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Treat, Dump, or Export? How Domestic and International Waste Management Policies Shape Waste Chain Outcomes

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Illegal or unwanted waste disposal methods such as dumping and export are prevalent in practice. To minimize the environmental harm of these methods, policymakers have implemented laws and regulations designed to combat them. Even so, violations are rampant as a high degree of heterogeneity between firms and proprietary information render monitoring imperfect. Decentralized waste disposal chains, a common form of inter-business organization in this sector, compound this problem as firms also have limited information available on their waste chain partner, creating complex interactions between firm behavior and policy interventions. Against this background, we analyze the effects of domestic and international waste regulations targeting dumping and export, respectively, on firm incentives and compliance. We develop a two-tier waste chain with a producer that generates waste and an operator that treats it. The producer's waste quality and the treatment operator's efficiency can be private information. Either party can avoid compliance cost by violating regulations where the producer can arrange for export and the operator can dump locally. Our analysis reveals that primarily focusing on penalizing dumping by treatment operators can worsen environmental harm. Solely focusing on penalizing low-quality waste exports, a common intervention in practice, can also backfire. Instead, penalizing producers for downstream dumping should be given consideration. In addition, the asymmetry in export burden between waste quality levels should be reduced.

Key words: waste management, information asymmetry, moral hazard, adverse selection, sustainable operations

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1. Introduction

Every year, millions of tons of waste are generated during manufacturing processes or post-use, much of it containing hazardous materials or substances. The preferred option for dealing with these hazardous wastes is treatment to minimize their environmental harm. Governments around the world have enacted regulations to induce treatment of hazardous wastes. In the European Union and US, regulations prohibit land disposal of untreated hazardous wastes (EPA 2001, Bourguignon 2018[a]) and producers now also have responsibility for the proper management of post-use products that contain hazardous materials, following the enactment of Extended Producer Responsibility (EPR) regulations. Moreover, Waste Shipment Regulations prohibit the trans-boundary movement of hazardous wastes to non-EU countries ('Basel ban') (Geeraerts et al. 2015). Nonetheless, investigations have revealed that these regulations may be violated when this is more profitable than following them (Europol 2017) such as for waste with hazardous content including industrial waste oil and post-use electronic waste (e-waste) (Rucevska et al. 2015).

Violations largely take one of two forms: Foreign export or local dumping. For example, in a landmark case, Trafigura was caught exporting their hazardous industrial waste oil to Côte d'Ivoire (BBC 2010). Interpol has noted illegal exports of hazardous post-use waste frequently take place within European e-waste take-back systems (Interpol 2015). Goodwill, operating within the Dell takeback program in the U.S., has been caught multiple times exporting e-waste in violation of the importing country's laws (BAN 2020). Globally, it is estimated that 75% of e-waste is exported, predominantly from the EU and US to developing countries, often illegally through mis-classification, bribery, or document forgery (EnviCrimeNet 2015, UNODC 2013).

Even when waste is not exported, it is not guaranteed to find proper treatment and may be dumped locally. For instance, Universal Recycling Technologies, a recycling partner of Samsung, illegally dumped truckloads of toxic waste (N.H. Department of Justice 2016). Only a little over a third of e-waste in the EU is handled in line with waste regulations (Eurostat 2018). It is estimated that 25% of industrial waste oil is illegally dumped or burned in the EU due to its high treatment cost (Bourguignon 2015). Illegal dumping is observed in other waste categories, too. For example, directors of Churngold Recycling Ltd. were caught having locally dumped 30,000 tons of toxic waste from an automotive factory in the UK (BBC 2017).

In this paper, we seek to understand how the regulatory climate interacts with waste chain economics and identify what climate would be most conducive to mitigating environmental harm by having more treatment emerge as the waste chain outcome. By "regulatory climate," we refer to the relative strength of export and anti-dumping regulations and/or enforcement efforts. By "waste chain outcome," we mean treatment, dumping, or export. To model the "waste chain," we use a canonical two-agent value chain consisting of a producer and a treatment operator. "Producer" in our model is to be interpreted as the original waste generator (e.g. Trafigura, Samsung) and any "organisation implementing extended producer responsibility obligations on their behalf" (European Parliament 2018), which includes waste collection and the contracting with a treatment operator. Such organizations include third parties like Goodwill in the Dell/Goodwill take-back program and Producer Responsibility Organizations (PROs), which manage post-consumer waste from several waste generators. The "treatment operator" is the end-of-the-line service provider in the domestic waste market contracted to undertake waste treatment, including recycling and recovery (e.g. Universal Recycling Technologies, Churngold Recycling). The producer can either buy treatment services from the operator or export[1] and the treatment operator can either treat the waste or violate regulations by dumping[2].

While many waste products can be transformed into goods with positive value through treatment, if the treatment cost is too high relative to the economic value of the output, export or dumping may prove economically more attractive. Therefore, the economics of waste treatment, which depends both on *waste characteristics* and the *sophistication of the treatment operator*, plays an important role in waste chain outcomes.

High-quality waste with no or limited hazardous material (e.g. 'green-listed' waste) is easier to treat or incorporate in the manufacture of new products. In contrast, low-quality and relatively hazardous waste (classified as 'amber' or 'red-listed' waste) is more onerous to treat and recovered materials have limited use (Rucevska et al. 2015). For example, an increase in hazardous substances in waste oil from manufacturing processes reduces the value of the re-refined product (UNEP 2012). Similarly, plastics found in e-waste contain different levels of brominated flame retardants. Mixtures with concentrations above 0.1% are amber-listed, have lower net recovery values and need more costly treatment processes than e-waste streams with lower concentrations (European Commission 2010). Therefore, in the pursuit to maximize profits, non-compliance may emerge for low-quality waste (Noel 2018, Bernard 2015, Interpol 2009). Turning to the sophistication of treatment operators, we note that these firms are not homogeneous. They use facilities that differ in type, age, quality of maintenance, and technology. The less sophisticated an operator, the lower value the firm can extract from treating the waste. This can influence an operator's incentive to skirt regulations and opt for noncompliance instead of treatment (Rucevska et al. 2015, Ino 2011).

In practice, waste and treatment operator characteristics are private information, which limits the effectiveness of monitoring (Europol 2017). First, the exact composition of the waste is the producer's private information as she is the one who produced it (Bernard 2015, Kellenberg 2012). For instance, the hazard level of industrial waste such as waste oil depends on the exact processes that generated it, information typically only known to the producer. Similarly, only the original producer of e-waste knows the exact material composition in its products. Imperfect monitoring

[1] Producers can only dispose of their own waste at the place of production if they can show the waste is non-hazardous or treated according to the best available techniques (EU Directive 2008/98/EC). Although dumping (e.g. illegal landfill) does not require the use of these facilities, a producer cannot credibly hide dumping activities without them. Since producers with treatment facilities are rare (European Commission 2014), we do not include dumping as a non-compliance option for producers in our model.

[2] Operators can in theory export the waste after they have obtained it, but investigations show that export typically happens before significant costs have been incurred from the waste (e.g. treatment, recycling, and even dismantling due to high labor cost) (Bisschop 2017, Geeraerts et al. 2015). Thus, in our model only the producer considers export as an option using either its own infrastructure or through third-parties such as waste brokers.

allows hazardous (amber-listed) waste to be classified as non-hazardous waste (e.g. green-listed or 'non-waste') to avoid export regulations (IMPEL 2011). Second, his ability to recover value from a range of waste qualities is the treatment operator's private information as value recovery depends on a complex set of internal capabilities and management practices (Shinkuma and Managi 2011, Levi and Nault 2004). Imperfect monitoring allows these firms to illegally dump waste that is not economic to treat. Relying on auditing and/or third-party certification to anticipate when dumping may occur is costly and has been largely unsuccessful as even certified companies are found to engage in non-compliant behavior (Europol 2017, Rucevska et al. 2015).

Waste and treatment operator characteristics being private information can also complicate waste chain relationships between firms. Producer concerns about intellectual property and data protection inhibit meaningful information sharing about their products (e.g. the amount and location of critical raw materials and hazardous substances in them) with operators (Orgalim 2020), which is cited as one of the main barriers to waste treatment by operators (EERA 2022). Even after receiving the waste, it is difficult for operators to ascertain the waste quality because the instruments they rely on to do so are known to be inefficient and costly (European Commission 2014) and because waste streams are not stable. For instance, electronics are fast-paced products with continuous changes in their design (Babbitt and Althaf 2021, EERA 2022) while PRO memberships as well as producers' waste contribution are dynamic (e.g., OECD (2016)). For industrial waste, different oils and substances are found to be mixed, causing the quality of feedstock for re-refiners to vary considerably (UNEP 2012).

Conversely, not having information about operator characteristics (which determines which operators have an incentive to dump) is problematic for producers since policies like EPR expect them to ensure that those they contract with to manage their waste are operating in compliance with regulations (called "duty of care"). Assessing these incentives is challenging even in ongoing relationships because legal business structures are often used for illicit activities (Europol 2017) and prominent companies with valid certifications commit violations (Rucevska et al. 2015). For example, Universal Recycling Technologies was accredited with E-stewards, a well-known certification, when caught dumping. Even if firms are caught dumping, this information can disappear quickly (e.g. Churngold recycling changed its name to South West Recycling Ltd after the dumping scandal.) Therefore, when a producer needs to contract with a treatment operator whose incentives it cannot adequately assess, the firm faces a dilemma: Is it worth purchasing costly treatment services and risk the waste will be dumped, when exporting is also an option?

As the above discussion makes clear, whereas the fundamental reason for noncompliance is profit-seeking behavior, these information asymmetries can create complex interactions between the regulatory climate and firm behaviors. Policy and enforcement efforts to encourage treatment have to date focused on where non-compliance is likely to occur: Banning the export of hazardous wastes (i.e., focusing on low-quality waste rather than the high-quality waste) and fining treatment operators who dump (i.e., focusing on the downstream agent rather than the upstream producer). At the same time, there is increased interest in measures that limit the export of not only hazardous but also non-hazardous waste (United Nations 2022) and in enforcement frameworks that ensure producers exercise their responsibility obligations, including exercising their duty of care in operator selection (European Parliament 2018). This landscape motivates our research questions:

- What are the equilibrium waste chain outcomes (Treat, Dump, or Export) in a market characterized by information asymmetry?
- Where should the legislative and enforcement focus be concentrated (on which agent and which waste type) so that treatment emerges as the waste chain outcome?

Answering them will inform agencies like Europol and the EPA in effectively targeting their efforts and reducing environmental harm.

A key contribution of our paper is modeling the two-agent waste chain subject to information asymmetry and analyzing the waste outcomes in this context. We conceptualize the market as a collection of producer - operator relationships (dyads). In some dyads, one side of information asymmetry may be resolved due to factors such as stable relationships or learning over time; in others both types of information asymmetry may persist. We therefore consider the market to consist of a mix of waste chain relationships exhibiting either type of single-sided information asymmetry or double-sided information asymmetry. Since most of the intuition that is derived from the more complete case of double-sided information asymmetry will carry over to the single-sided cases, for expositional convenience, we derive policy recommendations for the former first and then point out the differences with the latter.

The rest of the paper is organized as follows. In §2, we discuss our contributions to the related literature. §3 presents a holistic modeling framework with double-sided information asymmetry. §4 analyzes the corresponding equilibrium waste outcomes. §5 presents the effect of export regulations and domestic enforcement efforts on environmental harm and waste chain profits, and draws policy conclusions. In §6, we analyze the implications of alternative information structures including single-sided information asymmetry, quality verification by the operator, and quality uncertainty for the producer. §7 concludes with policy recommendations and future research directions.

2. Related Literature

A stream of research in environmental economics has studied the effect of policy measures on violations in waste disposal. This literature has analyzed the incentive structure toward dumping (e.g. Ino (2011), Walls et al. (2001), Fullerton and Kinnaman (1995), Copeland (1991), Smith (1972)) or export (e.g. Bernard (2015), Kellenberg (2012), Baggs (2009)) under imperfect monitoring and the effect of incentive structures on optimal policy measures, including EPR implementations and export regulations. A main finding is the pollution haven hypothesis, which stipulates that waste moves to the cheapest disposal option, and to avoid this move, regulatory differences between countries must be reduced (Kellenberg 2012). This finding is relevant in broader contexts: Drake and Just (2016) list instances where environmental regulations were ineffective due to asymmetry in regulatory stringency between regions and the expected cost of non-compliance was either too low (firms ignore regulations) or too high (firms abandon markets for cheaper alternatives).

A key contribution of our paper is modeling the two-agent waste chain subject to information asymmetry and analyzing the waste outcomes in this context, whereas the aforementioned literature has focused on the effect of regulatory differences between countries in single-agent models or complete information markets. As a result, we find that the pollution haven hypothesis gives an important albeit incomplete explanation of the violations we see in the market and of policies to address them. In particular, we find that regulatory differences between waste categories must be limited and that the emphasis on regulating low-quality waste can deteriorate waste outcomes.

Two exceptions to the single-agent and complete information studies are Shinkuma and Managi (2011) and Ichinose and Hosoda (2014). Shinkuma and Managi (2011) model incentives to dump or improperly treat waste residuals when the waste producer and the government are uninformed about the technological efficiency of the operator. In contrast to our paper, this work considers a uniform waste quality that is always common knowledge, thus disregarding one of the key barriers to treatment identified by operators (EERA 2022). Another key difference is that the treatment fee charged by the operator is not a strategic variable, meaning that the operator cannot use it to signal its efficiency and resolve the information asymmetry. This is an important drawback as our paper shows that the presence (and thus absence) of this information impacts the effectiveness of policy measures. Ichinose and Hosoda (2014) focus on how proprietary information on waste quality and the operator's disposal process lead to intentional and unintentional damages done by a treatment operator. In contrast to our model, they consider that operators have the same facilities and charge a fixed treatment fee. We incorporate different operator types to study how the presence of non-compliant operators can impact compliant ones and explore the role of price as a signal. Ichinose and Hosoda (2014) continue by analyzing how authorities should allocate the environmental cost between the guilty and innocent party to increase proper disposal. In practice, however, imperfect monitoring generally does not allow authorities to perfectly price environmental damage nor identify share of guilt. We therefore consider the effects of existing interventions that do not rely on this assumption. Importantly, we demonstrate that directly enforcing the areas where non-compliance is visible (i.e., fining the downstream operator for dumping or the producer for low-quality exports) may in fact backfire. Assuming that enforcement agencies and firms can perfectly identify the guilty parties (based on violations that became visible) may lead to exactly those types of interventions.

Within Operations Management, our research falls within the themes of responsibility violations and the reverse supply chain. Existing research on firm responsibility violations addresses the issue of information asymmetry among decentralized channel partners in traditional supply chains when a supplier can hide non-compliant behavior such as non-adherence to labor codes, using polluting practices, or other unethical behavior (Kalkanci and Plambeck 2020, Cho et al. 2019, Caro et al. 2018, Chen and Lee 2017, Guo et al. 2016, Short et al. 2016, Plambeck and Taylor 2016, Aral et al. 2014). These studies consider the possibilities for producers to reduce information asymmetry by using auditing schemes or publication of supplier lists as opposed to relying on regulatory interventions. In the context of regulatory penalties, Kim (2015) investigates the interplay between regulatory inspections and voluntary, preemptive noncompliance disclosure by a production firm. Levi and Nault (2004) consider government interventions that could induce firms to make a major conversion to cleaner plants and equipment when this is unobserved by policymakers.

We contribute to these studies by incorporating non-compliance in a waste chain when both agents can face incomplete information with respect to one another. In addition, previous studies considered a single firm that can be non-compliant, often modeled as an exogenous probability. In contrast, in our setting, non-compliance is an endogenous option for both agents. We find that this setting can induce adverse selection and additional moral hazard problems. To ensure that both agents comply, a combination of policy options is necessary to combat these market failures and to ensure that waste stays in the formal disposal process.

