginal foreign firm type equal to the lower bound 0.2 (in which case trade occurs always) and choosing the upper bound b (in which case trade never occurs). This is implemented by first imposing no tariffs and then discretely shifting to a positive tax that increases with the upper bound b.

Second, consider the case where domestic households are less exposed to the externalities, $\lambda = 1.75$ (left-hand side panel). Now, as we increase the upper-bound parameter b, there is also a threshold level for b at which the government switches from imposing no tariffs to imposing a strictly positive tax. For an intermediate range of values of the parameter b, this tax ensures that there is an interior marginal foreign firm type, and trade occurs only if externalities *exceed* that marginal type. Why would this be an optimal outcome from the perspective of the domestic economy? The answer is that brown production (high values for e) also has the benefit of being associated with low costs for the foreign producer, which, in turn, is passed through via low prices to the domestic economy. However, once the negative externalities e can be high enough, the tariff schedule yet again ensures that there is no trade between the domestic firm and the foreign firm. Such a tax is still increasing with the upper bound of the disclosure interval b. Overall, these results illustrate the intricate properties of optimal domestic taxation in response to foreign firms' disclosures.

Anticipating this domestic planner solution, the foreign firm chooses its optimal disclosure plan, which is characterized in the following proposition.

Proposition 6 (Optimal Disclosure)**.** *Suppose externalities are uniformly distributed, $e \sim U[\underline{e}, \overline{e}]$, $\lambda > 1$, and the government implements the domestic planner solution.*

1. *When $\lambda < 2$, the privately optimal disclosure plan chosen by the foreign firm ensures that trade occurs if and only if $u_H + u_D + u_F > 0$. The disclosure plan can be repre-*

sented by the function

$$D(e) = \begin{cases} \underline{e}, & \text{for } e \in [\underline{e}, e_1), \\ e_1, & \text{for } e \in [e_1, e_2), \\ e_2, & \text{for } e \in [e_2, e_3], \\ \cdots & \\ \overline{e}, & \text{for } e \in [\hat{e}, \overline{e}], \end{cases} \tag{32}$$

where the infinite sequence $\{e_1, e_2, \cdots\}$ *is defined by the recursive relation* $e_{i+1} = (2-\lambda)e_i + (v-c)$, *with* $e_0 \equiv \underline{e}$ *and* $\lim_{n\to\infty} e_n = \hat{e}$.

2. *When* $\lambda \geq 2$, *the privately optimal disclosure plan chosen by the foreign firm separates the domain into two disjoint intervals. The optimal disclosure plan can be represented by the function*

$$D(e) = \begin{cases} \underline{e}, & \text{for } e \in [\underline{e}, e_1], \\ e_1, & \text{for } e \in (e_1, \overline{e}], \end{cases} \tag{33}$$

where

$$e_1 = \frac{2(v-c) + 2\underline{e}}{\lambda} - \underline{e}. \tag{34}$$

Trade occurs with probability 1 when the foreign firm discloses $\underline{e}$ *and with probability 0 otherwise. Global surplus,* $(u_H + u_D + u_F)$, *is strictly negative when externalities take values in the interval* $(\hat{e}, e_1]$.

Proof. See Appendix. □

Proposition 6 shows that the parameter λ characterizing domestic households' exposures to environmental damages has first-order implications for the shape of disclosure plans and the extent to which government interventions effectuate behavior that maximizes global surplus. When the exposure to externalities is smaller ($\lambda < 2$), disclosure plans may feature more than two intervals and supply chain outcomes maximize global surplus. In fact, as we will illustrate below, foreign disclosures potentially become more precise in the presence of interventions by the domestic government. This happens when the private bilateral surplus from trade among supply chain partners is reduced by optimal tariffs but still remains positive. In those cases, the foreign supply chain partners find it optimal to choose more precise disclosures to avoid jeopardizing post-tax gains from trade under asymmetric information.

In contrast, when the exposure to externalities is larger ($\lambda > 2$), disclosures become binary when the government intervenes. Fundamentally, this occurs because the domestic government's ability to effectively screen the foreign firm by fine-tuning tariffs vanishes when the domestic sector is highly exposed to externalities. In this case, trade is plagued by severe adverse selection. Generally, a marginal tax increase has two opposing effects for domestic surplus: on the one hand, a tax increase raises domestic surplus conditional on trade occurring, as it lowers the price the domestic firm offers. However, on the other hand, such a price decrease also leads to the rationing of trade with higher-cost producers, which tend to be greener. Put differently, on average, the remaining pool of suppliers with which trade occurs is browner.

When the domestic sector is sufficiently strongly exposed to externalities ($\lambda > 2$), this second adverse selection effect is more potent and consistently dominates, implying that a marginal tax increase is counterproductive. As a result, given the information provided by a disclosure, the domestic government finds one of two tariffs optimal: either to impose punitive tariffs that eliminate trade altogether (if the expected net-surplus is negative) or to ensure trade occurs with all remaining types consistent with the provided disclosure (if the average net-surplus across these remaining supplier types is positive). In turn, anticipating such an extreme taxation policy, foreign disclosures optimally subsume the largest possible pool of relatively green producers under one disclosure (a "green" rating) with which trade occurs. The residual "brown" pool will be completely rationed. However, the "green" pool is excessively large, in the sense that it includes too many brown types and leads to the destruction of global surplus.

We illustrate the results of this section with the standard uniform distribution.

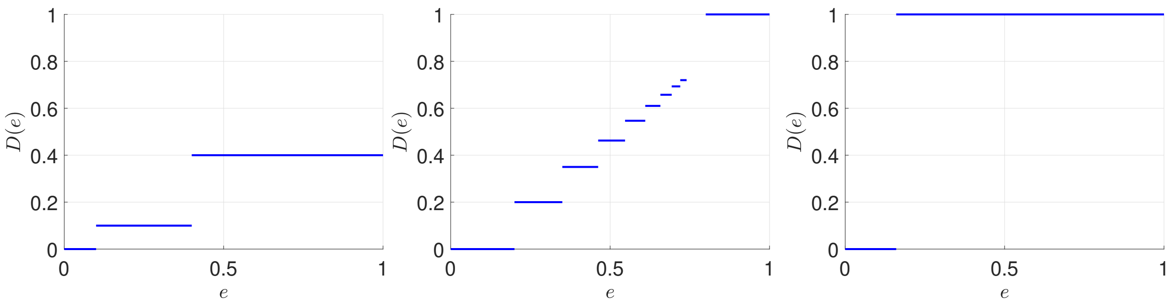
Example 2. Suppose the environmental externalities are uniformly distributed, $e \sim U[0,1]$, that is, $\underline{e} = 0$ and $\overline{e} = 1$, and suppose that $\delta = 1$.

No government interventions. Absent government interventions, an optimal disclosure plan for the foreign firm is given by:

$$D(e) = \begin{cases} 0, & \text{for } \ e \in [0, e_1), \\ e_1, & \text{for } \ e \in [e_1, e_2), \\ \dots \\ e_n, & \text{for } \ e \in [e_n, 1], \end{cases} \tag{35}$$

where the values $e_1 ... e_n$ are defined by the recursive sequence the recursive sequence $e_i = \frac{e_{i+1} - (v-c)}{2}$, where $e_{n+1} \equiv 1$ and where $n = \max_{i \in N^+} \{e_1 \geq 0\}$.

