Measuring Scope 3 Emissions: What are the Costs and Benefits?*

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Abstract

We adopt a financial-materiality approach in studying the costs and benefits of measuring Scope 3 emissions. Production by firms internally generates direct greenhouse gas emissions (Scope 1 emissions) while outsourcing to suppliers generates indirect emissions (Scope 3 emissions). Our analysis incorporates two frictions: 1) long-term negative environmental externalities caused by emissions, and 2) fragmentation in regulating emissions disclosures across jurisdictions. We show firms' failure to internalize the environmental externalities provides a rationale for mandating Scopes 1 and 3 emissions disclosures. However, such disclosures induce emissions leakage. Disciplining emissions leakage calls for setting complementary–rather than independent–disclosure requirements for Scopes 1 and 3 emissions. Our analysis underscores the importance of improving the reliability of Scope 3 emissions measurements given that measurements of Scope 1 emissions are highly reliable for public firms in Europe and the United States. Regulators can further enhance the disciplinary effects of Scope 3 emissions measurements by requiring the allocations of Scope 3 emissions in supply chains to individual firms, especially when allocating Scope 3 emissions is more reliable, and for firms/industries that are more prone to transition climate risk relative to physical climate risk.

Keywords: Scope 3 Emissions; Scope 1 Emissions; Financial Materiality; Environmental Externalities; Climate-Related Disclosures; Climate Risks; Physical Risk; Transition Risk; Greenhouse Gas Emissions; Direct and Indirect Emissions; Market Discipline; Real Effects.

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1 Introduction

Regulators and standard setters around the world have developed climate-related reporting requirements and standards to combat climate change.[1] The rationale for mandatory disclosure of climate-related information is that such information is financially material and influences investors' assessment of firms' future cash flows and thus the pricing of firms. Market pricing of climate-related risks would, in turn, rein in firms' polluting behavior.[2] Even though such a rationale seems compelling, mandatory disclosure of climate-related risks has been controversial.[3] First, given that many firms already voluntarily disclose such information in their financial statements, the net benefits of mandatory disclosures are unclear. Second, given that measurement of climate-related risks is unreliable, mandatory disclosures could hinder rather than improve market discipline.[4] Third, given fragmented regulation in climate reporting, mandatory disclosures could cause greenhouse gas (GHG) emissions leakage by inducing firms to outsource their production from jurisdictions with stringent measurement and disclosure policies, to jurisdictions with more lenient policies.[5] To explore these issues, we develop an economic framework to study the costs and benefits of measuring and disclosing GHG emissions.

In our framework, firms set their production plans either by producing internally or by outsourcing production to a foreign supplier.[6] The production technology pollutes the environment: each firm's production generates *direct* GHG emissions (Scope 1 emissions) if it produces internally and generates *indirect* GHG emissions (Scope 3 emissions) if it outsources production to the sup-

[1] U.S. Securities and Exchange Commission, "The Enhancement and Standardization of Climate-Related Disclosures for Investors" (SEC, 2024); International Sustainability Standards Board (ISSB), "Press Release: ISSB issues inaugural global sustainability disclosure standards," June 26, 2023; and European Financial Reporting Advisory Group (EFRAG), "Press Release: EFRAG Launches a Public Consultation on the Draft ESRS EDs," April 29, 2022.

[2] See e.g., Fama (2020) who argues that market forces discipline "dirty" firms via lower stock prices. Such lower prices, in turn, provide incentives to firms to become "clean" and, hence, be rewarded via higher prices.

[3] This is particularly true in the United States where the SEC's final climate rule (SEC, 2024) issued on March 6, 2024 is facing numerous lawsuits challenging the climate rule on various grounds. On April 4, 2024, the SEC voluntarily stayed implementation of the Climate Rules pending completion of judicial review of the consolidated Eighth Circuit petitions.

[4] A controversial aspect of climate-related disclosures is the disclosure of indirect emissions (Scope 3 emissions) in a company's value chains beyond the company's direct control, given the complexities involved in tracking and reporting this information, and the inherent difficulty in allocating indirect emissions to individual firms that share common upstream and downstream activities.

[5] Arguably, the concerns of emissions leakage serve as a rationale for other climate policies besides reporting policies, such as the Carbon Border Adjustment Mechanism recently introduced in the European Union (EU).

[6] As we discuss later, our setting may also be interpreted as one in which the firms who produce internally are publicly-traded firms while their supplier is a privately-held firm subject to less stringent regulation.

plier.[7] To capture measurement errors inherent in allocating indirect emissions in a firm's value chains beyond the firm's direct control, we assume that the firms share a common supplier. Each firm's production plan generates short-term profits but results in long-term losses due to rising climate risk from emissions. We capture firms' exposures to both *transition and physical climate risks*. Physical climate risk results from climatic events, such as wildfires, storms, and floods, that disrupt production facilities. The source of physical climate risk arises from longer-term shifts in climate patterns (e.g., sustained higher temperatures), and such risk is more likely to be driven by the total emissions by all firms operating in the economy, rather than emissions by any single enterprise. Conversely, transition climate risk is caused by the financial impact on firms transitioning to a low-carbon economy, such as changes in environmental policies, shifts in public preferences, and technological adaptations. Arguably, the source of the transition climate risk likely depends more on firms' own environmental footprints, compared to the source of the physical climate risk.

Our framework incorporates two frictions. First, because the level of physical climate risk is driven by the total emissions by all firms, our model features environmental externalities that greater productions and pollutions from other firms impair any individual firm's value. Environmental externalities play a central role in our framework as they provide a rationale for regulating emissions disclosures. Second, regulation over emissions reporting is currently fragmented across jurisdictions.[8] We capture such regulatory fragmentation by assuming that–while a regulator is able to impose requirements on measuring direct emissions from firms' productions in its own jurisdiction–the regulator is restricted from regulating measurements of indirect emissions from the supplier's production outside its jurisdiction. Arguably, fragmented climate-related reporting landscape is a key driving force behind the phenomenon of emissions leakage, which is a main focus

[7] In practice, the Greenhouse Gas Protocol defines Scope 1 emissions as " direct GHG emissions that occur from sources owned or controlled by the company," Scope 2 emissions as "those emissions primarily resulting from the generation of electricity purchased and consumed by the company," and Scope 3 emissions as "all other indirect emissions not accounted for in Scope 2 emissions." Accordingly, in our model, firms' direct emissions coincide with Scope 1 emissions, whereas their indirect emissions in the supply chain fall in the category of Scope 3 emissions. Because we do not model firms' emissions from energy consumptions, Scope 2 emissions disclosures are not pertinent to our study.

[8] For instance, in developed countries such as the United States and the EU, regulators develop and impose requirements on the climate-related reporting quality for firms in their own jurisdictions, whereas in emerging market and developing economies, the climate information architecture remains underdeveloped and "there is a lack of granular, quality climate data in these economies" (International Monetary Fund, 2022). Even within a single country such as the United States, there is fragmentation in climate reporting requirements across regulatory jurisdictions. For example, while the recent SEC climate rules in the United States do not require Scope 3 emissions disclosures and do not apply to privately-held companies, the state of California's sustainability laws do.

of our study.

We use our framework to study two climate reporting regimes: 1) a Scope-1-for-all regime in which both firms and their supplier report their direct emissions, where the supplier's direct emissions equal the firms' total indirect emissions, and 2) a Scopes-1-and-3 regime in which each firm reports not only its own direct emissions but also its share of the total indirect emissions of its supplier. Comparing the two regimes sheds light on the following issues that are key in designing climate-related reporting policies. First, what are the net benefits of including the supplier's direct emissions (hence firms' total indirect emissions) in climate disclosures, in addition to mandating only firms' own direct emissions? Second, what should be relation between the measurement and disclosure requirements for direct and indirect emissions? Third, under what circumstances should regulators favor the Scope-1-for-all regime over the Scopes-1-and-3 regime?

To answer these questions, we adopt a financial-materiality perspective: firms' climate-related risks and greenhouse gas emissions are financially material information that influences investors' assessment of firms' future cash flows and thus the pricing of firms. Our focus on financial materiality reflects the perspectives that US regulators and international standard setters have adopted in mandating disclosures of climate-related information to investors (SEC, 2024; International Financial Reporting Standards (IFRS), 2024).

Our analyses generate several results. Disclosures of firms' Scopes 1 and 3 emissions allow market participants to price firms' climate risks triggered by the environmental impacts of their operations. A higher price sensitivity to climate risks, in turn, induces firms to internalize *some* environmental costs of their productions, to the extent that these costs influence the market's assessment and pricing of firms' future cash flows. Market pricing, in turn, generates real effects by mitigating firms' excessive pollution. Stated differently, relative to no disclosure, emissions disclosure improves market pricing of firms' climate risks, inducing price-maximizing firms to disclose in the first place.

Absent regulation, the disclosure-pricing channel, however, does not induce firms to *fully* internalize *all* environmental costs of their productions, especially the ones in which firms' productions and emissions contribute to physical climate risk and thus negatively affect *other* firms' values. Because externalities are not fully priced by the market and therefore internalized by firms, they over-pollute relative to socially optimal levels, and have insufficient private incentives to disclose their climate performance. Accordingly, mandatory climate reporting increases efficiency relative to when such a mandate is absent. Nonetheless, because mandatory climate reporting entails measurement frictions, its efficacy in sustaining efficient market discipline hinges on the reliability or precision of measuring firms' direct and indirect emissions. More precise disclosure of firms' direct emissions disciplines their internal production choices and reduces their direct emissions. Similarly, more precise disclosure by the supplier regarding total indirect emissions disciplines firms' decisions to outsource production and curbs their indirect emissions. However, more precise disclosure of direct emissions triggers *emissions leakage* by inducing firms to outsource production to the supplier whose emissions are assessed and priced less accurately.

To mitigate emissions leakage, a potential solution would be to mandate the disclosure of information regarding firms' indirect emissions. We show that while introducing indirect emissions disclosures indeed mitigates emissions leakage, it also prompts *reverse emissions leakage*, inducing firms to shift productions from the supplier to their own internal facilities. Given reverse emissions leakage, we show that requiring indirect emissions disclosures improves total surplus if and only if the precision of measuring direct emissions is sufficiently high. In particular, as the precision of the indirect emissions measurement improves, the precision of the direct emissions measurement must also increase in order to make the improved indirect emissions measurement surplus-enhancing. Stated differently, our analysis suggests that direct emissions disclosure is a *complement rather than a substitute* to indirect emissions disclosure.

An important policy implication of our result is that a regulator should tailor the choice of the precision of direct emissions measurement to that of indirect emissions measurement. Put differently, our results suggest that regulators should *not* set the measurement and disclosure requirements in their own jurisdictions in isolation. Rather, they must coordinate their policies with their counterparts across the globe. Our analysis thus cautions against unilateral increases in emissions disclosure requirements in developed countries–as evidenced by recent regulatory moves in the United States and the EU–given the dearth of high-quality emission data in developing countries that are parts of the global supply chain. In this light, our result may help to reconcile the varying policy decisions towards mandating indirect emissions disclosure by regulators in the United States and the EU.

We also examine whether the regulator should require firms to measure and allocate their own share of the total indirect emissions from the supplier's production (i.e., producing their Scope 3 emissions) or simply require firms to report the total Scope 1 emissions of their common supplier (i.e., relying on the supplier's report). We show that the optimality of separating indirect emissions hinges on two features of firms' environments. First, if the measurement and allocation of indirect emissions to individual firms are sufficiently reliable, then separation is indeed desirable as it provides high-quality information that enhances market discipline. Second, perhaps more interestingly, whether separation is desirable hinges on firms' relative exposures to different types of climate risk–i.e., transition climate risks vs. physical climate risks–that have received a lot of attention in the policy debate. Our analysis suggests that regulators should require firms reporting both Scopes 1 and 3 emissions where firms are primarily exposed to transition climate risk (e.g., oil and gas companies). This is because each firm's transition climate risk is driven by its own Scopes 1 and 3 emissions; providing this firm-level emissions information thus improves market pricing and yields stronger disciplining effects. Conversely, regulators should allow only Scope 1 emissions reported by firms and their suppliers in industries where physical climate risk is the main source of climate risk (e.g., agriculture, aquaculture, and fishing industries) because the pricing of physical climate risk depends on information about the firms' total indirect emissions that equal the supplier's Scope 1 emissions.

1.1 Related literature

Our paper contributes to a growing theoretical literature on the role of Environmental, Social and Governance (ESG) concerns in capital markets. One strand of the literature considers the asset pricing implications of ESG in portfolio choice models, including Heinkel, Kraus, and Zechner (2001), Pastor, Stambaugh, and Taylor (2021), and Pedersen, Fitzgibbons, and Pomorski (2021). Similarly, Friedman and Heinle (2016) investigate asset pricing implications when investors have heterogeneous valuations and their utilities can depend on ESG performance. Smith (2024) shows, in the presence of short-sale constraints, how disclosing climate risk exposures enables investors to form efficient climate-hedging portfolios when investors have different preferences for climate risk exposures. Another strand of the literature analyzes governance strategies that induce socially responsible investment (see e.g., Broccardo, Hart, and Zingales, 2022; Chowdhry, Davies, and Waters, 2019; Edmans, Levit, and Schneemeier, 2022; Gollier and Pouget, 2022; Landier and Lovo, 2024; Laux and Mahieux, 2024; Oehmke and Opp, 2024). More closely related to our study, Biais and Landier (2022) investigate the role of regulation in a setting in which firms do not internalize the negative externalities of their greenhouse gas emissions. They study the interaction between firms, which can invest in green technologies, and a government, which can impose emission caps but has limited commitment power.

A third strand of the literature focuses on the economic consequences of ESG reporting.[9] Bonham and Riggs-Cragun (2022) use a moral hazard model to analyze how ESG activities can be motivated by incorporating ESG metrics in executive compensation contracts. Chaigneau and Sahuguet (2023) study how a socially responsible board can align the manager's interests in a principal-agent model with ESG ratings. Our study is more closely related to several recent papers that have studied the real effects of capital market responses on firms' ESG choices. Using rational expectations equilibria, Goldstein, Kopytov, Shen, and Xiang (2022) and Xue (2023) study how ESG reporting affects equilibrium prices when investors have both financial and ESG concerns. Goldstein *et al.* show that responsible investors can increase the cost of capital, because their trades reflect ESG performance rather than financial performance. Xue shows that more precise ESG disclosure is not necessarily desirable when investors care more about ESG due to the subtle interaction between ESG disclosures and market forces. He also shows that environmental externalities provide a rationale for mandating more precise climate disclosure. Friedman, Heinle, and Luneva (2023) also develop a model in which managers care about market prices. In their model, a manager exerts unobservable effort that affects a firm's ESG and cash flows. They analyze how greenwashing and financial misreporting interact. Aghamolla and An (2021) examine the effects of ESG disclosure in both voluntary and mandatory regimes. They show that mandatory ESG disclosure can lower investment efficiency. We also analyze the real effects of climate-related disclosures in a market setting. However, our study differs from the preceding real effects studies in several important ways. First, these previous studies generally assume that investors have inherent preferences for green activities. We, instead, adopt a financial-materiality perspective in that investors only care about firms' environmental activities insofar as these activities directly affect firms' long-term cash flows. Moreover, firms do not take into account the negative externalities from

[9] Christensen, Hail, and Leuz (2021) and Grewal and Serafeim (2020) review the literature on corporate sustainability and highlight the potential tradeoffs for firms and regulators.

their greenhouse gas emissions. In pricing firms, investors therefore need climate-related disclosures to assess firms' long-term environmental impact. Second, we take a measurement perspective and study the economic consequences of the fragmentation in cross-jurisdiction emissions measurements and disclosures. This allows us to study the trade-offs of mandating *only* direct emissions (Scope 1 emissions) disclosures vs. mandating *both* direct and indirect emissions (Scope 1 and Scope 3 emissions) disclosures, an issue that has received much attention recently. Lastly, our model distinguishes between two types of climate-related risks–i.e., transition climate risks vs. physical climate risks–that have received a lot of attention in the policy debate. By modeling how these two types of climate risks have differential long-term environmental impacts, we show how climate-related reporting requirements should be tailored to how firms are differentially exposed to these two types of climate risks.