The second relevant Operations Management stream studies the effect of environmental policies on the interactions between firms in the reverse supply chain. Although research on environmental management in the reverse supply chain has been a growing field (for an extensive review see Corbett and Klassen 2006, Souza 2013, Agrawal et al. 2019), there remains a strong need to understand firms' incentives and the economic impact of waste regulations to avoid unintended consequences of such regulations. One policy that has been extensively studied in operations management is Extended Producer Responsibility (EPR). Major focus areas include product design (Rahmani et al. 2020, Huang et al. 2019, Atasu and Souza 2013, Özdemir et al. 2012, Plambeck and Wang 2009), remanufacturing Esenduran et al. (2016), participation in collective or individual recycling schemes (Tian et al. 2019, Gui et al. 2018, 2016, Atasu and Subramanian 2012), and incentive coordination between producers, operators, and consumers (Jacobs and Özdemir 2012, Subramanian et al. 2009).

Our work is aligned with and contributes to this stream of research by identifying how operational decisions and supply chain interactions shape the outcomes of a given environmental policy, sometimes in unintended ways. We differ from existing studies by focusing on the effect of regulations on firm-level interactions, and in particular non-compliance, when agents operate under incomplete information. One of the key elements of our paper is the effect of the waste chain's information structure on the compliance incentives of the agents. To the best of our knowledge, only two studies have considered information asymmetry between firms in reverse chains, but they do not consider non-compliance options or regulatory interventions (Wei et al. 2015, Zhang et al. 2014). In addition, we consider the responses of both the producer and treatment operator to waste regulations as either agent can impact the economic and environmental outcomes of the waste chain through non-compliance.

3. Model Description

In this section, we present the waste chain model, outline the game in detail, and introduce key parameter assumptions. Table 1 summarizes our notation.

The waste chain. We develop a stylized two-agent model of the waste chain consisting of a producer (she) and a treatment operator (he). The producer is responsible for the environmentally sound management of waste from manufacturing processes and from post-use product obligations. To capture differentiated waste quality, we consider two producer types, $i = H$ (high) and $i = L$ (low), who generate high- and low-quality waste, respectively. The quality of the waste determines the revenue v_i that can be generated from it using the legally required treatment standard, where $0 \le v_L < v_H$. We assume that the quality $i \in \{H, L\}$ is only known to the producer, whereas the prior belief of the treatment operator is that the waste is H with probability h and L with probability $1 - h$, where $h \in (0, 1)$.

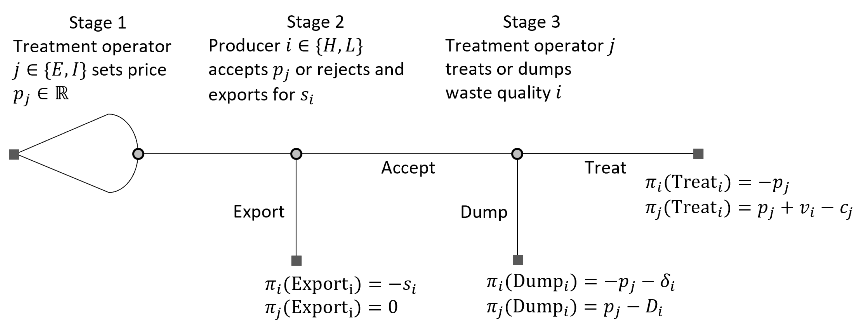
To capture differentiated treatment efficiency, we consider two treatment operator types, $j = E$ (efficient) or $j = I$ (inefficient). The efficiency of the operator determines the cost c_j the operator incurs if he decides to treat the waste, where treating with the inefficient technology is more costly ($c_I > c_E > 0$). Thus, the net cost of Operator I will be larger than that of Operator E for treating waste of a given quality, specifically $c_I - v_i > c_E - v_i$.[3] We assume that his efficiency level $j \in \{E, I\}$ is the operator's proprietary information, whereas the prior belief of the producer is that the operator is E with probability γ and I with probability $1 - \gamma$, where $\gamma \in (0, 1)$. The producer and operator characteristics are modeled as exogenous parameters in this waste chain as they depend on previous product design and facility technology investments.

[3] Here we assume that the cost of treatment is independent of waste quality. Alternatively, we can model the cost of treatment as a function of waste quality, where a lower waste quality is more costly to treat. This yields the same qualitative results since, for a given waste quality, Operator I will incur strictly higher cost: $c_I(v_i) > c_E(v_i)$.

Game specification. We formulate a three-stage game where the treatment operator sets the treatment price (Stage 1), the producer either decides to contract with the operator or to export her waste, legally or illegally, depending on its characteristics (Stage 2), and the treatment operator (if contracted) either dumps the waste domestically or treats it according to the legally required standard (Stage 3). Figure 1 illustrates the sequence of the agents' decisions and resulting profits.

Specifically, in Stage 1, Treatment Operator $j \in \{E, I\}$ sets his price p_j for providing waste management services for a standard batch size (waste services are typically priced by weight).[4] According to a European Commission report, operators set the prices for the waste management services which producers can choose to accept (European Commission 2014). Further evidence that operators have pricing power is provided by the inelasticity of demand for waste management services of potentially hazardous waste. The reason is that the amount of waste treatment required is set by EU legislation and national targets and hence demand is insensitive to the price (Baird et al. 2014, Van Daele et al. 2007). Therefore, we assume a sequential game where the operator moves first and sets the price, after which the producer responds.

Figure 1 **Waste Chain: Timing and Profits of Three-Stage Game**



In Stage 2, Producer $i \in \{H, L\}$ can purchase the treatment service at the quoted price or decide to export her waste at the cost of s_i ($\pi_i(\text{Export}_i) = -s_i$). Exporting waste L comes with an additional cost relative to waste H, for example due to the need to comply with or evade more stringent export, environmental, reporting, and safety regulations. To capture this, we assume $s_L > s_H$. The treatment operator is not involved in case of export and will have zero profit ($\pi_j(\text{Export}_i) = 0$).

At the last stage, the producer has contracted the services of the treatment operator for price p_j. After obtaining the price and receiving the waste, the operator decides whether to treat or dump. We assume that the operator must treat the waste to ascertain its market value v_i, i.e., receiving the waste is not sufficient to find out its quality. By treating, his profit is $\pi_j(\text{Treat}_i) = p_j + v_i - c_j$:

[4] The results hold when we analyze our model on the unit-level, rather than batch-level, including economies of scale and waste heterogeneity.

the price p_j minus the net cost of treatment $(c_j - v_i)$, which depends on the waste quality and his efficiency, while the producer profit is $\pi_i(\text{Treat}_i) = -p_j$. The operator may avoid the cost of treating altogether by dumping the obtained waste instead. In this case, local authorities may discover the violation, resulting in expected fines and reputation cost $D_i \geq 0$, leading to a profit of $\pi_j(\text{Dump}_i) = p_j - D_i$ for dumping waste i. Moreover, the violation may be traced back to the producer, who can suffer fines or goodwill loss as she did not fulfil her waste disposal responsibility. We denote this cost by $\delta_i \geq 0$, hence her profits are $\pi_i(\text{Dump}_i) = -p_j - \delta_i$ when contracting with Operator j. Note that dumping costs can be differentiated by waste quality with $D_L - D_H \geq 0$ and $\delta_L - \delta_H \geq 0$. The EPA, for example, regulates the land disposal of waste with hazardous components subject to higher restrictions and repercussions in case of violations (US Title 40 CFR-Subchapter 1 - part 268). We further assume $\delta_L - \delta_H \leq s_L - s_H$. Export regulations like the Basel Ban focus on increasing cost solely based on quality (Rucevska et al. 2015), whereas measures like EPR that could regulate δ_i apply more broadly, aiming to achieve proper treatment without mention of quality (e.g., European Parliament (2018)). As such, we consider a potential quality-based cost differential to be more prominent for export than for dumping violations.

Table 1 Key Notation

	Producer $i \in \{H, L\}$
π_i	Profit of the producer
s_i	Expected cost to export, where $s_L > s_H$
h	Prior probability that the producer type is $i = H$
δ_i	Expected cost of reputation loss and fines incurred by producer when the contracted treatment operator dumps
	Treatment Operator $j \in \{E, I\}$
π_j	Profit of the treatment operator
p_j	Treatment price charged by Operator j
c_j	Expected cost of treatment, where $c_E < c_I$
γ	Prior probability that the operator type is $j = E$
v_i	Expected post-treatment recovery value of waste, where $v_H > v_L$
$\overline{v}$	Average recovery value of waste, where $\overline{v} = hv_H + (1-h)v_L$
D_i	Expected cost of reputation loss and fines incurred by operator when he dumps
Π^{WC}	Waste Chain Profit $(\pi_i + \pi_j)$

Assumptions. We make some assumptions in order to focus on markets where there is an incentive to deviate from compliance, but not regardless of waste quality or operator efficiency.

Assumption 1. (i) $D_L \geq c_E - v_L$; (ii) $D_L < c_I - v_L$ (iii) $hD_H + (1-h)D_L \geq c_I - hv_H - (1-h)v_L$

Assumption 1 ensures that we consider a meaningful market where dumping is not the default option. In particular, Operator I dumps if and only if he believes that he received waste L, whereas Operator E treats the waste regardless of its quality. To see this, note that at Stage 3, Operator

j chooses between treating or dumping in order to maximize his profit, depending on the value of the waste after treatment (Ino 2011). If the net cost of treating is less than the expected cost of dumping (i.e., $D_i \geq c_j - v_i$), the operator chooses to treat and be compliant, otherwise he prefers to dump. Condition (i) ensures that Operator E is better off treating the waste, regardless of its quality, since $v_H > v_L$. Condition (ii) ensures Operator I is better off dumping waste L. Condition (iii) ensures that if Operator I is uncertain about the quality of the waste he receives (prior belief h), treating the waste in stage 3 is more profitable than dumping.

Assumption 2. (i) $s_H \geq c_I - v_H$; (ii) $s_L \geq c_E - v_L$.

Recall that the producer's outside option is to export at cost s_i, so she is not willing to incur a cost larger than s_i for treatment. Assumption 2 ensures that – provided the operator intends to treat at $t = 3$ – there exists a price where the manufacturer is better off getting her waste treated and the treatment operator can make a positive profit. Part (i) ensures this for waste H regardless of the operator type, while part (ii) ensures it for the efficient operator receiving waste L.[5]

Market failures. Two types of market failures often arise as a result of incomplete information: adverse selection and moral hazard. In our model, when the producer's waste quality is unknown to the operator, there exist prices for which both producer types contract with the operator, as well as prices that only Producer L accepts. Choosing a price from the latter range induces adverse selection as only Producer L accepts it (thus revealing her type to the operator). Moral hazard emerges when the operator dumps the waste even if the producer prefers treatment. Moreover, the producer may be unable to identify this behavior a priori.

Evaluation of Policies. We evaluate the impact of domestic and international policy measures in §5 along two dimensions: the expected values of environmental harm EH and waste chain profit Π^{WC}. Waste chain profit is defined as the sum of the operator and producer profits. Environmental harm is a direct result of the waste outcome. We assume dumping and export produce strictly more environmental harm than proper treatment, which we normalize to zero.

We vary cost parameters associated with the domestic and international policy measures to illustrate their impact on environmental harm and waste chain profits. These implicitly capture the combined effect of regulatory stringency and enforcement effort on the two agents. Where regulation is still evolving, as in international export, we will primarily refer to "regulatory stringency" as the lever for change, and where regulation is more established, as in domestic dumping, we will primarily refer to "enforcement effort" as the lever for change.

[5] Since Operator I would dump waste L, we do not make an assumption for that case.

4. Analysis

Our analysis uncovers three types of perfect Bayesian Nash equilibria, which we call the Breakdown, Full Compliance, and Partial Compliance equilibria. When equilibrium multiplicity arises, we select the non-Pareto dominated equilibrium, if such an equilibrium exists. If multiplicity remains, we apply the undefeated equilibrium refinement developed by Mailath et al. (1993) that is well-suited for signaling games with double-sided information asymmetry. When there exists a unique equilibrium that is non-Pareto dominated and undefeated, we refer to this equilibrium as *the unique* equilibrium and when it coexists with other undefeated, non-Pareto dominated equilibria, we refer to it as *an* equilibrium in the propositions. The equilibria are analyzed under weak and strong domestic anti-dumping enforcement efforts (captured by (D_i, δ_i)), relative to the strength of export regulations (captured by s_i). In §4.1, we focus on the case of a weak domestic anti-dumping enforcement climate compared to the export regulation climate, and proceed in §4.2 to analyze how stronger anti-dumping enforcement efforts impact equilibrium outcomes by triggering displacement effects (shifting dumping to export). All proofs are provided in the Appendix.

4.1. Weak domestic enforcement

In this section, we explore the equilibrium outcomes when the aggregate of the domestic anti-dumping enforcement efforts are weak relative to the export regulations. Specifically, we focus on $D_L + \delta_L \le s_L$ (we explain this threshold in §4.2).

Breakdown Equilibrium: In this equilibrium, treatment only occurs when waste H is paired with Operator E, i.e. waste is primarily dumped or exported. Both operator types pool on price but separate on the disposal method. The pooled equilibrium price p^* is higher than the willingness to pay of Producer H, simultaneously creating an adverse selection and a moral hazard problem. Specifically, adverse selection arises as Producer H prefers to export her waste rather than paying the operator p^*. Due to this adverse selection, the waste that remains domestically is revealed to be L. Consequently, treatment only occurs in the $\{L, E\}$ dyad and moral hazard arises as Operator I dumps the waste it receives, but cannot be distinguished from E.

We formalize these findings in Proposition 1 and summarize them in Table 2.

Proposition 1. *When $D_L + \delta_L \le s_L$, in the Breakdown equilibrium, both operator types pool on $p^* = s_L - (1-\gamma)\delta_L$. Producer H exports and Producer L contracts with the treatment operator. Finally, Operator I dumps while Operator E treats the waste he receives.*

Breakdown is the unique equilibrium[6] *if and only if*

$$s_H \le h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L). \tag{Bd}$$

Environmental harm is $EH_{BD} = (1-\gamma)(1-h) \times EH(Dump_L) + h \times EH(Export_H)$.

Waste chain profits are $\Pi^{WC}_{BD} = \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)(D_L + \delta_L) - hs_H$.

Table 2 Prices and Profits in the Breakdown Equilibrium when $D_L + \delta_L \leq s_L$

	Waste L	Waste H	Price
Operator I	**Dump** $\pi_L = -p^* - \delta_L$ $\pi_I = p^* - D_L$	**Export** $\pi_H = -s_H$ $\pi_I = 0$	$p^* = s_L - (1-\gamma)\delta_L$
Operator E	**Treat** $\pi_L = -p^*$ $\pi_E = p^* + v_L - c_E$	**Export** $\pi_H = -s_H$ $\pi_E = 0$	

Note. Each cell includes: (i) waste outcome, (ii) producer's profit π_i, (iii) operator's profit π_j, or pooling price p^*.

In Breakdown, the export cost of waste H is low compared to that of waste L ($s_L - s_H$ is large). Recall that a lower export cost decreases the producer's willingness to pay for local treatment. In this equilibrium, Operator E prefers to charge a high price $p^* = s_L - (1-\gamma)\delta_L$ and only contract with waste producer L instead of deviating to a lower price $\tilde{p} = s_H$, which would lead to contracting with both producer types. This non-deviation condition can be written as (Bd), which serves to illustrate that all else being equal, the export cost of waste H must be small relative to the cost of its low-quality counterpart.

Interestingly, there are two key reasons in Breakdown that lead to a lack of proper treatment. First, treatment operators can be paid to treat the waste while in fact dumping it due to moral hazard. In practice this undermines the legitimacy of waste treatment services (Rucevska et al. 2015, Europol 2017). Second, due to adverse selection we find that valuable waste is lost abroad because it is cheaper than contracting locally. In practice, this can leave domestic recycling programs to manage low value items (OECD 2016).

