Environmental Policy: An Unintended "Booster" of Competition Policy?[*]

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Abstract

We investigate how emission fees affect the effectiveness of competition policy (audits, leniency, and whistleblower programs) at deterring collusion. When competition policy is absent, emission fees do not affect the sustainability of collusion. When competition policy is present, however, we show that fees amplify the effectiveness of audits, leniency, and whistleblower programs at deterring collusive practices. Our results suggest that leniency and whistleblower programs can reduce rewards in regulated industries without diminishing their impact. Our findings are robust to production costs being convex, differentiated products, industries with more than two firms, and firms competing in prices.

Keywords: Collusion deterrence, Environmental regulation, Competition policy, Audits, Leniency programs, Whistleblower programs.

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1 Introduction

Firms investigated for collusive practices often emit various types of pollutants, thus also being subject to environmental regulation. Recent examples include the European Union's truck cartel case involving firms such as Volvo/Renault, Daimler, MAN, and DAF, which colluded from 1997-2001 and were fined €2.93 billion in 2016, see EC Press Release (2016); with these firms also being regulated under EU standards for CO_2 and NO_X emissions for heavy vehicles. Similarly, the steel abrasives cartel, involving companies Winoa, Ervin, and MTS, colluded during 2003-2010 and was fined €30 million by the European Commission, see EC Press Release (2014); with these firms being subject to the EU Industrial Emissions Directive, which limits pollutants from steel manufacturers. In the United States, the Department of Justice (DOJ) investigated and fined a group of auto part companies $2 billion for collusion from 2000-2010; see Connor (2013). These firms are regulated by the Resource Conservation and Recovery Act (RCRA) on hazardous waste, given their extensive use of metals, plastics, and solvents in manufacturing. Finally, the freight forwarding cartel, where companies such as Schenker AG, Panalpina, and Kuhne colluded in 2002-2007, was fined by the DOJ with $50.27 million in 2010; see DOJ Press Release (2010). These firms are simultaneously subject to the Clean Air Act, regulating the CO_2 emissions of freight logistics and transport vehicles. Other examples abound, including the lysine cartel, the marine hose cartel, the LCD screen cartel, or the electrolytic capacitor cartel.[1]

The use of competition policy to deter collusion has been extensively analyzed, yet the role of environmental regulation has been largely overlooked. In this study, we examine if the presence of emission fees makes competition policy more effective at preventing collusion —acting as a "booster"— or, instead, hinders its effectiveness. We show that the coexistence of two regulatory authorities makes competition policy more effective.

Following Aubert et al. (2006), we consider an industry where firms evaluate whether or not to collude. In this context, every firm chooses whether to communicate with its rival. If at least one firm does not communicate, evidence of collusion does not exist, so firms cannot be fined by the competition authority (CA), and compete à la Cournot. If both firms communicate, however, they start colluding, and evidence exists for the CA to prosecute and fine them.

For presentation purposes, we first study a benchmark setting without competition policy, where we show that emission fees hinder collusion. To understand this point, note that a per-unit emission fee acts like a cost increase, reducing profits under all market regimes. However, this reduction is

[1] In the case of the lysine cartel, Archer Daniels Midland, Ajinomoto, and Kyowa Kakko colluded in 1992-95, and were fined by the DOJ with $105 million in 1997. Lysine manufacturing produces ammonia emissions and nitrogen byproducts, which are regulated by the Clean Air Act. In the marine hose cartel, Dunlop Oil & Marine, Trelleborg Industrie SAS, and Bridgestone colluded in the 1986-2007 period, and were fined by the DOJ with over $131 million. These firms were subject to the Clean Water Act, which mandates strict controls on oil discharge and volatile organic compounds. Similarly, in the LCD screen cartel, firms LG Display, Sharp, and Chunghwa Picture Tubes colluded in 2001-2006, and the DOJ fined them with $585 million in total in 2008. These firms were subject to RCRA because of their use of hazardous substances in the production of LCD screens, such as arsenic, lead, and cadmium. Similarly, the electrolytic capacitor cartel involved companies such as Panasonic, NEC Tokin, and Rubycon, colluding in 1998-2014, and were fined by the EU commission in 2023 with €254 million. Capacitor manufacturing is also subject to the RCRA, along with the Clean Water Act, because of the use of hazardous chemicals and industrial effluents.

asymmetric: a deviating firm increases its output, facing a larger tax burden from the emission fee, implying that deviation profits fall more significantly than those under collusion or competition. As a consequence, both the current profit gain and the future profit loss from deviating decrease as the emission fee becomes more stringent, but the latter decreases more substantially than the former. This reduces the threat from future punishments, making deviations more attractive. In summary, environmental regulation per se hampers collusion; as shown by Turner (2022) and Azacis and Collie (2018) in the context of per-unit and ad-valorem taxes.

We then examine competition policy, considering three programs: audits, leniency, and whistleblowing. Under audits, the CA seeks evidence of collusion, finding it with positive probability; as in Aubert et al. (2006). In this setting, we show that collusion is hindered by emission fees, due to a direct and indirect effect on collusion. First, an increase in after-tax costs gives rise to a well-known direct effect, namely, the profit gain from deviating decreases more substantially than that from continuing collusion, reducing firms' incentives to collude. However, the presence of environmental regulation gives rise to a new, *indirect* effect on collusive incentives. Higher production costs implies less pollution that, in turn, require less stringent emission fees, lowering firms' net costs, and ultimately facilitating collusion. We show that the former (positive) effect dominates, thus hindering collusion. This effect is, however, smaller when emission fees are present than absent. A similar argument applies when pollution becomes more severe, requiring more stringent fees, which hamper collusion. Nonetheless, this finding is not analogous to that from cost increases, due to the presence of an indirect effect of taxation.