Our study is also related to a stream of recent empirical work that documents the real effects of ESG reporting. Tomar (2023) examines the effects of the United States GHG Reporting Program and shows that facilities reduce their GHG emissions following the disclosure of emissions data. Chen, Hung, and Wang (2018) find a comparable effect in China. Similarly, Jouvenot and Krueger (2021) investigate the consequences of a law that mandates publicly listed firms in the UK to disclose their GHG emissions in a standardized way in their annual reports. They show that firms respond to the law by reducing GHG emissions. In another related study, Bonetti, Leuz, and Michelon (2023) show that disclosure of hydraulic fracturing wells and fracturing fluids creates public pressure, which in turn encourages the internalization of negative environmental externalities.

Finally, there is a voluminous literature that studies the impact of regulatory policies on emissions leakage (i.e., pollution shifting). The conventional approach for mitigating negative externalities generated by firms involves imposing either Pigouvian taxes and/or tradable pollution permits to induce firms to internalize such externalities. However, regulatory responses to climate change have been strongly impeded by free-riding issues: each country bears the full cost of reducing its emissions while receiving only a small fraction of the benefits. The possibility of emissions leakage further exacerbates this issue (Tirole, 2012). Most environmental economics papers studying emissions leakage focus on the consequences of introducing an emissions tax in a limited number of jurisdictions (see, e.g., Babiker, 2005; Gerlagh and Kuik, 2014; Maria and Van der Werf, 2008; Van Der Ploeg and De Zeeuw, 1992). Ambec, Esposito, and Pacelli (2024) and Bohringer, Rosendahl, and Storrosten (2017) analyze policies that could mitigate carbon leakage, such as a Carbon Border Adjustment Mechanism. Several recent empirical papers provide evidence consistent with carbon leakage. For instance, Dai, Duan, Liang, and Ng (2024) provide robust evidence that firms outsource part of their carbon emissions to foreign suppliers. Similarly, Chen, Lin, Sulaeman, and Xu (2023) find that United States polluting firms increase their emissions and receive bank financing at lower costs after the sudden United States withdrawal from the 2015 Paris Agreement. Our study shows how another more recent regulatory tool such as disclosure regulation may both discipline firms' pollution behavior and induce them to partially internalize externalities. An important takeaway from our paper is in the absence of cross-country coordination, disclosure regulation may also lead to emissions leakage particularly in jurisdictions where high-quality emission data that are parts of the global supply chain is relatively sparse and even lacking. Consistent with our findings, the empirical studies by Jiang (2023) and Yang, Muller and Liang (2023) show that firms shift some pollution from regulated reporting facilities to their non-reporting facilities after the introduction of the United States GHG Reporting Program. In addition, Downar, Ernstberger, Reichelstein, Schwenen, and Zaklan (2021) and Deng, Hung and Wang (2023) examine the effects of the 2013 UK carbon disclosure regulation, which mandates the reporting of Scopes 1 and 2 emissions but not Scope 3 emissions. The empirical evidence supports the mechanisms in our model. In particular, Downar *et al.* report that, after the mandate, affected firms reduced their Scope 1 direct emissions by 8%. Furthermore, Deng *et al.* find that affected UK firms reduced their Scopes 1 and 2 emissions but increased their Scope 3 emissions (i.e., emissions of their foreign suppliers). Finally, Lu, Peng, Shin, and Yu (2023) provide evidence suggesting that mandating ESG disclosure leads firms to transfer ESG risks to suppliers in countries with more opaque ESG disclosures.

2 The Model

2.1 Environment

Our environment consists of $N \geq 2$ domestic firms, indexed by $i \in \{1, 2, ..., N\}$, that share a common foreign supplier, indexed by F, and a domestic regulator who designs the measurement

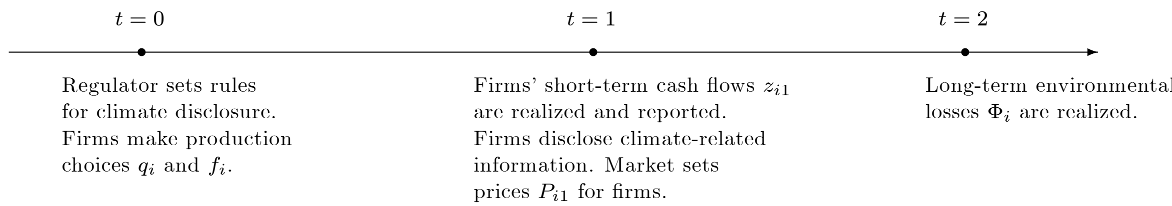

Figure 1: Timeline of the model.

rules for climate-related disclosures.[10] Figure 1 summarizes the timing of events.

At $t = 0$, each firm i simultaneously chooses its production plan. The production of each firm requires two inputs, one produced internally by firm i and one that firm i outsources to the supplier. Denote the units of firm i's internal production by $q_i \geq 0$ and the units outsourced by firm i to the supplier by $f_i \geq 0$. For climate-related disclosures to affect firms' production and pollution incentives, we assume that the firms' production choices are not directly observable to outsiders; instead, they can be inferred from the firm's accounting report (e.g., Kanodia and Sapra, 2016; Kanodia, Sapra, and Venugopalan, 2004; Jiang, Kanodia, and Zhang, 2023).

The firm's production plan $\{q_i, f_i\}$ generates a stochastic gross cash flow X_i at $t = 1$, where $E\left[\widetilde{X}_i\right] = q_i + f_i \geq 0$. For simplicity, we assume that, when each firm acquires the input from the supplier, the firm has all the bargaining power so that the supplier always breaks even.[11] Accordingly, the firm internalizes all the production costs that are given by

$$C\left(q_i, f_i\right) = \frac{q_i^2}{2} + \frac{f_i^2}{2} + c_s q_i f_i, \tag{1}$$

where $c_s > 0$. Note that the production cost function $C\left(q_i, f_i\right)$ exhibits the usual properties, i.e., it is increasing and convex in the production quantities $\{q_i, f_i\}$. The coefficient $c_s > 0$ implies that the firm's choices of internal and outsourced production $\{q_i, f_i\}$ are *strategic substitutes*, i.e., increasing q_i increases the marginal cost of producing f_i, inducing the firm to decrease f_i, and vice versa. This assumption reflects firms' limited management scope or limited capacity in processing inputs from different sources, i.e., firms' internal inputs or those from the supplier (e.g., Peng and Roell, 2008;

[10] As mentioned earlier, our model could also be interpreted as one with public firms subject to disclosure regulations and a private supplier not subject to regulations. We provide further discussion of this point in Section 2.3.

[11] In practice, interactions between firms and their suppliers could depend on many factors including the operating and financial conditions of the related parties, the environmental information disclosed, etc. To focus on the disciplinary role of capital markets given climate-related reporting, we abstract away from modeling how climate-related reporting may influence the interactions between firms and their suppliers.

Liang and Nan, 2014; Calzolari and Denicolo, 2015; Arozamena, Weinshelbaum, and Wolfstetter, 2018). More importantly, strategic substitutability between the two production choices implies that firms have incentives to shift production to their supplier if such firms face more stringent climate-related regulation in their jurisdictions.[12] This feature allows us to capture the issue of *carbon/emissions leakage* that businesses transfer productions to jurisdictions with less stringent emission reporting requirements, which has drawn considerable attention in both policy debates and academic studies (SEC, 2024; Dai, Duan, Liang, and Ng, 2024; Chen, Lin, Sulaeman, and Xu, 2023).[13]

At $t = 1$, firms' production plans $\{q_i, f_i\}$ generate short-term cash flows, denoted by

$$z_{i1} \equiv X_i - C\left(q_i, f_i\right).$$

We assume that there is an accounting system that measures and reports firm i's short-term cash flows z_{i1} to the market. To study the issue of climate-related disclosures, we assume that firms' production processes have long-term environmental impacts. Firm i's production of input q_i generates the following *direct* emissions of greenhouse gases

$$e_i = q_i + \gamma_i, \tag{2}$$

where $\gamma_i \sim N\left(0, \sigma_\gamma^2\right)$ and is independent of all other random variables. Equation (2) captures the feature that a larger scale of production generates more emissions in the sense of first-order stochastic dominance (FOSD). Nonetheless, the exact environmental impacts of firms' operations are likely non-deterministic, e.g., the emission of greenhouse gases from a firm is a stochastic function of the firm's production as the emission level likely depends on many other (random) factors in the environment.[14] Similarly, each firm i that outsources the production of some input

[12] Note that if $c_s < 0$, firms' production choices would be strategic complements, eliminating firms' incentives to shift production across jurisdictions.

[13] For instance, in its final rule of climate-related disclosures, the SEC acknowledges that "(t)o avoid direct costs of compliance or to simply report a lower emissions amount in their required disclosures, some registrants may take steps to reorganize their business in order to shift certain parts of their Scope 1 and Scope 2 emissions into the Scope 3 emissions category." (p. 784, SEC, 2024).

[14] In practice, firms could adopt abatement technologies to reduce their emissions. Additionally, regulators could also provide incentives to firms to invest in abatement technologies by subsidizing these investments, e.g., the clean energy tax incentives under the Inflation Reduction Act (IRA). The regulatory policy regarding subsidies for emissions abatement may interact with the regulation of emissions disclosures, to the extent that both policies serve the common

f_i to its supplier results in the following *indirect* emissions of greenhouse gases

$$e_{iF} = f_i + \gamma_{iF},$$

where $\gamma_{iF} \sim N\left(0, \sigma_F^2\right)$ and is independent of all other random variables.[15] Accordingly, the total indirect emissions from the supplier's production for all firms are given by

$$e_F = \sum_{i=1}^{N} e_{iF}. \tag{3}$$

The total long-term environmental impacts of firms' and their supplier's productions generate climate risks that we capture as a long-term loss

$$\Phi_i = \underbrace{k_T(e_i + e_{iF})}_{\text{transition climate risk}} + \underbrace{k_P \sum_{j=1}^{N}(e_j + e_{jF})}_{\text{physical climate risk}}, \tag{4}$$

for each firm i that is realized at $t = 2$ where the coefficients $k_T > 0$ and $k_P > 0$ are common knowledge. Firm i's environmental loss, as captured in Equation (4), reflects two categories of climate change risk. The first category is a transition climate risk that depends on each firm's own emissions. The second category is a physical climate risk driven by the total emissions of all firms rather than any individual ones.

In practice, firms are exposed to both transition and physical climate risks (e.g., Bua, Kapp, Ramella, and Rognone, 2022). The physical climate risk results from climatic events, such as wildfires, storms, and floods. The source of physical climate risk arises from longer-term shifts in climate patterns (e.g., sustained higher temperatures), which is likely driven by the operation of the global economy rather than any single enterprise. Conversely, the transition climate risk is caused by the financial impact of the transition to a low-carbon economy on firms, such as changes in environmental policies, shifts in public preferences, technological adaptations, etc. Arguably, the

goal of reducing emissions. In an Online Appendix, we investigate an extension of our model with regulatory subsidies for emissions abatement.

[15] Because the foreign productions of all firms (f_i) are produced by the same supplier, the noise terms (γ_{iF}) are likely to be correlated across all firms. For simplicity, we assume that the noise terms for two different firms are independent of each other. Introducing correlations between them would significantly complicate our analysis without generating significant incremental insight.

source of the transition climate risk is more likely to depend more on firms' own environmental footprints compared to the source of the physical climate risk. For example, oil and gas companies are more likely to face a stiff transition climate risk, whereas companies that have already adopted green technologies are less exposed to transition climate risk. Stated differently, a key feature of transition climate and physical risks captured in our framework is that the *source/driver* of physical climate risk is more likely to be the total emissions by all firms in the economy, whereas the *source* of transition climate risk is more likely to be each firm's own emissions.[16] We henceforth refer to the coefficient k_P in Equation (4) as firm i's exposure to physical climate risk, and to the coefficient k_T as firm i's exposure to transition climate risk.[17]

The firms are priced in a risk-neutral competitive market at $t = 1$. Accordingly, each firm's price P_{i1} is given by the market's expectation of its total cash flows conditional on the market's information set, i.e.,

$$P_{i1} = \underbrace{z_{i1}}_{\text{short-term cash benefits}} - \underbrace{E_1\left[\widetilde{\Phi}_i|\text{market's information}\right]}_{\text{market's beliefs about long-term environmental losses}}. \quad (5)$$

The term $E_1[\cdot]$ denotes the market's expectations with respect to its information at $t = 1$ and that information includes not only the reported cash flow z_{i1} but also information about the firm's direct and indirect emissions that we discuss in the next section.

At $t = 0$, firm i's management chooses its production plan $\{q_i, f_i\}$ to maximize the expectation of its price P_{i1} at $t = 1$:[18]

$$\max_{q_i, f_i} E_0\left[\widetilde{P}_{i1}|q_i, f_i\right],$$

where $E_0[\cdot]$ denotes the firm's expectations with respect to its information at $t = 0$.

Climate-related disclosures help market participants better assess and therefore price a firm's

[16] Transition climate risk may depend on the total emissions by all firms, because, for instance, regulators are more likely to impose tougher climate-related regulations facing the rise of physical climate risk (driven by the increase in the total emissions). Stated differently, the two types of climate risks may interact. For simplicity, we abstract away from modeling the interaction between climate risks; accordingly, conditional on regulatory policy (and physical climate risk), each firm's financial loss from transition climate risk is likely to be driven by its own emissions.

[17] We assume firms' exposures to physical and transition risks are homogeneous across firms. In practice, these exposures could be heterogeneous. In an Online Appendix, we analyze a setting that introduces heterogeneity in firms' climate risk exposures.