From a policy perspective, this equilibrium can be considered as worse than the others because the lack of proper waste treatment creates the greatest expected environmental harm.

Full Compliance Equilibrium: In this equilibrium, waste is treated regardless of its quality and the efficiency of the operator; neither moral hazard nor adverse selection is observed. To attain this equilibrium, the operator must be willing to set his price equal to the lowest willingness to pay in the market $p^* = s_H$ regardless of his type, since any higher would induce Producer H to export her waste. The producer purchases the offered treatment service regardless of her type, resulting in an expected waste quality of $\overline{v} = hv_H + (1-h)v_L$, which gets treated per Assumption 1 (iii). We formalize these findings in Proposition 2 and summarize them in Table 3.

PROPOSITION 2. *When $D_L + \delta_L \leq s_L$, in the Full Compliance equilibrium, the operator types pool on $p^* = s_H$, which both producer types accept. Waste is treated regardless of its quality.*

Full Compliance is the unique equilibrium if and only if (¬ Bd) (i.e., (Bd) is not satisfied) and

$$s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L). \tag{FC}$$

[6] Recall that this means it is the unique non-Pareto dominated and undefeated equilibrium.

Full Compliance is an equilibrium if and only if ($\neg$ Bd), ($\neg$ FC), and $s_H \geq \max\{c_I - \overline{v}, s_L - \delta_L\}$.

Environmental harm is $EH_{FC} = 0$.

Waste chain profits are $\Pi^{WC}_{FC} = hv_H + (1-h)v_L - \gamma c_E - (1-\gamma)c_I$.

Table 3 Price and Profits in the Full Compliance Equilibrium when $D_L + \delta_L \leq s_L$

	Waste L	Waste H	Price
Operator I	**Treat** $\pi_L = -p^*$ $\pi_I = p^* + v_L - c_I$	**Treat** $\pi_H = -p^*$ $\pi_I = p^* + v_H - c_I$	$p^* = s_H$
Operator E	**Treat** $\pi_L = -p^*$ $\pi_E = p^* + v_L - c_E$	**Treat** $\pi_H = -p^*$ $\pi_E = p^* + v_H - c_E$	

Note. Each cell includes: (i) waste outcome, (ii) producer's profit π_i, (iii) operator's profit π_j, or pooling price p^*.

We obtain Full Compliance because information asymmetry obscures the true nature of the waste, i.e., Operator I cannot selectively dump waste L and treat waste H. Conditions in the proposition illustrate that for Full Compliance to be either an equilibrium or the unique equilibrium, the price s_H, i.e., the export cost of waste H, must be sufficiently high ($s_L - s_H$ is small). Specifically, Condition (FC) ensures that the expected profit of Operator I when charging $p^* = s_H$ and treating both types of waste is at least as much as the profit when charging $\tilde{p} = s_L - \delta_L$, which would only be accepted by Producer L and followed by dumping.

From a policy perspective, this can be considered as the most attractive outcome as all agents comply and the expected environmental harm is lowest, since treatment is the only outcome. The conditions for the Full Compliance equilibrium to emerge require that s_H, i.e., the export cost of waste H, is sufficiently large. Although bans and restrictions on low-quality, hazardous waste are common, especially in Europe, export regulations on high-quality waste are limited. This suggests that the Full Compliance equilibrium would not be likely to emerge under the current regulatory climate, which is consistent with observations. We will elaborate on this in the next section.

Partial Compliance Equilibrium: In this equilibrium, only Operator E treats. The operator's type is revealed due to different pricing strategies. Operator E treats both waste types by setting $p^*_E = s_H$. Operator I sets a price p^*_I that is only accepted by Producer L and for which Producer H prefers to export, i.e., adverse selection reveals the low-quality nature of the waste received by Operator I. This waste is subsequently dumped by Operator I per Assumption 1. We formalize these findings in Proposition 3 and summarize them in Table 4.

PROPOSITION 3. *Under* $D_L + \delta_L \leq s_L$, *in the Partial Compliance equilibrium, Operator I sets* p^*_I. *Only Producer L contracts with Operator I, who dumps the waste. Operator E sets* $p^*_E = s_H$, *and gets and treats both types of waste.*

Partial Compliance (with $p_I^* = s_L - \delta_L$) is the unique equilibrium if and only if ($\neg$ FC), ($\neg$ Bd), and $s_H < s_L - \delta_L$.

Partial Compliance (with $\max(D_L, s_H - \delta_H) < p_I^* \leq s_L - \delta_L$) is an equilibrium if and only if ($\neg$ FC), ($\neg$ Bd) and $s_H \geq s_L - \delta_L$. It coexists with the Full Compliance equilibrium when $s_H \geq c_I - \overline{v}$ and with other Partial Compliance equilibria satisfying p_I^* otherwise.

Environmental harm is $EH_{PC} = (1-\gamma)\,[h \times EH(Export_H) + (1-h) \times EH(Dump_L)]$.

Waste chain profits are $\Pi_{PC}^{WC} = \gamma(hv_H + (1-h)v_L - c_E) - (1-\gamma)(hs_H + (1-h)(D_L + \delta_L))$.

Table 4 Prices and Profits in the Partial Compliance Equilibrium when $D_L + \delta_L \leq s_L$

	Waste L	Waste H	Price
Operator I	**Dump** $\pi_L = -p_I^* - \delta_L$ $\pi_I = p_I^* - D_L$	**Export** $\pi_H = -s_H$ $\pi_I = 0$	$p_I^* \leq s_L - \delta_L$
Operator E	**Treat** $\pi_L = -p_E^*$ $\pi_E = p_E^* + v_L - c_E$	**Treat** $\pi_H = -p_E^*$ $\pi_E = p_E^* + v_H - c_E$	$p_E^* = s_H$

Note. Each cell includes: (i) waste outcome, (ii) producer's profit π_i, (iii) operator's profit π_j, or price p_j^*.

This proposition states that if neither (FC) nor (Bd) hold, i.e., $s_L - s_H$ is at an intermediate level, there is a region where Partial Compliance is an equilibrium. The operator's type is signaled in Partial Compliance so, as opposed to Breakdown, Producer L is aware of the intention of Operator I to dump and lowers her willingness to pay. As such, Operator I must charge a lower price than in Breakdown to contract with Producer L.

From a policy perspective, this equilibrium is an intermediate outcome. Per Propositions 1-3, the expected environmental harm is worse than in Full Compliance, but it is an improvement over Breakdown since waste is now treated in the $\{H, E\}$ dyad instead of being exported.

4.2. Stronger domestic enforcement

This subsection explores the effect of stronger domestic anti-dumping enforcement. We find that higher domestic enforcement levels can replace dumping with export. We call this the "displacement effect." There exist two major tipping points where the displacement effect occurs. In Partial Compliance, dumping is replaced by exporting when $D_L + \delta_L > s_L$. In Breakdown, stronger domestic enforcement is needed to curb dumping, namely $D_L + (1-\gamma)\delta_L \geq s_L$. The reason for this higher tipping point is the price that can be charged despite dumping. In Breakdown, moral hazard under incomplete information allows Operator I to make himself indistinguishable from Operator E who treats, and thus charge a higher price. As a result, more is needed to curb dumping in Breakdown than in Partial Compliance where the prices signal the type and intention of the operator. We provide the exact necessary and sufficient conditions for the equilibria under stronger domestic enforcement in Propositions B.1 and B.2 in the Appendix, and highlight the displacement conditions in Lemma 1.

LEMMA 1. *Dumping of waste L by Operator I is replaced by export for $D_L + \delta_L > s_L$ in the Partial Compliance equilibrium, and for $D_L + (1-\gamma)\delta_L \geq s_L$ in the Breakdown equilibrium.*

A clear example of the displacement effect is seen for e-waste where most EU member states have a strong regulatory climate against domestic e-waste dumping, making export, even when it is illegal, an attractive option (EnviCrimeNet 2015). These findings are consistent with the pollution haven hypothesis, which stipulates that waste moves to the cheapest disposal option (Kellenberg 2012). Conversely, strengthening export regulations can retain low-quality waste in the local market but does not guarantee its proper treatment due to moral hazard. Domestic and/or international enforcement efforts therefore may not eliminate non-compliant behavior, but merely relocate the waste between local dumping and international export.

5. Policy implications

In this section, we explore the implications of changing export restrictions and domestic anti-dumping enforcement on the environmental harm EH resulting from the waste outcome. In formulating our policy recommendations, we focus on minimizing environmental harm since the overarching objective of environmental policy measures like the Basel Ban and anti-dumping regulations is to protect human health and the environment (e.g., United Nations (2019), U.S. Title 40 CFR). As dumping and export are more harmful for the environment than proper treatment, our recommendations will focus on measures that attain more treatment: moving from Breakdown to Partial Compliance or from Partial Compliance to Full Compliance.

Many existing measures, including export bans, have experienced industry push-back (Basel Action Network 2013, 2019b). As such, we simultaneously analyze the impact of our recommendations on waste chain profits and identify the conditions under which environmental harm reduction is accompanied by increased profits such that policy makers identify measures that are less likely to be subject to industry push-back. A summary of the results can be found in Table 5 in Appendix B with the full analysis and conditions provided in Appendix C.

5.1. Export restrictions

This section evaluates the effect of changes in the stringency of internationally orientated regulations and which waste categories they target in particular. For instance, in December 2019, the Basel Ban Amendment became international law, which means that countries will be required to have legislation or other measures in place to stop waste exports in violation of the Basel Ban Amendment (Basel Action Network 2019a). In addition, EU legislators are currently considering a proposal to further strengthen those export penalties (European Parliament 2022), significantly increasing the expected cost of exporting low-quality waste illegally (s_L).

Export restrictions are important for the domestic market as they influence how well local operators can compete with the outside market. We show that the difference in export burden between waste categories is crucial in determining equilibrium outcomes. We will explain this finding by first illustrating the impact on the waste outcome of strengthening s_L and then s_H. Recall that when the difference $s_L - s_H$ is large, Breakdown emerges per Proposition 1, when $s_L - s_H$ is intermediate, Partial Compliance emerges per Proposition 3, and when s_H is sufficiently close to s_L ($s_L - s_H$ small), Full Compliance emerges per Proposition 2. The conditions for these equilibria also depend on the penalties for domestic dumping, which is discussed in §5.2.

To illustrate how a sole increase in s_L can backfire, consider starting with a policy climate such that the equilibrium is Partial Compliance under weak domestic enforcement (corresponding to an intermediate level of $s_L - s_H$ and Table 4).[7] Strengthening export regulations on waste L, s_L, increases $s_L - s_H$ and could therefore result in the equilibrium switching to Breakdown. To see this, recall that a higher s_L means that exporting becomes less attractive for Producer L. Operator I, who only contracts with Producer L in Partial Compliance, can respond to a higher s_L by increasing his price $p_I^* \leq s_L - \delta_L$ without risking that Producer L resorts to export. Operator E, who contracts with both producer types in Partial Compliance, cannot raise his price $p_E^* = s_H$ without Producer H switching to export as export cost s_H remains unchanged. If the opportunity cost of keeping Producer H's business becomes too high, Operator E will also raise his price, inducing adverse selection and leading to Breakdown.

If the Basel Ban becomes sufficiently stringent for Breakdown to emerge, EH increases, attaining the exact opposite of what authorities intended. In addition, we find that waste chain profits decrease (Corollary 5 in Appendix C). The reason is that the net treatment value $v_H - c_E$ is not extracted and the price s_H is paid to exporters outside the supply chain instead of to a local operator, thus reducing chain profits by $-\gamma h(s_H + v_H - c_E)$.

This example illustrates how export regulations that only focus on avoiding the export of low-quality waste can backfire. This is one of the most revealing results of our paper. To restate the example above in more general terms, when export regulations increase the price an operator can charge the low-end market, at some point, serving only the low-end market becomes more attractive than serving the full market. Consequently, high-quality waste is exported rather than treated domestically, resulting in a degradation in both environmental and waste chain profit outcomes. Moreover, we can expect industry push-back against strengthening the Ban, which is in line with what we observe in practice (Basel Action Network 2013, 2019b).

[7] The results also hold under stronger domestic enforcement levels, as shown in Section B and C of the Appendix.

To avoid this unintended outcome, the opportunity cost of forgoing the high-quality market needs to be increased as well. This can be attained through an increase in s_H. This would retain an intermediate level of $s_L - s_H$ such that the condition for Breakdown is not satisfied. If s_H increases (in concert with s_L), Operator E maintains his incentive to charge $p^* = s_H$ and treat the whole market. Moreover, by strengthening s_H even further such that $s_L - s_H$ becomes smaller, the conditions of the Full Compliance equilibrium can be satisfied. In other words, to improve waste outcomes we need more symmetric export regulations between waste categories to ensure that the costs s_L and s_H do not drift too far apart. Such coordinated intervention can avoid an increase in EH and a loss in waste chain profits.

Attaining Full Compliance has clear benefits as it strictly reduces EH compared to Partial Compliance or Breakdown. However, since it is achieved through an increase in export cost, it is less evident if the waste chain could benefit. Interestingly, we find that waste chain profits can improve despite the greater export cost, but only when certain conditions are met. To illustrate, we use Partial Compliance again as our starting point. Moving to Full Compliance, profits improve through two changes. First, waste H is now treated by Operator I instead of exported, so the net treatment value $v_H - c_I$ is retained within the waste chain. Second, waste L is no longer dumped by Operator I, saving the waste chain from incurring dumping cost $D + \delta$ (or from incurring export cost if the displacement effect was triggered). However, instead of being dumped (or exported), waste L is now treated by Operator I and this can be more costly for the chain ($v_L - c_I < 0$). Waste chain profit will only improve if eliminating the cost of dumping or exporting waste L and generating value from treating waste H outweigh the net cost of treating waste L. We state our results more formally in Corollary 1.

COROLLARY 1. *More stringent export regulation on waste L can increase EH by leading to Breakdown where Producer H exports. Industry push-back can be expected as this also reduces waste chain profits. Combining this measure with appropriately tailored export regulations on waste H counters this adverse selection problem and can even reduce EH by leading to Full Compliance where both waste types are treated. We find waste chain profits improve if eliminating the cost of dumping or exporting waste L and generating value from treating waste H outweigh the net cost of treating waste L.*

Existing literature on environmental economics has argued the importance of reducing regulatory differences between countries to reduce the trans-boundary movement of waste. These studies focus on the effect of regulatory changes on the compliance of a single firm, whereas in reality, waste chains consist of multiple agents. Our contribution to this literature is to model interactions between two key agents in a decentralized waste chain, which reveals a new dimension: the necessity of reducing regulatory differences between waste categories. If export regulations on high-quality waste are sufficiently stringent, environmental harm is reduced and under certain conditions waste chain profits also benefit.

Export regulations can help achieve more treatment, but these regulations may need to be complemented with local anti-dumping enforcement efforts. This intervention is discussed next.