We also find that competition policy becomes more effective with than without emission fees. In the absence of fees, the profit gain from deviating is unaffected by audits, whereas its profit loss decreases in the expected fine, making deviations more attractive. When emission fees are present, audits become more effective at deterring collusion if, intuitively, the profit loss from deviation is more sensitive to fees than its profit gain, thus making deviations less threatening, and providing firms with more incentives to deviate.

Then, we consider leniency programs, in which the CA offers reduced penalties, such as shorter prison sentences or lower fines, to firms that cooperate by providing evidence of collusion. In the EU truck case, MAN obtained immunity by cooperating with investigators; Daimler, Volvo/Renault, IVECO, DAF accepted a settlement; while Scania did not settle and received the full fine in a later decision.[2] In this scenario, penalty reduction can be less generous when the industry faces emission fees than otherwise.

Comparing audits and leniency programs, our results align with existing findings that the latter are more effective than the former at deterring collusion, producing a "leniency premium." Nonetheless, this premium decreases when pollution is more severe. Consequently, the leniency premium that arises in the absence of emission fees diminishes in highly polluting industries.

In whistleblower programs, the CA offers a reward to employees reporting evidence of collusion

[2] Similarly, Winoa received a reduced fine in the steel abrasives cartel, Yazaki did in the auto parts cartel, and Schenker AG did in the freight forwarding cartel.

to the investigators. In this context, emission fees also boost its effectiveness. As with leniency programs, we find a "whistleblowing premium," relative to audits alone. When comparing whistleblower and leniency programs, however, our results indicate that the former are more effective at deterring collusion when rewards are high.

For robustness, we consider four extensions. First, we allow for convex production costs, which provides firms with stronger incentives to collude to ameliorate their diseconomies of scale. The presence of emission fees, however, makes competition policy more effective at deterring collusion. In addition, this boosting effect becomes larger as cost convexities are more severe. In other words, while collusion is more unlikely to arise in markets with diseconomies of scale, our results suggest that emission fees further hinder collusion in this type of industries. Alternatively, CAs can focus their monitoring on industries that are not subject to environmental regulation. A similiar argument applies to the other extensions, namely, differentiated products, more competitive markets, and price competition.

Our results suggest that CAs using audits to deter collusion can allocate less resources to monitoring regulated firms, as higher detection probabilities and stricter fines more effectively deter collusion in these industries. In essence, the CA can strategically shift resources towards firms that are not being regulated by an environmental agency, perhaps because their emissions are not too damaging, such as technology, banking, or media industries; while reducing the monitoring of collusion in highly polluting sectors.

Similar results apply to leniency or whistleblower programs, where CAs can reduce rewards when environmental regulations are present, relative to cases without regulation. Many countries have adopted these programs over the past decades,[3] but they are often politically unpopular among consumers, who view them as granting leniency to collusive firms choosing to cooperate with authorities. Our findings imply that targeted reductions in leniency incentives can help ensure these programs remain effective and more political acceptable.

Related literature. Our study contributes to the literature analyzing the collusion-deterring effect of leniency and whistleblower programs. Following the seminal work by Motta and Polo (2003) and Aubert et al. (2006), several articles have examined their effect on firms' collusive price path, Chen and Harrington (2007); allow for partial and full leniency programs, Buccirossi and Spagnolo (2008); allow for different firm characteristics, Harrington (2008); multi-market collusion (in the "Amnesty Plus" option), Chen and Rey (2013); the maximal collusive price, Houba et al. (2015); or allow for nonleniency enforcement to be endogenous, Harrington and Chang (2015). For a literature review, see Borrell et al. (2014) and Marvao and Spagnolo (2018). While these studies focus on different extensions from Aubert et al. (2006), they consider that firms are not being

[3] Examples include South Korea (leniency program in 1997, whistleblower program in 2011); Japan (2006 and 2009, respectively); Brazil (2000 and 2016); Australia (2005 and 2019); Canada (2000 and 2019); China (2008 and 2015); India (2009 and 2021); the United Kingdom (2003 and 2017); and South Africa (2003 and 2017). Many of these laws follow the model of the DOJ Corporate Leniency Program (established in 1993) and the Criminal Antitrust Anti-Retaliation Act (2020) in the United States, as well as the EU Leniency Notice (1996) and the Directive 2019/1937 on Whistleblower Protection (2019).

regulated by other government agencies, such as the Environmental Protection Agency (EPA). We examine how the overlap of competition and environmental policy can lead to complementarities, making antitrust policy more effective. Empirical studies have also examined the US leniency program, Miller (2009); the EU program, Brenner (2009) and Hoang et al. (2014); and other features, such as how organizational characteristics of cartels affect cartel duration and resilience against leniency policies, see Levenstein and Suslow (2011).[4]

Our paper also contributes to the environmental economics literature studying how emission fees in polluting oligopolies facilitates or hinders competition, see Levinson (1996), Amir et al. (1999), and Holland and Moore (2003); how environmental standards raise firms' costs, promoting market concentration, Katsoulacos and Xepapadeas (1996) and Greaker (2006), or hindering it, Porter and van der Linde (1995); how emission fees and standards affect decisions to invest in green R&D and relocate, see Ranocchia and Lambertini (2021); or how environmental R&D joint ventures cartels facilitate firms' ability to collude in their output decisions, see Chiou and Hu (2001) and Iida (2020).[5] This literature, however, does not explicitly consider competition policy, such as audits or leniency programs, thus overlooking the interaction between an environmental agency and CA in the same industry, potentially complementing each other; as recently suggested in the literature review by Inderst and Thomas (2023).