[18] Alternatively, we could assume that the firm maximizes a weighted average of the prices at $t = 1$ and $t = 2$, i.e., $\alpha E_0[P_{i1}|q_i, f_i] + (1 - \alpha) E_0[P_{i2}|q_i, f_i]$, where $0 \leq \alpha \leq 1$ and the date-2 price $P_{i2} = z_{i1} - \Phi_i$, since the long-term loss Φ_i is already realized at $t = 2$. We assume $\alpha = 1$ in order to focus exclusively on our goal of studying the real effects of climate-related disclosures/measurements in affecting firms' polluting incentives.

climate risks Φ_i from its emissions. We now augment our economic framework with climate-related measurements and disclosures.

2.2 Climate-related measurements and disclosures

The firms and their supplier install measurement systems (e.g., continuous emission monitoring systems (CEMS)) to measure the emissions $\{e_i, e_F\}$ from their productions. The systems generate the following noisy reports

$$y_i = e_i + \varepsilon_i, \tag{6}$$

$$y_F = e_F + \varepsilon_F, \tag{7}$$

where the measurement noises $\widetilde{\varepsilon}_i \sim N\left(0, \sigma_\varepsilon^2\right)$ and $\widetilde{\varepsilon}_F \sim N\left(0, \sigma_{\varepsilon F}^2\right)$ are independent of all other random variables. Accordingly, the variances σ_ε^2 and $\sigma_{\varepsilon F}^2$ capture the precision of measuring each firm's direct emissions and the total indirect emissions by the supplier, respectively. To capture the friction that the emissions reporting regulatory landscape is fragmented across jurisdictions, we assume that the regulator is able to influence the precision of measuring direct emissions from firms' production within its jurisdiction, but less likely to directly influence the precision of measuring indirect emissions by the supplier operating outside its jurisdiction. Arguably, such regulatory fragmentation is a key driving force behind the phenomenon of emissions leakage, which is a main focus of our study. We therefore assume that, at $t = 0$, the regulator only sets the measurement precision σ_ε^2 of direct emissions, but takes as given the measurement precision $\sigma_{\varepsilon F}^2$ of the indirect emissions by the supplier. We discuss this assumption more thoroughly in Section 2.3.

At $t = 0$, in addition to regulating precision of measuring direct emissions, the regulator also mandates rules governing how firms should *report* information about emissions at $t = 1$. A key focus in the emissions disclosure requirements is to delineate "emissions that are directly attributable to the reporting entity from those that are indirectly attributable to the company's activities" (SEC, 2024). Regulators in different jurisdictions have adopted varying approaches to the design of climate reporting policies. In July 2023, the European Union (EU) mandated all three Scopes of emissions disclosures in the Corporate Sustainability Reporting Directive (CSRD) whereas in March 2024, the SEC in the United States required only Scope 1 and Scope 2 emissions disclosures. To shed light on the design of emissions disclosures and the implications of these varying approaches, we study two reporting regimes.

Scope-1-for-all regime Firms need to report not only their direct emissions, y_i in Equation (6), but also the *total* indirect emissions of their common supplier, y_F in Equation (7). Note that in this regime, all firms–including both the firms and their supplier–report their own direct emissions (Scope 1 emissions) because the commingled indirect emissions of all the firms are their supplier's direct emissions (Scope 1 emissions). For ease of exposition, we thereafter refer to the signal y_F as either the Scope 1 emissions disclosure by the supplier or the commingled indirect emissions disclosure of all the firms.

An important goal of our analysis is to assess the cost and benefit of mandating in firms' climate reports their indirect emissions, which, in the most primitive form, are the supplier's Scope 1 emissions. In that vein, we assume that regulators' reporting policies serve as the main channels for the public dissemination and measurement of emissions information, including Scope 1 emissions by the supplier. As noted earlier, the SEC in the United States–unlike the EU–mandates no public dissemination of such indirect emissions. By setting the precision of measuring indirect emissions $\sigma_{\varepsilon F} = \infty$, we use the Scope-1-for-all regime to evaluate the SEC's reporting policy of not requiring disclosure of indirect emissions information.

Scopes-1-and-3 regime Firms need to report not only their direct emissions y_i (i.e., Scope 1 emissions) but each firm must also identify and allocate its share of the supplier's total indirect emissions y_{iF} (i.e., each firm's individual Scope 3 emissions), which is given by

$$y_{iF} = e_{iF} + \omega_i,$$

where $\widetilde{\omega}_i \sim N\left(0, \sigma_\omega^2\right)$ and is independent of all other random variables.

The measurement noises $\{\omega_i\}_{i=1}^N$ capture the inherent limitation firms face in their attempts to separate their supplier's total indirect emissions, resulting in the widely-noted issue of *double counting* in the practice of allocating the total emissions.[19] In practice, due to a lack of coor-

[19] The Greenhouse Gas Protocol explicitly recognizes the issue of allocating the total emission data from suppliers into multiple downstream firms: "(f)or example, a single production facility may produce many different products and co-products, while activity data (used to calculate GHG emissions) is collected for the plant as a whole. In this

dination, firms make independent attempts to measure and identify their share of the indirect emissions in their supply chains, resulting in heterogeneity in firms' measurements and reporting of carbon emissions. Therefore, these measurement noises ω_i in allocating indirect emissions need not perfectly offset each other across firms. The SEC explicitly recognizes such *measurement heterogeneity* in their latest Climate Rule to "enhance and standardize climate-related disclosures."[20] In our environment, we assume that these noises need not cancel each other, i.e., $\sum_{i=1}^{N} \omega_i \neq \varepsilon_F$, where ε_F is the measurement noise in the supplier's total indirect emissions. This, in turn, implies that aggregating all firms' reports of indirect emissions does not necessarily equal the total indirect emissions reported by the supplier, i.e., $\sum_{i=1}^{N} y_{iF} \neq y_F$.

2.3 Discussion of key assumptions

We now discuss several key assumptions of the model.

First, regulation over emissions reporting is fragmented across jurisdictions. To capture this fragmentation, we have interpreted our model as a cross-country setting in which domestic firms facing more stringent climate regulation compared to their foreign supplier. For instance, in developed countries such as the United States and the EU, regulators have developed and imposed requirements on measuring emissions from productions of firms in their own jurisdiction. However, in emerging markets and developing economies, emissions disclosures remain voluntary and lack reliability. Moreover, due to jurisdiction limits, such disclosures are less likely to be directly influenced/regulated by regulators in the United States and the EU, but instead subject to some form of emissions disclosure requirements in foreign jurisdictions that are less stringent. A crucial feature of our framework is that the operations of the economy (and investors' decisions) depend

case, the facility's energy use and emissions need to be allocated to its various outputs. Similarly, a company may purchase components from a supplier that manufactures a wide variety of products for many different customers. In this case, the supplier's activity data or emissions data need to be allocated among the various products so its customers know the emissions attributable to the specific products they buy, based on the fraction of total supplier production that is related to the customer's purchases." (Greenhouse Gas (GHG) Protocol, 2011) In such allocations, the GHG Protocol notes that "double counting is an inherent part of Scope 3 accounting." Shrimali (2021) also notes that "(a)cross supply chains double counting is when the Scope 1 emission of an upstream entity is being assigned entirely to multiple immediate downstream entities that split up the use of the product from the upstream entity."

[20] Specifically, the SEC (p. 22, 2024) notes that "the current state of climate-related disclosure has resulted in inconsistent, difficult to compare, and frequently boilerplate disclosures, and has therefore proven inadequate to meet the growing needs of investors for more detailed, consistent, reliable, and comparable information about climate-related effects on a registrant's business and financial condition to use in making their investment and voting decisions." Arguably, in allocating their share of indirect emissions, different firms likely apply different measurement standards, use different measurement procedures/systems, and prepare their emissions report with different personnels, etc.

on a supplier's emissions disclosures that cannot be directly regulated due to jurisdiction limits. Therefore, our setting may also be interpreted as one in which the firms who produce internally are publicly-traded firms while their supplier is privately-held. For example, in the United States, the SEC's climate rule only applies to publicly-held firms and not to privately-held firms.[21] Therefore, the private supplier's incentives to disclose its emissions may be driven by other considerations (e.g., demands by its own investors).

Second, our specification of the market pricing of emissions information in Equation (5) reflects the financial materiality perspective United States regulators and international standard setters commonly adopt in mandating disclosures of climate-related information to investors.[22] Under this perspective, firms' reported emissions matter only to the extent that they influence the market assessment of firms' future cash flows (i.e., the long-term environmental loss $\widetilde{\Phi}_i$), and thus the pricing of the firms. Accordingly, to focus on financially material emissions information, we abstract away from modeling investors/firms' green preferences, which, in practice, are probably heterogeneous among market participants, changing over time, and not directly measurable. This focus also implies the implications from our analysis are more likely to apply to regulation adopting the financial-materiality perspective (e.g., the SEC and IFRS), but perhaps less applicable to climate reporting standards adopting the perspective of impact/double materiality (e.g., the Global Reporting Initiative (GRI)).

Third, we assume that firms' climate risk exposures $\{k_T, k_P\}$ are known to market participants. In practice, firms' climate risk exposures are likely to be uncertain, raising another issue of measuring and reporting firms' climate risk exposures. For instance, the SEC's final climate rule (SEC, 2024) requires both reporting climate risk exposures in the front end of the financial report (e.g., Risk Factors, Description of Business, or Management's Discussion and Analysis of Financial Condition and Results of Operations), and separately reporting Scopes 1 and 2 GHG emissions. Our focus on emissions reporting thus pertains to the SEC's latter requirement, whereas a model with uncertain climate risk exposures pertains to the former requirement. To gain sharper insights on

[21] In the extreme, in response to rising environmental regulations, public firms may divest pollutive plants to private buyers (Duchin, Gao and Xu, 2024). We do not consider such endogenous shift in regulatory boundaries acknowledging it is an interesting direction for future research.

[22] In its final rules of climate-related disclosures, SEC (2024) requires "information about a registrant's climate-related risks that have materially impacted, or are reasonably likely to have a material impact on, its business strategy, results of operations, or financial condition." See also IFRS (2024) on how the climate reporting standards proposed by its International Sustainability Standards Board (ISSB) approach materiality.

the implications of measuring and reporting GHG emissions, we make the modeling choice of characterizing GHG emissions disclosure policies, leaving the study of climate risk exposures disclosure policies for future research. In addition, our assumption that climate risk exposures are known has some empirical support in recent work that develop approaches to quantify climate risk exposures of firms and industries from publicly available data (see, e.g., Bua, Kapp, Ramella, and Rognone, 2022; Jung, Engle, Ge, and Zeng, 2023).

Finally, we impose parametric restrictions to ensure interior solutions of firms' production choices. As it turns out, this assumption reduces to

$$1 > k_T + k_P N, \text{ and } c_s < 1 - k_T - k_P < 1. \tag{8}$$

The first part of (8) ensures that the expected total cash flows from firms' production at $t = 1$ exceed the expected total environmental losses incurred at $t = 2$. The second part of (8) ensures that, in firms' production costs (1), the degree of strategic substitutability c_s is not too large so that equilibrium production choices are interior.[23]

3 Analysis

3.1 Benchmarks

First-best Before we begin the main analysis, we show that, *even in the absence of measurement frictions*, firms would engage in excessive pollution relative to socially optimal levels. We therefore start with a first-best economy, where a social planner sets the production plans of all firms, $\{q_i, f_i\}_{i\in\{1..N\}}$, to maximize the *ex ante* total surplus

$$W = \sum_{i=1}^{N} E_0 \left[X_i - C(q_i, f_i) - \Phi_i\right], \tag{9}$$

where the production costs and the long-term environmental losses are given in (1) and (4), respectively. In this benchmark, the social planner internalizes *all* the benefits and costs of production,

[23] Note that the assumption $c_s < 1$ ensures that firms' two production inputs $\{q_i, f_i\}$ are *imperfect* substitutes so that both inputs would be chosen in equilibrium. In fact, if $c_s = 1$, firms' production cost function $C(q_i, f_i) = (q_i + f_i)^2/2$, so that the two inputs would be perfect substitutes in the production plan. In that case, firms' equilibrium production choices would result in corner solutions.

including the long-term environmental losses from firms' production plans. The following lemma characterizes the first-best production plans $\{q^{FB}, f^{FB}\}$.[24]

Lemma 1 *In the first-best benchmark, the social planner chooses*

$$q^{FB} = f^{FB} = \frac{1 - k_T - k_P N}{1 + c_s} > 0. \tag{10}$$

Full information We next consider a full information economy–in which measurement frictions about firms' emissions are still absent–but, unlike the first-best economy, firms do not internalize the environmental externalities of their productions on others. Specifically at $t = 1$, for all $i \in \{1, 2, ..., N\}$, market participants perfectly observe firm i's direct emissions, $e_i = q_i + \gamma_i$, and indirect emissions, $e_{iF} = f_i + \gamma_{iF}$, and set a price P_{i1} based on such full information. At $t = 0$, each firm i chooses its production plan $\{q_i, f_i\}$ to maximize its own expected date-1 price (as opposed to the total surplus of all firms), i.e., firm i solves

$$\max_{q_i, f_i} E_0 [P_{i1}] .$$

The following lemma characterizes each firm's production plan $\{q^{FI}, f^{FI}\}$ under full information.

Lemma 2 *In the full information benchmark, each firm chooses*

$$q^{FI} = f^{FI} = \frac{1 - k_T - k_P}{1 + c_s} \geq q^{FB} = f^{FB}.$$

Moreover, the total surplus W^{FB} in a first-best economy is strictly larger than the total surplus W^{FI} in a full information economy, i.e.,

$$W^{FI} = W^{FB} - \frac{k_P^2 N(N-1)^2}{1 + c_s},$$

and the surplus loss $\frac{k_P^2 N(N-1)^2}{1+c_s} > 0$ is increasing in both N and k_P.

In the full information benchmark, each firm chooses *larger* production quantities than in the first-best benchmark. This result is driven by the environmental externalities such that–even under

[24] Note that both $q^{FB} > 0$ and $f^{FB} > 0$ hold because of Assumption (8).

full information–*the social cost* of firms' emissions, i.e., the sum of the long-term environmental losses borne by all firms, $\sum_{i=1}^{N} \Phi_i$, is not fully priced by the market and internalized by each firm in setting its own production decisions. Specifically, the social cost of any firm's emissions consists of two components: 1) its own transition and physical climate risks, reducing the firm's own future cash flows, and 2) all the other firms' physical climate risks, hurting the other firms' values. Full information about emissions enables market participants to price firms' climate risks, inducing firms to internalize the first component of the social cost of emissions, to the extent that this cost influences the market's assessment of firms' future cash flows. The pricing of each firm's value, however, reflects only the market's assessment of how emissions affect the firm's own future cash flows. It does not induce firms to internalize the second component of the social cost of emissions–that each firm's emissions contribute to the physical climate risk–and thus negatively affect all the *other* firms' values, i.e., the externalities. Because the externalities are not fully priced by the market, firms over-produce and therefore over-pollute, relative to the first-best economy in which the social planner fully internalizes the social cost of emissions. Intuitively, the surplus loss in the full information economy relative to the first-best economy should be increasing in the magnitude of the unpriced social cost. Indeed, Lemma 2 illustrates that the larger the number of firms, N, in the economy, the greater the unpriced social cost (externalities) so that the firms' over-production incentives worsen resulting in a larger loss in surplus from excessive emissions. Similarly, the larger each firm's exposure to physical climate risks, i.e., the larger k_P is, the greater the social cost resulting in a larger loss in surplus.