Domestic planner solution. Suppose the government imposes an optimal conditional tariff scheme that implements the domestic planner solution as stated in Proposition 5. Further, the foreign firm chooses the corresponding optimal disclosure schedule as stated in Proposition 6.



(a) No intervention & $(v-c)=0.2$ **(b)** Intervention & $\lambda=1.25$ **(c)** Intervention & $\lambda=2.5$

Figure 3: The figure illustrates the optimal disclosure plans chosen by the foreign government absent intervention (left-hand side panel) and in the presence of the optimal domestic tariff scheme (middle and right-hand side panels).

Figure 3 compares the optimal disclosure plan conditional on no government intervention (left-hand side panel) and in the presence of the optimal domestic tariff scheme (middle and right-hand side panels). When government does not intervene (see Panel (a), the foreign firm optimally provides a relatively granular disclosure plan that splits the domain of externalities into three intervals. Doing so ensures that trade occurs for all externality levels, despite the presence of lower gains from trade. In contrast, once the government tariffs transactions conditional on such disclosures (see Panels (b) and (c)), the disclosure depends on the level of λ. When $\lambda < 2$ (see Panel (b)), the disclosure features a more granular plan when externality is low while a large pooling type when externality is high. The intuition is as follows. Note that the surpluses get smaller as we incorporate households' disutility from externality, comparing to the no-intervention benchmark. As a result of smaller surpluses, granular disclosures are needed to ensure trade to occur. When $\lambda > 2$ (see Panel (c)), the foreign government chooses a less granular plan with only two intervals, and where the lowest interval pools more types, comparing to the no-intervention benchmark.

Overall, these results reveal that when international trade involves countries that have substantially different exposures to the environmental damages, tax schedules should generally be a non-linear function of disclosed externalities. This prescription contrasts with the presence of one common price for emissions in carbon credit markets in practice. Moreover, our analysis reveals how the goal of penalizing high-externality production interferes with the precision of disclosures, highlighting the limits of optimal government interventions that target domestic firms' import practices.

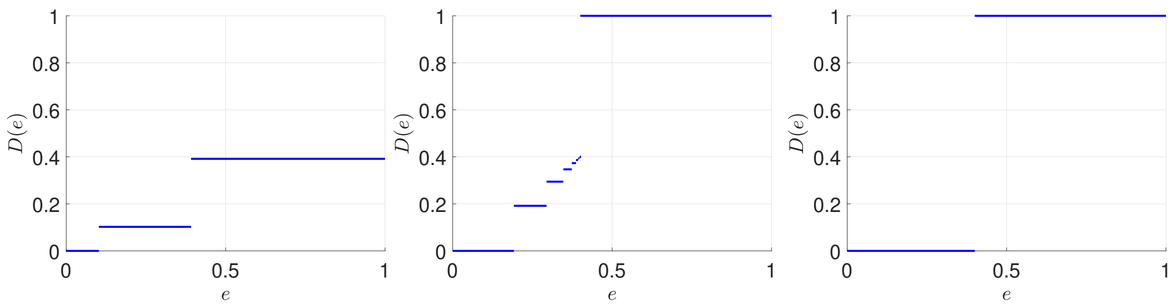
4 Robustness and Extensions

In this section, we consider variations to our baseline model to examine the robustness of our results. First, we analyze the case where externalities follow a truncated normal distribution. Second, we analyze what would happen if the domestic firm, rather than the foreign firm, could choose the disclosure plan. Third, we consider an alternative timing assumption with "interim" disclosure choices that occur after the foreign firm has learnt its type.

4.1 Normally Distributed Environmental Externalities

We analyze the case where externalities follow a truncated normal distribution. We consider optimal disclosure plans chosen by the foreign firm both absent interventions and in the presence of the optimal domestic tariff scheme. Importantly, we again examine how households' exposure to externalities shapes equilibrium outcomes.

Figure 4 considers a parameterization with a relatively low exposure of households to externalities. Absent interventions, the foreign firm chooses a fairly coarse disclosure plan with three potential signals (see Panel (a)). In contrast, in the presence of government interventions (Panel (b)), the optimal disclosure plan becomes increasingly granular as externalities approach $\hat{e} \approx 0.4$, the level where global surplus turns negative. Interestingly, in this case the anticipation of government tariffs and the associated reduction in gains from trade between the domestic and foreign firm necessitates more informative disclosures to avoid inefficient trade break downs. This result obtains specifically when the domestic sector has a relatively low exposure to externalities (here $\lambda = 1.5$)). In contrast, Figure 4 illustrates the case where households are more strongly exposed to externalities; here we increase the exposure parameter to to $\lambda = 3$. In this case, government interventions reduce the precision of disclosures, as shown in Panel (c) of Figure 4.



(a) No intervention **(b)** Intervention & $\lambda = 1.5$ **(c)** Intervention & $\lambda = 3$

Figure 4: The figure illustrates the foreign firm's privately optimal disclosure plan with and without government intervention. Externalities follow $e \sim N(0.5, 1)$, truncated from below at 0, and from above at 1.

4.2 Disclosure Plans Chosen by the Domestic Firm

So far, we have assumed that the disclosure plan is chosen by the foreign government. In this section, we instead study the case when the disclosure plan is chosen by the domestic firm. As before, such a disclosure plan could for example be enforced by an international rating agency that is tasked with measuring and reporting environmental pollution or emissions.

The timing of the game is now as follows:

1. The domestic firm chooses a disclosure plan represented by a function $D : [\underline{e}, \overline{e}] \to S$.

2. The government chooses a tariff schedule that is a function of the possible disclosures S.

3. The foreign firm privately observes e.

4. A signal according to the disclosure plan $D(e)$ is released and becomes publicly known.

5. The domestic firm makes a take-it-or-leave-it offer to the foreign firm.

6. The foreign firm accepts or rejects the offer.

7. International production occurs conditional on an acceptance and payoffs are realized.

Absent interventions by the domestic government, the domestic firm would always choose a perfectly revealing disclosure plan. This is because the domestic firm then can extract all rents by levering its market power. However, once the domestic government may intervene with tariffs, the domestic firm may choose a coarse disclosure plan, in particular for sufficiently high values of λ. The following proposition formalizes this result in the case where externalities are uniformly distributed.