To our knowledge, only Damania (1996) explicitly considers polluting firms colluding in their output decisions. While Damania (1996) examines the interaction between pollution taxes and firms' incentives to adopt abatement technologies in an oligopolistic supergame, his analysis does not incorporate any form of competition policy. Instead, he focuses on how emission taxes may sustain collusion by reducing the profitability of deviation, potentially discouraging investment in pollution control. In contrast, our framework explicitly models the presence of a CA and shows that emission fees, rather than facilitating collusion, can amplify the deterrent effect of antitrust tools.

Other studies explore the effect of taxation on collusion. Azacis and Collie (2018) show that under constant marginal costs, ad valorem and specific taxes have the same impact on the critical discount factor; but with increasing marginal costs, ad valorem taxes facilitate collusion. In contrast, Turner (2022) finds that with asymmetric costs, ad valorem taxation raises the critical discount factor, hindering collusion. These articles, however, treat taxes as exogenous cost shifters, ignoring the interaction of taxation and CA. By contrast, we allow for endogenous regulation (emission fees) and examine how this regulation interacts with competition policy tools.

[4] Similarly, other studies test the effectiveness of leniency programs at deterring collusion in controlled experiments, such as Bigoni et al. (2012) and Hinloopen and Onderstal (2014), which measure how the probability of firms being audited and the generosity of the rewards affect their decision to collude; or Andres et al. (2021), which allows for firms to openly communicate, showing that they are more likely to collude, even when facing leniency programs.

[5] Other articles analyze how subsidies for green technology adoption may increase firm competition, although disproportionally benefiting large incumbents; see Requate and Unold (2003), Jaffe et al. (2005), and Ambec and Barla (2006). Similarly, other articles study how environmental quality standards can lead to product differentiation, providing an advantage to firms able to comply with higher standards, see Erikson (2004), Conrad (2005), and Greaker and Midttomme (2016).

The paper is organized as follows. Section 2 presents the model and section 3 identifies equilibrium behavior without competition policy, with audits, leniency programs, and whistleblower programs. Section 4 extends our analysis allowing for convex production costs, several firms, product differentiation, and price competition. Section 5 concludes.

2 Model

Consider an industry with two firms playing an infinitely repeated game, facing inverse demand function $p(Q)$, where Q denotes aggregate output, $p'(Q) < 0$ and $p''(Q) \geq 0$, and cost function $C(q_i)$, where $C'(q_i) > 0$ and $C''(q_i) \geq 0$. When firms compete, every firm i chooses output $q_i^C(t)$, earning profit $\pi^C(t)$, where superscript C denotes competition and $t \geq 0$ represents emission fees. When firms coordinate their output decisions to maximize joint profits, every firm selects $q_i^M(t)$, yielding individual profit $\pi^M(t)$, where superscript M denotes monopoly. Finally, if a firm unilaterally deviates from the collusive agreement (denoted with D), choosing output $q_i^D(t)$, it earns a deviating profit $\pi^D(t)$ during one period, and then firms revert to competition profits $\pi^C(t)$ thereafter, i.e., grim-trigger strategy. Profits satisfy $\pi^D(t) \geq \pi^M(t) \geq \pi^C(t)$.

We assume that collusion cannot occur without communication among firms, and that this communication generates hard evidence that the CA finds with probability $\rho \in [0, 1]$, yielding a fine $F > 0$. This evidence can also be provided to the CA by one of the colluding firms, depending on the revelation mechanism that we consider. Finally, the stream of profits is discounted by $\delta \in [0, 1]$. The time structure follows Aubert et al. (2006) where, for presentation purposes, we first consider environmental regulation as exogenous and later relax this assumption.

1. In the first stage, every firm chooses whether to communicate.
2. In the second stage:
   (a) If both firms choose to communicate, evidence is generated and an infinitely-repeated game of output competition ensues, where every firm chooses, in each stage, its output level and whether to bring evidence to the CA.
   (b) If at least one firm chooses not to communicate, evidence does not exist, and firms compete à la Cournot in every period.[6]
3. If no firm brings evidence to the CA, this agency can still find evidence with probability ρ.

3 Exogenous regulation

Profit sensitivity. Before analyzing collusive incentives, we examine how more stringent emission fees produce a different effect on collusive and Cournot profits, $\pi_t^M(t)$ and $\pi_t^C(t)$ respectively, where

[6] Following Aubert et al. (2006), a cartel requires mutual communication to agree on the collusive allocation. Only when both firms communicate does hard evidence exist, which the CA detects with probability α. If at least one firm refuses to communicate, no hard evidence is generated and the (repeated) Cournot outcome ensues.

subscript t denotes the first-order derivative with respect to emission fee t.