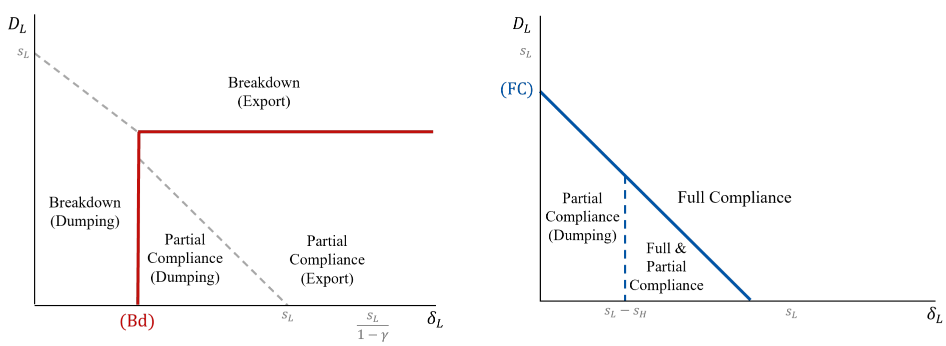
5.2. Domestic anti-dumping enforcement

In this section, we evaluate the effect of a change in the strength of domestic enforcement against dumping, and in particular the relative cost incurred by the producer (δ_i) versus the operator (D_i). As dumping occurs for waste L, D_L and δ_L are the key targets, meaning that for domestic enforcement, the cost level is important rather than the cost differential ($D_L - D_H$ and $\delta_L - \delta_H$). We will show that not just the aggregate dumping penalty $D_L + \delta_L$ but also the relative penalty incurred by the operator versus the producer can be crucial in determining the equilibrium outcome. Specifically, targeting the producer in addition to the operator can be an effective measure against non-compliance. We also identify backfiring conditions of which policy makers should be aware.

To convey the intuition behind our findings, we will rely on Figure 2 that depicts two examples of a regime graph for different, fixed export policy climates (s_H, s_L). The graph on the left shows that, when $s_L - s_H$ is large to intermediate, domestic policies (D_L, δ_L) can lead to either Breakdown or Partial Compliance. Conversely, the graph on the right shows that when $s_L - s_H$ is intermediate to small, Full Compliance or Partial Compliance can arise depending on domestic policies (D_L, δ_L).

Figure 2 Examples of Equilibria as a Function of the Domestic Policy Climate (D_L, δ_L) for two Export Policy Climates (s_L, s_H)

(a) $s_L - s_H$ large to intermediate (b) $s_L - s_H$ intermediate to small



Note. The solid, colored lines partition the domestic enforcement space into regions corresponding to different equilibria in the (D_L, δ_L) space for a fixed (s_L, s_H) pair. The dashed, grey lines represent the two tipping conditions per Lemma 1 that mark the displacement effect.

First, we discuss the impact of strengthening aggregate domestic enforcement efforts ($D_L + \delta_L$). When the cost of exporting waste is not too asymmetric ($s_L - s_H$ small), this intervention can be highly effective and lead to the treatment of both waste types, as illustrated in Figure 2b. Consider starting in Partial Compliance (below the blue, solid line) where Operator I induces adverse selection and dumps. An increase in either D_L or δ_L can discourage this behavior, and help satisfy the conditions of Full Compliance where waste is treated by both operator types, strictly reducing EH. As mentioned in the previous section, moving from Partial to Full Compliance can also benefit waste chain profits under certain conditions. Importantly, this result does not necessarily hold for a different set of export regulations, e.g., Full Compliance is never the equilibrium in Figure 2a. This example illustrates the complementarity of domestic enforcement efforts and export regulations.

Corollary 2. *When the profile of export regulations is not too asymmetric ($s_L - s_H$ small), strengthening domestic enforcement ($D_L + \delta_L$) can reduce EH by leading to Full Compliance if the change satisfies Proposition 2. Waste chain profits improve if eliminating the cost of dumping waste L and generating value from treating waste H outweigh the net cost of treating waste L.*

However, there are nuances to strengthening domestic enforcement: the firm that is targeted may matter. These nuances are best seen in Figure 2a where the cost of exporting waste H is relatively low ($s_L - s_H$ large). First, strengthening domestic enforcement by targeting the treatment operator (increasing D_L) can backfire as it encourages Operator E to induce adverse selection. To explain this finding, consider starting in the Partial Compliance regime, but now in Figure 2a below the red line. Here, an increase in D_L (vertical shift) can lead to the Breakdown equilibrium and cause Producer H to export her waste, increasing EH. To explain why, recall that in Partial Compliance, Operator E signals his type with his price and treats the entire market, while Operator I dumps waste L. However, if dumping cost increases, it is no longer profitable for Operator I to contract with Producer L (see §4.2 or Proposition B.2). As Operator I prices himself out of the market, the threat of Operator I pooling on the price and dumping (which would have undermined the profit of Operator E) is eliminated. Operator E can thus raise his price and only serve waste L without the threat of Operator I participating in the market.

In addition to an increase in EH, we also find a strict decrease in waste chain profits: the treatment of waste H by Operator E generated a positive value in Partial Compliance, but is now exported in Breakdown. Thus, a market that functions relatively well (Operator E treats both waste categories) can be negatively affected if ill-placed enforcement efforts remove the threat of moral hazard, further increasing the export of valuable waste (Operator E only treats waste L) and undermining local waste chains. We formalize these findings in the following corollary.

Corollary 3. *Stronger domestic enforcement efforts targeted to the operator (D_L) can backfire and increase EH. Starting from Partial Compliance, it can lead to the Breakdown equilibrium if the change satisfies Proposition B.2(iii). This also strictly reduces waste chain profits.*

We now turn to analyzing the effect of targeting the producer with anti-dumping enforcement. This can be achieved through e.g., fines for not meeting responsibility requirements in general or by including names of upstream firms when reporting on dumping infractions, increasing the cost through goodwill loss. We already noted this can improve waste outcomes by discouraging adverse selection by I (Corollary 2). We identify another such set of conditions by considering the Breakdown equilibrium on the left of the red line in Figure 2a as the starting point. Recall that under Breakdown, waste H is exported and waste L is dumped by Operator I (Table 2). Under moral hazard, the pooling price $p^* = s_L - (1-\gamma)\delta_L$ emerges, where the producer's willingness to pay is reduced. Exacerbating the consequences of dumping for the producer lowers that pooling price, encouraging Operator E to signal his type and treat the complete market. The resulting signaling price eliminates moral hazard from I being indistinguishable and lead to Partial Compliance. Although not illustrated in this figure, an increase in δ_L can also lead to Full Compliance under different export regulations. In contrast, an increase in the dumping cost D_L incurred by the treatment operator (vertical shift in Figure 2a within the Breakdown region) does not improve the waste management outcome other than displacing waste L between dumping and export.

An increase in δ_L can thus reduce EH, but results in a cost increase for the waste chain. Again, we find that waste chain profits can improve despite the greater dumping cost when certain conditions are met. For example, moving from Breakdown to Partial Compliance, chain profits improve as waste H is treated by Operator E instead of exported, so the treatment value is retained within the waste chain. However, when local enforcement is weak, Operator I continues to dump waste L in Partial Compliance, and will thus face a greater reduction in the producer's willingness to pay due to a higher δ_L. Waste chain profits improve if the benefits of additional treatment offset the loss from an increase in δ_L. Interestingly, if local enforcement is sufficiently strong such that dumping is eliminated in Partial Compliance, an increase in δ_L always improves waste chain profits.

Corollary 4. *Stronger domestic enforcement efforts targeted to the producer (δ_L)*

i. can reduce EH by leading to Partial Compliance as E signals his type if the change satisfies Propositions 3 or B.1(ii). If the change satisfies Proposition 3, waste chain profits improve if treating waste H is sufficiently profitable for Operator E. If the change satisfies Proposition B.1(ii), waste chain profits always improve.

ii. can reduce EH by leading to Full Compliance as E signals his type if the change satisfies Proposition 2 or B.1(i). Waste chain profits improve if the eliminated cost of dumping waste L and the gained value of treating waste H outweigh potential losses of treating waste L.

Combining Corollaries 2 - 4, we conclude that targeting the producer is a more robust anti-dumping measure as it can only reduce EH and can improve waste chain profits, while targeting the treatment operator is a policy approach that should be implemented more judiciously. In particular, it is effective when combined with a sufficiently high export cost but can otherwise backfire by increasing environmental harm and reducing waste chain profits.

Comparing anti-dumping enforcement and export regulations, we see that both δ_L and s_H can lead to lower environmental harm and an increase in waste chain profits, but their effectiveness depends on the policy climate. Specifically, a sufficient increase in s_H can always lower environmental harm whereas δ_L is only effective when there is an occurrence of dumping, i.e., domestic enforcement is relatively weak. However, when moving from Breakdown to Partial Compliance, increasing δ_L may improve waste chain profits under a broader set of parameter values than increasing s_H. As such, moving from Breakdown to Partial Compliance through producer responsibility may be less likely to undermine local waste chains.

In the environmental economics literature, the dumping cost for the producer and operator are rarely separated as the studies either incorporate only one of those agents (e.g. Ino (2011), or only consider the cost for which an agent is directly responsible, such as emissions for producers or disposal for operators (e.g. Walls et al. (2001)). By capturing the cost (e.g. fines, reputation loss) for the producer from dumping, we find that the compliance and waste management outcomes can depend on who is targeted with anti-dumping regulations and under what conditions.

5.3. Summary Findings regarding Export and Anti-Dumping Policies

We briefly summarize our main findings from this section:

1. Strengthening export regulations on high-quality waste to make export regulations more symmetric increases the opportunity cost of forgoing the high-quality market thus reducing adverse selection. This can lead to waste being treated regardless of the quality or the efficiency of treatment facilities (Corollary 1). This strictly reduces environmental harm and can improve waste chain profits.
2. An increase in the dumping cost for the producer is an effective, complementary measure to export regulations on high-quality waste as it reduces the high-quality producer's willingness to pay when dumping activities occur, reducing adverse selection and eliminating moral hazard (Corollaries 2, 4.i, and 4.ii). This strictly reduces environmental harm and can improve waste chain profits.
3. Producer responsibility for low-quality waste and export regulations of high-quality waste can both lower environmental harm, but depending on the initial policy climate, export regulations reduce environmental harm under a broader set of conditions, whereas producer responsibility may be better at mitigating negative impacts on waste chain profits (Corollary 5).
4. If domestic enforcement efforts are not designed in conjunction with export regulations, they can undermine waste chain profits and increase environmental harm (Corollary 3).

6. Alternative Information Structures

We relax several assumptions on the information structure and explore their implications for our findings and recommendations outlined in §5.3. For ease of exposition, we assume in this section that the domestic anti-dumping costs (D, δ) do not depend on waste quality.

6.1. Single-sided Information Asymmetry

Our key recommendations are derived under double-sided information asymmetry, but relationships can emerge within the waste market where one side of the information asymmetry is more dominant than the other. For example, if the producer routinely contracts with the same operator, the operator may become better informed of the waste quality. Although we cannot tailor policy to the particular information structure of each market relationship (i.e., the Basel Ban applies to all low-quality waste exports, regardless of whether that quality was common knowledge between the firms), it is important to understand the impacts of policy recommendations on the relationships with different information structures. We thus explore the implications of our policy recommendations made under double-sided asymmetry on market relationships where there exists single-sided asymmetry (i.e., where either quality is known or efficiency is known).

6.1.1. Known Waste Quality We characterize the equilibrium outcomes when the producer is uninformed about the operator's type, whereas the operator is informed about the producer's type. Within these relationships, we find that treatment arises when waste is H or the operator is E, but not for the $\{I, L\}$ dyad. In this case, it is dumped when $D \leq s_L - (1-\gamma)\delta$ and exported otherwise. As in our main model, policies that change D, δ, or s_L can therefore cause displacement.

Waste H can be identified and is therefore always treated, but for waste L we continue to see the moral hazard problem. Similar to what we found in Breakdown under weak domestic enforcement efforts, because Operator I is indistinguishable from E, the pooling price is weighted by L's expectation of her waste being dumped ($p_L^* = s_L - (1-\gamma)\delta$), thereby undermining the profits of the compliant Operator E. An increase in δ, per Corollary 4, will continue to combat this problem: moral hazard caused by I being indistinguishable is eliminated as Operator E can profitably use his price to signal his type. Under known waste quality, the same outcome can alternatively be achieved by an increase in D (without the backfiring risk noted in Corollary 3).

The remaining recommendations proposed under double-sided asymmetry combat inefficiencies that do not occur in this dyad, such as adverse selection. Implementing them will however have no negative impact, so our qualitative recommendations can be safely applied to this market segment.

6.1.2. Known Efficiency We characterize the equilibrium outcomes when the producer is informed about the operator's type and the operator is uninformed about the producer's type. Each operator now independently forms their best response strategy, as their type is common knowledge.

We find that Operator E either treats all waste (like the behavior of E in Full and Partial Compliance) or induces adverse selection by charging a high price that is rejected by H, leaving only waste L to be treated (like the behavior of E in Breakdown). Operator I similarly either treats all waste (like the behavior of I in Full Compliance), or charges a high price that is rejected by waste H (like the behavior of I in Partial Compliance and Breakdown). Waste L is then dumped for $D+\delta \leq s_L$ and exported otherwise.

We find that an increase in s_H continues to combat adverse selection by increasing the opportunity cost of forgoing the high-quality waste market (as in Corollary 1). An increase in $D+\delta$ discourages adverse selection by I (as in Corollary 2). However, since there is no moral hazard from I being indistinguishable, an increase in δ does not encourage E to signal his type and treat both waste types (as in Corollary 4). The effect of strengthening δ and D are therefore the same, which could lead to a continued legislative focus on fining the operator (increasing D).

Combining the findings in 6.1.1 and 6.1.2, we conclude that recommended measures derived from the double-sided information analysis can be applied to markets where single- and double-sided information asymmetry are thought to co-exist, but the converse is not necessarily true.

First, under single-sided asymmetry, an increase in δ is never more effective in achieving a particular goal than an increase in D. When efficiency is known, an increase in δ encourages treatment by Operator I by discouraging adverse selection, but does not impact treatment decisions of Operator E. When quality is known, an increase in δ eliminates moral hazard, but does not encourage treatment. In either case, D would have the same effect. In contrast, under double-sided asymmetry, an increase in D is less effective than targeting δ in eliminating moral hazard and discouraging adverse selection. A second interaction effect is the backfiring risk from increasing in D (Corollary 3), which does not occur in dyads operating under single-sided information asymmetry. Thus, in markets where regulators recognize the prevalence of double-sided information asymmetry, they should exercise particular prudence when considering imposing penalties on treatment operators.

6.2. Quality Verification by the Treatment Operator

Our model assumes that the treatment operator cannot ascertain the quality of waste without going through the treatment process. Instruments that sort products by recyclability or other characteristics have been shown to be inefficient and costly to implement (European Commission 2014). Our current assumption is based on these observations. We recognize, however, that as technology progresses, there may be cases where a treatment operator can perform a (costly) assessment of the waste quality after having obtained it but before processing it. We therefore extend the model to allow the operator to perform a quality check of cost T that perfectly reveals waste quality prior to deciding his disposal method, conditional on the producer contracting him for his waste management services. Assumptions 1 and 2 remain unchanged.

We find that when the cost of quality assessment is sufficiently low, the Full Compliance equilibrium disappears and a new, Near-Full Compliance equilibrium, appears. In this equilibrium, the efficient operator treats without quality verification, similar to Full Compliance, but the inefficient operator verifies the quality. He subsequently dumps if the check reveals the waste is of low quality, and treats otherwise. In contrast to the Full Compliance equilibrium, moral hazard can emerge as the pooling price becomes $p^* = \min\{s_H, s_L - (1-\gamma)\delta\}$. This means that when $s_L - (1-\gamma)\delta < s_H$, the cost of dumping will be shared between the compliant and non-compliant operator.

A low-cost quality assessment has several implications for our findings in §5.3. We find that adverse selection is less likely to occur, and high-quality waste is more easily retained and treated in the country of origin, when it can be more easily identified. As such, strengthening export regulations on high-quality waste continues to be beneficial. The main disadvantage is that operators can also use this information to identify low-quality waste and dump it. This incentive can create additional moral hazard problems: The profits of the efficient operator are negatively affected due to the dumping activities being hidden. This mechanism is similar to the issue of moral hazard under incomplete information in the Breakdown equilibrium (Proposition 1) of the original model, except that high-quality waste is still treated. We also find that strengthening and tailoring penalties for dumping in conjunction with export regulations will help forestall this outcome. Specifically, an increase in the dumping cost for the producer continues to be an effective, complementary measure to export regulations on high-quality waste. One exception where this measure can be ineffective is when the moral hazard condition holds ($s_L - (1-\gamma)\delta < s_H$). Therefore, in the presence of quality verification, we must take additional care that the export cost of high-quality waste (s_H) is tailored in conjunction with δ to avoid satisfying the moral hazard condition.