Proposition 7. *Suppose e follows a uniform distribution $U[0,\overline{e}]$ and $\delta = 1$. When the domestic firm chooses the disclosure plan, full disclosure is weakly optimal for $\lambda < \frac{7+\sqrt{17}}{4}$. Otherwise, when $\lambda \geq \frac{7+\sqrt{17}}{4}$, the domestic firm chooses the disclosure plan described in* (33) *(i.e., a coarse disclosure plan with two ratings).*

The first part of Proposition 7 shows that the domestic firm would not want to choose a disclosure regime that leaves any relevant information asymmetries when the domestic sector has a relatively low exposure to externalities (for $\lambda < \frac{7+\sqrt{17}}{4}$). When λ is sufficiently small, the domestic firm expects that its government will not impose any tariffs even under full disclosure. In this case, full disclosure is best for the domestic firm as it facilitates extracting all rents from the foreign firm. As λ increases, the domestic firm anticipates that, under full disclosure, its government starts to impose tariffs for high emissions types that render trading with those types privately unprofitable. It is worth noting that in this case, full disclosure is generally only one of many optimal disclosure plans, in the following sense. Suppose, for example, the cutoff of the emission type over which trade does not occur in equilibrium is e_1 (because of tariffs being imposed for all firms that are browner than e_1). Then a disclosure plan that is perfectly revealing for $e < e_1$ and that pools all types with $e \geq e_1$ is also optimal for the domestic firm. This is because regardless of the disclosure signals for $e > e_1$, the government would impose a tax such that trade does not occur with these types, and the domestic firm's payoff would be identical to that under full disclosure.

However, once λ reaches a critical value, the domestic firm is better of imposing a coarse disclosure plan with just two ratings. Anticipating that its government will condition tariffs on disclosures and would, under full disclosure, eliminate trade with a wide range of foreign firm types, such a disclosure is no long optimal. Instead, the domestic firm optimally chooses a plan that pools as many green foreign firm types under one rating as possible, mirroring the binary disclosure plan in Proposition 5. However, in Proposition 5, this disclosure plan with two ratings was chosen when $\lambda > 2$. Instead, when the domestic firm chooses the plan, this occurs when $\frac{7+\sqrt{17}}{4} > 2$. That is, whenever the domestic firm chooses the binary disclosure plan (33), the foreign firm would choose the same plan.

In sum, even when the domestic firm can choose the disclosure regime, excessive pooling with coarse ratings emerges in equilibrium, in particular when the domestic sector is sufficiently strongly exposed to externalities.

4.3 Interim Disclosure

In our baseline analysis, we considered the case where the disclosure regime is chosen based on a decision maker that knows the distribution of e but not its specific realization. This assumption is particularly reasonable if one envisions a setting where a foreign government chooses a disclosure regime for its firms ex ante, anticipating the distribution of firms that subside in the foreign country. In contrast, if an individual foreign firm chooses its disclosure plan, it might be reasonable to assume that this firm already has private information when it makes that choice. Correspondingly, we now study the robustness of our results to such an "interim" disclosure game (see also Grossman (1981a) and Milgrom (2008b)).

While multiple equilibria emerge in such a game due to signaling concerns, we will show that the equilibrium outcomes characterized in our baseline analysis also obtain in the case of interim disclosure under sensible equilibrium refinements. The timeline of the game we now study is illustrated in Figure 5.

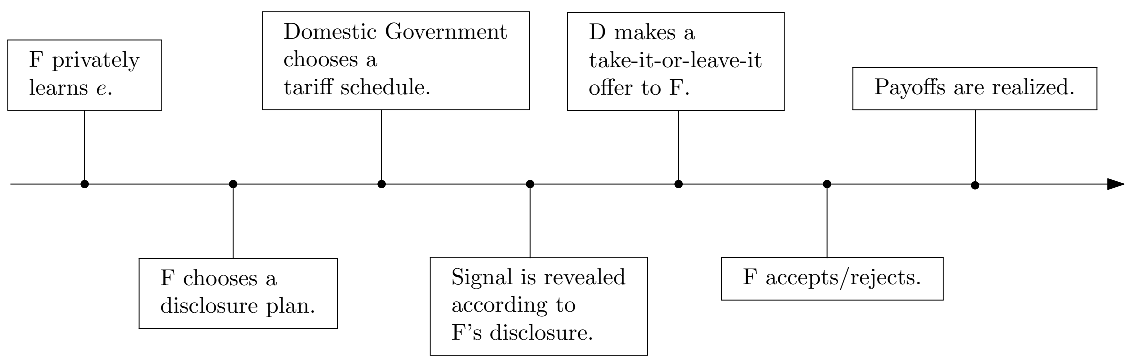


Figure 5: Timeline. The figure illustrates the timeline of the game with interim disclosure.

We make two remarks. First, since $D(e)$ is now chosen by the foreign firm after it observes e, we can interpret $D(e)$ as a pure-strategy message that the foreign firm sends in this signaling game. Upon receiving a signal s, other agents form beliefs about the the foreign firm's type e, which we denote by the distribution function $\mu(s) \in \Delta([\underline{e}, \overline{e}])$.[7] Then the domestic firm quotes a price, which we now denote as $p(\tau, s)$, to maximize his expected profit, and the foreign firm decides whether to accept. The foreign firm's optimal strategy in that last stage is simply to accept the offer if and only if the quoted price is weakly higher than its production cost, $(c-e)$. For ease of exposition, we do not introduce extra notation for this final stage and directly impose that the foreign firm follows this dominant strategy.

Definition 2. *A* $(\tau(\cdot), D(\cdot), \mu(\cdot), p(\cdot,\cdot))$ *profile forms a perfect Bayesian equilibrium of the interim game if:*

[7] We use $\Delta([\underline{e}, \overline{e}])$ to denote the set of all possible probability distributions on $[\underline{e}, \overline{e}]$.

1. *For every possible signal s, the tariff schedule* $\tau(s)$ *maximizes the domestic welfare.*

2. *For every possible signal s and tariff* $\tau(s)$, $p(\tau,s)$ *maximizes the domestic firm's expected profit* $\max_p (v - p - \tau(s)) \cdot \Pr_{\mu(s)}[c - e \leq p]$.

3. *For every* $e \in [\underline{e}, \overline{e}]$, $D(e)$ *solves* $\arg\max_s \{\max[p(\tau(s),s) - (c-e), 0]\}$, *where* $e \in D(e)$.

4. *For every s in the range of D (i.e., every Borel set s that can be disclosed in equilibrium), the domestic sector's belief* $\mu(s)$ *is obtained by applying Bayes' rule given the particular signal s.*

Since beliefs are unrestricted following off-equilibrium deviations, there exist beliefs such that the domestic firm (who has market power) drives the foreign firm's information rents to zero following any off-equilibrium deviation in disclosure. This leads to the existence of multiple perfect Bayesian equilibria with various degrees of information revelation, as opposed to a unique equilibrium with full revelation as in Grossman (1981a) and Milgrom (2008b).[8]

Given this equilibrium multiplicity, we restrict our attention to the sets of equilibria that survive the following two refinements. First, we consider as *foreign-firm-preferred equilibria* the set of equilibria that are not dominated among foreign firm types — in the Pareto sense — by another equilibrium based on their interim payoffs. Second, we consider an alternative equilibrium refinement known as Grossman-Perry-Farrell, based on the perfect sequential equilibrium of Grossman and Perry (1986) and the neologism-proof equilibrium of Farrell (1993).[9] This refinement is commonly used in models of verifiable disclosure

[8]For instance, either full disclosure, partial disclosure, or no disclosure can be supported in equilibrium if the seller has the following beliefs: if for any s not in the range of D (that is, whenever s is an off-equilibrium signal), the belief $\mu(s)$ assigns probability 1 to type $\bar{e}(s)$, where $\bar{e}(s) \equiv \sup s$ (recall that s is a Borel set). Here, an equilibrium is said to feature full disclosure if $\mu(D(e))$ assigns probability 1 to type e, whereas it is said to feature no disclosure if $D(e) = [\underline{e}, \overline{e}]$ for all $e \in [\underline{e}, \overline{e}]$, and thus $\mu([\underline{e}, \overline{e}])$ is equal to $G(e)$, the prior distribution of e.