Lemma 1. *An increase in fee t satisfies $0 \geq \pi_t^C(t) > \pi_t^M(t)$ if and only if*

$$p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t} > \frac{q_i^C(t) - q_i^M(t)}{q_i^C(t)}. \tag{C1}$$

Intuitively, a more stringent fee produces a price effect under Cournot (left-hand side) that exceeds the percentage output reduction that firms experience when colluding (right-hand side). The price effect captures the positive externality that a more stringent fee generates on firm i's profits by forcing its rival to reduce its output, thus increasing prices. When this positive externality is large enough, firms are less affected by an increase in the emission fee when they compete à la Cournot than when they collude. We consider condition C1 throughout the paper.

We next analyze the sensitivity of profits to emission fees when firms deviate, thus providing a full ranking.

Lemma 2. *An increase in fee t satisfies $0 > \pi_t^M(t) > \pi_t^D(t)$ if and only if*

$$p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} < \frac{q_i^D(t) - q_i^M(t)}{q_i^D(t)} \tag{C2}$$

implying that $0 \geq \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$.

Therefore, a more stringent fee yields a price effect that is lower than the percentage output increase from deviation. Condition C2 implies that the positive externality that firm j generates on firm i's profits is small, entailing that a higher fee affects profits the most when firm i unilaterally deviates from collusion. Our next analysis considers that C2 holds, guaranteeing a full ranking in profit sensitivity to emission fees.

Example 1 illustrates that conditions C1 and C2 are satisfied in common modeling settings.

Example 1. Consider an inverse demand $p(Q) = 1 - Q$, a marginal cost c, where $1 > c \geq 0$; and a per-unit emission fee t. In this setting, output levels are $q_i^C = \frac{1-c-t}{3}$, $q_i^M = \frac{1-c-t}{4}$, and $q_i^D = \frac{3(1-c-t)}{8}$, and profits are $\pi^C(t) = \left(q_i^C(t)\right)^2$, $\pi^M(t) = 2\left(q_i^M(t)\right)^2$, and $\pi^D(t) = \left(q_i^D(t)\right)^2$, which satisfy $\pi^D(t) \geq \pi^M(t) \geq \pi^C(t)$; see Appendix 1 for more details. A marginal increase in emission fee t entails that $\pi_t^C(t) = -\frac{2(1-c-t)}{9}$, $\pi_t^M(t) = -\frac{(1-c-t)}{4}$, and $\pi_t^D(t) = -\frac{9(1-c-t)}{32}$, implying that $0 \geq \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$ holds.

The same argument extends to other settings, such as industries with convex costs (Appendix 2), firms selling differentiated products (Appendix 3), more than two firms (Appendix 4), or firms compete in prices (Appendix 5), where $0 \geq \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$ is also satisfied.

As we show below, Lemmas 1 and 2 do not necessarily imply that more stringent environmental regulation hinders collusion. While deviations are the most affected by emission fees, the sustainability of collusion depends on whether profit gains from deviation, $\pi^D(t)-\pi^M(t)$, are more affected by a marginal change in the emission fee than the associated profit loss, $\pi^D(t)-\pi^C(t)$.

3.1 No competition policy

As a benchmark, we first study a setting where firms face no probability of being caught colluding, $\rho = 0$. Then, we analyze how their behavior is affected by audits, leniency, and whistleblower programs, focusing on the role of environmental regulation at hindering collusion.

In this setting, collusion can be sustained in the infinitely-repeated game if

$$\frac{1}{1-\delta}\pi^M(t) \geq \pi^D(t) + \frac{\delta}{1-\delta}\pi^C(t)$$

since audits do not exist. After rearranging, yields

$$\pi^D(t) - \pi^M(t) \leq \frac{\delta}{1-\delta}\left[\pi^M(t) - \pi^C(t)\right] \tag{1}$$

where the left-hand side measures the profit gain from deviating, $PG(t) \equiv \pi^D(t) - \pi^M(t)$, which is positive since $\pi^D(t) \geq \pi^M(t)$; while the right-hand side captures the discounted profit from continuing collusion, which is also positive because $\pi^M(t) \geq \pi^C(t)$. In addition, let $PL(t) \equiv \pi^D(t) - \pi^C(t)$ denote the profit loss from abandoning collusion.

Differentiating $PG(t)$ and $PL(t)$ with respect to t, yields $PG_t(t) = \pi_t^D(t) - \pi_t^M(t)$ and $PL_t(t) = \pi_t^D(t) - \pi_t^C(t)$, respectively, where

$$0 > PG_t(t) > PL_t(t)$$

since $0 \geq \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$. Therefore, a more stringent environmental regulation decreases both the profit gain from deviations and the future profit loss from abandoning collusion (i.e., both $PG_t(t)$ and $PL_t(t)$ are negative). The profit gain, however, is less hurt than the profit loss, which occurs because collusion profits decrease more significantly than Cournot profits after regulation becomes more stringent, that is, $0 \geq \pi_t^C(t) > \pi_t^M(t)$.