Lemma 2 also suggests a role for mandatory disclosure in our environment. As firms do not internalize the social cost of emissions that contribute to the physical climate risk, their private incentives to disclose their climate performance are insufficient.[25] In the presence of measurement frictions, mandatory disclosure induces firms to internalize a larger portion of the social costs of emissions: by increasing the precision of emissions measurements, regulators can improve the efficacy of market discipline, thereby inducing firms to internalize the impact of their productions on long-term environmental losses. We next turn to our main analysis in which the emissions of

[25]We formally study firms' private choices of their climate emissions disclosures later in Section 3.5 and show that in the absence of physical climate risk, firms' private incentives to disclose coincide with those of the regulator. However, in the presence of physical climate risk, such private incentives are insufficient. Therefore, the rationale for mandating disclosures arises from externalities and not from firms caring about prices.

firms' productions are not directly observable but must be inferred based on the measurement rules under the prevailing mandatory reporting regimes.

3.2 Equilibrium production plans under Scope-1-for-all regime

We first derive the market price of firm i at $t = 1$ given the information available to the market, including the climate-related disclosures, $\left\{\{y_j\}_{j=1}^N, y_F\right\}$, and the market's conjecture of the firms' equilibrium production plans $\left\{\hat{q}_j, \hat{f}_j\right\}_{j=1}^N$.[26] Substituting (4) into (5) yields

$$P_{i1} = z_{i1} - k_T E_1\left[\widetilde{e}_i | y_i, \hat{q}_i\right] - k_T E_1\left[\widetilde{e}_{iF} | y_F, \hat{f}_i\right] - k_P E_1\left[\sum_{j=1}^N \left(\widetilde{e}_j + \widetilde{e}_{jF}\right) | \left\{y_j, \hat{q}_j, \hat{f}_j\right\}_{j=1}^N, y_F\right]. \quad (11)$$

In pricing firm i, the market needs to estimate the emissions from firm i's own productions $\{e_i, e_{if}\}$, and the total emissions from all firms' productions, $\sum_{j=1}^N (e_j + e_{jF})$. First, the market uses the direct emissions disclosure y_i and its conjecture of the firm's internal production $\hat{q}_i$ to estimate the firm's direct emissions e_i, i.e.,

$$E_1\left[\widetilde{e}_i | y_i, \hat{q}_i\right] = E_1\left[q_i + \widetilde{\gamma}_i | y_i, \hat{q}_i\right] = \hat{q}_i + \beta_D \left(y_i - \hat{q}_i\right), \quad (12)$$

where $\beta_D \equiv \frac{\sigma_\gamma^2}{\sigma_\gamma^2 + \sigma_\varepsilon^2} \in [0, 1]$ is the weight placed on the direct emissions disclosure. Note that the weight β_D is monotone in the precision of direct emissions measurement σ_ε^2 and, for analytical convenience, we henceforth refer to β_D as the precision of direct emissions measurement.

Second, the market uses the commingled indirect emissions disclosure y_F (i.e., the Scope 1 emissions reported by the supplier) and its conjecture of the firms' outsourced production $\{f_j\}_{j=1}^N$ to estimate firm i's indirect emissions e_{iF} from its production outsourced to the supplier, i.e.,

$$E_1\left[\widetilde{e}_{iF} | y_F, \hat{f}_i\right] = E_1\left[f_i + \widetilde{\gamma}_{iF} | y_F, \hat{f}_i\right] = \hat{f}_i + \beta_{IC}\left(y_F - \sum_{j=1}^N \hat{f}_j\right), \quad (13)$$

where $\beta_{IC} \equiv \frac{\sigma_F^2}{N\sigma_F^2 + \sigma_{\varepsilon F}^2} \in [0, 1/N]$ denotes the weight the market places on the commingled indirect emissions disclosure and captures the precision of such disclosure. Note that β_{IC} decreases in N so that when more firms are commingled in the disclosure y_F, such disclosure is less informative

[26] We later verify that the market's conjectures are correct in equilibrium.

about the share of indirect emissions attributable to any individual firm.

Lastly, the market aggregates its estimates of the emissions of all firms, i.e., (12) and (13), and computes its estimate of the total emissions from all productions, i.e.,

$$E_1\left[\sum_{j=1}^{N}(\widetilde{e}_j+\widetilde{e}_{jF})\,|\,\left\{y_j,\hat{q}_j,\hat{f}_j\right\}_{j=1}^{N},y_F\right]=\sum_{j=1}^{N}\hat{q}_j+\sum_{j=1}^{N}\hat{f}_j+\beta_D\sum_{j=1}^{N}(y_j-\hat{q}_j)+N\beta_{IC}\left(y_F-\sum_{j=1}^{N}\hat{f}_j\right). \tag{14}$$

Next, we derive each firm's equilibrium production choices that maximize the expectation of the date-1 price $E_0\left[\widetilde{P}_{i1}\right]$. Substituting (12), (13) and (14) into P_{i1}, and using $E_0\left[\widetilde{y}_i\right]=q_i$ and $E_0\left[\widetilde{y}_F\right]=\sum_{j=1}^{N}f_j$ yields the following maximization problem for each firm

$$\begin{aligned}\max_{q_i,f_i}\quad & q_i+f_i-\frac{q_i^2}{2}-\frac{f_i^2}{2}-c_sq_if_i-k_T\left(\hat{q}_i+\beta_D\left(q_i-\hat{q}_i\right)+\hat{f}_i+\beta_{IC}\sum_{j=1}^{N}(f_j-\hat{f}_j)\right)\\ & -k_P\left(\sum_{j=1}^{N}\hat{q}_j+\sum_{j=1}^{N}\hat{f}_j+\beta_D\sum_{j=1}^{N}(q_j-\hat{q}_j)+N\beta_{IC}\sum_{j=1}^{N}(f_j-\hat{f}_j)\right).\end{aligned} \tag{15}$$

Taking the first-order conditions yields the equilibrium productions $\{q^*,f^*\}$ that we summarize next.

Proposition 1 *For a given precision β_{IC} of commingled indirect emissions measurement, and precision β_D of the direct emissions measurement, each firm's equilibrium production plan is*

$$q^*=\frac{1-(k_T+k_P)\beta_D-c_s(1-(k_T+k_PN)\beta_{IC})}{1-c_s^2}>0,$$

and

$$f^*=\frac{1-(k_T+k_PN)\beta_{IC}-c_s(1-(k_T+k_P)\beta_D)}{1-c_s^2}>0.$$

With the equilibrium production plans characterized, we first assess them from a social surplus standpoint that considers both firms' production profits and the social cost of emissions. We summarize our results in the following corollary.

Corollary 1 *Both the total expected emissions and the expected social cost of emissions in equilibrium are larger than those in the first-best benchmark, i.e., $\sum_{i=1}^{N}(q^*+f^*)\geq\sum_{i=1}^{N}(q^{FB}+f^{FB})$*

and $E_0\left[\sum_{i=1}^{N}\Phi_i(q^*,f^*)\right] \geq E_0\left[\sum_{i=1}^{N}\Phi_i(q^{FB},f^{FB})\right]$*. Firms over-produce and over-pollute in equilibrium in the sense that a marginal decrease in either internal or outsourced productions improves the total social surplus, i.e.,* $\frac{\partial W}{\partial q}|_{q=q^*,f=f^*} \leq 0$ *and* $\frac{\partial W}{\partial f}|_{q=q^*,f=f^*} \leq 0$.

Corollary 1 suggests that firms' equilibrium production plans generate excessive total emissions, and, accordingly, result in a larger social cost of emissions, relative to those under the first-best benchmark. Consequently, curbing firms' productions leads to surplus gains. Firms' over-production and over-polluting incentives are driven by two reasons. First, as discussed earlier, the market price does not fully capture the externality part of the social emissions cost that each firm's emissions contribute to the physical climate risk and thus negatively affect all the other firms' value. Because these environmental externalities are not fully priced, firms do not internalize them and set production levels generating excessive emissions. This force is also present in the absence of measurement frictions. Second, such inefficiency in productions is further exacerbated by the measurement frictions about firms' emissions, which create a hurdle for market participants to assess firms' emissions, and price the climate-related long-term losses accurately. The pricing inaccuracy, in turn, weakens market discipline and contributes to firms' over-pollution incentives.

A natural follow-up question is whether regulating climate-related disclosures enhances market discipline and curbs firms' over-polluting incentives. The following corollary sheds light on this question.

Corollary 2 *In equilibrium, each firm's internal production* q^* *decreases in the precision* β_D *of the direct emissions measurement and increases in the precision* β_{IC} *of the indirect emissions measurement , i.e.,*

$$\frac{\partial q^*}{\partial \beta_D} \leq 0 \text{ and } \frac{\partial q^*}{\partial \beta_{IC}} \geq 0.$$

Conversely, the firm's outsourced production f^* *increases in the precision* β_D *of the direct emissions measurement and decreases in the precision* β_{IC} *of the indirect emissions measurement , i.e.,*

$$\frac{\partial f^*}{\partial \beta_D} \geq 0 \text{ and } \frac{\partial f^*}{\partial \beta_{IC}} \leq 0.$$

Corollary 2 indicates that regulating climate-related disclosures may not necessarily be a panacea: it may either discipline or aggravate firms' over-pollution incentives. On the one hand, more precise disclosure of firms' direct emissions disciplines internal production choices and reduces direct emissions. Intuitively, more precise disclosure improves the efficiency in pricing the direct emissions from firms' internal productions, thus facilitating the market discipline of firms' pollution incentives. In response, firms shrink their internal productions in order to avert the adverse market consequences associated with over-pollution. In a similar vein, more precise disclosure by the supplier regarding the total indirect emissions also helps to discipline firms' choices to outsource production and curbs their indirect emissions.

On the other hand, our analysis also points to a downside of more precise disclosure. In particular, mandating more precise disclosure of direct emissions induces firms to shift some of their productions to the supplier, which leads to greater indirect emissions. Our result thus lends support to the argument of carbon/emissions leakage that businesses transfer productions to jurisdictions with less stringent emission reporting requirements. Intuitively, when the improved direct emissions measurement allows the market to price firms' direct emissions more accurately and lower the price for firms with greater direct emissions, the strengthened market discipline also forces firms to outsource more of their productions to the supplier, where the environmental impacts of their indirect emissions are assessed and priced relatively less accurately.

A policy prescription to mitigate emissions leakage is to mandate the disclosure of information regarding firms' *indirect emissions*, as such disclosure would improve the efficiency in pricing firms' indirect emissions and thus discipline their productions outsourced to the supplier. We next derive the regulator's equilibrium reporting policies that balance the costs and benefits of emissions leakages.

3.3 Equilibrium reporting policies under Scope-1-for-all regime

In setting the reporting policies, regulators have two choices. First, they choose whether to include in the reporting policy the disclosure of indirect emissions, which, in the most primitive form, are the supplier's Scope 1 emissions. Second, regulators fine-tune the precision of measuring direct emissions. We characterize the two choices in sequential order.

Costs and benefits of including indirect emissions We compare the equilibrium outcomes and the *ex ante* total surplus under the Scope-1-for-all regime with those of a regime that does not report any information about indirect emissions. As mentioned earlier, the latter can be obtained as a special case of the Scope-1-for-all regime by setting the precision of measuring the supplier's Scope 1 emissions $\beta_{IC} = 0$ (i.e., $\sigma_{\varepsilon F} = \infty$). The following proposition characterizes the effects of including indirect emissions information in the reporting policies.

Proposition 2 *Denote firms' production plans in the regime that does not report indirect emissions as* $\left\{q^{direct}, f^{direct}\right\}$ *and firms' production plans in the Scope-1-for-all regime as* $\{q^*, f^*\}$. *Including indirect emissions in the reporting policies:*

1. *decreases firms' outsourced productions and indirect emissions, i.e.,* $f^* \leq f^{direct}$*;*

2. *increases firms' internal productions and direct emissions, i.e.,* $q^* \geq q^{direct}$*;*

3. *improves the ex ante total surplus if and only if the precision of direct emissions measurement is above a threshold* $\hat{\beta}_D$*, i.e.,* $W^{commingled} \geq W^{direct}$ *if and only if*

$$\beta_D \geq \hat{\beta}_D \equiv \frac{(k_T + k_P N)\left(1 - (1 - \frac{\beta_{IC}}{2})/c_s\right)}{k_T + k_P}.$$

   $\hat{\beta}_D$ *is increasing in precision* β_{IC} *of indirect emissions measurement and* $\left\{W^{commingled}, W^{direct}\right\}$ *denote the surplus when firms' total indirect emissions are included and not included in the reporting policies, respectively.*

Proposition 2 illustrates that introducing indirect emissions disclosures indeed brings up a benefit in reducing firms' indirect emissions levels. However, mandating the disclosure also comes with a cost as it induces firms to increase their internal productions and thus direct emissions, compared to when the regulator only requires disclosures of direct emissions. Stated differently, while introducing the indirect emissions disclosure mitigates emissions leakage, it also prompts *reverse emissions leakage*. In fact, emissions leakage and reverse emissions leakage are simply two sides of the same coin. Mandating tighter disclosure requirements on emissions in one jurisdiction induces firms to shift their productions to another jurisdiction where disclosure requirements are laxer. Accordingly, considering the effects of reverse leakage, mandating disclosure of *both* direct and indirect emissions may not *necessarily* benefit the total surplus.

Proposition 2 also suggests that introducing *indirect* emissions disclosures improves the total surplus *if and only if* the precision of measuring *direct* emissions is sufficiently high.[27] Moreover, as the precision of indirect emissions measurements improves, the precision of measuring direct emissions must increase in order to make the improved indirect emissions disclosures surplus-enhancing. Note that this result stands in stark contrast to the conventional wisdom that higher-quality indirect emissions disclosures should be mandated in *more* situations regardless of the quality of direct emissions disclosures. To see the intuition, recall that emissions leakage is most severe if the quality of direct emissions disclosures is sufficiently high and/or the quality of indirect emissions disclosures is sufficiently poor. Conversely, reverse leakage is of greater concern if the quality of the indirect emissions disclosure improves and/or that of the direct emissions disclosure deteriorates. Therefore, it is socially desirable to mandate the disclosure of indirect emissions when direct emissions measurement is more precise but indirect emissions measurement is less so, and thus the concern of emissions leakage dominates relative to that of reverse emissions leakage, and vice versa.

Optimal precision of measuring direct emissions An implication of Proposition 2 is that the costs and benefits of introducing disclosures of indirect emissions are ambiguous and, importantly, depend on the precision of measuring direct emissions. Arguably, regulators enjoy some discretion of governing the precision of measuring direct emissions; for instance, regulators may require firms to collect more information (or install more precise emission monitoring systems) regarding emissions within their regulatory jurisdictions. Given that regulators have the flexibility of tailoring the precision of measuring direct emissions, how should they choose such precision optimally to balance the considerations of both emissions leakage and reverse emissions leakage? Perhaps more importantly, could regulators tailor the precision of measuring direct emissions optimally to the measurements of indirect emissions, thus eliminating the adverse effects of indirect emissions measurements? To answer these questions, we next derive the optimal precision of measuring direct emissions.