[9]We adopt the terminology "Grossman-Perry-Farrell" from Gertner et al. (1988), Lutz (1989), and Bertomeu and Cianciaruso (2018).

(see, e.g., Bertomeu and Cianciaruso (2018) and the references therein). Instead of comparing equilibria in a Pareto sense as above, this refinement eliminates equilibria with off-equilibrium beliefs that are deemed unreasonable given agents' incentives to deviate from their equilibrium strategies. To streamline the exposition, we defer the formal definition of a Grossman-Perry-Farrell equilibrium to the proof of Proposition 8 in the appendix. We now state our result for the interim disclosure game.

Proposition 8. *An equilibrium disclosure plan of the ex-ante disclosure game can be sustained in both a foreign-firm-preferred equilibrium and a Grossman-Perry-Farrell equilibrium of the interim disclosure game.*

Proposition 8 shows that the results of the baseline model apply in the case of interim disclosure under sensible equilibrium refinements. Specifically, the fact that the disclosure plan from our baseline model is a foreign-firm-preferred equilibrium echoes the result that a foreign government would choose this disclosure regime ex ante, anticipating the distribution $G(e)$ of its firms.

5 Conclusion

In this paper, we analyze voluntary environmental disclosures in the context of global supply chains and study a government's optimal reliance on such disclosures in regulations. We show that tariff schedules should generally be a non-linear function of the environmental externalities disclosed by a foreign trade partner, contrasting with the notion of a common price for CO2 emissions in carbon credit markets. Our analysis reveals how penalizing trade with foreign firms that reveal the brownness of their production technologies can interfere with the precision of their disclosures, but whether it does so crucially depends on the domestic sector's exposure to externalities.

A Appendix: Proofs

Proof of Proposition 1. We first show the following lemma.

Lemma 3. *Given any two partition cutoffs e_{s-1} and e_{s+1} with $s \geq 2$ that satisfy the constraint $e_{s-1} \geq lb(lb(e_{s+1}))$, the interior cutoff e_s that maximizes the foreign firm's expected payoff is either equal to $rb(e_{s-1})$ or equal to $lb(e_{s+1})$.*

Proof. The foreign firm's marginal cost of increasing e_s is given by the partial derivative of the expected price offered by the domestic firm with respect to e_s:

$$\frac{\partial \left(\sum_{s=1}^{n} \left(G(e_{s+1}) - G(e_s)\right)(c - e_s)\right)}{\partial e_s} = -(G(e_{s+1}) - G(e_s)) + g(e_s)(e_s - e_{s-1}). \tag{A1}$$

We first show that for any two partition cutoffs e_{s-1} and e_{s+1} with $s \geq 2$ that satisfy $e_{s-1} \geq lb(lb(e_{s+1}))$, the marginal cost (A1) as a function of e_s crosses zero at most once. Setting equation (A1) equal to zero and rearranging, we obtain:

$$\frac{g(e_s)(e_s - e_{s-1})}{G(v_{s+1}) - G(v_s)} = 1. \tag{A2}$$

Note that $h_s(e) = \frac{g(e)}{G(e_{s+1}) - G(e)}$, and thus, $\frac{\partial (h_s(e)(e - e_{s-1}))}{\partial e} = h_s'(e)(e - e_{s-1}) + h_s(e) > 0$ for $e \in (e_{s-1}, e_{s+1})$, implying that the left-hand-side of equation (A2) is an increasing function of e_s. Thus, the marginal cost (A1) crosses zero at most once from above. Then the expected price offered by the domestic firm is first decreasing and then increasing in e_s for $e_s \in [lb(e_{s+1}), rb(e_{s-1})]$. Consequently, the foreign firm's expected payment must reach its maximum when e_s is equal to either $rb(e_{s-1})$ or equal to $lb(e_{s+1})$. □

Lemma 2 dramatically reduces the set of partition cutoffs that can be optimal. Given any two neighboring partition cutoffs e_{s-1} and e_{s+1} that do not immediately violate the efficiency constraints, the optimal interior cutoff e_s takes one of two possible candidate values: $rb(e_{s-1})$

or $lb(e_{s+1})$. The Φ-function represents the foreign firm's expected net benefit of choosing, given some generic neighboring partition cutoffs u and w, an interior cutoff $\tilde{e}$ that is equal to $lb(w)$ rather than equal to $rb(u)$. Since Φ is assumed to be non-negative, it implies that for any generic neighboring partition cutoffs u and w, the optimal interior cutoff $\tilde{e}$ that is equal to $lb(w)$. Thus, the optimal disclosure is obtained by sequentially applying $lb(\cdot)$ starting from $\overline{e}$.

Proof of Proposition 2. Given a generic disclosure that implies $e \in [a,b)$, we characterize the marginal type with which the domestic firm chooses to trade. The domestic firm's problem is

$$\max_{p} \frac{G(b)-G(c-p)}{G(b)-G(a)} \left[v-p-\lambda \, \mathbb{E}[e|e \geq c-p]\right].$$

Given the marginal type $x \equiv c-p$, the problem can be rewritten as

$$\max_{x} \frac{G(b)-G(x)}{G(b)-G(a)} \left[v-c+x-\lambda \, \mathbb{E}[e|e \geq x]\right],$$

and equivalently,

$$\max_{x} (G(b)-G(x)) \left[v-c+x\right] - \lambda \int_{x}^{b} e dG(e).$$

Let

$$d(x) = (G(b)-G(x)) \left[v-c+x\right] - \lambda \int_{x}^{b} e dG(e). \tag{A3}$$

We note that $d(x)$ does not depend on a. Thus, the pricing of the domestic firm does not rely on the left end of the disclosure interval a. This implies that under the optimal disclosure plan, trade either occurs with probability 1 or 0. To see that, we argue by contradiction. If trade occurs with a probability between 0 and 1, which implies that there is an interior type $e_o \in (a,b)$ who is just indifferent between accepting or rejecting D's quoted price. Now consider another disclosure plan that makes $[a,b]$ finer by disclosing $[a,e_o)$ and $[e_o,b)$ and keeps everything else the same. By doing so, the foreign firm's payoff is unaffected in the $[e_o,b)$ because the left end e_o does not affect the domestic firm's pricing decision. But this finer disclosure plan can weakly improve F's payoff in the signal $[a,e_o)$ because trade does not occur in the original disclosure plan while trade occurs with some probability in the new disclosure plan.