Alternatively, the above result shows that a one-percent increase in t produces a larger percentage decrease in $PL(t)$ than in $PG(t)$. In particular, let $\varepsilon_{PG,t} \equiv \frac{PG_t(t)}{PG(t)}t$ denote the profit-gain elasticity and, similarly, $\varepsilon_{PL,t} \equiv \frac{PL_t(t)}{PL(t)}t$ represent the profit-loss elasticity to a marginal increase in t; both being unambiguously negative since $0 > PG_t(t) > PL_t(t)$. Therefore, elasticities satisfy $0 > \varepsilon_{PG,t} \geq \varepsilon_{PL,t}$. We next identify the minimal discount factor that solves equation (1).

Lemma 3. *Without competition policy, collusion can be supported if* $\delta \geq \overline{\delta}(t) \equiv \frac{PG(t)}{PL(t)}$*, where* $\overline{\delta}(t)$ *satisfies* $\overline{\delta}(t) \in (0, 1)$*. In addition,* $\overline{\delta}(t)$ *increases in* t *under all admissible conditions.*

Therefore, collusion can be supported if firms assign a sufficiently high value to future payoffs, $\delta \geq \overline{\delta}(t)$; a well-known result in the literature. As expected, cutoff $\overline{\delta}(t)$ increases when the profit gain from deviating becomes more attractive, i.e., higher $\pi^D(t)$ and, in turn, a higher $PG(t)$; or when reverting to competition becomes less threatening, i.e., higher $\pi^C(t)$ and lower $PL(t)$. In both cases, collusion is hindered.

The comparative statics of cutoff $\overline{\delta}(t)$ indicate that collusion is hindered by more stringent environmental regulation, which holds because $0 > \varepsilon_{PG,t} \geq \varepsilon_{PL,t}$. Intuitively, an increase in t produces a smaller reduction in the profit gain from deviation, $\varepsilon_{PG,t}$, than in the profit loss, $\varepsilon_{PL,t}$. As a consequence, deviations become less threatening (smaller profit loss), ultimately making them relatively more attractive, and hindering incentives to collude.

Our above result embodies the case of $\varepsilon_{PG,t} > \varepsilon_{PL,t}$, implying that regulation strictly increases $\overline{\delta}(t)$, thus hindering collusion; and the case where $\varepsilon_{PG,t} = \varepsilon_{PL,t}$, entailing that regulation does not affect $\overline{\delta}(t)$, and collusive incentives are unaffected. The latter arises in several types of markets and cost functions, as Example 2 illustrates.

Example 2. Consider the setting in Example 1 with linear costs. In this context, the profit gain from deviation is $PG(t) = \frac{(1-c-t)^2}{64}$, its derivative is $PG_t(t) = -\frac{(1-c-t)}{32}$, and its associated elasticity is $\varepsilon_{PG,t} = \frac{PG_t(t)}{PG(t)}t = -\frac{2t}{1-c-t}$. Similarly, the profit loss is $PL(t) = \frac{17(1-c-t)^2}{576}$, its derivative is $PL_t(t) = -\frac{17(1-c-t)}{288}$, where $PL_t(t) < PG_t(t) < 0$. Its associated elasticity, $\varepsilon_{PL,t}$, coincides with $\varepsilon_{PG,t}$, since $\varepsilon_{PL,t} = \frac{PL_t(t)}{PL(t)} = -\frac{2t}{1-c-t}$, implying that collusive incentives are unaffected by an increase in the emission fee. Indeed, collusion holds in this setting if and only if $\delta \geq \overline{\delta} = \frac{9}{17}$.

A similar argument applies to settings where firms experience convex costs (Appendix 2), they sell differentiated products (Appendix 3), multiple firms are active (Appendix 4), or they compete in prices (Appendix 5). In all cases, elasticities coincide with those under linear costs, that is, $\varepsilon_{PG,t} = \varepsilon_{PL,t} = -\frac{2t}{1-c-t}$, implying that collusion is unaffected by environmental regulation.

3.2 Audits

Consider now a setting where the CA uses audits to detect collusion, i.e., no revelation mechanism. If at least one firm chooses to not communicate, they both earn $\pi^C(t)$. If both firms communicate, firm i earns $\pi^M(t) - \rho F$ when both collude, but increases its profit to $\pi^D(t) - \rho F$ if it unilaterally deviates to $q_i^D(t)$. The fine is not large enough to deter collusion, i.e., $\pi^M(t) - \rho F > \pi^C(t)$ holds, or $PL(t) - PG(t) > \rho F$. In this context, collusion is sustained if

$$\underbrace{\left(\pi^D(t) - \rho F\right) - \left(\pi^M(t) - \rho F\right)}_{\pi^D(t)-\pi^M(t)} \leq \frac{\delta}{1-\delta}\left[\left(\pi^M(t) - \rho F\right) - \pi^C(t)\right]. \tag{2}$$

While profits under collusion, M, and deviation, D, are affected by the expected fine, the instantaneous gain from cheating, in the left-hand side of equation (2), is unaffected, $\pi^D(t) - \pi^M(t)$, thus coinciding with that in equation (1). The discounted profit from continuing collusion, however, decreases because of a probable audit, i.e., the right-hand side of (2) is smaller than that of (1). Therefore, collusion is less likely to arise with than without audits.[7]

[7] As expected, equation (2) is analogous to equation (2) in Aubert et al. (2006), except for profits in each scenario being a function of t.