Governments can pursue measures to reduce the cost of quality verification by treatment operators, including information-based approaches or technology subsidies. Contrasting the results with the main model, if the local policy climate is such that Breakdown emerges, quality verification would strictly reduce environmental harm as high-quality waste will be treated instead of exported. There is, however, a caveat: Under quality verification, inefficient operators will be able to perfectly identify and subsequently dump low-quality waste, rendering Full Compliance unattainable. As such, maintaining quality uncertainty could in fact be valuable and improve waste management outcomes in cases where the other policy levers can attain Full Compliance.

6.3. Quality Uncertainty

Our model assumes that the producer knows the quality of her own waste. In some cases, the agent contracting the treatment operator may not be the original producer of the waste. For instance, since the introduction of take-back regulations, producers in Europe have created entities called

Producer Responsibility Organizations that aggregate wastes of members and act on their behalf to fulfill responsibility requirements. In other cases, producers assign designated collection partners that collect post-use waste on their behalf. In these instances, the agent acting on the producer's behalf may have uncertainty with respect to the exact quality of the waste stream it is managing.

To capture this, we adapt our model such that the producer is uncertain about the quality of her waste, but has an informative signal about the most likely quality level. We re-define conditions paralleling Assumptions 1 and 2 (the waste is treated except when the producer with the lower expected waste quality works with an inefficient operator) and re-solve the model. We find that the equilibrium structure is robust with respect to quality uncertainty: The same three equilibrium outcomes (Breakdown, Full Compliance, and Partial Compliance) emerge. Referring back to the key findings in §5.3, reducing the asymmetry in export cost between waste categories remains important. Adverse selection is eliminated by ensuring that exporting high-quality waste is sufficiently costly, which increases the price operators can charge in the domestic market (Corollary 1). Strengthening domestic enforcement efforts continue to be a highly effective complement to export regulations and lead to the treatment of both waste types (Corrolary 2), provided they are carefully tailored in conjunction with export regulations to avoid them backfiring (Corollaries 3 and 4).

7. Concluding Remarks and Recommendations

This work was inspired by discussions with Europol officers who recognized the challenges of determining what enforcement actions to prioritize while operating under imperfect information. Our analysis yielded the following insights:

The asymmetry in export burden between waste categories should be reduced: Existing single-agent studies have shown the importance of reducing regulatory differences between countries to avoid the pollution haven effect. We find that the pollution haven hypothesis gives an important but incomplete explanation of the violations we see in the market. Our results suggest that with multi-agent problems, we need to reduce the asymmetry in regulatory stringency (reflected in the export cost) between waste categories to reduce environmental harm. This is because export regulations directly influence how well local treatment operators can compete with the outside market. When only low-quality waste is costly to export, adverse selection pushes prices up, driving providers of high-quality waste abroad whereas moral hazard exacerbates local dumping. In other words, regulations targeted at one market failure (the export of low-quality waste) can spill over to market segments that were functioning well (the local treatment of high-quality waste), increasing environmental harm and reducing waste chain profits. Consider the Basel Ban Amendment, which exhibits this characteristic by only making export of low-quality waste costly. A later amendment will mean that in 2025 this unbalance and risk of spill-overs will be reduced on the one hand (both hazardous and non-hazardous e-waste will be listed in the annexes of the Basel Ban Amendment) but exacerbated on the other (measures were also put in place that exclusively focus on penalizing low-quality exports).

Penalizing producers for downstream dumping should be given more consideration: We find that domestic anti-dumping enforcement can complement export measures in reducing environmental harm. Increasing the cost of dumping on treatment operators can eliminate moral hazard and encourage treatment, but may also cause a displacement effect upstream, causing formerly dumped waste to be illegally exported instead. Increasing the dumping cost borne by producers instead can be particularly effective as it penalizes non-compliant operators through a reduction in willingness to pay for services. In the EU, EPR implementations explicitly call for the establishment of "an adequate monitoring and enforcement framework with a view to ensuring that producers of products (...) implement their extended producer responsibility obligations." Although such enforcement is still nascent, our finding supports holding the producer responsible for downstream violations.

Domestic anti-dumping enforcement efforts must be carefully crafted in conjunction with export regulations: First, setting dumping and export regulations jointly can avoid these regulations from backfiring: when the cost of exporting high-quality waste is low, increasing the dumping cost on the treatment operator too much can encourage export and increase environmental harm. A policy climate with costlier high-quality waste exports can avert this danger. Second, dumping and export regulations can both lower environmental harm, but in some policy climates export regulations are more effective at reducing environmental harm, whereas in others anti-dumping enforcement is better at mitigating negative impacts on waste chain profits. Thus, the export regulation and domestic enforcement levers should be designed to work effectively in concert to avoid regulations backfiring and to mitigate potential industry push-back.

Salience of market-wide information structure: As noted in the introduction, waste chain relationships can exhibit either single- or double-sided information asymmetry, and the prevalence of these relationship types may vary. At the same time, a given policy applies to the entire market and cannot be tailored to each waste chain relationship. Our analysis shows that the above recommendations deriving from the double-sided information asymmetry analysis are suitable in markets where single-sided information asymmetry are also present. The converse, however, is not necessarily true. Increasing penalties on treatment operators, a strategy that combats moral hazard or adverse selection in single-sided asymmetry relationships, can be less effective or even backfire under double-sided asymmetry. Therefore, in markets where regulators assess both market failures to be prevalent simultaneously, they should be particularly judicious in imposing these penalties.

Discussion of Limitations and Future Research. Policies like EPR state that producers must assume the responsibility to set up systems to ensure the proper management of their hazardous waste. The producer can designate third-parties like PROs or NGOs to act on their behalf. As this work focuses on upstream export and downstream dumping, we do not micromodel the specific agent deciding to export within that collective. Still, the complexity of the export chain is an interesting setting with oftentimes multiple agents involved. Future work could simplify the domestic market and instead capture potentially complex interactions between the agents involved in export (OEM, third-parties, brokers, etc).

The waste and operator characteristics are modeled as exogenous parameters as they depend on previous product design and facility technology investments. If these characteristics change (via producer product and process redesign or operator investment in treatment technology), the market characteristics and/or the agents' expectation about their channel partner would change accordingly. Although this may influence waste outcomes, our policy recommendations which focus on improving those outcomes continue to hold. Targeted incentives for producers to improve post-use recovery value or for operators to invest in treatment technology could however complement our recommendations. For instance, our sensitivity analyses show that a greater expected waste quality in the market and lower unit treatment cost let waste treatment emerge as a preferred strategy under more asymmetric export regulations. Thus, a potential future research area on this topic is the investigation of product design and technology investment incentives to uncover this potential complementarity.

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Appendix

A. Method

We solve the game depicted in Figure 1 using backward induction starting in period 3. When multiplicity arises, we select the Pareto efficient equilibrium, if it exists, and apply the undefeated equilibrium refinement by Mailath et al. (1993). The refinement requires beliefs about out-of-equilibrium actions to be valid only if those actions correspond to an alternative equilibrium. This refinement is appropriate for our setting with double-sided information asymmetry and a receiver (in addition to the sender) that can be of different types. For the interested reader, we refer to Bajaj (2018), Wang (2020). We use the following definition, adapted from Mailath et al. (1993):

Definition 1 (Undefeated Equilibrium). Equilibrium σ' is defeated if it coexists with another equilibrium σ and there exists a price p such that:

(D1.1) price p is off-equilibrium for σ' ($\forall j \in \{E, I\}$ $p'_j \neq p$) but on the equilibrium path of σ and chosen by operator type(s) in $K = \{j \in \{E, I\} | p_j = p\}$ (i.e., $K \neq \varnothing$).

(D1.2) the operator type(s) that play p in equilibrium σ are at least as well off and at least one is strictly better-off in equilibrium σ than in equilibrium σ': $\forall j \in K : E\Pi_j \geq E\Pi'_j$ and $\exists j \in K : E\Pi_j > E\Pi'_j$.

(D1.3) $\exists j_1 \in K$ s.t. producer's belief about operator type j_1 after observing price p ($i.e., Pr(j_1|p)$) in equilibrium σ' is different from the conditional probabilities $\frac{Pr(j_1)\alpha_{j_1}}{Pr(j_1)\alpha_{j_1} + Pr(j_2)\alpha_{j_2}}$ with $\{j_1, j_2\} = \{E, I\}$ and

$\alpha_j = 1$ if $j \in K$ and $E\Pi_j > E\Pi'_j$

$\alpha_j \in [0, 1]$ if $j \in K$ and $E\Pi_j = E\Pi'_j$

$\alpha_j = 0$ if $j \notin K$.

Consider equilibrium σ with prices (p_E, p_I) chosen by type E and I on the equilibrium path and (Π_E, Π_I) as their expected profits. If $p_E = p_I$, σ is a pooling equilibrium and otherwise a separating equilibrium. (p'_E, p'_I) and (Π'_E, Π'_I) are the prices and profits on the equilibrium path of σ'.

Lemma A.1. *When the producer has the worst off-equilibrium beliefs, i.e., the operator is type I, let's consider σ and σ' coexisting for a given set of parameters. If the following conditions are satisfied, then σ defeats σ':*

(a) $p_E \notin \{p'_E, p'_I\}$

(b) $\Pi_E > \Pi'_E$ *and, if* $p_E = p_I$, $\Pi_I \geq \Pi'_I$.

Proof Let K be the set of operator types which choose p_E in σ. When $p_E \neq p_I$, $K = \{E\}$ and, when $p_E = p_I$, $K = \{E, I\}$. Using Definition 1, we show when σ defeats σ'. (D1.1) Condition (a) and $K \neq \varnothing$ mean that p_E is off-equilibrium path in σ' with at least one type of operator playing p_E in σ. (D1.2) The first part of condition (b) means that the expected profit of E is greater in σ than in σ'. The second part means that if σ is pooling, i.e., I also plays price p_E in σ, then I is no worse-off in σ than in σ'. (D1.3) In σ', p_E is off-equilibrium path and thus the producer has the worst beliefs, i.e., the operator is of type I. This belief is different from the positive probability that type E selected p_E conditional on the operator's type $\in K$ (i.e., this probability is $\gamma/(\gamma + (1-\gamma)\alpha_I) > 0$ with $\alpha_I = 0$ if $I \notin K$, $\alpha_I = 1$ if $I \in K$ and $\Pi_I > \Pi'_I$, and $\alpha_I \in [0, 1]$ if $I \in K$ and $\Pi_I = \Pi'_I$).

B. Equilibrium Outcomes

We now solve the game under incomplete information using backward induction starting in period 3. A qualitative summary of the key results can be found in Table 5.

		Breakdown		**Partial Compliance**		**Full Compliance**	
		L	H	L	H	L	H
Waste Outcome	I	Dump/Export	Export	Dump/Export	Export	Treat	Treat
	E	Treat	Export	Treat	Treat	Treat	Treat
Price		pooling iff $D_L + (1-\gamma)\delta_L \leq s_L$ separating otherwise		separating		pooling	
Export policy		$s_L - s_H$ large		$s_L - s_H$ intermediate		$s_L - s_H$ small	
Domestic policy		δ_L small or D_L very large		$D_L + \delta_L$ small to intermediate		$D_L + \delta_L$ large	
EH		$(1-\gamma)(1-h)EH(\text{Dump}_L/\text{Export}_L)$ $+hEH(\text{Export}_H)$		$(1-\gamma)(1-h)EH(\text{Dump}_L/\text{Export}_L)$ $+(1-\gamma)hEH(\text{Export}_H)$		0	

Table 5 Summary of the results

We use the following endogenous off-equilibrium prices.

Period 3: When $\tilde{p} > p_H$, the operator believes $Pr[H|p_j \text{ accepted}] = 0$. If he is type I, he will then proceed to dump. When $\tilde{p} \leq p_H$, the operator believes $Pr[H|\tilde{p} \text{ accepted}] = h$ and if he is of type I, he then proceeds to treat. The profit maximising strategy of type E is to treat for any belief.

Period 2: Producer of type H rejects when $\tilde{p} > p_H$ and of type L rejects when $\tilde{p} > p_L$. The producer beliefs $\Pr[j = I|\tilde{p}]$=1 and, if she accepts $\tilde{p}$ at $t = 2$, $E\Pi_H(\text{Accept } \tilde{p}) = -\tilde{p} - \delta_H > E\Pi_L(\text{Accept } \tilde{p}) = -\tilde{p} - \delta_L$, while if she rejects $E\Pi_H(\text{Reject } \tilde{p}) = -s_H > E\Pi_L(\text{Reject } \tilde{p}) = -s_L$. Given $\delta_L - \delta_H \leq s_L - s_H$, it must be that if type H accepts, L accepts ($\tilde{p} \leq s_H - \delta_H < s_L - \delta_L$); and if L rejects, H rejects. It therefore must be that $p_H \leq p_L$.

Price $\tilde{p}$	Producer H	Producer L
$\tilde{p} \leq p_H \leq p_L$	$E\Pi(\text{Accept}) = -\tilde{p}$	$E\Pi(\text{Accept}) = -\tilde{p}$
$p_H < \tilde{p} \leq p_L$	$E\Pi(\text{Reject}) = -s_H$	$E\Pi(\text{Accept}) = -\tilde{p} - \delta_L$
$\tilde{p} > p_L$	$E\Pi(\text{Reject}) = -s_H$	$E\Pi(\text{Reject}) = -s_L$

Using the table, we can derive the conditions for the off-equilibrium prices: $H(\text{Accept iff } \tilde{p} \leq p_H)$ is true only if $\tilde{p} \leq s_H$ (to ensure $\tilde{p} \leq p_H$ is accepted) and $\tilde{p} \geq s_H - \delta_H$ (to ensure $\tilde{p} > p_H$ is rejected). $L(\text{Accept iff } \tilde{p} \leq p_L)$ is true only if $\tilde{p} \leq s_L$ (to ensure $\tilde{p} \leq p_H$ is accepted), $\tilde{p} \leq s_L - \delta_L$ (to ensure $p_H < \tilde{p} \leq p_L$ is accepted), and $\tilde{p} \geq s_L - \delta_L$ (to ensure $\tilde{p} > p_L$ is rejected). Thus, when $p_H < p_L$, it must be that $s_H - \delta_H \leq p_H \leq s_H$ and $p_L = s_L - \delta_L$. When $p_H = p_L$, it must be that $s_L - \delta_L \leq p_H = p_L \leq s_H$.

Before proving the results presented in the paper, we characterize the equilibria in a series of lemmas. Lemmas B.1 to B.5 derive the necessary and sufficient conditions for equilibrium existence. If several equilibria of the same type exist and condition (a) in Lemma A.1 holds, the undefeated equilibrium selects the one that yields the highest profit for the efficient treatment operator. Lemmas B.6 to B.14 give the necessary and sufficient conditions when there is multiplicity between equilibria of different types.

Lemma B.1. **Breakdown Equilibrium - weaker domestic enforcement (pooling):**

1. *Both operator types choose* p^* *in period 1.*
2. *In period 2, the beliefs are* $Pr[E|p^*] = \gamma$ *and* $Pr[E|\tilde{p}] = 0$ *for* $\tilde{p} \neq p^*$. *Only Producer* L *accepts* p^*. *If the price is* $\tilde{p} \neq p^*$, *both accept if* $\tilde{p} \leq p_H$, *both reject if* $\tilde{p} > p_L$, *and* H *rejects while* L *accepts if* $p_H < \tilde{p} \leq p_L$.