Substituting the equilibrium production choices $\{q^*, f^*\}$ in Proposition 1 into the total surplus in (9) yields the equilibrium total surplus $W^{commingled} \equiv W(q^*, f^*)$, where "*commingled*" stands

[27] Note that the threshold $\hat{\beta}_D$ defined in Proposition 2 can be negative for certain parameter values. For instance, when β_{IC} is sufficiently small, $\hat{\beta}_D$ is negative, in which case introducing the commingled indirect emissions disclosure always improves the total surplus. Intuitively, this is the case when reverse leakage is of the least concern.

that the Scope-1-for-all regime includes the Scope 1 emissions disclosure by the supplier that equals the commingled indirect emissions of all firms. Note that changing the precision of direct emissions measurement β_D affects the equilibrium surplus only indirectly through shifting firms' equilibrium production choices. Accordingly, taking the first-order condition of $W^{commingled}$ with respect to β_D yields

$$\frac{\partial q^*}{\partial \beta_D}\frac{\partial W^{commingled}}{\partial q^*} + \frac{\partial f^*}{\partial \beta_D}\frac{\partial W^{commingled}}{\partial f^*} = 0. \tag{16}$$

Note that the terms $\frac{\partial W^{commingled}}{\partial q^*}$ and $\frac{\partial W^{commingled}}{\partial f^*}$ represent the marginal effects of firms' production choices on the total surplus. Recall from Corollary 1 that increasing firms' equilibrium production choices reduces the total surplus, i.e., $\frac{\partial W^{commingled}}{\partial q^*} \leq 0$, and $\frac{\partial W^{commingled}}{\partial f^*} \leq 0$. In addition, recall more direct emissions disclosures discipline firms' internal productions but causes firms to outsource their productions to the supplier, i.e., $\frac{\partial q^*}{\partial \beta_D} \leq 0$ and $\frac{\partial f^*}{\partial \beta_D} \geq 0$. Therefore, the first term in (16) is positive and represents the benefit of improving the direct emissions disclosure in mitigating firms' excessive direct emissions, which increases the total surplus, whereas the second term is negative and represents the endogenous cost of improving the disclosure in inducing excessive indirect emissions, which impairs the total surplus. Solving the first-order condition (16) yields the optimal precision β_D^* of measuring direct emissions that we characterize next.

Proposition 3 *Given the precision β_{IC} of commingled indirect emissions measurement, the optimal precision of measuring direct emissions $\beta_D^*(\beta_{IC})$ is set as follows:*

- *If $\beta_{IC} \geq 1 - \frac{k_P(N-1)}{c_s(k_T+k_P N)}$, $\beta_D^*(\beta_{IC}) = 1\ \forall \beta_{IC}$.*
- *Otherwise, if $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_P N)}$,*

$$\beta_D^*(\beta_{IC}) = \frac{(k_T + k_P N)(1 - c_s(1-\beta_{IC}))}{k_T + k_P} \in (0,1)\ \forall \beta_{IC}.$$

$\beta_D^*(\beta_{IC})$ increases in the precision of commingled indirect emissions measurement, i.e., $\frac{\partial \beta_D^*}{\partial \beta_{IC}} \geq 0$.

A main take-away of Proposition 3 is that the regulator should tailor the optimal choice of the precision of measuring direct emissions to the precision of indirect emissions measurements. When firms' disclosures of indirect emissions become more precise, the regulator should also require more precise disclosure of their direct emissions. Stated differently, direct emissions disclosure is a *complement rather than a substitute*, to indirect emissions disclosure, and vice versa. In this light, our analysis sends a word of caution against some popular beliefs calling for greater disclosure of direct emissions (Scope 1 emissions) despite the lack of reliable indirect emissions disclosure (Scope 3 emissions), or even to compensate for such lack of disclosure.

The intuition for Proposition 3 lies, again, in the considerations of emissions leakage and reverse emissions leakage. When the indirect emissions disclosure is relatively poor, i.e., β_{IC} is small so that the main concern is emissions leakage, the regulator should mandate a lower precision of direct emissions measurement to mitigate firms' incentives to shift their productions to the supplier. Conversely, as the quality of indirect emissions disclosures improves, i.e., as β_{IC} increases, the concern of reverse emissions leakage looms larger. Accordingly, anticipating the increase in firms' direct emissions (triggered by the reverse emissions leakage), the regulator should raise the disclosure requirements β_D of direct emissions to discipline firms' incentives of shifting production to their internal facilities.

Proposition 3 suggests that regulators should *not* set the disclosure requirements in their own jurisdictions in isolation. Instead, much like that addressing climate risk requires global cooperation, regulators must also keenly coordinate their disclosure policies with their counterparts across the globe. In particular, our analysis cautions against unilateral increases in emissions disclosure requirements in developed countries, as evidenced by recent regulatory moves in Europe and the United States, especially considering that high-quality emission data in developing countries that are parts of the global supply chain is relatively sparse and even lacking.

Lastly, we revisit the question of whether the regulator should require both direct and indirect emissions disclosures when setting the measurement precision optimally. Toward this end, we again compare the total surpluses between the Scope-1-for-all regime and one that excludes firms' indirect emissions (i.e., the supplier's Scope 1 emissions), evaluated at the optimal measurement precision, $\beta_D^*(\beta_{IC})$ and $\beta_D^*(\beta_{IC}=0)$, respectively. Our analysis shows that, while introducing the indirect emissions disclosure may hurt the total surplus for a *given* precision of measuring direct emissions, such downsides are eliminated when the regulator sets the measurement precision *optimally*. The following proposition establishes that at the optimal measurement precision, introducing the indirect emissions disclosure always improves the total surplus.

Proposition 4 *When the regulator optimally tailors the precision of measuring firms' direct emissions under the Scope-1-for-all regime, including the indirect emissions disclosure always improves the ex ante total surplus, i.e.,* $W^{commingled} \geq W^{direct}$.

Comparing and contrasting Propositions 2 and 4 yields the implications of our analysis for mandating disclosure of firms' indirect emissions, which is a key policy choice that regulators are contemplating. We show that the desirability of such mandate hinges critically on regulators' capability to set the disclosure policy regarding direct emissions optimally. While regulators arguably enjoy certain discretion in tailoring their measurement and disclosure requirements, regulators likely face high hurdles in implementing the optimal disclosure policy regarding direct emissions, especially considering that, by Proposition 3, setting the optimal disclosure requires significant regulatory flexibility of tailoring disclosure requirements to various parameters in firms' environments, including coordinating emissions disclosure with other jurisdictions. In this light, our result may help to reconcile the varying policy decisions towards mandating indirect emissions disclosure by regulators in Europe and in the United States.

3.4 Scope-1-for-all vs. Scopes-1-and-3 regimes

A major concern that plagues the disclosure of indirect emissions is that multiple firms often share a common supplier, where the supplier only collects and reports the total emissions. In this case, one may argue that, from an information standpoint, each firm should attempt to separate and allocate the total emissions into the portion attributable to the firm itself (Greenhouse Gas Protocol, 2011). To shed light on the costs and benefits of such allocation, we now analyze the equilibrium outcomes in the Scopes-1-and-3 regime and then compare it with those in the Scope-1-for-all regime.

Separating indirect emissions without double counting A key measurement friction in separating indirect emissions is the issue of double counting, i.e., the total emissions by the supplier y_F does not necessarily equal the aggregate of all downstream firms' reports of separated indirect emissions, $\sum_{i=1}^{N} y_{iF} \neq y_F$. Before investigating the implications of double-counting, we first consider a benchmark without double counting in allocating indirect emissions.

Specifically, each firm i reports a noisy signal about its direct emissions $y_i = e_i + \varepsilon_i$ and a noisy signal about the portion of indirect emissions attributable to the firm itself $y_{iF} = e_{iF} + \omega_i$, as specified in the Scopes-1-and-3 regime of the Model section. In addition, we impose the no-double-counting requirement that $\sum_{i=1}^{N} y_{iF} = y_F$. Note that with this requirement, one of the firms' indirect emissions signals $\{y_{iF}\}_{i=1}^{N}$ becomes redundant (i.e., contains no incremental information conditional on the other signals); accordingly, there are $N-1$ relevant signals about separated indirect emissions, and the total indirect emissions y_F. Without loss of generality, we assume that the last signal y_{NF} is redundant. For simplicity, we continue to assume that the noise terms ω_i in the remaining $N-1$ signals of y_{iF} are independent of all other random variables.

It is straightforward to see that, absent double counting, the Scopes-1-and-3 regime provides strictly more information than in the Scope-1-for-all regime. In the latter regime, the market learns a single signal y_F about firms' total indirect emissions, whereas in the former regime, the market not only recovers the reported total indirect emissions y_F by aggregating all firms' reports of indirect emissions, but also learns additional noisy signals $\{y_{iF}\}_{i=1}^{N-1}$ about each firm's allocation of indirect emissions. This, in turn, enhances the efficiency of pricing firms' emissions and thus disciplines their productions in the Scopes-1-and-3 regime. We next summarize this result.

Proposition 5 *Suppose that there is no double counting in separating indirect emissions, i.e.,* $\sum_{i=1}^{N} y_{iF} = y_F$. *At the optimal precision of measuring direct emissions in each regime, the Scope-1-and-3 regime always yields a higher total surplus than the Scope-1-for-all regime.*

Proposition 5 thus lends some support to policy initiatives towards separating indirect emissions, as long as such separation entails no double counting.[28] This result thus echoes the calls for measuring and disclosing firms' shares of Scope 3 emissions in the supply chain. Nonetheless, observers also recognize the prevalence of double counting in the practice of allocating indirect emissions (e.g., Shrimali, 2021), an issue we turn to next.

Separating indirect emissions with double counting We first derive the market price P_{i1} given the information available to the market. The market price is the same as the one in (11), except that besides using the disclosure of direct emissions, the market now additionally uses

[28] In practice, firms could be strategic in measuring and allocating their share of indirect emissions. In addition to the double counting issue that we study, such misallocation could arguably make separating emissions even less desirable. To focus on the reliability of emissions measurements, we do not consider firms' strategic allocations in the main analysis. However, as an extension to our main model, in an online Appendix, we analyze a setting in which heterogeneous firms misallocate their shares of indirect emissions. We thank an anonymous reviewer for bringing up this point.

the disclosure of separated indirect emissions, i.e., $\{y_j, y_{jF}\}_{j=1}^{N}$, to infer firms' direct and indirect emissions. Note first that the market's estimates of the direct emissions e_i are identical to those in the Scope-1-for-all regime. Nonetheless, because the market now receives a separate disclosure of each firm's allocation of the total indirect emissions, its estimates of firms' indirect emissions e_{iF} differ. We write such estimates as

$$E_1\left[\widetilde{e}_{iF}|y_{iF}, \hat{f}_i\right] = \hat{f}_i + \beta_{IS}\left(y_{iF} - \hat{f}_i\right), \tag{17}$$

where the weight $\beta_{IS} \equiv \frac{\sigma_F^2}{\sigma_F^2+\sigma_\omega^2} \in [0,1]$ placed on the separated indirect emissions disclosures captures the precision of such disclosure.

Lastly, the market aggregates its estimates of the emissions from all individual firms' productions, i.e., (12) and (17), and computes the total emissions of all productions as

$$E_1\left[\sum_{j=1}^{N}(\widetilde{e}_j + \widetilde{e}_{jF})\,|\left\{y_j, y_{jF}, \hat{q}_j, \hat{f}_j\right\}_{j=1}^{N}\right] = \sum_{j=1}^{N}\hat{q}_j + \sum_{j=1}^{N}\hat{f}_j + \beta_D\sum_{j=1}^{N}(y_j - \hat{q}_j) + \beta_{IS}\sum_{j=1}^{N}\left(y_{jF} - \hat{f}_j\right). \tag{18}$$

Given the market's estimates of firms' emissions and long-term losses, we solve firms' equilibrium production plans, denoted by $\{q^{**}, f^{**}\}$, and the regulator's optimal choice of the precision of direct emissions measurement, denoted by β_D^{**}, in the Scopes-1-and-3 regime, following a procedure similar to the one used in the Scope-1-for-all regime. For brevity, we omit the detailed derivations and state the equilibrium outcomes in the following proposition.

Proposition 6 *Given the precision β_{IS} of separated indirect emissions measurement, and the precision β_D of the direct emissions measurement, each firm's equilibrium production plan is*

$$q^{**} = \frac{1-(k_T+k_P)\beta_D - c_s(1-(k_T+k_P)\beta_{IS})}{1-c_s^2} > 0,$$

and

$$f^{**} = \frac{1-(k_T+k_P)\beta_{IS} - c_s(1-(k_T+k_P)\beta_D)}{1-c_s^2} > 0.$$

Given the precision β_{IS} of separated indirect emissions measurement, the optimal precision $\beta_D^{**}(\beta_{IS})$ of the direct emissions measurement is as follows.

- *If* $\beta_{IS} \geq \frac{c_s(k_T+k_P N)-k_P(N-1)}{c_s(k_T+k_P)}$, $\beta_D^{**}(\beta_{IS}) = 1 \ \forall \beta_{IS}$.
- *Otherwise, if* $\beta_{IS} < \frac{c_s(k_T+k_P N)-k_P(N-1)}{c_s(k_T+k_P)}$,

$$\beta_D^{**}(\beta_{IS}) = \frac{(k_T + k_P N)(1 - c_s) + c_s(k_T + k_P)\beta_{IS}}{k_T + k_P} \in (0, 1) \ \forall \beta_{IS}.$$

Moreover, $\beta_D^{**}(\beta_{IS})$ *increases in the indirect emissions measurement precision, i.e.,* $\frac{\partial \beta_D^{**}}{\partial \beta_{IS}} \geq 0$.

A comparison of Propositions 3 and 6 illustrates that many implications of our analysis in the Scope-1-for-all regime extend to those in the Scopes-1-and-3 regime. For instance, the effects of both emissions leakage and reverse emissions leakage are still present when indirect emissions are allocated to firms, i.e., firms' productions f^{**} outsourced to the supplier increase in the precision β_D of the direct emissions measurement and firms' internal productions q^{**} increase in the precision β_{IS} of the separated indirect emissions measurement. The presence of emissions leakage and reverse emissions leakage, in turn, implies that the regulator should still tailor the optimal precision choice β_D^{**} of direct emissions measurement to β_{IS}, the precision of the separated indirect emissions measurement.

With the equilibrium in the Scopes-1-and-3 regime characterized, we next compare the total surplus of the Scopes-1-and-3 and the Scope-1-for-all regimes in order to characterize the conditions under which separating indirect emissions is desirable.