Proposition 1. *Under audits, collusion can be sustained if* $\delta \geq \overline{\delta}_A(t) \equiv \frac{PG(t)}{PL(t)-\rho F}$*, where* $\overline{\delta}_A(t)$ *satisfies* $\overline{\delta}_A(t) \in (0,1)$*,* $\overline{\delta}_A(t) \geq \overline{\delta}(t)$*, and unambiguously increases in* ρ*,* F*, and* t*. Furthermore, the derivatives* $\frac{\partial \overline{\delta}_A(t)}{\partial \rho}$ *and* $\frac{\partial \overline{\delta}_A(t)}{\partial F}$ *increase in* t *for all admissible parameters.*

As expected, the presence of audits make collusion less likely to arise, i.e., $\overline{\delta}_A(t) \geq \overline{\delta}(t)$, as in Aubert et al. (2006). Proposition 1 also shows that $\overline{\delta}_A(t)$ increases in the stringency of the emission fee, as in Lemma 3.

The effectiveness of audits at deterring collusion is measured by $\frac{\partial \overline{\delta}_A(t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_A(t)}{\partial F}$, that is, the increase in $\overline{\delta}_A(t)$ when audits are more likely (higher ρ) or fines become more severe (higher F). Proposition 1 shows that this effectiveness is increasing in the stringency of environmental regulation, i.e., the cross-partial derivatives $\frac{\partial^2 \overline{\delta}_A(t)}{\partial \rho \partial t}$ and $\frac{\partial^2 \overline{\delta}_A(t)}{\partial F \partial t}$ are both positive. Intuitively, these cross-partials represent the "boosting" effect that emission fees have on competition policy, as they can complement the latter by making it more effective at hindering collusion.

Example 3. In the context of Example 2, collusion can be sustained if

$$\delta \geq \overline{\delta}_A(t) = \frac{9\,(1-c-t)^2}{17\,(1-c-t)^2 - 576\rho F},$$

which satisfies $\overline{\delta}_A(t) \geq \overline{\delta}(t) = \frac{9}{17}$, increases in ρ and F, in the stringency of emission fee t, and derivatives $\frac{\partial \overline{\delta}_A(t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_A(t)}{\partial F}$ are increasing in t, yielding a booster under all parameter conditions. A similar argument applies to all extensions in Appendices 2-5.

3.3 Leniency programs

Consider now that the CA offers a reduced fine to the firm reporting collusion, R, which satisfies $0 \geq R > -\rho F$.[8] In this setting, the sustainability condition for collusion is

$$\left(\pi^D(t) + R\right) - \left(\pi^M(t) - \rho F\right) \leq \frac{\delta}{1-\delta}\left[\left(\pi^M(t) - \rho F\right) - \pi^C(t)\right] \tag{3}$$

which is more demanding than equation (2) since $R > -\rho F$. In particular, the discounted value of collusion is unaffected by the leniency program, and the right-hand side of equation (3) coincides with that in (2). The instantaneous gain from defection, however, is now more attractive due to the reduced fine, implying that the left-hand side in equation (3) is higher than that in (2).

Proposition 2. *Under leniency programs, collusion can be sustained if* $\delta \geq \overline{\delta}_L(t) \equiv \frac{PG(t)+R+\rho F}{PL(t)+R}$*, where* $\overline{\delta}_L(t)$ *satisfies* $\overline{\delta}_L(t) \in (0,1)$*,* $\overline{\delta}_L(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}(t)$*, and unambiguously increasing in* ρ*,* F*,* R*, and* t*. Furthermore, the derivatives* $\frac{\partial \overline{\delta}_L(t)}{\partial \rho}$ *and* $\frac{\partial \overline{\delta}_L(t)}{\partial F}$ *increase in* t *under all conditions.*

Therefore, the leniency program makes deviation more appealing because the reporting firm pays a smaller fine, relative to audits alone, implying that $\overline{\delta}_L(t) \geq \overline{\delta}_A(t)$. The presence of emission fees

[8] If, instead, $0 > -\rho F > -R$, a firm reporting collusion would experience a more severe punishment than when it does not report collusion; not being a corporate leniency program.

amplify this effect: as shown under no competition policy, emission fees produce a larger reduction in the profit loss than in the profit gain from deviation, making the latter more attractive, hindering collusion under all parameter conditions. The introduction of leniency programs increase the profit gain from deviation, while leaving its profit loss unaffected. As a consequence, emission fees, which unambiguously hinder collusion under no competition policy, emphasize this effect with leniency programs, making cheating even more attractive.

Example 4. Continuing with Example 3, the minimal discount factor sustaining collusion with leniency programs is

$$\delta \geq \overline{\delta}_L(t) = \frac{9\left[(1-c-t)^2 + 64\left(R + \rho F\right)\right]}{17(1-c-t)^2 + 576R}.$$

which unambiguously increases in ρ, F, R, and t. Furthermore, the derivatives $\frac{\partial \overline{\delta}_L(t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_L(t)}{\partial F}$ are increasing in t, implying that more stringent emission fees boost the effectiveness of competition policy, and suggesting that both policies are complementary (see Appendix 1 for more details).