We are left to show that when trade occurs, the ex post global welfare must be nonnegative. Suppose otherwise under an optimal disclosure plan, there is a signal $[a,b)$ under which trade occurs with probability 1 but the global welfare at b is negative. Computing the derivative of d with respect to x, we have

$$d'(x) = G(b) - G(x) - g(x)\left[v - c + (1-\lambda)x\right].$$

Suppose the global welfare at b is negative, it follows that $d'(b)$ is weakly positive. the domestic firm's first order condition around $x = a$ must be weakly negative, otherwise the domestic firm can deviate by inducing a slightly higher marginal type. Let $h(x) = \frac{d'(x)}{g(x)}$, then $h(a) \leq 0$ and $h(b) \geq 0$. By Lagrange's mean value theorem, there exists x_0 such that $h'(x_0) = \frac{h(b)-h(a)}{b-a} \geq 0$. Note that $h'(x) = \left(\frac{(G(b)-G(x))}{g(x)}\right)' - (1-\lambda)$. Plugging into x_0, it follows that

$$\lambda \geq 1 - \left(\frac{(G(b)-G(x_0))}{g(x_0)}\right)'. \tag{A4}$$

We next prove the following lemma.

Lemma 4. *Suppose the hazard rate $\frac{g(e)}{1-G(e)}$ is an increasing function. Let $\tilde{G}$ denote a truncated version of distribution G and $\tilde{g}$ is the associated probability density function, then $\frac{\tilde{g}(e)}{1-\tilde{G}(e)}$ is also an increasing function.*

Proof. Suppose the truncation is denoted by $[a,b]$, then $\tilde{G}(e) = \frac{G(e)-G(a)}{G(b)-G(a)}$ and $\tilde{g}(e) = \frac{g(e)}{G(b)-G(a)}$.

Note that $\frac{1-G(e)}{G(b)-G(e)} = 1 + \frac{1-G(b)}{G(b)-G(e)}$, which is an increasing function of e. Then, $\frac{\tilde{g}(e)}{1-\tilde{G}(e)} = \frac{g(e)}{G(b)-G(e)} = \frac{g(e)}{1-G(e)} \frac{1-G(e)}{G(b)-G(e)}$, which is increasing because it is equal to the product of two positive increasing functions. □

Returning to the proof of the proposition, let $\underline{\lambda} = \min\{1 - \left(\frac{(G(b)-G(x))}{g(x)}\right)'\}$, which is greater than 1 because $\frac{(G(b)-G(x))}{g(x)}$ is a decreasing function by the above lemma. Now suppose $\lambda < \underline{\lambda}$. It follows that the ex post global welfare must be nonnegative whenever trade occurs, because otherwise (A4) would be violated. This concludes the proof of the proposition. □

Proof of Proposition 3. Given a generic disclosure that implies $e \in [a,b)$, we characterize the cutoff type D induces to trade. D's problem is

$$\max_p \frac{G(b)-G(c-p)}{G(b)-G(a)} \left[v - p - \lambda\, \mathbb{E}[e|e \geq c-p]\right].$$

Let $x = c - p$, the problem can be rewritten as

$$\max_x \frac{G(b)-G(x)}{G(b)-G(a)} \left[v - c + x - \lambda\, \mathbb{E}[e|e \geq x]\right].$$

Equivalently,

$$\max_x (G(b)-G(x)) \left[v - c + x\right] - \lambda \int_x^b edG(e).$$

Let $d(x) = (G(b)-G(x)) \left[v - c + x\right] - \lambda \int_x^b edG(e)$, which is linear in λ. We have

$$\frac{\partial^3 d}{\partial x^2 \partial \lambda} = \frac{\partial (xg(x))}{\partial x} > 0.$$

This is to say that for sufficiently large λ, $d(x)$ is convex in x.

Returning to the proof of the proposition, we argue by contradiction. Suppose under F's optimal disclosure schedule, trade is efficient. That is, the disclosure schedule separates types above $\hat{e}$ and types below $\hat{e}$. Assume that one of the disclosure implies $e \in [e', \hat{e})$, where

$e' \geq \underline{e}$. We shall consider a small perturbation in the disclosure schedule such that F earns a higher ex ante expected payoff, which leads to a contradiction. For ease of exposition, we let $e' = \underline{e}$ so that there are two disclosures: $\{[\underline{e}, \hat{e}), [\hat{e}, \overline{e}]\}$. Consider the following disclosure schedule: $\{[\underline{e}, \hat{e}+\varepsilon), [\hat{e}+\varepsilon, \overline{e}]\}$. When $e \in [\hat{e}+\varepsilon, \overline{e}]$, there is no trade due to negative social surplus, so nothing changes comparing to the original disclosure schedule.

Next, we claim that we can choose ε so that D still induces trading for all $e \in [\underline{e}, \hat{e}+\varepsilon)$. Setting $a = \underline{e}, b = \hat{e}+\varepsilon$. D;s expected payoff function $d(x)$ is convex for large enough λ. So D induces either $x = \hat{e}+\varepsilon$ or $x = \underline{e}$. Since inducing $x = \hat{e}+\varepsilon$ implies no trade, it implies that $d(\hat{e}+\varepsilon) = 0$. If we choose ε small enough $d(\underline{e}) > 0$. This is because in the original disclosure schedule $[\underline{e}, \hat{e})$, D's payoff by inducing $\underline{e}$ is strictly positive. By continuity argument, when ε is small enough, $d(\underline{e}) > 0$ under the new disclosure schedule.

Now, F's payoff is strictly higher under the new disclosure schedule than under the original schedule, since types in $[\hat{e}, \hat{e}+\varepsilon)$ are earning strictly positive payoffs. Overall, the original disclosure schedule can not be the equilibrium outcome. So the equilibrium can not feature efficient trade. Using the arguments in the case with no interventions, the case with simple tariff scheme and the arguments in Glode, Opp, and Zhang (2018), the equilibrium can not feature inefficiently low trade. As a result, the only possibility is that equilibrium features inefficiently excessive trade. □

Proof of Proposition 4. We note that e^* is interior since $e^* \in (a,b)$. Thus, the first order condition holds:

$$1 - G(e^*) = (v - c + (1-\lambda)e^*)g(e^*).$$

Consider the domestic firm's problem when there is a tariff $\tau = \lambda e^* - (1-\delta)v$. The FOC is

$$1 - G(e) = (\delta v - c - \tau + e)g(e) = (v - c - \lambda e^* + e)g(e).$$

Thus, $e = e^*$ satisfies the above condition. Moreover, since $\frac{1-G(e)}{g(e)} - e$ is a decreasing function of e, the FOC has at most one solution. Overall, with a tariff $\tau = \lambda e^* - (1-\delta)v$, the domestic firm optimally charges a price that induces the threshold e^* over which type foreign firms accept the price.

Proof of Proposition 5. We first consider the domestic planner solution when $\lambda < 2$:

$$p = \arg\max_p (v - \lambda E[e|e \geq c-p, e \in [a,b)] - p)(b-(c-p)).$$

Since $\lambda < 2$, from the first order condition we find that $e^* = \frac{b-(v-c)}{2-\lambda}$. We first assume $e^* \in (a,b)$, that is, $a < \frac{b-(v-c)}{2-\lambda} < b$. Suppose a tariff is imposed so that D's payoff is $v-p-\tau$ when there is a trade. Following the same argument, the optimal threshold $e^* = \frac{b-(\delta v-\tau-c)}{2}$. Setting $\frac{b-(\delta v-\tau-c)}{2} = \frac{b-(v-c)}{2-\lambda}$, we obtain $\tau = \frac{\lambda(b-\delta v+c)-2(1-\delta)v}{2-\lambda}$.