Proposition 7 *At the optimal precision of direct emissions measurement in each regime, relative to the Scope-1-for-all regime, separating indirect emissions improves the total surplus, i.e.,* $W^{separated} \geq W^{commingled}$, *if and only if*

$$\frac{\beta_{IS}}{\beta_{IC}} \geq \frac{k_T + k_P N}{k_T + k_P}.$$

Separating indirect emissions improves total surplus relative to leaving them commingled when

1. *either the precision of the separated indirect emissions measurement* β_{IS} *is sufficiently high, or the precision of the commingled indirect emissions measurement* β_{IC} *is sufficiently low, and/or*

2. *firms' exposures to transition climate risk k_T are sufficiently large, or their exposures to physical climate risk k_P are sufficiently small.*

The first part of Proposition 7 captures concerns often made about the reliability of measuring indirect emissions: whenever reporting commingled indirect emissions already conveys high-quality information but separation entails material measurement errors, forcing firms to report separated indirect emissions may impair market discipline and reduce social surplus. Conversely, if separation of indirect emissions generates highly precise disclosures of each firm's allocation of indirect emissions (i.e., the noise ω_i is small), then separation is desirable as it improves the market discipline of firms' production choices and improves the total surplus.

The second part of Proposition 7 states that the costs and benefits of allocating indirect emissions to individual firms depend not only on the reliability of the different reporting regimes, but also on firms' relative exposures to different types of climate risks. Separating indirect emissions is more likely to be socially desirable if firms are more exposed to transition climate risk. The intuition for this result is as follows. Recall that when a firm is more exposed to transition climate risk relative to physical climate risk (i.e., k_T is large relative to k_P), its long-term environmental loss depends more on its own emissions, as opposed to the total emissions by all firms. Accordingly, estimating the firm' long-term environmental loss requires precise information about the firm's own share of indirect emissions, where the separated indirect emissions disclosure excels. Conversely, when a firm is relatively more exposed to physical climate risk (i.e., k_P is large relative to k_T), its long-term environmental loss is driven more by the total indirect emissions of all firms, regarding which the commingled indirect emissions disclosure contains relatively more information.

Our analysis speaks to the policy debate on the two approaches towards measuring greenhouse gas emissions. Many observers favor a "simple and clear" solution that requires only Scope 1 emissions for all firms.[29] Our analysis supports these arguments insofar when separating indirect emissions induces significant measurement errors. In addition, our analysis yields a new insight. Given the issues of emissions leakages and reverse emissions leakages (especially in the context of the

[29] For instance, Leuz (2022) notes that "the simplest and clearest measure is Scope 1. To be sure, by being the narrowest emissions-reporting option, it creates the strongest incentives for shifting activities. However, it doesn't include other companies' emissions, so avoids double counting at the aggregate level. Moreover, if all companies worldwide, public and private, were to report their Scope 1 emissions, all corporate emissions would be accounted for somewhere, and one could add up reported emissions to obtain the total corporate emissions of a sector or an economy." Heal (2023) makes a similar point.

global supply chain), firms' relative exposures to different types of climate risk (e.g., transition climate risk vs. physical climate risk) also play important roles in determining the preferred approach for measuring and reporting emissions. In particular, our analysis suggests that regulators should adopt a measurement system with both Scope 1 and Scope 3 emissions in industries where firms are primarily exposed to transition climate risk (e.g., oil and gas companies). Conversely, regulators should favor a Scope-1-for-all measurement system in industries where physical climate risk is the main source of climate risk (e.g., agriculture, aquaculture, and fishing industries). In this regard, a policy implication of our study is that the disclosure standards for indirect emissions should be industry-specific. The latter implication echoes the industry approach that underlies some current sustainability reporting standards such as the ones set by the Sustainability Accounting Standards Board.[30]

3.5 Firms' choices of direct emissions precision

In our main analysis, we have argued that due to environmental externalities, firms do not have sufficient private incentives to disclose information about their emissions and thus focused on studying *mandatory* disclosures of firms' greenhouse gas emissions and their economic consequences. We now formally establish this result by analyzing firms' private choices of the precision of direct emissions measurements in the Scope-1-for-all regime.[31] The analysis is similar to that in the main model so we provide it in the Appendix. The following lemma characterizes firms' equilibrium choices of the precision of direct emissions measurement.

Lemma 3 *Denote each firm's equilibrium choice of the precision of direct emissions measurement as β_D^{firm}. We have*

$$\beta_D^{firm}(\beta_{IC}) = \frac{(k_T + k_P)(1 - c_s) + c_s(k_T + k_P N)\beta_{IC}}{k_T + k_P} \in (0, 1)\ \forall \beta_{IC}.$$

[30] For instance, the Sustainability Accounting Standards Board (SASB) advocates for an "industry-specific" approach in setting sustainability reporting standards, and "develops sustainability disclosure standards at the industry level, focusing on issues that are closely tied to resource use, sustainability impacts, business models, regulation, and other factors at play in the industry." (SASB, 2022)

[31] Considering the fragmentation in climate reporting, it is likely more challenging for firms to privately influence the precision of measuring their indirect emissions (i.e., the supplier's Scope 1 emissions), since these indirect emissions occur during the production of the supplier. Accordingly, we focus on analyzing firms' private choices of the direct emissions disclosure precision β_D, fixing the commingled indirect emissions disclosure precision β_{IC}. The analysis of firms' precision choices in the Scope-1-and-3 regime is analogous so we omit it for brevity.

Moreover, the ex ante total surplus is larger under firms' equilibrium choices than when the direct emissions measurement is absent (i.e., $\beta_D = 0$).

Lemma 3 confirms that, in the present of measurement frictions, firms do indeed have private incentives to disclose their direct emissions. The intuition is straightforward. Relative to no disclosure, firms' disclosure of direct emissions mitigates the measurement frictions about their emissions and improves market pricing, which motivates firms to disclose in the first place.

We next compare firms' *private* choices of measurement precision with the optimal mandatory measurement precision given in Proposition 3. The following proposition implies that, in the presence of externalities, firms' private incentives to disclose are insufficient and mandating more disclosure (at least weakly) improves the total surplus.

Proposition 8 *The comparison between the firms' choices of direct emissions measurement precision β_D^{firm} and the optimal measurement precision β_D^* is as follows.*

- *Absent externalities, i.e., $k_P \to 0$, firms' choices of measurement precision coincide with the optimal mandatory measurement precision, i.e., $\beta_D^{firm} \to \beta_D^*$.*
- *With externalities, i.e., $k_P > 0$, firms' choices of measurement precision are less than the socially optimal ones, i.e., $\beta_D^{firm} < \beta_D^*$.*

Proposition 8 is intuitive. Absent externalities, since firms are symmetric, maximizing each firm's individual payoff is isomorphic to maximizing the total of all firms' payoffs. Accordingly, firms' private choices of measurement precision coincide with the optimal mandatory measurement precision. In the presence of externalities, however, more disclosure of an individual firm's direct emissions affects not only the firm's own payoff but also the long-term losses for all the other firms. As long as some disclosure of direct emissions is beneficial (i.e., when the risk of emissions leakage is not too severe, or, equivalently, when the precision of the commingled indirect emissions measurement β_{IC} is sufficiently large), firms' private choices of the direct emissions measurement precision are lower than the socially optimal level, because firms do not internalize the benefits of the disclosure in lowering the long-term environmental losses of the others. In this light, Proposition 8 provides a justification for the role of mandatory disclosures in regulating firms' climate-related disclosure, as studied in our main analysis.

4 Conclusions and Discussions

We study the costs and benefits of climate-related disclosures in a setting in which the quality and enforcement of disclosure policies vary across jurisdictions. We believe our framework provides a natural first step in understanding the role that market prices play in disciplining firms' polluting incentives to the extent that 1) regulators such as the SEC require the public dissemination of climate-related information to all market participants because these participants would price any financially material information, and 2) firms care about the pricing of climate risks that affect their future cash flows and could plausibly take actions to mitigate negative pricing impacts.

By adopting a financial-materiality perspective, an important limitation of our study is that we focus exclusively on climate disclosure regulation and do not consider other tools such as carbon taxes and/or tradeable pollution permits. Arguably, the latter tools may have more direct impacts on firms' polluting incentives so that disclosure might not be a substitute for more targeted regulation. However, relative to other climate regulatory tools, we believe that disclosure is potentially less intrusive. It is therefore important to empirically quantify the magnitude of the disclosure tool that we study and compare it with that of other tools such as carbon taxes or caps. Moreover, we believe that what makes disclosure different from other climate tools is that proper measurement and disclosure of direct and indirect emissions sustains the efficacy of many other tools.[32] We hope that future research could adapt our framework to study the interaction of climate disclosure regulation with other climate regulatory tools.

Another key assumption of our paper is the presence of fragmented climate regulatory landscape. Regulations cannot cross jurisdictions as firms' operations do: firms in one jurisdiction can therefore avoid undesirable regulation by outsourcing to suppliers in another jurisdiction especially when the quality and enforcement of environmental standards vary across jurisdictions. To understand the root cause of such fragmentation, as a natural follow-up to our study, one could model the political economy of regulations, i.e., the determinants of regulators' dispersed incentives in different jurisdictions.

Finally, by analyzing and deriving some properties of the optimal measurement system for car-

[32] For instance, a motivation for introducing emissions disclosures in the EU is to support the carbon trading system. In particular, EU (2024) notes "The monitoring and reporting of greenhouse gas emissions must be robust, transparent, consistent and accurate for the EU emissions trading system (EU ETS) to operate effectively."

bon emissions, we believe our analysis can generate implications for designing carbon accounting systems in practice. However, the *exact* implementation of the optimal measurement system is beyond the scope of our paper. Interestingly, recent studies such as Kaplan and Ramanna (2021), Reichelstein (2022), and Penman (2024) have begun to explore the implementation of carbon accounting systems grounded in fundamental accounting structures and principles. A promising venue for future research, in our view, is then to build the properties of the optimal measurement system implied by our economic analysis into the ongoing development of carbon accounting systems.

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Appendix: Proofs

Proof. of Lemma 1: Substituting (1) and (4) into (9) yields the social planner's optimization problem

$$\max_{\{q_i,f_i\}_{i=1}^N} W = \sum_{i=1}^N \left\{ q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T(q_i + f_i) - k_P \sum_{j=1}^N (q_j + f_j) \right\}.$$

All the firms are *ex-ante* identical and the social planner therefore sets $q_i = q$ and $f_i = f$ for firm $i \in \{1, ..., N\}$. Taking the first-order conditions with respect to q and f yields

$$\begin{aligned} 1 - q - c_s f - k_T - k_P N &= 0, \\ 1 - f - c_s q - k_T - k_P N &= 0. \end{aligned}$$

Solving the first-order conditions yields the first-best production choices in the lemma. The condition $q^{FB} > 0$ is equivalent to

$$1 - k_T - k_P N > 0,$$

which is satisfied given our assumption in (8). Next, taking the second-order conditions yields

$$\begin{aligned} \frac{\partial^2 W}{\partial q^2} &= -N < 0, \\ \frac{\partial^2 W}{\partial f^2} &= -N < 0, \\ \frac{\partial^2 W}{\partial q \partial f} &= -N c_s < 0. \end{aligned}$$

We obtain $\frac{\partial^2 W}{\partial q^2}\frac{\partial^2 W}{\partial f^2} - \left(\frac{\partial^2 W}{\partial q \partial f}\right)^2 = N^2(1 - c_s^2)$, which is positive given our assumption in (8). Therefore, $\{q^{FB}, f^{FB}\}$ is a maximum. ■

Proof. of Lemma 2: Firm i's maximization problem at $t = 0$ is

$$\max_{q_i, f_i} E_0 [P_{i1}],$$

which can be rewritten as

$$\max_{q_i,f_i} E_0\left[z_{i1} - E_1\left[\Phi_i|e_i, e_{-i}, f_i + \gamma_{iF}, f_{-i} + \gamma_{-iF}\right]\right],$$

which is equivalent to

$$\max_{q_i,f_i} E_0\left[X_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - E_1\left[k_T(e_i + f_i + \gamma_{iF}) + k_P(e_F + \sum_{j=1}^{N} e_j)|e_i, e_{-i}, f_i + \gamma_{iF}, f_{-i} + \gamma_{-iF}\right]\right].$$

Thus, firm i's maximization problem becomes

$$\max_{q_i,f_i} q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T(q_i + f_i) - k_P\left(\sum_{j=1}^{N} q_j + f_j\right).$$

Taking the first-order condition with respect to q_i yields

$$1 - q_i - c_s f_i - k_T - k_P = 0.$$

Similarly, taking the first-order condition with respect to f_i yields

$$1 - f_i - c_s q_i - k_T - k_P = 0.$$

Solving the first-order conditions yields the full information production choices $q_i = q^{FI}$ and $f_i = f^{FI}$ in the lemma. Next, taking the second-order conditions yields

$$\begin{aligned} \frac{\partial^2 E_0[P_{i1}]}{\partial q_i^2} &= -1 < 0, \\ \frac{\partial^2 E_0[P_{i1}]}{\partial f_i^2} &= -1 < 0, \\ \frac{\partial^2 E_0[P_{i1}]}{\partial q_i \partial f_i} &= -c_s < 0. \end{aligned}$$

We obtain $\frac{\partial^2 E_0[P_{i1}]}{\partial q_i^2}\frac{\partial^2 E_0[P_{i1}]}{\partial f_i^2} - \left(\frac{\partial^2 E_0[P_{i1}]}{\partial q_i \partial f_i}\right)^2 = 1 - c_s^2$, which is positive given our assumption in (8). Therefore, $\{q^{FI}, f^{FI}\}$ is a maximum.

Moreover, we have $q^{FI} \geq q^{FB}$ if and only if

$$\frac{1 - k_T - k_P}{1 + c_s} \geq \frac{1 - k_T - k_P N}{1 + c_s},$$

which is always satisfied given that $N \geq 2$.