For illustration purposes, figure 1a depicts $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$ as a function of the emission fee, t, evaluated at $c = R = 0$ and $\rho = F = \frac{1}{20}$.[9] While both $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$ increase in the stringency of the emission fee, t, thus hindering collusion, their difference $\overline{\delta}_L(t) - \overline{\delta}_A(t)$ increases in t if and only if $t < 0.44$; as illustrated in the left-hand side of figure 1b. Therefore, a more stringent fee expands the "leniency premium," i.e., the advantage of leniency programs at deterring collusion relative to audits alone, as measured by the difference $\overline{\delta}_L(t) - \overline{\delta}_A(t)$. In particular, the leniency premium is positive in the absence of emission fees, $\overline{\delta}_L(0) - \overline{\delta}_A(0) > 0$, in the vertical intercept of figure 1b; then increases when emission fees are present but not stringent, and finally decreases. Hence, audits and leniency programs become similarly effective at preventing collusion when emission fees

[9] In this context, the initial condition $\pi^M(t) - \rho F > \pi^C(t)$ becomes $\frac{1}{400} = \rho F < \pi^M(t) - \pi^C(t) = \frac{(1-t)^2}{72}$ or, after rearranging, $t < 1 - \frac{3}{5\sqrt{2}} \simeq 0.57$, which is the upper bound on the horizontal axis. Otherwise, the expected fine is large enough to deter collusion, and both $\overline{\delta}_A(t)$ and $\overline{\delta}_L(t)$ exceed 1, as shown in the figure, indicating that collusion cannot be sustained for any values of δ. In addition, condition $R > -\rho F$ holds in this setting since $0 > -\frac{1}{400}$, implying that the CA's reward eliminates fines.

are stringent.

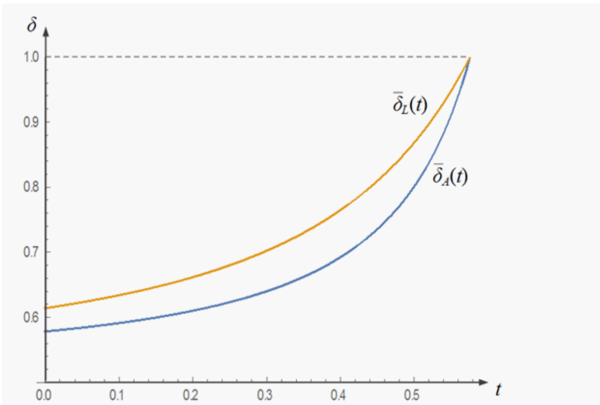

Fig 1a. $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$.

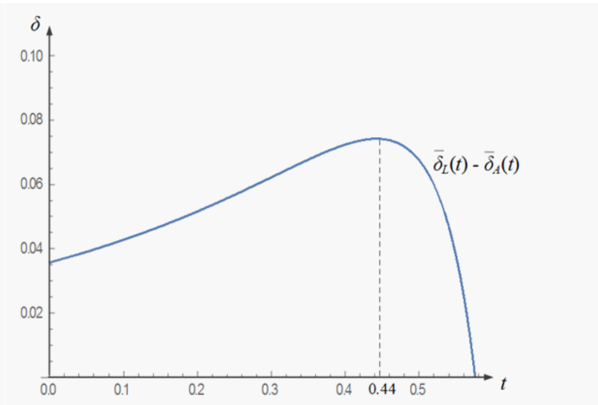

Fig. 1b. Leniency premium, $\overline{\delta}_L(t) - \overline{\delta}_A(t)$.

3.4 Whistleblower programs

Whistleblower programs typically provide a positive reward, B, to employees reporting evidence to the CA. The colluding firm needs to compensate with a "bribe" B the n employees who know about its collusive practices and could be reporting it to the CA, for a total bribe of nB in each period, as in Aubert et al. (2006).

As a consequence, the per-period profits under audits are reduced by nB when firms collude, $\pi^M(t) - \rho F - nB$, and when one deviates, $\pi^D(t) - \rho F - nB$; whereas competition profits are unaffected, $\pi^C(t)$. As in section 3.2, we consider that the expected fine and total bribes are not large enough to deter collusion, $\pi^M(t) - \rho F - nB > \pi^C(t)$, or $\rho F + nB < PL(t) - PG(t)$.

Then, collusion can be sustained if

$$\frac{1}{1-\delta}\left(\pi^M(t) - \rho F - nB\right) \geq \left(\pi^D(t) - \rho F - nB\right) + \frac{\delta}{1-\delta}\pi^C(t)$$

or, after rearranging,

$$\pi^D(t) - \pi^M(t) \leq \frac{\delta}{1-\delta}\left[\left(\pi^M(t) - \rho F - nB\right) - \pi^C(t)\right] \tag{4}$$

which is more stringent than with audits, in equation (2), thus hindering collusion.