We discuss the case $e^* \leq a$ or $e^* \geq b$.

- Suppose $e^* \leq a$, or $a \geq \frac{b-(v-c)}{2-\lambda}$. D's optimal price under the domestic planner solution is given by $c-a$, in which case the cut-off type is a. Since when a tariff is imposed the optimal threshold $\frac{b-(\delta v-\tau-c)}{2}$, government can implement the same outcome by imposing a tariff such that $\frac{b-(\delta v-\tau-c)}{2} = a$, equivalently, $\tau = 2a-b+\delta v-c$.

- Suppose $e^* \geq b$, or $\frac{b-(v-c)}{2-\lambda} \geq b$. D's optimal price under the domestic planner solution is given by $c-b$, in which case the threshold is b. Since when a tariff is imposed the optimal threshold $\frac{b-(\delta v-\tau-c)}{2}$, government can implement the same outcome by imposing a tariff such that $\frac{b-(\delta v-\tau-c)}{2} = b$, equivalently, $\tau = \delta v - c + b$.

Next consider $\lambda > 2$. The domestic planner solution is given by the following program.

$$p = \arg\max_{e^*=c-p} (v - \lambda E[e|e \geq e^*, e \in [a,b)] - p)(b-e^*).$$

As we discussed in the proof of Proposition 6, the above program is convex in e. So the optimal e^* is either a or b. There are two possibilities.

- If $v-\lambda\frac{a+b}{2}-(c-a)\geq 0$, D's optimal price under the domestic planner solution is given by $c-a$, in which case the cut-off type is a. Since when a tariff is imposed the optimal threshold $\frac{b-(\delta v-\tau-c)}{2}$, government can implement the same outcome by imposing a tariff such that $\frac{b-(\delta v-\tau-c)}{2}=a$, equivalently, $\tau=2a-b+\delta v-c$.

- Otherwise, D's optimal price under the domestic planner solution is given by $c-b$, in which case the cut-off type is b. Since when a tariff is imposed the optimal threshold $\frac{b-(\delta v-\tau-c)}{2}$, government can implement the same outcome by imposing a tariff such that $\frac{b-(\delta v-\tau-c)}{2}=b$, equivalently, $\tau=b+\delta v-c$.

□

Proof of Proposition 6. Following the proof of Proposition 3, when G is a uniform distribution and $e\in[a,b)$, D's problem is

$$\max_x(b-x)\left[v-c+x-\lambda\frac{x+b}{2}\right].$$

When $\lambda<2$, D's objective function is concave. From the first order condition, the optimal $x=\frac{b-(v-c)}{2-\lambda}$. We note that if $b>\hat{e}$, then $\frac{b-(v-c)}{2-\lambda}>b$, since $v-c=(\lambda-1)\hat{e}$ and $\lambda>1$. In this case, D's optimal $x=b$, yielding a zero profit. This observation implies that if the right end side of an interval is greater than $\hat{e}$, then there is no trade. Thus, F optimally discloses $[\hat{e},\overline{e}]$, which induces no trade. It is left to solve the optimal disclosure schedule for $e\in[\underline{e},\hat{e})$. We assume that the disclosure schedule is given by

$$[\underline{e},e_1),[e_1,e_2),\cdots$$

We write $e_0=\underline{e}$ for convenience. We first observe that the arguments in Glode, Opp, and

Zhang (2018) apply, and trade occurs with probability 1 when $e \in [e_i, e_{i+1})$. This implies that $e_i \geq \frac{e_{i+1}-(v-c)}{2-\lambda}$. F's expected payoff is given by

$$\begin{aligned}
&\sum_{i=0}^{\infty} \int_{e_i}^{e_{i+1}} (e - e_i)\, de \\
&= \sum_{i=0}^{\infty} \frac{(e_{i+1} - e_i)^2}{2}.
\end{aligned}$$

Define the following two functions. $rb(\cdot)$ is the right bound of an interval such that trade occurs with probability 1, $lb(\cdot)$ is the left bound of an interval such that trade occurs with probability 1,

$$\begin{aligned}
rb(e) &= (2-\lambda)e_i + (v-c) \\
lb(e) &= \frac{e_i - (v-c)}{2-\lambda}.
\end{aligned}$$

Suppose $e_{i-1} > \frac{e_{i+1}-(v-c)}{2-\lambda}$, we ask which value of e_i maximizes F's expected payoff. We note that F's expected payoff is a quadratic function of e_i with a positive coefficient on e_i^2. This suggests that to maximize F's expected payoff, e_i should achieve the boundary values, i.e., $rb(e_{i-1})$ or $lb(e_{i+1})$. Moreover, the quadratic function is minimized at $\frac{e_{i-1}+e_{i+1}}{2}$. We next show that whether $rb(e_{i-1})$ is always further from $\frac{e_{i-1}+e_{i+1}}{2}$ than $lb(e_{i+1})$

$$\begin{aligned}
&rb(e_{i-1}) + lb(e_{i+1}) > e_{i-1} + e_{i+1} \\
\Leftrightarrow &(2-\lambda)e_{i-1} + v - c + \frac{e_{i+1} - (v-c)}{2-\lambda} > e_{i-1} + e_{i+1} \\
\Leftrightarrow &-e_{i-1} - \frac{v-c}{2-\lambda} + \frac{e_{i+1}}{2-\lambda} > 0,
\end{aligned}$$

which holds given the assumption $e_{i-1} > \frac{e_{i+1}-(v+h-c)}{2-\lambda}$. As a result, to maximize F's expected payoff, $e_i = rb(e_{i-1})$. Repeatedly applying this result, we obtain the optimal disclosure in the proposition.

When $\lambda > 2$, D's objective function $(b-x)\left[v-c+x-\lambda\frac{x+b}{2}\right]$ is convex in x. Thus, the maximum is achieved at the two extremes when $x = a$ or $x = b$. Since $x = b$ yields a zero profit, D is willing to quote $x = a$ if and only if

$$v-c+a-\lambda\frac{a+b}{2} > 0. \tag{A5}$$

Equivalently,

$$b < \frac{2(v-c)+(2-\lambda)a}{\lambda}. \tag{A6}$$

We next show that under the optimal disclosure plan, there are at most one signal realization that leads to trade between D and F. We argue by contradiction. Suppose D is willing to quote the lower bound when $e \in [\underline{e}, a)$ and when $e \in [a, b)$, then D is also willing to quote the lower bound when $e \in [\underline{e}, b)$.

We observe that

$$b < \frac{2(v-c)+(2-\lambda)a}{\lambda} \tag{A7}$$

$$< \frac{2(v-c)+(2-\lambda)\underline{e}}{\lambda} \tag{A8}$$

where the first inequality comes from (A6) and the second inequality comes from $a > \underline{e}$. Applying (A6) again, it is evident that D is also willing to quote the lower bound when $e \in [\underline{e}, b)$.