At $t = 0$, firms' total surplus is given by

$$\begin{aligned} W &= \sum_{i=1}^{N} E_0 \left[X_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T(e_i + f_i + \gamma_{iF}) - k_P \left(e_F + \sum_{j=1}^{N} e_j \right) \right] \\ &= \sum_{i=1}^{N} \left[q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T(q_i + f_i) - k_P \sum_{j=1}^{N} (q_j + f_j) \right]. \end{aligned}$$

Substituting for $q_i = q^{FB}$ and $f_i = f^{FB}$, yields the total surplus in the first-best regime

$$\begin{aligned} W^{FB} &= N \left[q^{FB} + f^{FB} - \frac{(q^{FB})^2}{2} - \frac{(f^{FB})^2}{2} - c_s q^{FB} f^{FB} - k_T(q^{FB} + f^{FB}) - k_P N \left(q^{FB} + f^{FB} \right) \right] \\ &= N \frac{(1 - k_T - k_P N)^2}{1 + c_s}. \end{aligned}$$

Furthermore, substituting for $q_i = q^{FI}$ and $f_i = f^{FI}$ yields

$$\begin{aligned} W^{FI} &= N \left[q^{FI} + f^{FI} - \frac{(q^{FI})^2}{2} - \frac{(f^{FI})^2}{2} - c_s q^{FI} f^{FI} - k_T(q^{FI} + f^{FI}) - k_P N \left(q^{FI} + f^{FI} \right) \right] \\ &= \frac{N(1 - k_T - k_P)(1 - k_T - k_P(2N - 1))}{1 + c_s} \\ &= W^{FB} - \frac{k_P^2 N (N - 1)^2}{1 + c_s}. \end{aligned}$$

■

Proof. of Proposition 1: Differentiating (15) with respect to q_i and f_i yields

$$1 - q_i - c_s f_i - \beta_D (k_T + k_P) = 0, \tag{19}$$

and

$$1 - f_i - c_s q_i - \beta_{IC} (k_T + k_P N) = 0. \tag{20}$$

Solving the first-order conditions yields:

$$q^* = \frac{1-(k_T+k_P)\beta_D - c_s(1-(k_T+k_PN)\beta_{IC})}{1-c_s^2}$$

and

$$f^* = \frac{1-(k_T+k_PN)\beta_{IC} - c_s(1-(k_T+k_P)\beta_D)}{1-c_s^2}.$$

The condition $q^* > 0$ is equivalent to

$$1-(k_T+k_P)\beta_D > c_s(1-(k_T+k_PN)\beta_{IC}),$$

which is satisfied given that our assumption in (8) implies $1-k_T-k_P > c_s$. Similarly, the condition $f^* > 0$ is equivalent to

$$1-(k_T+k_PN)\beta_{IC} > c_s(1-(k_T+k_P)\beta_D),$$

which is satisfied given that our assumption in (8) implies $1-k_T-k_P > c_s$. Using similar steps as in the proof of Lemma 2, one can easily check that $\{q^*, f^*\}$ is a maximum by deriving the second-order conditions. ■

Proof. of Corollary 1:

Recall that

$$W(q,f) = N\left[q+f-\frac{q^2}{2}-\frac{f^2}{2}-c_sqf-k_T(q+f)-k_PN\,(q+f)\right].$$

Thus, using the first-order conditions in (19) and (20), we get

$$\begin{aligned}\frac{\partial W}{\partial q}|_{q=q^*,f=f^*} &= N(1-q^*-c_sf^*-k_T-k_PN)\\ &= N(\beta_D(k_T+k_P)-k_T-k_PN) \leq 0\end{aligned}$$

and

$$\begin{aligned}\frac{\partial W}{\partial f}|_{q=q^*,f=f^*} &= N(1-f^*-c_sq^*-k_T-k_PN)\\ &= N(\beta_{IC}\,(k_T+k_PN)-k_T-k_PN) \leq 0.\end{aligned}$$

The two inequalities follow directly given that $\beta_D \in [0,1]$ and $\beta_{IC} \in [0, 1/N]$.

Moreover, the condition $q^* + f^* \geq q^{FB} + f^{FB}$ is equivalent to

$$\frac{1-(k_T+k_P)\beta_D - c_s(1-(k_T+k_PN)\beta_{IC})}{1-c_s^2} + \frac{1-(k_T+k_PN)\beta_{IC} - c_s(1-(k_T+k_P)\beta_D)}{1-c_s^2} \geq 2\frac{(1-k_T-k_PN)(1-c_s)}{1-c_s^2},$$

which is equivalent to

$$(1-c_s)((k_T+k_PN)-(k_T+k_P)\beta_D) + (1-c_s)(k_T+k_PN)(1-\beta_{IC}) \geq 0.$$

This last condition is always satisfied given that our assumption in (8) implies $1 > c_s$.

Finally, the condition $E_0\left[\sum_{i=1}^N \Phi_i(q^*, f^*)\right] \geq E_0\left[\sum_{i=1}^N \Phi_i(q^{FB}, f^{FB})\right]$ is equivalent to

$$N(k_T+k_PN)(q^*+f^*) \geq N(k_T+k_PN)(q^{FB}+f^{FB}),$$

which is always satisfied given that $q^* + f^* \geq q^{FB} + f^{FB}$. ■

Proof. of Corollary 2: The comparative statics of $\{q^*, f^*\}$ can be observed directly from their expressions. ■

Proof. of Proposition 2: The first two parts follow directly from the comparative statics of $\{q^*, f^*\}$ with respect to β_{IC} as given in Proposition 1. To prove the last part regarding the surplus comparison, we first derive the equilibrium production choices under the direct-emission-only regime by substituting $\beta_{IC} = 0$ into $\{q^*, f^*\}$ in Proposition 1, which yields

$$q^{direct} = \frac{1-(k_T+k_P)\beta_D - c_s}{1-c_s^2}$$

and

$$f^{direct} = \frac{1-c_s(1-(k_T+k_P)\beta_D)}{1-c_s^2}.$$

Substituting $\left\{q^{direct}, f^{direct}\right\}$ and $\{q^*, f^*\}$ into the *ex ante* total surplus W in (9) yields the total surplus under the direct-emission-only and the Scope-1-for-all regimes, W^{direct} and $W^{commingled}$, respectively. Taking the difference of the two surpluses yields

$$\begin{aligned} & W^{commingled} - W^{direct} \\ = & \frac{N(k_T + k_P N)(2c_s(k_T + k_P)\beta_D + (k_T + k_P N)(2 - \beta_{IC}) - 2c_s(k_T + k_P N))\beta_{IC}}{2(1 - c_s^2)}. \end{aligned} \quad (21)$$

Hence $W^{commingled} \geq W^{direct}$ if and only if

$$2c_s(k_T + k_P)\beta_D + (k_T + k_P N)(2 - \beta_{IC}) - 2c_s(k_T + k_P N) \geq 0,$$

which is equivalent to

$$\beta_D \geq \frac{2(k_T + k_P N) - \frac{1}{c_s}(k_T + k_P N)(2 - \beta_{IC})}{2(k_T + k_P)}.$$

■

Proof. of Proposition 3: Using the total surplus in (9), we can rewrite (16) as

$$\frac{\partial q^*}{\partial \beta_D}(1 - q^* - c_s f^* - k_T - k_P N) + \frac{\partial f^*}{\partial \beta_D}(1 - f^* - c_s q^* - k_T - k_P N) = 0. \quad (22)$$

Using the equilibrium production choices $\{q^*, f^*\}$ in Proposition 1, we obtain

$$\frac{\partial f^*}{\partial \beta_D} = \frac{c_s(k_T + k_P)}{1 - c_s^2} = -c_s \frac{\partial q^*}{\partial \beta_D}. \quad (23)$$

Substituting $\{q^*, f^*\}$ and (23) into (22) and solving the equation yield

$$\beta_D = \frac{(k_T + k_P N)(1 - c_s(1 - \beta_{IC}))}{k_T + k_P} \geq 0.$$

To complete the proof, we derive the second-order condition of the maximization problem

$$\begin{aligned} \frac{1}{N}\frac{\partial^2 W}{\partial \beta_D^2} = & \frac{\partial^2 q^*}{\partial \beta_D^2}[(1 - k_T - k_P N) - c_s(1 - k_T - k_P N) - q^* + f^* c_s - c_s f^* + c_s q^* c_s] \\ & - \left(\frac{\partial q^*}{\partial \beta_D}\right)^2 - \left(\frac{\partial f^*}{\partial \beta_D}\right)^2 - 2c_s \frac{\partial q^*}{\partial \beta_D}\frac{\partial f^*}{\partial \beta_D}. \end{aligned} \quad (24)$$

At the optimal $\beta_D = \beta_D^*$, $\frac{\partial W}{\partial \beta_D} = 0$. Thus, we get

$$\begin{aligned}
\frac{1}{N}\frac{\partial^2 W}{\partial \beta_D^2} &= -\left(\frac{\partial q^*}{\partial \beta_D}\right)^2 - \left(\frac{\partial f^*}{\partial \beta_D}\right)^2 - 2c_s \frac{\partial q^*}{\partial \beta_D}\frac{\partial f^*}{\partial \beta_D} \\
&\leq -c_s\left(\frac{\partial q^*}{\partial \beta_D}\right)^2 - c_s\left(\frac{\partial f^*}{\partial \beta_D}\right)^2 - 2c_s \frac{\partial q^*}{\partial \beta_D}\frac{\partial f^*}{\partial \beta_D} \\
&= -c_s\left(\frac{\partial q^*}{\partial \beta_D} + \frac{\partial f^*}{\partial \beta_D}\right)^2 \\
&\leq 0,
\end{aligned} \tag{25}$$

which implies that $\beta_D = \beta_D^*$ is a maximum. Note that, to have an interior $\beta_D^* \in (0,1)$, we need

$$\frac{1}{c_s} < \frac{(k_T + k_P N)(1-\beta_{IC})}{k_P(N-1)},$$

which is equivalent to

$$\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T + k_P N)},$$

which yields the condition in the proposition. If this condition is not met, $\beta_D^* = 1$.

Lastly, when $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$, taking the derivative of β_D^* with respect to β_{IC} yields

$$\frac{\partial \beta_D^*}{\partial \beta_{IC}} = \frac{c_s(k_T + k_P N)}{k_T + k_P} \geq 0.$$

■

Proof. of Proposition 4: We compare the firm surplus under the direct-emission-only and under the Scope-1-for-all regimes at the optimal direct emissions measurement precision. If $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$, substituting β_D^* in Proposition 3 into the equilibrium total surplus in (9) yields

$$W^{commingled} = W^{FB} - \frac{(k_T + k_P N)^2 (1-\beta_{IC})^2 N}{2},$$

where

$$W^{FB} = N\frac{(1 - k_T - k_P N)^2}{1 + c_s},$$

represents the total surplus evaluated at the first-best production choices. Note that $W^{commingled}$

is increasing in β_{IC}. Similarly, if $\beta_{IC} \geq 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$, at $\beta_D = \beta_D^* = 1$, we get

$$\frac{\partial W^{commingled}}{\partial \beta_{IC}} = -\frac{N(k_T + k_PN)(c_s k_P(N-1) - (k_T + k_PN)(1-\beta_{IC}))}{1 - c_s^2} \geq 0.$$

Accordingly, $W^{commingled} \geq W^{commingled}|_{\beta_{IC}=0}$, where the latter is the total surplus under the direct-emission-only regime. ■

Proof. of Proposition 5: We only solve the equilibrium under the Scopes-1-and-3 regime without double counting, as we have solved the equilibrium under the Scope-1-for-all regime earlier. We solve the model by first deriving the market price of the firm at $t = 1$ given the information available to the market, including the climate-related disclosures, $\{y_j, y_{jF}\}_{j=1}^N$, and the market's conjecture of firms' equilibrium production plans $\left\{\hat{q}_j, \hat{f}_j\right\}_{j=1}^N$. The market price of firm i at $t = 1$ is given by

$$P_{i1} = z_{i1} - k_T E_1[\widetilde{e}_i|y_i, \hat{q}_i] - k_T E_1\left[\widetilde{e_{iF}}|y_{iF}, y_F, \left\{\hat{f}_j\right\}_{j=1}^N\right] - k_P E_1\left[\sum_{j=1}^N (\widetilde{e}_j + \widetilde{e}_{jF}) \mid \left\{y_j, y_{jF}, \hat{q}_j, \hat{f}_j\right\}_{j=1}^N\right].$$

The market uses the direct emissions disclosure y_i and the conjecture of the firm's internal production $\hat{q}_i$ to estimate the direct emissions e_i, i.e.,

$$E_1[\widetilde{e}_i|y_i, \hat{q}_i] = E_1[q_i + \widetilde{\gamma}_i|y_i, \hat{q}_i] = \hat{q}_i + \beta_D(y_i - \hat{q}_i). \tag{26}$$

In addition, the market uses the separated indirect emissions disclosures y_{iF}, the total indirect emission disclosure y_F, and the conjecture of the firms' productions $\left\{\hat{f}_j\right\}_{j=1}^N$ to estimate the indirect emissions e_{iF}, i.e.,

$$E_1\left[\widetilde{e}_{iF}|y_{iF}, y_F, \left\{\hat{f}_j\right\}_{j=1}^N\right] = E_1\left[f_i + \widetilde{\gamma}_{iF}|y_{iF}, y_F, \left\{\hat{f}_j\right\}_{j=1}^N\right].$$

Hence, we get

$$\begin{aligned} E_1\left[f_i + \widetilde{\gamma}_{iF}|y_{iF}, y_F, \left\{\hat{f}_j\right\}_{j=1}^N\right] &= \hat{f}_i + \beta_{ISi}(y_{iF} - E_1\left[y_{iF}|\hat{f}_i\right]) + \beta_{ISF}(y_F - E_1\left[y_F|\left\{\hat{f}_j\right\}_{j=1}^N\right]) \\ &= \hat{f}_i + \beta_{ISi}(y_{iF} - \hat{f}_i) + \beta_{ISF}(y_F - \sum_{j=1}^N \hat{f}_j), \end{aligned}$$

where the coefficients β_{ISi} and β_{ISF} are given by

$$\beta_{ISi} = \frac{cov(f_i + \widetilde{\gamma}_{iF}, y_{iF})var(y_F) - cov(f_i + \widetilde{\gamma}_{iF}, y_F)cov(y_F, y_{iF})}{var(y_F)var(y_{iF}) - cov^2(y_F, y_{iF})}$$

and

$$\beta_{ISF} = \frac{cov(f_i + \widetilde{\gamma}_{iF}, y_F)var(y_{iF}) - cov(f_i + \widetilde{\gamma}_{iF}, y_{iF})cov(y_F, y_{iF})}{var(y_F)var(y_{iF}) - cov^2(y_F, y_{iF})}.$$

Thus, we get

$$\beta_{ISi} = \frac{\sigma_F^2(N\sigma_F^2 + \sigma_{\varepsilon F}^2) - \sigma_F^4}{(N\sigma_F^2 + \sigma_{\varepsilon F}^2)(\sigma_F^2 + \sigma_\omega^2) - \sigma_F^4} = \frac{\beta_{IS}(1 - \beta_{IC})}{1 - \beta_{IS}\beta_{IC}}$$

and

$$\beta_{ISF} = \frac{\sigma_F^2(\sigma_F^2 + \sigma_\omega^2) - \sigma_F^4}{(N\sigma_F^2 + \sigma_{\varepsilon F}^2)(\sigma_F^2 + \sigma_\omega^2) - \sigma_F^4} = \frac{\beta_{IC}(1 - \beta_{IS})}{1 - \beta_{IS}\beta_{IC}},$$

where $\beta_{IS} = \frac{\sigma_F^2}{\sigma_F^2 + \sigma_\omega^2}$ and $\beta_{IC} = \frac{\sigma_F^2}{N\sigma_F^2 + \sigma_{\varepsilon F}^2}$. Furthermore, the market aggregates its estimates of the emissions of all individual firms' productions, and computes the total emissions of all productions as

$$\begin{aligned} & E_1\left[\sum_{j=1}^N (\widetilde{e}_j + \widetilde{e}_{jF}) \,|\, \left\{y_j, y_{jF}, \hat{q}_j, \hat{f}_j\right\}_{j=1}^N\right] \\ = \ & \sum_{j=1}^N \hat{q}_j + \beta_D \sum_{j=1}^N (y_j - \hat{q}_j) + \sum_{j=1}^N \left[\hat{f}_j + \beta_{ISj}(y_{jF} - \hat{f}_j) + \beta_{ISF}(y_F - \sum_{i=1}^N \hat{f}_i)\right]. \end{aligned} \tag{27}$$