3. *In period 3, the beliefs are $Pr[H|p^*$ accepted$] = 0$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I dumps after p^*, but after $\tilde{p} \neq p^*$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p^* = s_L - (1-\gamma)\delta_L$, this equilibrium exists iff the following conditions are satisfied:

- $s_H - \delta_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$
- $D_L \leq s_L - (1-\gamma)\delta_L$

Proof **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p^*, Operator I believes $Pr[H|p_j \text{ accepted}] = 0$, he will then proceed to dump.

Period 2: If the price is p^*, Producer i believes $Pr[E|p^*] = \gamma$ and thus $E\pi_i(\text{Accept}) = -p^* - (1-\gamma)\delta_i$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p^* \leq s_i - (1-\gamma)\delta_i$ and rejects otherwise. Consequently, H rejects p^* and L accepts p^* iff $s_H - (1-\gamma)\delta_H < p^* \leq s_L - (1-\gamma)\delta_L$.

Period 1: For Operator E, setting p^* such that $s_H - (1-\gamma)\delta_H < p^* \leq s_L - (1-\gamma)\delta_L$ leads to $E\Pi_E = (1-h)(p^* + v_L - c_E)$, which cannot be smaller than the profits in any of the deviations:

- choosing $\tilde{p} \leq p_H$: $E\Pi_E = \tilde{p} + \overline{v} - c_E$,
- choosing $p_H < \tilde{p} \leq p_L$: $E\Pi_E = (1-h)(\tilde{p} + v_L - c_E)$,
- choosing $\tilde{p} > p_L$: $E\Pi_E = 0$.

For Operator I, setting p^* such that $s_H - (1-\gamma)\delta_H < p^* \leq s_L - (1-\gamma)\delta_L$ leads to $E\Pi_I = (1-h)(p^* - D_L)$, which cannot be smaller than the profits in any of the deviations:

- choosing $\tilde{p} \leq p_H$: $E\Pi_I = \tilde{p} + \overline{v} - c_I$,
- choosing $p_H < \tilde{p} \leq p_L$: $E\Pi_I = (1-h)(\tilde{p} - D_L)$,
- choosing $\tilde{p} > p_L$: $E\Pi_I = 0$.

Two cases emerge: $p_H < p_L$ and $p_H = p_L$. We take p_H and p_L as small as possible to relax the conditions. If there exists p^* and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad s_H - (1-\gamma)\delta_H < p^* \leq s_L - (1-\gamma)\delta_L$

1. $p^* \geq c_E - v_L$ to guarantee $E\Pi_E \geq 0$;
2. $p^* \geq D_L$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

3. $s_H - \delta_H \leq h(c_E - v_H) + (1-h)p^*$ otherwise E deviates to $p_H = s_H - \delta_H$;
4. $s_H - \delta_H \leq c_I - \overline{v} + (1-h)(p^* - D_L)$ otherwise I deviates to $p_H = s_H - \delta_H$;
5. $s_L - \delta_L \leq p^*$ otherwise E and I deviate to $p_L = s_L - \delta_L$.

$p_H = p_L$

3. $s_L - \delta_L \leq h(c_E - v_H) + (1-h)p^*$ otherwise E deviates to $p_H = s_L - \delta_L$;
4. $s_L - \delta_L \leq c_I - \overline{v} + (1-h)(p^* - D_L)$ otherwise I deviates to $p_H = s_L - \delta_L$;
5. $s_L - \delta_L \leq s_H$ to guarantee $s_L - \delta_L \leq p_H = p_L \leq s_H$.

The undefeated Breakdown equilibrium must have $p^* = s_L - (1-\gamma)\delta_L$. Using Lemma A.1, $\forall\, p' < s_L - (1-\gamma)\delta_L$ with $K = \{E, I\}$, $\Pi_E > \Pi'_E$ and $\Pi_I > \Pi'_I$. Condition (2) implies condition (1) per Assumption 1(i) $D_L \geq c_E - v_L$, and (3) implies (4) per Assumption 1(ii) $D_L < c_I - v_L$. The set of conditions for $p_H < p_L$ is binding.

LEMMA B.2. **Full Compliance Equilibrium (pooling)**

1. *Both operator types choose p^* in period 1.*
2. *In period 2, the beliefs are $Pr[E|p^*] = \gamma$ and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq p^*$. Both producer types accept p^*. If the price is $\tilde{p} \neq p^*$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p^*$ accepted$] = h$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I treats after p^*, but after $\tilde{p} \neq p^*$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p^* = s_H$, this equilibrium exists iff the following conditions are satisfied:

- $s_H \geq c_I - \overline{v}$
- $s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L)$ *when* $s_H < s_L - \delta_L$

Proof **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p^*, Operator I believes $Pr[H|p_j$ accepted$] = h$; he will then proceed to treat.

Period 2: If the price is p^*, Producer i believes $Pr[E|p^*] = \gamma$ and since both operator types treat in period 3, $E\pi_i(\text{Accept}) = -p^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p^* \leq s_i$ and rejects otherwise. Consequently, both producer types accept p^* iff $p^* \leq s_H$.

Period 1: For Operator E, setting p^* such that $p^* \leq s_H$ leads to $E\Pi_E = p^* + \overline{v} - c_E$. For Operator I, setting p^* such that $p^* \leq s_H$ leads to $E\Pi_I = p^* + \overline{v} - c_I$. These profits cannot be smaller than the profits in any of the deviations outlined in Lemma B.1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists p^* and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow \quad p^* \leq s_H$

1. $p^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;
2. $p^* \geq c_I - \overline{v}$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

3. $p^* \geq s_H - \delta_H$ otherwise E and I deviate to $p_H = s_H - \delta_H$;
4. $p^* \geq h(c_E - v_H) + (1-h)(s_L - \delta_L)$ otherwise E deviates to $p_L = s_L - \delta_L$;
5. $p^* \geq c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L)$ otherwise I deviates to $p_L = s_L - \delta_L$.

$p_H = p_L$

3. $p^* \geq s_L - \delta_L$ otherwise E and I deviate to $p_H = s_L - \delta_L$;
4. $s_L - \delta_L \leq s_H$ to guarantee $s_L - \delta_L \leq p_H = p_L \leq s_H$.

The undefeated Full Compliance equilibrium must have $p^* = s_H$. Using Lemma A.1, $\forall\ p' < s_H$ with $K = \{E, I\}$, $\Pi_E > \Pi'_E$ and $\Pi_I > \Pi'_I$. Condition (2) implies (1) since $c_E < c_I$ and for the case $p_H < p_L$, condition (5) implies (4) per Assumption 1(ii) $D_L > c_I - v_L$. Condition (3) always holds with the undefeated price.

Lemma B.3. **Partial Compliance Equilibrium - weak domestic enforcement (separating)**

1. *Operator types E and I choose p_E^* and p_I^* respectively in period 1.*
2. *In period 2, the beliefs are $Pr[E|p_E^*] = 1$, $Pr[E|p_I^*] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p_E^*, p_I^*)$. Producer H accepts p_E^* but rejects p_I^* and Producer L accepts both p_E^* and p_I^*. If the price is $\tilde{p} \neq (p_E^*, p_I^*)$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*

3. *In period 3, the beliefs are* $Pr[H|p_E^* \text{ accepted}] = h$, $Pr[H|p_I^* \text{ accepted}] = 0$, $Pr[H|\tilde{p} \text{ accepted}] = 0$ *if* $\tilde{p} > p_H$ *and* $Pr[H|\tilde{p} \text{ accepted}] = h$ *if* $\tilde{p} \leq p_H$. *Operator* E *always treats while* I *dumps after* p_I^*, *but after* $\tilde{p} \neq (p_E^*, p_I^*)$, I *dumps iff* $\tilde{p} > p_H$ *and treats otherwise.*

With $p_E^* = \min(s_H, c_I - \overline{v} + (1-h)(p_I^* - D_L))$ *and* $s_H - \delta_H \leq p_I^* \leq s_L - \delta_L$, *this equilibrium exists iff the following conditions are satisfied:*

- $p_E^* \geq s_H - \delta_H$
- $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta_L)$
- $p_I^* = s_L - \delta_L$ *when* $s_H < s_L - \delta_L$
- $p_I^* \geq D_L$

Proof **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_I^*, Operator I believes $Pr[H|p_j \text{ accepted}] = 0$; he will then proceed to dump. If the price is p_E^*, he believes the price is accepted by both producer types ($Pr[H|p_E \text{ accepted}] = h$), then he proceeds to treat.

Period 2: If the price is p_E^*, Producer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \leq s_i$ and rejects otherwise. Consequently, both producer types accept p_E^* iff $p_E^* \leq s_H$.

If the price is p_I^*, Producer i believes $Pr[E|p_I^*] = 0$ and thus $E\pi_i(\text{Accept}) = -p_I^* - \delta_i$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i - \delta_i$ and rejects otherwise. Consequently, H rejects p_I^* and L accepts p_I^* iff $s_H - \delta_H < p_I^* \leq s_L - \delta_L$.

Period 1: For Operator E, setting p_E^* such that $p_E^* \leq s_H$ leads to $E\Pi_E = p_E^* + \overline{v} - c_E$. For Operator I, setting p_I^* such that $s_H - \delta_H < p_I^* \leq s_L - \delta_L$ leads to $E\Pi_I = (1-h)(p_I^* - D_L)$. These profits cannot be smaller than the profits in any of the deviations outlined in in Lemma B.1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow$ $p_E^* \leq s_H$ and $s_H - \delta_H < p_I^* \leq s_L - \delta_L$

1. $p_E^* \geq h(c_E - v_H) + (1-h)p_I^*$ otherwise E deviates to $s_H - \delta_H < p_I^* \leq s_L - \delta_L$;
2. $p_E^* \geq c_E - \overline{v}$ to guarantee $E\Pi_E \geq 0$;
3. $p_E^* \leq c_I - \overline{v} + (1-h)(p_I^* - D_L)$ otherwise I deviates to $p_E^* \leq s_H$;
4. $p_I^* \geq D_L$ to guarantee $E\Pi_I \geq 0$;

$p_H < p_L$

5. $p_E^* \geq s_H - \delta_H$ otherwise E deviates to $p_H = s_H - \delta_H$;
6. $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta_L)$ otherwise E deviates to $\tilde{p} = s_L - \delta_L$;
7. $s_H - \delta_H \leq c_I - \overline{v} + (1-h)(p_I^* - D_L)$ otherwise I deviates to $p_H = s_H - \delta_H$;
8. $p_I^* \geq s_L - \delta_L$ otherwise I deviates to $p_L = s_L - \delta_L$.

$p_H = p_L$

5. $p_E^* \geq s_L - \delta_L$ otherwise E deviates to $p_H = s_L - \delta_L$;
6. $s_L - \delta_L \leq s_H$

The undefeated Partial Compliance equilibrium must have $p_E^* = \min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D_L)\}$. Using Lemma A.1, $\forall\ p' < \min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D_L)\}$ with $K = \{E\}$, $\Pi_E > \Pi'_E$. When $s_H < s_L - \delta_L$, there exists a single undefeated Partial Compliance equilibrium with $p_I^* = s_L - \delta_L$. Otherwise, there are multiple with $s_H - \delta_H \le p_I^* \le s_L - \delta_L$. Condition (2) is implied by condition (1), condition (4), and Assumption 1(i) $D_L \ge c_E - v_L$. For the case $p_H < p_L$, conditions (3) and (5) imply condition (7); and condition (6) is implied by conditions (1) and (8).

Lemma B.4. **Partial Compliance Equilibrium - strong domestic enforcement (separating)**

1. *Operator types E and I choose p_E^* and p_I^* respectively in period 1.*
2. *In period 2, the beliefs are $Pr[E|p_E^*] = 1$, $Pr[E|p_I^*] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p_E^*, p_I^*)$. Both producer types accept p_E^* and reject p_I^*. If the price is $\tilde{p} \neq (p_E^*, p_I^*)$, both accept if $\tilde{p} \le p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \le p_L$.*
3. *In period 3, the beliefs are $Pr[H|p_E^*$ accepted$] = h$ and $Pr[H|p_I^*$ accepted$] = 0$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \le p_H$. Operator E always treats while I does not receive any waste after p_I^*, but after $\tilde{p} \neq (p_E^*, p_I^*)$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*

With $p_E^* = \min(s_H, c_I - \overline{v})$ and $p_I^* > s_L - \delta_L$, this equilibrium exists iff the following conditions are satisfied:

- *$p_E^* \ge h(c_E - v_H) + (1-h)(s_L - \delta_L)$ when $s_H < s_L - \delta_L$*
- *$D_L \ge s_L - \delta_L$ when $s_H < s_L - \delta_L$*
- *$p_E^* \ge s_H - \delta_H$ when $s_H < s_L - \delta_L$*

Proof **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_E^*, Operator I believes $Pr[H|p_j \text{ accepted}] = h$; he will then proceed to treat. For p_I^* there can be two cases that lead to this equilibrium since I does not receive waste in equilibrium: (1) if beliefs are $Pr[H|p_I^* \text{ accepted}] = 0$, then Operator I proceeds to dump after p_I^*, and (2) if beliefs are $Pr[H|p_I^* \text{ accepted}] = h$, then Operator I treats after p_I^*.

Period 2: If the price is p_E^*, Producer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \le s_i$ and rejects otherwise. Consequently, both producer types accept p_E^* iff $p_E^* \le s_H$.

If the price is p_I^*, Producer i believes $Pr[E|p_I^*] = 0$. If (1) $E\pi_i(\text{Accept}) = -p_I^* - \delta_i$ and $E\pi_i(\text{Reject}) = -s_i$ then she accepts for $p_I^* \le s_i - \delta_i$ and rejects otherwise. If (2) $E\pi_i(\text{Accept}) = -p_I^*$ and $E\pi_i(\text{Reject}) = -s_i$ then she accepts for $p_I^* \le s_i$ and rejects otherwise. Consequently, both producer types reject p_I^* iff (1) $p_I^* > s_L - \delta_L$ or (2) $p_I^* > s_L$. We proceed with (1) without loss of generality.

Period 1: For Operator E, setting p_E^* such that $p_E^* \le s_H$ leads to $E\Pi_E = p_E^* + \overline{v} - c_E$. For Operator I, setting p_I^* such that $p_I^* > s_L - \delta_L$ or $p_I^* > s_L$ leads to $E\Pi_I = 0$. These profits cannot be smaller than the profits in any of the deviations outlined in Proposition 1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow$ $p_E^* \le s_H$ and $p_I^* > s_L - \delta_L$

1. $p_E^* \ge c_E - \overline{v}$ to guarantee $E\Pi_E \ge 0$;

2. $p_E^* \leq c_I - \overline{v}$ otherwise I deviates to $p_E^* \leq s_H$;

$p_H < p_L$

3. $p_E^* \geq s_H - \delta_H$ otherwise E deviates to $p_H = s_H - \delta_H$;
4. $s_H - \delta_H \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_H - \delta_H$;
5. $p_E^* \geq h(c_E - v_H) + (1-h)(s_L - \delta_L)$ otherwise E deviates to $p_L = s_L - \delta_L$;
6. $D \geq s_L - \delta_L$ otherwise I deviates to $p_L = s_L - \delta_L$.

$p_H = p_L$

3. $p_E^* \geq s_L - \delta_L$ otherwise E deviates to $p_H = s_L - \delta_L$;
4. $s_L - \delta_L \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_L - \delta_L$;
5. $s_H \geq s_L - \delta_L$ to guarantee $s_L - \delta_L \leq p_H = p_L \leq s_H$.

The undefeated Partial Compliance equilibrium must have $p_E^* = \min\{s_H, c_I - \overline{v}\}$ and any $p_I^* > s_L - \delta_L$ or $p_I^* > s_L$, depending on beliefs. Using Lemma A.1, $\forall\ p' < \min\{s_H, c_I - \overline{v}\}$ with $K = \{E\}$, $\Pi_E > \Pi_E'$.

Conditions (1) and (3) always hold and conditions (2) and (3) imply condition (4).