Overall, there is at most one signal realization that leads to trade. Applying (A6):

$$e^o = \frac{2(v-c)+(2-\lambda)\underline{e}}{\lambda}$$

□

Combining the results of Propositions 5 and 6 we obtain the following equilibrium results. We first consider the case when $\lambda < 2$. When the disclosure is $[e_i, e_{i+1})$, the government prefers to induces a price of $c - e_i$ so that trade always occurs. If a tariff τ_i is levied, D's optimal price is given by $c - \frac{e_{i+1}-(\delta v - \tau - c)}{2}$. Setting it equal to $c - e_i$,

$$\tau_i = (\delta v - c) - (e_{i+1} - 2e_i).$$

Since $e_{i+1} = (2-\lambda)e_i + (v - c)$, we solve

$$e_i = \hat{e} - (2-\lambda)^i(\hat{e} - \underline{e}).$$

With algebraic manipulation, we obtain

$$\begin{aligned}
\tau_i &= (\delta v - c) - (e_{i+1} - 2e_i) \\
&= \delta v - c + \hat{e} - \lambda(2-\lambda)^i(\hat{e} - \underline{e}) \\
&= \lambda e_i + (\delta v - c) - (\lambda - 1)\hat{e}.
\end{aligned}$$

Upon the signal $[\hat{e}, \overline{e}]$, the government prefers to induces a price of $c - \overline{e}$ so that trade never occurs. The minimal tariff is given by $(\delta v - c) - (\overline{e} - 2\overline{e}) = \delta v - c + \overline{e}$.

We next consider $\lambda \geq 2$. When the disclosure is $[e^o, \overline{e}]$, then government prefers to induces no trade between D and F. In this case, government can impose a large enough tariff so that D's optimal pricing induces no trade with F. Let τ^H denote the tariff. Then D's problem is

$$\max_x (\delta v - c - \tau^H + x)(1 - \frac{x - e^o}{\overline{e} - e^o})$$

FOC implies

$$(\overline{e} - x) - (\delta v - c - \tau^H + x) = 0$$

Thus, $x^* = \frac{\overline{e}-(\delta v-c-\tau^H)}{2}$. No trade requires that

$$\frac{\overline{e}-(\delta v-c-\tau^H)}{2} \geq \overline{e}$$

Equivalently,

$$\tau^H \geq \overline{e}+\delta v-c$$

Now consider $e \in [\underline{e}, e^o)$. Let τ^L denote the tariff. Then D's problem is

$$\max_x (\delta v - c - \tau^L + x)(e^o - x)$$

Then $x^* = \frac{e^o-(\delta v-c-\tau^L)}{2}$. Full trade requires that

$$\frac{e^o-(\delta v-c-\tau^L)}{2} \leq \underline{e}.$$

Equivalently,

$$\tau^L \leq 2\underline{e} - e^o + \delta v - c$$

Plugging in e^o,

$$\tau^L \leq 3\underline{e} - \frac{2(v-c)+2\underline{e}}{\lambda} + \delta v - c$$

Overall, if the tariff scheme (τ^L, τ^H) satisfies the above two conditions, then D would optimally quote a price that induces trade when $e \in [\underline{e}, e^o)$ and that induces no trade when $e \in [e^o, \overline{e}]$. $\square$

Proof of Proposition 7. To solve for D's optimal disclosure plan, we first need to solve for government's optimal tariff conditional on a disclosure that informs $e \in [a, b)$. This problem is identical to what we learned in Proposition 5. Applying the proposition, the optimal tariff is given by the following.

1. Suppose $\lambda < 2$

   (a) If $a \geq \frac{b-(\delta v-c)}{2-\lambda}$, the optimal tariff is $\tau = 0$.

   (b) If $a < \frac{b-(\delta v-c)}{2-\lambda} < b$, the optimal tariff is $\tau = \frac{\lambda(b-\delta v+c)}{2-\lambda}$.

   (c) If $\frac{b-(\delta v-c)}{2-\lambda} \geq b$, the optimal tariff is $\tau = b+\delta v-c$.

2. Suppose $\lambda > 2$

   (a) If $v-\lambda\frac{a+b}{2}-(c-a) \geq 0$, the optimal tariff is $\tau = 0$.

   (b) Otherwise, the optimal tariff is $\tau = b+\delta v-c$.

First, we consider the case when $\lambda < 2$. We first claim that under D's optimal disclosure plan, we should not expect case (b). We argue by contradiction. Suppose $a < \frac{b-(\delta v-c)}{2-\lambda} < b$. Then D can choose a new disclosure plan, which inherits the existing one but divides the interval $[a,b)$ into two subintervals $[a, \frac{b-(\delta v-c)}{2-\lambda})$ and $[\frac{b-(\delta v-c)}{2-\lambda}, b)$. By doing so, D does not lose when $e \in [\frac{b-(\delta v-c)}{2-\lambda}, b)$ but strictly gains when $e \in [a, \frac{b-(\delta v-c)}{2-\lambda})$, a contradiction. Next, we observe that trade occurs with zero probability under case (c), so D earns a zero profit whenever $\frac{b-(\delta v-c)}{2-\lambda} \geq b$. Thus far, we have shown that D earns a nonzero profit only in case (a). In case (a), $a \geq \frac{b-(\delta v-c)}{2-\lambda}$. Recall that the threshold at which global surplus is zero is given by $\hat{e} = \frac{\delta v-c}{\lambda-1}$. We note that whenever $b > \hat{e}$, we also have $\frac{b-(\delta v-c)}{2-\lambda} \geq b$, which is in case (c). So D does not gain to pool types above $\hat{e}$. For types below $\hat{e}$, by choosing case (a), government always charges a zero tariff. Thus, for $e \leq \hat{e}$, the finest disclosure will give D the maximal possible surplus by charging a price such that F breaks even. Note that in case (c), the finest disclosure also gives D a zero profit. Overall, the finest disclosure constitutes an optimal disclosure for D.

Second, we consider the case when $\lambda > 2$. Similarly, D can only earn a positive profit when $\delta v-\lambda\frac{a+b}{2}-(c-a) \geq 0$ holds. There are two possibilities. First, it is possible that for any disclosure $b \leq \hat{e}$, in which case, D prefer the finest disclosure and his expected payoff is given by

$$\int_{\underline{e}}^{\hat{e}} (\delta v - (c-e))dG(e) = \frac{(\delta v - c)(\hat{e} - \underline{e}) + \frac{1}{2}(\hat{e})^2 - \frac{1}{2}\underline{e}^2}{\overline{e} - \underline{e}}.$$

Second, unlike the case with $\lambda < 2$, it is now possible that $b > \hat{e}$. In this case, D prefers finest disclosure for $e \leq a$ and pool all types between $[a,b)$, where $\delta v - \lambda \frac{a+b}{2} - (c-a) \geq 0$. His expected payoff is given by

$$\begin{aligned} &\int_{\underline{e}}^{a} (\delta v - (c-e))dG(e) + \int_{a}^{b} (\delta v - c + a)dG(e) \\ &= \frac{(\delta v - c)(a - \underline{e}) + \frac{1}{2}a^2 - \frac{1}{2}\underline{e}^2 + (b-a)(\delta v - c + a)}{\overline{e} - \underline{e}}. \end{aligned}$$