Next, we derive each firm's equilibrium production choices that maximize the expectation of the date 1 price $E_0\left[\widetilde{P}_{i1}\right]$. Substituting the expressions (26) and (27) into P_{i1}, and using $E_0\left[\widetilde{y}_{iF}\right] = f_i$ and $E_0\left[\widetilde{y}_F\right] = \sum_{j=1}^N f_j$ yields the following maximization problem for firm i:

$$\begin{aligned} & \max_{q_i, f_i} q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T\left[\hat{q}_i + \beta_D\left(q_i - \hat{q}_i\right) + \hat{f}_i + \beta_{ISi}(f_i - \hat{f}_i) + \beta_{ISF}\sum_{j=1}^N (f_j - \hat{f}_j)\right] \\ & -k_P\Bigg(\sum_{j=1}^N \hat{q}_j + \sum_{j=1}^N \hat{f}_j + \beta_D \sum_{j=1}^N (q_j - \hat{q}_j) + \sum_{j=1}^N \beta_{ISj}(f_j - \hat{f}_j) + N\beta_{ISF}\sum_{j=1}^N (f_j - \hat{f}_j)\Bigg). \end{aligned}$$

Differentiating the objective function with respect to q_i and f_i yields

$$1 - q_i - c_s f_i - \beta_D(k_T + k_P) = 0,$$

and

$$1 - f_i - c_s q_i - \beta_{ISi}\left(k_T + k_P\right) - \beta_{ISF}\left(k_T + k_P N\right) = 0.$$

Recall that $\beta_{ISi} = \frac{\beta_{IS}(1-\beta_{IC})}{1-\beta_{IS}\beta_{IC}}$ and $\beta_{ISF} = \frac{\beta_{IC}(1-\beta_{IS})}{1-\beta_{IS}\beta_{IC}}$. Hence, firm i's optimal production plan is

$$q^{ND} = \frac{(1-(k_T+k_P)\beta_D)(1-\beta_{IC}\beta_{IS})}{(1-c_s^2)(1-\beta_{IC}\beta_{IS})} - \frac{c_s(1-(k_T+k_PN)\beta_{IC}-(k_T+k_P+(1-2k_T-k_P(N+1))\beta_{IC})\beta_{IS})}{(1-c_s^2)(1-\beta_{IC}\beta_{IS})}.$$

and

$$f^{ND} = \frac{1-(k_T+k_PN)\beta_{IC}-(k_T+k_P+(1-2k_T-k_P(N+1))\beta_{IC})\beta_{IS}}{(1-c_s^2)(1-\beta_{IC}\beta_{IS})} - \frac{c_s(1-(k_T+k_P)\beta_D)(1-\beta_{IC}\beta_{IS})}{(1-c_s^2)(1-\beta_{IC}\beta_{IS})}.$$

The conditions $q^{ND} > 0$ and $f^{ND} > 0$ are satisfied given that our assumption in (8) implies $1 - k_T - k_P > c_s$. Using similar steps as in the proof of Lemma 2, one can easily check that $\left\{q^{ND}, f^{ND}\right\}$ is a maximum by deriving the second-order conditions.

Next, substituting the equilibrium production choices $\left\{q^{ND}, f^{ND}\right\}$ into the total surplus in (9) gives the equilibrium level of the total surplus $W\left(q^{ND}, f^{ND}\right)$. Taking the first-order condition of $W\left(q^{ND}, f^{ND}\right)$ with respect to β_D and solving the first-order condition yields the optimal precision β_D^{ND} in the Scopes-1-and-3 regime without double counting, which is given by:

$$\beta_D^{ND} = \min\left(\frac{(k_T+k_PN)(1-\beta_{IC}\beta_{IS}) - c_s(k_T(1-\beta_{IS})+k_P(N-\beta_{IS}))(1-\beta_{IC})}{(k_T+k_P)(1-\beta_{IC}\beta_{IS})}, 1\right).$$

Note that $\beta_D^{ND} \in (0,1)$ if and only if

$$\beta_{ISi}\left(k_T + k_P\right) + \beta_{ISF}\left(k_T + k_P N\right) < k_T + k_P N - \frac{1}{c_s} k_P(N-1).$$

For brevity, we focus on the interior solution, i.e., $\beta_D^{ND} \in (0,1)$, in the reminder of the proof. Using similar steps as in the proof of Proposition 3, one can easily check that β_D^{ND} is a maximum by deriving the second-order condition. Substituting the equilibrium production choices $\left\{q^{ND}, f^{ND}\right\}$ and the optimal measurement precision β_D^{ND} into the total surplus (9) yields the equilibrium level of the total surplus in the Scopes-1-and-3 regime without double counting $W^{ND} \equiv W\left(q^{ND}, f^{ND}; \beta_D^{ND}\right)$.

Lastly, we compare the firms' total surplus in the Scope-1-for-all reporting regime $W^{commingled}$ and in the Scopes-1-and-3 regime without double counting W^{ND}. If $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_P N)}$, the difference of the two can be rewritten as:

$$W^{commingled} - W^{ND} = \frac{1}{2(1-\beta_{IC}\beta_{IS})^2}\Big(N(1-\beta_{IC})^2(k_T(1-\beta_{IC}) + k_P(1-N\beta_{IC})) \times \beta_{IS}(-2(k_T+k_P N) + (k_T + k_P + k_T\beta_{IC} + k_P N\beta_{IC})\beta_{IS})\Big) \leq 0.$$

Similarly, if $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_P N)}$ is not satisfied, β_D^* is a corner solution and one can also easily check that $W^{commingled} - W^{ND} \leq 0$. Hence, absent double counting, the Scopes-1-and-3 regime always dominates the Scope-1-for-all regime. ■

Proof. of Proposition 6: Substituting (12), (17) and (18) into P_{i1}, and taking the expectations using $E_0[y_i] = q_i$ and $E_0[y_F] = \sum_{j=1}^N f_j$ yields the following maximization problem for each firm

$$\max_{q_i, f_i} q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - \Big(k_T\left[\hat{q}_i + \beta_D(q_i - \hat{q}_i)\right] + k_T\left[\hat{f}_i + \beta_{IS}\left(f_i - \hat{f}_i\right)\right] + k_P\Big(\sum_{j=1}^N \hat{q}_j + \sum_{j=1}^N \hat{f}_j + \beta_D \sum_{j=1}^N (q_j - \hat{q}_j) + \beta_{IS}\sum_{j=1}^N \left(f_j - \hat{f}_j\right)\Big)\Big).$$

Taking the first-order conditions yields

$$\begin{aligned} 1 - q_i - c_s f_i - \beta_D(k_T + k_P) &= 0, \\ 1 - f_i - c_s q_i - \beta_{IS}(k_T + k_P) &= 0. \end{aligned}$$

Solving the first-order conditions yields the equilibrium production choices $\{q^{**}, f^{**}\}$ in the proposition. The conditions $q^{**} > 0$ and $f^{**} > 0$ are satisfied given that our assumption in (8) implies $1 - k_T - k_P > c_s$. Using similar steps as in the proof of Lemma 2, one can easily check that $\{q^{**}, f^{**}\}$ is a maximum by deriving the second-order conditions.

Next, substituting the equilibrium production choices $\{q^{**}, f^{**}\}$ into the total surplus in (9) gives the equilibrium level of the total surplus $W(q^{**}, f^{**})$. Taking the first-order condition of $W(q^{**}, f^{**})$ with respect to β_D and solving the first-order condition yields the optimal precision

β_D^{**} in the proposition. Using similar steps as in the proof of Proposition 3, one can easily check that β_D^{**} is a maximum by deriving the second-order condition. Note that, if $\beta_{IS} < \frac{c_s(k_T+k_PN)-k_P(N-1)}{c_s(k_T+k_P)}$, taking the derivative of β_D^{**} with respect to β_{IS} yields

$$\frac{\partial \beta_D^{**}}{\partial \beta_{IS}} = c_s > 0.$$

■

Proof. of Proposition 7: Substituting the equilibrium production choices $\{q^{**}, f^{**}\}$ and the optimal measurement precision β_D^{**} in Proposition 6 into the total surplus (9) yields the equilibrium level of the total surplus in the Scopes-1-and-3 regime $W^{separated} \equiv W\left(q^{**}, f^{**}; \beta_D^{**}\right)$.

First, when $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$ and $\beta_{IS} < \frac{c_s(k_T+k_PN)-k_P(N-1)}{c_s(k_T+k_P)}$, we can rewrite the difference between the total surplus $W^{separated}$ in the Scopes-1-and-3 regime and the total surplus $W^{commingled}$ in the Scope-1-for-all regime as follows

$$\begin{aligned} & W^{commingled} - W^{separated} \\ & \qquad = \frac{((k_T + k_PN)\beta_{IC} - (k_T + k_P)\beta_{IS})((k_T + k_PN)(2 - \beta_{IC}) - (k_T + k_P)\beta_{IS})}{2}. \end{aligned}$$

Accordingly, $W^{commingled} \leq W^{separated}$ can be rewritten as

$$(k_T + k_PN)\beta_{IC} - (k_T + k_P)\beta_{IS} \leq 0,$$

which is equivalent to

$$\frac{\beta_{IS}}{\beta_{IC}} \geq \frac{k_T + k_PN}{k_T + k_P}.$$

Second, if $\beta_{IC} \geq 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$ and $\beta_{IS} \geq \frac{c_s(k_T+k_PN)-k_P(N-1)}{c_s(k_T+k_P)}$, then $\beta_D^{*} = \beta_D^{**} = 1$. The condition $W^{commingled} - W^{separated} > 0$ is equivalent to

$$\frac{N((k_T + k_PN)\beta_{IC} - (k_T + k_P)\beta_{IS})((k_T + k_PN)(2 - \beta_{IC}) - (k_T + k_P)\beta_{IS} - 2c_sk_P(N-1))}{2(1-c_s^2)} > 0,$$

which is equivalent to $\frac{\beta_{IS}}{\beta_{IC}} < \frac{k_T+k_PN}{k_T+k_P}$.

Finally, if $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$ is not satisfied and $\beta_{IS} < \frac{c_s(k_T+k_PN)-k_P(N-1)}{c_s(k_T+k_P)}$ is satisfied, or if $\beta_{IS} < \frac{c_s(k_T+k_PN)-k_P(N-1)}{c_s(k_T+k_P)}$ is not satisfied and $\beta_{IC} < 1 - \frac{k_P(N-1)}{c_s(k_T+k_PN)}$ is satisfied, one can check that $W^{commingled} \leq W^{separated}$ is also equivalent to $\frac{\beta_{IS}}{\beta_{IC}} \geq \frac{k_T+k_PN}{k_T+k_P}$. ■

Proof. of Lemma 3: We derive the firms' equilibrium choice of precision of direct emissions measurement β_D^{firm}. Substituting $\hat{q}_i = q_i$ and $\hat{f}_i = f_i$ into firm i's objective function, firm i's maximization problem becomes

$$\max_{\beta_D} q_i + f_i - \frac{q_i^2}{2} - \frac{f_i^2}{2} - c_s q_i f_i - k_T(q_i + f_i) - k_P \sum_{j=1}^{N}(q_j + f_j).$$

Thus, the first-order condition with respect to β_D yields

$$\frac{\partial q_i}{\partial \beta_D} + \frac{\partial f_i}{\partial \beta_D} - q_i\frac{\partial q_i}{\partial \beta_D} - f_i\frac{\partial f_i}{\partial \beta_D} - c_s q_i\frac{\partial f_i}{\partial \beta_D} - c_s f_i\frac{\partial q_i}{\partial \beta_D} - k_T\frac{\partial q_i}{\partial \beta_D} - k_T\frac{\partial f_i}{\partial \beta_D} - k_P(\frac{\partial q_i}{\partial \beta_D} + \frac{\partial f_i}{\partial \beta_D}) = 0.$$

Substituting the equilibrium production choices, $q_i = q^*$ and $f_i = f^*$, the interior solution to this previous equation is given by

$$\beta_D = \frac{(k_T + k_P)(1 - c_s) + c_s(k_T + k_PN)\beta_{IC}}{k_T + k_P}.$$

Note that $\frac{(k_T+k_P)(1-c_s)+c_s(k_T+k_PN)\beta_{IC}}{k_T+k_P} < 1$ is equivalent to

$$c_s(k_T + k_PN)\beta_{IC} < c_s(k_T + k_P),$$

which is always satisfied. Hence, in the Scope-1-for-all regime, the firms' equilibrium choice of precision of direct emissions measurement is

$$\beta_D^{firm}(\beta_{IC}) = \frac{(k_T + k_P)(1 - c_s) + c_s(k_T + k_PN)\beta_{IC}}{k_T + k_P} \in (0, 1).$$

Using similar steps as in the proof of Proposition 3, one can easily check that $\beta_D^{firm}(\beta_{IC})$ is a maximum by deriving the second-order condition.

Moreover, the difference between the ex-ante total surplus under the firms' equilibrium choice of precision of direct emissions measurement and the ex-ante total surplus in the absence of direct emissions disclosure is

$$N\frac{(k_T+k_PN)^2(1-c_s(1-\beta_{IC}))^2}{2(1-c_s^2)}>0.$$

■

Proof. of Proposition 8: We compare β_D^{firm} and β_D^*. The condition

$$\frac{(k_T+k_P)(1-c_s)+c_s(k_T+k_PN)\beta_{IC}}{k_T+k_P}\leq\frac{(k_T+k_PN)(1-c_s(1-\beta_{IC}))}{k_T+k_P},$$

can be reduced to

$$(k_T+k_PN)(1-c_s)\geq(k_T+k_P)(1-c_s),$$

which is always satisfied given that $N\geq 2$ and our assumption in (8) implies $1>c_s$. Note that, if $k_P=0$,

$$\frac{(k_T+k_P)(1-c_s)+c_s(k_T+k_PN)\beta_{IC}}{k_T+k_P}=\frac{(k_T+k_PN)(1-c_s(1-\beta_{IC}))}{k_T+k_P}.$$

Otherwise, when $k_P\neq 0$, we get the following comparison.

- If $c_s(k_T+k_PN)(1-\beta_{IC})\leq k_P(N-1)$, then $\beta_D^*(\beta_{IC})=1$ and

$$\beta_D^{firm}(\beta_{IC})=\frac{(k_T+k_P)(1-c_s)+c_s(k_T+k_PN)\beta_{IC}}{k_T+k_P}<\beta_D^*(\beta_{IC}).$$

- Otherwise, if $c_s(k_T+k_PN)(1-\beta_{IC})>k_P(N-1)$,

$$\beta_D^{firm}(\beta_{IC})=\frac{(k_T+k_P)(1-c_s)+c_s(k_T+k_PN)\beta_{IC}}{k_T+k_P}$$
$$<\beta_D^*(\beta_{IC})=\frac{(k_T+k_PN)(1-c_s(1-\beta_{IC}))}{k_T+k_P}\in(0,1).$$

■