Lemma B.5. **Breakdown Equilibrium - strong domestic enforcement (separating)**

1. *Operator types E and I choose p_E^* and p_I^* respectively in period 1.*
2. *In period 2, the beliefs are $Pr[E|p_E^*] = 1$, $Pr[E|p_I^*] = 0$, and $Pr[E|\tilde{p}] = 0$ for $\tilde{p} \neq (p_E^*, p_I^*)$. Producer H rejects p_E^* and p_I^* while Producer L accepts p_E^* and rejects p_I^*. If the price is $\tilde{p} \neq (p_E^*, p_I^*)$, both accept if $\tilde{p} \leq p_H$, both reject if $\tilde{p} > p_L$, and H rejects while L accepts if $p_H < \tilde{p} \leq p_L$.*
3. *In period 3, the beliefs are $Pr[H|p_E^*$ accepted$] = 0$ and $Pr[H|p_I^*$ accepted$] = 0$, $Pr[H|\tilde{p}$ accepted$] = 0$ if $\tilde{p} > p_H$ and $Pr[H|\tilde{p}$ accepted$] = h$ if $\tilde{p} \leq p_H$. Operator E always treats while I does not receive any waste after p_I^*, but after $\tilde{p} \neq (p_E^*, p_I^*)$, I dumps iff $\tilde{p} > p_H$ and treats otherwise.*[8]

With $s_H < p_E^* = \min(D_L, s_L)$ and $p_I^* > s_L - \delta_L$, this equilibrium exists iff the following conditions are satisfied:

- $D_L \geq s_L - \delta_L$
- $s_H - \delta_H \leq h(c_E - v_H) + (1-h)p_E^*$

Proof **Period 3:** Regardless of waste quality, Operator E's profit maximizing strategy is to treat at $t = 3$. When the price is p_E^*, Operator I believes $Pr[H|p_E^*$ accepted$] = 0$, he will then proceed to dump. Since I does not receive waste in equilibrium, there can be two cases for p_I^* that lead to this equilibrium: (1) if beliefs are $Pr[H|p_I^*$ accepted$] = 0$, then Operator I proceeds to dump after p_I^*, and (2) if beliefs are $Pr[H|p_I^*$ accepted$] = h$, then Operator I proceeds to treat after p_I^*.

Period 2: If the price is p_E^*, Producer i believes $Pr[E|p_E^*] = 1$ and thus $E\pi_i(\text{Accept}) = -p_E^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_E^* \leq s_i$ and rejects otherwise. Consequently, only L accepts p_E^* iff $s_H < p_E^* \leq s_L$.

If the price is p_I^*, Producer i believes $Pr[E|p_I^*] = 0$. If (1) then $E\pi_i(\text{Accept}) = -p_I^* - \delta_i$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i - \delta_i$ and rejects otherwise. If (2) then $E\pi_i(\text{Accept}) = -p_I^*$ and $E\pi_i(\text{Reject}) = -s_i$. Hence, she accepts for $p_I^* \leq s_i$ and rejects otherwise. Consequently, H and L reject p_I^* iff (1) $p_I^* > s_L - \delta_L$ or (2) $p_I^* > s_L$. Without loss of generality, we proceed with (1).

[8] Same results hold for $Pr[H|p_I^*$ accepted$] = h$, but then I must set $p_I^* > s_L$ instead of $p_I^* > s_L - \delta_L$

Period 1: For Operator E, setting p_E^* such that $s_H < p_E^* \leq s_L$ leads to $E\Pi_E = (1-h)(p_E^* + v_L - c_E)$. For Operator I, setting p_I^* such that $p_I^* > s_L - \delta_L$ or $p_I^* > s_L$ leads to $E\Pi_I = 0$. These profits cannot be smaller than the profits in any of the deviations outlined in Proposition 1.

We take p_H and p_L as small as possible when $p_H < p_L$ and when $p_H = p_L$ to relax the conditions. If there exists $\{p_E^*, p_I^*\}$ and $\{p_H, p_L\}$ satisfying either set of conditions, this equilibrium exists:

$\rightarrow$ $s_H < p_E^* \leq s_L$ and $p_I^* > s_L - \delta_L$

1. $p_E^* \geq c_E - v_L$ to guarantee $E\Pi_E \geq 0$;
2. $p_E^* \leq D_L$ otherwise I deviates to p_E^*;

$p_H < p_L$

3. $s_H - \delta_H \leq h(c_E - v_H) + (1-h)p_E^*$ otherwise E deviates to $p_H = s_H - \delta_H$;
4. $s_H - \delta_H \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_H - \delta_H$;
5. $p_E^* \geq s_L - \delta_L$ otherwise E deviates to $p_L = s_L - \delta_L$;
6. $s_L - \delta_L \leq D_L$ otherwise I deviates to $p_L = s_L - \delta_L$.

$p_H = p_L$

3. $s_L - \delta_L \leq h(c_E - v_H) + (1-h)p_E^*$ otherwise E deviates to $p_H = s_L - \delta_L$;
4. $s_L - \delta_L \leq c_I - \overline{v}$ otherwise I deviates to $p_H = s_L - \delta_L$;
5. $s_L - \delta_L \leq s_H$ to guarantee $s_L - \delta_L \leq p_H = p_L \leq s_H$.

The undefeated Breakdown equilibrium must have $p_E^* = \min(D_L, s_L)$ and any $p_I^* > s_L - \delta_L$ or $p_I^* > s_L$, depending on beliefs. Using Lemma A.1, $\forall\ p' < \min\{D_L, s_L\}$ with $K = \{E\}$, $\Pi_E > \Pi_E'$.

For $p_H < p_L$, conditions (2) and (3) imply condition (4) per Assumption 1(i) $D_L \geq c_E - v_L$, and conditions (2) and (5) imply condition (6). After refinement, condition (1) always holds per Assumption 1(i) $D_L \geq c_E - v_L$ and Assumption 2(ii) $s_L \geq c_E - v_L$.

Equilibria selection in case of coexistence

When equilibria characterized in Lemmas B.1-B.5 coexist, we select the Pareto efficient equilibrium (if it exists) and apply the undefeated equilibrium refinement.

LEMMA B.6. **Full Compliance vs Partial Compliance (weak)** *When the equilibria coexist, Partial Compliance per Lemma B.3 is defeated when (FC) holds and multiplicity remains when (FC) does not hold. As such, $p_E^* = s_H$ is the undefeated price in Partial Compliance.*

Proof Using Lemma A.1, let σ be a Partial Compliance equilibrium and σ' a Full Compliance equilibrium with $p'^* < p_E^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi_E' = p'^* + \overline{v} - c_E$, i.e., $p_E^* > p'^*$. Using the undefeated prices per Lemmas B.2 and B.3, Full Compliance defeats Partial Compliance in coexistence when $\min\{s_H, c_I - \overline{v} + (1-h)(p_I^* - D_L)\} > s_H$ which can never happen. Now let σ be a Full Compliance equilibrium and σ' a Partial Compliance equilibrium with $p^* > {p_E'}^*$ and $p^* \neq {p_I'}^*$ (satisfying (a)). σ defeats σ' in coexistence when $\Pi_E = p^* + \overline{v} - c_E > \Pi_E' = {p_E'}^* + \overline{v} - c_E$, i.e., ${p_E'}^* < p^*$, and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi_I' = (1-h)({p_I'}^* - D_L)$, i.e., $p^* \geq c_I - \overline{v} + (1-h)({p_I'}^* - D_L)$. Using the undefeated prices, Full Compliance always defeats Partial Compliance when

$$s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L). \tag{FC}$$

When (FC) does not hold, multiplicity may remain. Specifically, for $s_H \geq s_L - \delta_L$, there is multiplicity between Full Compliance and several Partial Compliance equilibria (see Lemma B.3).
In the knife-edge case $s_H = c_I - \overline{v} + (1-h)(p_I^* - D_L)$, both are undefeated but Full Compliance Pareto dominates. The operator is indifferent regardless of type. If the producer is of type H, she is indifferent as $p^* = {p'_E}^*$. If the producer is of type L, she prefers Full Compliance as in Partial Compliance she can get matched with the more costly Operator I.

Lemma B.7. **Full Compliance vs Partial Compliance (strong)** *When the equilibria coexist, Partial Compliance per Lemma B.4 is defeated when $s_H \geq c_I - \overline{v}$. As such, $p_E^* = s_H$ is the undefeated price in Partial Compliance.*

Proof Let σ be a Partial Compliance equilibrium and σ' a Full Compliance equilibrium with $p'^* > p_E^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $p_E^* > p'^*$. Using the undefeated prices per Lemmas B.2 and B.3, Full Compliance defeats Partial Compliance in coexistence when $\min\{s_H, c_I - \overline{v}\} > s_H$ which can never happen. Now let σ be a Full Compliance equilibrium and σ' a Partial Compliance equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = {p'_E}^* + \overline{v} - c_E$, i.e., ${p'_E}^* < p^*$, and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = 0$, i.e., $p^* \geq c_I - \overline{v}$. Using the undefeated prices, Full Compliance defeats Partial Compliance in coexistence when $s_H > c_I - \overline{v}$. In the knife-edge case $s_H = c_I - \overline{v}$, both are undefeated but Full Compliance is efficient for the same reason as in Lemma B.6.

Lemma B.8. **Full Compliance vs Breakdown (weak)** *When the equilibria coexist, Full Compliance per Lemma B.2 is defeated when $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$ and Breakdown per Lemma B.1 when $s_H \geq c_I - \overline{v} + (1-h)(s_L - (1-\gamma)\delta_L$.*

Proof Let σ be a Breakdown equilibrium and σ' a Full Compliance equilibrium with $p^* > p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = p'^* + \overline{v} - c_E$, i.e., $p'^* < h(c_E - v_H) + (1-h)p^*$ and $\Pi_I = (1-h)(p^* - D_L) \geq \Pi'_I = p'^* + \overline{v} - c_I$. The first condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas B.1 and B.2, Breakdown defeats Full Compliance in coexistence when $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$. Now, let σ be a Full Compliance equilibrium and σ' a Breakdown equilibrium with $p^* \notin p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$ and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = (1-h)(p'^* - D_L)$. The second condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas B.1 and B.2, Full Compliance defeats Breakdown in coexistence when $s_H \geq c_I - \overline{v} + (1-h)(s_L - (1-\gamma)\delta_L$.

Lemma B.9. **Full Compliance vs Breakdown (strong)** *When the equilibria coexist, Full Compliance per Lemma B.2 defeats Breakdown per Lemma B.5.*

Proof Let σ be a Full Compliance equilibrium and σ' a Breakdown equilibrium with $p^* \neq {p'_E}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^* + \overline{v} - c_E > \Pi'_E = (1-h)({p'_E}^* + v_L - c_E)$, i.e., $p^* > h(c_E - v_H) + (1-h){p'_E}^*$ and $\Pi_I = p^* + \overline{v} - c_I \geq \Pi'_I = 0$. The second condition is binding per Assumption 1(ii). Using the undefeated prices per Lemmas B.1 and B.2, Full Compliance defeats Breakdown when $s_H \geq c_I - \overline{v}$, which is whenever Full Compliance exists. Note that this condition is non-binding for Breakdown to be undefeated due to the (Bd-s) condition (to be discussed). We let

$$s_H \geq c_I - \overline{v}. \tag{FC-s}$$

Lemma B.10. **Partial Compliance (weak) vs Breakdown (weak)** *When the equilibria coexist, Partial Compliance per Lemma B.3 is defeated when (Bd) holds and Breakdown per Lemma B.1 otherwise.*

Proof Let σ be a Breakdown equilibrium and σ' a Partial Compliance equilibrium with $p^* > {p'_E}^*$ and $p^* > {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = {p'_E}^* + \overline{v} - c_E$, i.e., ${p'_E}^* < h(c_E - v_H) + (1-h)p^*$ and $\Pi_I = (1-h)(p^* - D_L) \geq \Pi'_I = (1-h)({p'_I}^* - D_L)$. Using the undefeated prices per Lemmas B.1, B.3, and B.6, the latter restriction is always satisfied and thus Breakdown defeats Partial Compliance in coexistence when $s_H < h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p^*_E \notin p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = {p'_E}^* + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$. Using the undefeated prices, Partial Compliance defeats Breakdown in coexistence when (Bd) does not hold and $D_L \leq s_L - \delta_L$. We break the equality in the knife-edge case $s_H = h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$ in favor of the preference of I, given that E is indifferent. Let

$$s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L). \tag{Bd}$$

Lemma B.11. **Partial Compliance (weak) vs Partial Compliance (strong)** *When the equilibria coexist, Partial Compliance per Lemma B.3 is efficient when $D_L \leq s_L - \delta_L$.*

Proof Since the undefeated p^*_E is the same in these equilibria, neither is defeated. Using Pareto efficiency, we find that for $D_L < s_L - \delta_L$, operator of type I strictly prefers Partial Compliance (weak) and all other agents are indifferent. For $D_L = s_L - \delta_L$, all agents are indifferent. From a global welfare standpoint, it can be argued that dumping of waste L in the country of origin is preferred over export. Let

$$D_L \leq s_L - \delta_L. \tag{1}$$

Lemma B.12. **Breakdown (weak) vs Breakdown (strong)** *When the equilibria coexist, Breakdown per Lemma B.5 is defeated when $D_L \leq s_L - (1-\gamma)\delta_L$.*

Proof Let σ be a Breakdown (weak) equilibrium and σ' a Breakdown (strong) equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = (1-h)({p'_E}^* + v_L - c_E)$ and $\Pi_I = (1-h)(p^* - D_L) \geq \Pi'_I = 0$. Using the undefeated prices per Lemmas B.1 and B.5 Breakdown (weak) defeats Breakdown (strong) in coexistence when $D_L < s_L - (1-\gamma)\delta_L$. For $D = (1-\gamma)\delta_L$, Breakdown (weak) is efficient due to producer L's preference and the indifference of the other agents. Let

$$D_L \leq s_L - (1-\gamma)\delta_L. \tag{2}$$

Lemma B.13. **Breakdown (weak) vs Partial Compliance (strong)** *When the equilibria coexist, Partial Compliance is defeated when (Bd) holds and Breakdown is defeated otherwise.*

Proof Let σ be a Breakdown (weak) equilibrium and σ' a Partial Compliance (strong) equilibrium with $p^* > {p'_E}^*$ and $p^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p^* + v_L - c_E) > \Pi'_E = {p'_E}^* + \overline{v} - c_E$ and $\Pi_I = (1-h)(p^* - D_L) \geq \Pi'_I = 0$. Using the undefeated prices per Lemmas B.1, B.4, and B.7 Breakdown defeats Partial Compliance in coexistence when (Bd) holds. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p^*_E \neq p'^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p^*_E + \overline{v} - c_E > \Pi'_E = (1-h)(p'^* + v_L - c_E)$, or when (Bd) does not hold. We break the equality in the knife-edge case $s_H = h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$ in favor of the preference of I, given that E is indifferent.