To maximize D's expected payoff, he would choose the largest possible b. That is, $\delta v - \lambda \frac{a+b}{2} - (c-a) = 0$, equivalently $b = \frac{2}{\lambda}(\delta v - c + a) - a$. We can verify that the above equation is a convex function of a. So D would choose $a = \underline{e}$ or $a = \hat{e}$. Choosing $a = \hat{e}$ is optimal whenever

$$(\delta v - c)(\frac{\delta v - c}{\lambda - 1} - \underline{e}) + \frac{1}{2}\left(\frac{\delta v - c}{\lambda - 1}\right)^2 - \frac{1}{2}\underline{e}^2 \geq \left(\frac{2}{\lambda}(\delta v - c + \underline{e}) - 2\underline{e}\right)(\delta v - c + \underline{e}).$$

When $\underline{e} = 0$, the above condition can be further simplified to

$$\frac{1}{\lambda - 1} + \frac{1}{2(\lambda - 1)^2} > \frac{2}{\lambda},$$

which holds whenever $\lambda < \frac{7+\sqrt{17}}{4} \approx 2.78$. Overall, when $\lambda < 2.78$, D chooses the finest disclosure; when $\lambda > 2.78$, D chooses the disclosure plan (33), which coincides with F's disclosure, i.e., disclosure with two ratings.

Proof of Proposition 8. We first show how to construct a strategy profile that supports the optimal disclosure plan of the ex ante game in the interim game. Suppose the optimal disclosure plan of the ex ante game is denoted by $D : [\underline{e}, \overline{e}] \to S$. In the interim game, consider a candidate equilibrium in which:

1. Disclosure follows the ex ante disclosure $D(e)$.

2. For every possible signal s, the tariff schedule $\tau(s)$ maximizes the domestic welfare.

3. For $s \in S$, the belief $\mu(s)$ is given by G conditional on s. For any $s \notin S$ (that is, whenever s is an off-equilibrium signal), the belief $\mu(s)$ assigns probability 1 to type $\bar{e}(s)$.

4. For every possible signal s, $p(s)$ maximizes $\max_p (\delta v - p - \tau) Pr_{\mu(s)}[c - e \leq p]$.

We can show that the constructed strategy profile forms a foreign-firm-preferred equilibrium. By contradiction, suppose $(\tau_1(\cdot), D_1(\cdot), \mu_1(\cdot), p_1(\cdot))$ is an equilibrium that dominates $(\tau(\cdot), D(\cdot), \mu(\cdot), p(\cdot))$ among F types in the Pareto sense based on their interim payoffs. Let $S_1 = \{D_1(e) : e \in [\underline{e}, \bar{e}]\}$ and consider an ex ante disclosure $D_1 : [\underline{e}, \bar{e}] \to S_1$. Since $\mu_1(\cdot)$ is obtained by applying Bayes' rule on the equilibrium path, F's expected payoff under the disclosure D_1 of the ex ante game is equal to his expected payoff under the $(\tau_1(\cdot), D_1(\cdot), \mu_1(\cdot), p_1(\cdot))$ equilibrium of the interim game. It then follows that F's expected payoff under the disclosure plan $D_1(\cdot)$ is strictly higher than the one under the disclosure plan $D(\cdot)$ in the ex ante game, contradicting the fact that $D(\cdot)$ is an optimal disclosure plan of the ex ante game.

Before we move to the second part of the proof, we need to formalize the definition of Grossman-Perry-Farrell equilibrium. Denote by $U(e, s, \mu(s))$ the foreign firm's utility if his valuation is e, he sends a message s, and the domestic firm quotes an optimal price given the belief function $\mu(s)$. For any signal s that is a Borel set in $[e_L, e_H]$ (including off-equilibrium messages), denote by μ_s the actual distribution of e conditional on $e \in s$. As in Bertomeu and Cianciaruso (2018), we define a Grossman-Perry-Farrell equilibrium by ruling out the existence of self-signaling sets.

Definition 3. *A pure-strategy perfect Bayesian equilibrium of the interim disclosure game* $(\tau(\cdot), D(\cdot), \mu(\cdot), p(\cdot))$ *is called a "Grossman-Perry-Farrell equilibrium" if there does not exist a self-signaling set, which is defined as a non-empty Borel set* $s \subset [e_L, e_H]$ *such that:*

$$s = \{e \in s : U(e, s, \mu_s) > U(e, D(e), \mu(D(e)))\}. \tag{A9}$$

We now show that the constructed strategy profile above also forms a Grossman-Perry-Farrell equilibrium of the interim game. We argue by contradiction, that is, suppose there exists a self-signaling set s_0 in that case. Let $S = \{D(e) : e \in [\underline{e}, \overline{e}]\}$ be the set of signals that are on the equilibrium path. We first show that $s_0 \notin S$. Otherwise, the signal s_0 is on the equilibrium path: $s_0 \in S$, implying that for some $e_0 \in s_0$, $D(e_0) = s_0$. Then, $U(v_0, s_0, \mu_{s_0}) = U(v_0, D(v_0), \mu(D(v_0)))$,where $U(e, s, \mu(s))$ is the F's utility if his type is e, he sends a message s, and D quotes an optimal price given the belief $\mu(s)$. Recall also that μ_s is the distribution of e conditional on $e \in s$. contradicting the fact that s_0 is a self-signaling set.

Now we turn to the ex ante game. Let $S_2 = S \cup \{s_0\}$. Consider the following ex ante disclosure plan $D_2 : [\underline{e}, \overline{e}] \to S_2$:

$$D_2(e) \equiv \begin{cases} D(e) & \text{if } e \notin s_0, \\ s_0 & \text{otherwise.} \end{cases} \tag{A10}$$

For F whose types are not in s_0, their payoffs are equal to their payoffs under the $(\tau(\cdot), D(\cdot), \mu(\cdot), p(\cdot))$ equilibrium of the interim game. For F whose type is $e \in s_0$, his payoff is now given by $U(e, s_0, \mu_{s_0})$, which is strictly greater than $U(e, D(e), \mu(D(e)))$. Thus, the ex ante disclosure plan $D_2(\cdot)$ yields a strictly higher expected payoff for F than the disclosure plan $D(\cdot)$, contradicting the fact that $D(\cdot)$ is an optimal disclosure plan of the ex ante game. $\square$

B Appendix: Additional Results

B.1 Unconditional Tariff Schemes

With an unconditional tariff, we can rewrite the domestic firm's payoff conditional on trade occurring as follows:

$$u_D = (\delta v - \tau) - p. \tag{A11}$$

Note that the domestic firm and the foreign firm in this case solve problems that are equivalent to the ones absent government interventions, except that one needs to replace the variable δv by $(\delta v - \tau)$. As a result, when the foreign firm chooses an optimal disclosure plan, trade occurs if and only if the bilateral surplus of the two firms, after accounting for tariffs, is positive, that is, when:

$$u_D + u_F \geq 0 \quad \Leftrightarrow \quad e \geq c - \delta v + \tau. \tag{A12}$$

As a result, unconditional tariffs ($\tau > 0$) lead to the rationing of *low-externality* (that is, relatively green) transactions relative to the case absent government interventions. If those greener transactions are desirable from the perspective of the domestic country, the unconditional tariff backfires, since it only suppresses trade in those cases.

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