Lemma B.14. **Partial Compliance (strong) vs Breakdown (strong)** *When the equilibria coexist, Breakdown per Lemma B.5 is defeated when $s_H \geq h(c_E - v_H) + (1-h)\min\{D_L, s_L\}$ and Partial Compliance is defeated otherwise.*

Proof Let σ be a Breakdown (strong) equilibrium and σ' a Partial Compliance (strong) equilibrium with $p_E^* > {p'_E}^*$ and $p_E^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = (1-h)(p_E^* + v_L - c_E) > \Pi'_E = {p'_E}^* + \overline{v} - c_E$. Using the undefeated prices per Lemmas B.5, B.4, and B.7 Breakdown defeats Partial Compliance when $s_H < h(c_E - v_H) + (1-h)\min\{D_L, s_L\}$. Now, let σ be a Partial Compliance equilibrium and σ' a Breakdown equilibrium with $p_E^* \neq {p'_E}^*$ and $p_E^* \neq {p'_I}^*$ (satisfying (a)). σ defeats σ' when $\Pi_E = p_E^* + \overline{v} - c_E > \Pi'_E = (1-h)({p'_E}^* + v_L - c_E)$. In the knife-edge case $s_H = h(c_E - v_H) + (1-h)\min\{D_L, s_L\}$ Partial Compliance is efficient given the preference of producer L and indifference of the other agents. Let

$$s_H < h(c_E - v_H) + (1-h)\min\{D_L, s_L\}. \tag{Bd-s}$$

Proof of Proposition 1:

Proof Combining Lemmas B.1, B.8, B.10, B.13 and B.12 gives the following conditions for Breakdown (weak) to be the undefeated equilibrium (and efficient if it exists) when $D_L \leq s_L - \delta_L$:

- (Bd) holds: $s_H \leq h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$
- with $p^* = s_L - (1-\gamma)\delta_L$

Proof of Proposition 2:

Proof Combining Lemmas B.2, B.6, B.7, B.8, and B.9 give the following conditions for Full Compliance to be the undefeated equilibrium (and efficient if it exists) when $D_L \leq s_L - \delta_L$:

- (FC) holds: $s_H \geq c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L)$
- (Bd) does not hold: $s_H > h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$
- with $p^* = s_H$

Full Compliance is *an* undefeated equilibrium when $s_H \geq s_L - \delta_L$, $s_H \geq c_I - \overline{v}$, (FC) does not hold, and (Bd) does not hold (with $p^* = s_H$).

Proof of Proposition 3:

Proof Combining Lemmas B.3, B.6, B.10, and B.11 give the following conditions for Partial Compliance to be the unique undefeated (and efficient if it exists) equilibrium when $D_L \leq s_L - \delta_L$:

- $s_H < s_L - \delta_L$
- (FC) does not hold: $s_H < c_I - \overline{v} + (1-h)(s_L - \delta_L - D_L)$
- (Bd) does not hold: $s_H > h(c_E - v_H) + (1-h)(s_L - (1-\gamma)\delta_L)$
- with $p_E^* = s_H$ and $p_I^* = s_L - \delta_L$

Partial Compliance is *an* undefeated equilibrium when $s_H \geq s_L - \delta_L$, (FC) does not hold, and (Bd) does not hold (with $p_E^* = s_H$ and $\min(D_L, s_H - \delta_H) < p_I^* \leq s_L - \delta_L$).

Proposition B.1. *For $D_L + \delta_L > s_L$ and $D_L + (1-\gamma)\delta_L < s_L$:*

(i) the conditions for the Breakdown equilibrium are unchanged.

(ii) Full Compliance is the unique equilibrium iff $s_H \geq c_I - \overline{v}$ and ($\neg$ Bd), in which case both operator types

set $p^* = s_H$ *and treat all waste.*

(iii) Partial Compliance is the unique equilibrium iff $s_H < c_I - \overline{v}$ *and (*$\neg$ *Bd), in which case Operator I sets* $p_I^* > s_L - \delta_L$ *and receives no waste, and Operator E sets* $p_E^* = s_H$ *and treats all waste.*

Proof By combining Lemmas B.1, B.2, B.4, B.7, B.8, B.11, and B.13 for $s_L - \delta_L < D_L \le s_L - (1-\gamma)\delta_L$ the above conditions emerge.

Proposition B.2. *Under* $D_L + (1-\gamma)\delta_L \ge s_L$*,*

(i) Breakdown is the unique equilibrium iff (Bd-s) holds, in which case Operator I sets $p_I^* > s_L - \delta_L$ *and receives no waste, and Operator E sets* $p_E^* = \min\{D_L, s_L\}$ *and treats waste L.*

(ii) Full Compliance is the unique equilibrium iff $s_H \ge c_I - \overline{v}$*, automatically satisfying (*$\neg$ *Bd-s).*

(iii) Partial Compliance is the unique equilibrium iff $s_H < c_I - \overline{v}$ *and (*$\neg$ *Bd-s), in which case Operator I sets* $p_I^* > s_L - \delta_L$ *and receives no waste, and Operator E sets* $p_E^* = s_H$ *and treats all waste.*

Proof By combining Lemmas B.2, B.4, B.5, B.7, B.9, B.12, and B.14 for $D_L > s_L - (1-\gamma)\delta_L$ the above conditions emerge.

C. Alignment between Environment Harm and Waste chain profits

We compute the ex-ante expected values of environmental harm and waste chain profit and define alignment conditions based on whether reductions in environmental harm, achieved through a specific policy lever, also has the potential to improve waste chain profits.

Environmental Harm: We assume that the environmental harm EH of proper treatment is less than of dumping or export, $EH(\text{Treat}) < EH(\text{Dump or Treat})$, and normalize it to zero, $EH(\text{Treat}) = 0$.

1. Breakdown $D_L + \delta_L < s_L - (1-\gamma)\delta_L$ (Prop 1, B.1): $EH_{BD} = (1-\gamma)(1-h)EH(\text{Dump}_L) + hEH(\text{Export}_H)$
2. Full Compliance (Proposition 2): $EH_{FC} = 0$
3. Partial Compliance $D_L + \delta_L \le s_L - \delta_L$ (Prop 3): $EH_{PC} = (1-\gamma)(hEH(\text{Export}_H) + (1-h)EH(\text{Dump}_L))$
4. Partial Compliance $D_L + \delta_L > s_L - \delta_L$ (Prop B.1): $EH_{PC} = (1-\gamma)(hEH(\text{Export}_H) + (1-h)EH(\text{Export}_L))$
5. Breakdown $D_L + \delta_L \ge s_L - (1-\gamma)\delta_L$ (Prop B.2): $EH_{BD} = (1-\gamma)(1-h)EH(\text{Export}_L) + hEH(\text{Export}_H)$

As an example, item 1. can be interpreted as follows: in Breakdown under weak domestic enforcements, environmental harm is the probability of the $\{I, L\}$ dyad emerging times the harm of dumping L, plus the probability of a dyad with H emerging times the harm of exporting H. As such, $EH_{FC} < EH_{PC} < EH_{BD}$.

Waste Chain Profits: Waste chain profit Π_{WC} is the sum of the operator and producer's expected profits. As such, the price paid to the operator by the producer thus cancels out when analyzing the profits at the supply chain level. We can derive the following profits:

Alignment conditions: With $EH_{FC} < EH_{PC} < EH_{BD}$, for alignment we need $\Pi_{FC}^{WC} \ge \Pi_{PC}^{WC} \ge \Pi_{BD}^{WC}$. We find the following, derived from Table 6:

Corollary 5. *When an increase in* s_L *creates a move from Partial Compliance to Breakdown, EH and* Π^{WC} *deteriorate (**A1**).*

Breakdown	under $D_L + (1-\gamma)\delta_L \le s_L$	$\Pi^{WC}_{BD} = \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)(D_L + \delta_L) - hs_H$
	under $D_L + (1-\gamma)\delta_L > s_L$	$\Pi^{WC}_{BD} = \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)s_L - hs_H$
Partial Compliance	under $D_L + \delta_L \le s_L$	$\Pi^{WC}_{PC} = \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)s_L - (1-\gamma)hs_H + \gamma h(v_H - c_E)$
	under $D_L + \delta_L > s_L$	$\Pi^{WC}_{PC} = \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)s_L - (1-\gamma)hs_H + \gamma h(v_H - c_E)$
Full Compliance		$\Pi^{WC}_{FC} = \overline{v} - \gamma c_E - (1-\gamma)c_I$

*When an increase in s_H creates a move from Breakdown to Partial Compliance, Π^{WC} improves iff the change Δs_H is not too large relative to the benefit of E treating H (**A1**). When Δs_H creates a move to Full Compliance, Π^{WC} improves iff the potential cost of I treating L is not too high relative to the benefit of avoiding dumping or export, plus the benefit of E treating H and/or I treating H (**A2**).*

*When an increase in δ_L creates a move from Breakdown to Partial Compliance in $D_L + \delta_L \le s_L$, Π^{WC} improves iff $\Delta\delta_L$ is not too large relative to the benefit of E treating H. When $\Delta\delta_L$ creates a move from Breakdown to Partial Compliance in $D_L + (1-\gamma)\delta_L < s_L < D_L + \delta_L$, Π^{WC} always improves (**A1**). When $\Delta\delta_L$ creates a move to Full Compliance, Π^{WC} improves iff the cost of I treating L is not too high relative to the benefit of avoiding dumping or export, plus the benefit of E treating H and/or I treating H (**A2**).*

*When an increase in D_L creates a move from Partial to Full Compliance ($D_L + \delta_L \le s_L$), Π^{WC} improves iff the potential cost of I treating L is not too high relative to the benefit of avoiding dumping, plus the benefit of I treating H (**A2**). However, when ΔD_L creates a move from Partial Compliance to Breakdown ($D_L + (1-\gamma)\delta_L \ge s_L$), EH and Π^{WC} always deteriorate (**A1**). As such, increasing D_L can backfire.*

Proof: Let policy measure $\Delta x = x^t - x^{t-1}$ attain an equilibrium change, then for alignment we need $\Pi^{WC}_{PC}(x^t) \ge \Pi^{WC}_{BD}(x^{t-1})$, $\Pi^{WC}_{FC}(x^t) \ge \Pi^{WC}_{PC}(x^{t-1})$, and $\Pi^{WC}_{FC}(x^t) \ge \Pi^{WC}_{BD}(x^{t-1})$. Taking $\Pi^{WC}_{PC}(x^t) \ge \Pi^{WC}_{BD}(x^{t-1})$ as an example, we can derive the condition by solving the inequality $\gamma(\overline{v} - c_E) - (1-\gamma)(1-h)(D+\delta) - (1-\gamma)hs^t_H \ge \gamma(1-h)(v_L - c_E) - (1-\gamma)(1-h)(D+\delta) - hs^{t-1}_H$, or $(1-\gamma)h\Delta s_H \le \gamma h(v_H - c_E + s^{t-1}_H)$, or $\Delta s_H \le \frac{\gamma}{(1-\gamma)}(s^{t-1}_H + v_H - c_E)$. Intuitively, as Δs_H triggers a switch from Breakdown to Partial Compliance, profits increase by $\gamma h(s^{t-1}_H + v_H - c_E)$ as H is treated instead of exported in the $\{E, H\}$ dyad. However, H continues to be exported in the $\{I, H\}$ dyad in Partial Compliance, which becomes more costly, so profits decrease by $(1-\gamma)h\Delta s_H$.

In Table 6, we list the conditions for which a reduction in environmental harm coincides with an increase in waste chain profits. We denote Δx in the first column as an increase in the policy measures s_L, s_H, δ_L, and D_L that trigger an equilibrium switch. The second column lists the conditions for which waste chain profits increase when switching from Breakdown to Partial Compliance (**A1**), the third from Partial Compliance to Full Compliance (**A2**), and the last from Breakdown to Full Compliance (**A3**). N/A denotes that the policy measure cannot generate the equilibrium switch. A negative Δx denotes a backfiring effect: an increase in that policy measure would result in a reverse switch, increasing environmental harm. For example, in (**A1**) under $D_L + \delta_L \le s_L$, an increase in s_L can only cause a switch from Partial Compliance ($\neg$Bd), ($\neg$FC) to Breakdown (Bd). Waste chain profits would strictly suffer from this switch as the increase in export of H is costlier to the supply chain than treatment: $s_H \ge c_E - v_H$.

	Breakdown → Partial Compliance **A1:** $\Pi^{WC}_{BD} \leq \Pi^{WC}_{PC}$	Partial → Full Compliance **A2:** $\Pi^{WC}_{PC} \leq \Pi^{WC}_{FC}$	Breakdown → Full Compliance **A3:** $\Pi^{WC}_{BD} \leq \Pi^{WC}_{FC}$
$D_L + \delta_L \leq s_L$			
	(Bd) → (¬Bd), (¬FC)	(¬Bd), (¬FC) → (¬Bd), (FC)	(Bd)→ (¬Bd), (FC)
$-\Delta s_L$	always true: $s_H \geq c_E - v_H$	$\left\{ \begin{array}{c} h(v_H - c_I + s_H^{t-1}) + \\ (1-h)(D_L^{t-1} + \delta_L^{t-1} + v_L - c_I) \\ \geq 0 \end{array} \right.$	$\left\{ \begin{array}{c} (1-\gamma)h(v_H - c_I + s_H^{t-1}) + \\ (1-\gamma)(1-h)(D_L + \delta_L^{t-1} + v_L - c_I) \\ +\gamma h(v_H - c_E + s_H^{t-1}) \geq 0 \end{array} \right.$
Δs_H	$\Delta s_H \leq \frac{\gamma}{(1-\gamma)}(v_H - c_E + s_H^{t-1})$		
$\Delta \delta_L$	$\Delta \delta_L \leq \frac{\gamma h(v_H - c_E + s_H)}{(1-h)(1-\gamma)}$		
ΔD_L	N/A		N/A
$D_L + (1-\gamma)\delta_L < s_L < D_L + \delta_L$			
	(Bd) → (¬Bd), (¬FC-s)	(¬Bd), (¬FC-s) → (¬Bd), (FC-s)	(Bd)→ (¬Bd), (FC-s)
$-\Delta s_L$	always true: $D_L + \delta_L > s_L^{t-1}$	N/A	$\left\{ \begin{array}{c} (1-\gamma)h(v_H - c_I + s_H^{t-1}) + \\ (1-\gamma)(1-h)(D_L + \delta_L^{t-1} + v_L - c_I) \\ +\gamma h(v_H - c_E + s_H^{t-1}) \geq 0 \end{array} \right.$
Δs_H	$\Delta s_H \leq \frac{\gamma}{(1-\gamma)}(v_H - c_E + s_H^{t-1}) +$ $\frac{(1-h)}{h}(D_L + \delta_L - s_L)$	$(1-\gamma)h(v_H - c_I + s_H^{t-1}) +$ $(1-\gamma)(1-h)(s_L + v_L - c_I) \geq 0$	
$\Delta \delta_L$	always true: $\gamma h(v_H - c_E + s_H) +$ $(1-\gamma)(1-h)(D_L + \delta_L^{t-1} - s_L) \geq 0$	N/A	
ΔD_L	N/A	N/A	N/A
$D_L + (1-\gamma)\delta_L \geq s_L$			
	(Bd-s) → (¬Bd-s), (¬FC-s)	(¬Bd-s), (¬FC-s) → (FC-s)	
$-\Delta s_L$	always true: $-\Delta s_L \leq 0$	N/A	
Δs_H	$\Delta s_H \leq \frac{\gamma}{(1-\gamma)}(v_H - c_E + s_H^{t-1})$	$(1-\gamma)h(v_H - c_I + s_H^{t-1}) +$ $(1-\gamma)(1-h)(s_L + v_L - c_I) \geq 0$	
$\Delta \delta_L$	N/A	N/A	
$-\Delta D_L$	always true: $\gamma h(v_H - c_E + s_H) \geq 0$	N/A	

Table 6 Alignment conditions

Note: Some changes in policy measures are considered < 0. For these, an increase in stringency would backfire and create a reverse switch (i.e., from Partial Compliance to Breakdown).

Contrasting s_H and δ_L: In most cases, both s_H and δ_L can create a move from Breakdown to Partial Compliance. However, waste chain profits always improve for $\Delta\delta_L$ under $D + (1-\gamma)\delta_L < s_L < D_L + \delta_L$. Improvement in profits is more likely for $\Delta\delta_L$ than s_H under $D_L + \delta_L \leq s_L$ if $h > 0.5$. In most cases, only s_H can create a move from Partial to Full Compliance, except when $D_L + \delta_L \leq s_L$. Moving from Breakdown to Partial Compliance through δ_L can be less likely to undermine local waste chains, whereas moving from Partial to Full Compliance can be more effective using s_H.