Proposition 3. *With whistleblower programs, collusion can be sustained if* $\delta \geq \overline{\delta}_W(t) \equiv \frac{PG(t)}{PL(t)-(\rho F+nB)}$. *Cutoff* $\overline{\delta}_W(t)$ *satisfies* $\overline{\delta}_W(t) \in (0,1)$, *and unambiguously increases in* ρ, F, n, B, *and* t. *In addition,* $\overline{\delta}_W(t)$ *satisfies* $\overline{\delta}_W(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}$ *for all parameter values, and* $\overline{\delta}_W(t) \geq \overline{\delta}_L(t)$ *if and only if* $nB > \frac{[PL(t)-PG(t)-\rho F](\rho F+R)}{PG(t)+\rho F+R}$. *Finally, the derivatives* $\frac{\partial \overline{\delta}_W(t)}{\partial \rho}$ *and* $\frac{\partial \overline{\delta}_W(t)}{\partial F}$ *increase in* t *for all admissible parameters.*

Results are, then, analogous to audits, but now collusion can be further deterred with new policy tools, i.e., increasing n and B. More stringent environmental regulation still hinders collusion (i.e., $\overline{\delta}_W(t)$ unambiguously increases in fee t) and can boost the effectiveness of competition policy.

While whistleblower programs are more effective than audits at deterring collusion, $\overline{\delta}_W(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}$, its performance relative to leniency programs depends on the magnitude of bribes, nB; as shown in Proposition 3. When they are sufficiently high, whistleblower perform better than leniency programs, but the opposite ranking holds otherwise. The following example illustrates this result.

Example 5. Continuing with Example 3, collusion can be sustained under whistleblower programs if

$$\delta \geq \overline{\delta}_W(t) \equiv \frac{9(1-c-t)^2}{17\,(1-c-t)^2 - 576(\rho F + nB)}.$$

which increases in ρ, F, n, B, and t. In addition, derivatives $\frac{\partial \overline{\delta}_W(t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_W(t)}{\partial F}$ also increase in the stringency of the emission fee, t, implying that competition policy becomes more effective at deterring collusion.

In addition, $\overline{\delta}_W(t)$ lies above $\overline{\delta}_A(t)$ for all parameter values, and the "whistleblower premium," $\overline{\delta}_W(t) - \overline{\delta}_A(t)$, increases in the fee stringency, implying that $\overline{\delta}_W(t)$ is more sensitive to emission fees than $\overline{\delta}_A(t)$. Proposition 3 shows that, in contrast, $\overline{\delta}_W(t)$ lies above $\overline{\delta}_L(t)$ only when total bribes, as captured by nB, are sufficiently high. In our ongoing example, $\overline{\delta}_W(t) > \overline{\delta}_L(t)$ if and only if $nB > \frac{8\left[(1-c-t)^2 - 72\rho F\right](\rho F + R)}{9[(1-c-t)^2 + 64(\rho F + R)]}$ or, alternatively, after solving for t, when the emission fee is sufficiently stringent, $t \geq t_{W,L} \equiv (1-c) - \frac{24(\rho F + nB)(R + \rho F)}{[(8(R+\rho F) - 9nB)(\rho F + nB)(R + \rho F)]^{1/2}}$. Figure 2a superimposes $\overline{\delta}_W(t)$ on figure 1a, considering $n = 1$ and $B = \frac{1}{1{,}000}$, where $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$ are unaffected by parameters n and B.[10]

Cutoff $\overline{\delta}_W(t)$ is, however, lower than $\overline{\delta}_L(t)$ when $t < t_{W,L}$, which includes the case of $t = 0$, where emission fees are absent, thus indicating that leniency programs are more effective at deterring collusion than whistleblower programs, at least when bribes and fees are low (as depicted in figure 2a). When emission fees are stringent, however, the opposite ranking holds since $\overline{\delta}_W(t)$ lies above $\overline{\delta}_L(t)$ for all $t \geq t_{W,L} = 0.32$. The same argument applies when bribes are high (figure 2b, $B = \frac{1}{200}$), since $\overline{\delta}_W(t)$ lies above $\overline{\delta}_L(t)$ for all emission fees, t.

[10] Solving for t in initial condition $\rho F + nB < \frac{(1-c-t)^2}{72} = PL(t) - PG(t)$, yields $t < (1-c) - 6\sqrt{2}\sqrt{\rho F + nB}$, which in this context becomes $t < 1 - \frac{3\sqrt{7/10}}{5} \simeq 0.49$ when $B = \frac{1}{1{,}000}$ in figure 2a, and $t < 1 - \frac{3\sqrt{3/2}}{5} \simeq 0.27$ when $B = \frac{1}{200}$ in figure 2b. Figure 2a should, then, have an upper bound of $t < 0.49$ on the horizontal axis. For comparison purposes, we consider the same domain as in figure 1a. A similar argument applies to figure 2b.

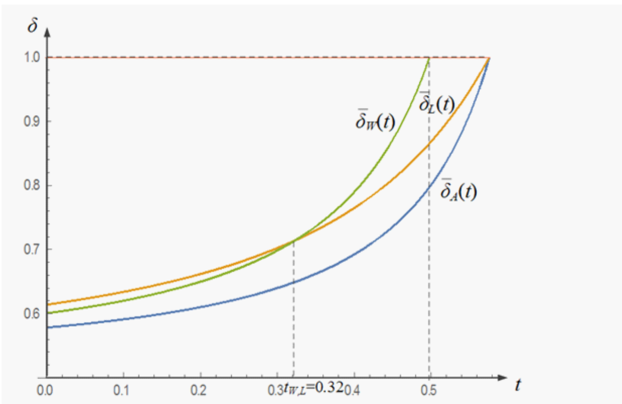

Fig 2a. $\overline{\delta}_W(t)$, $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$ - Low bribes.

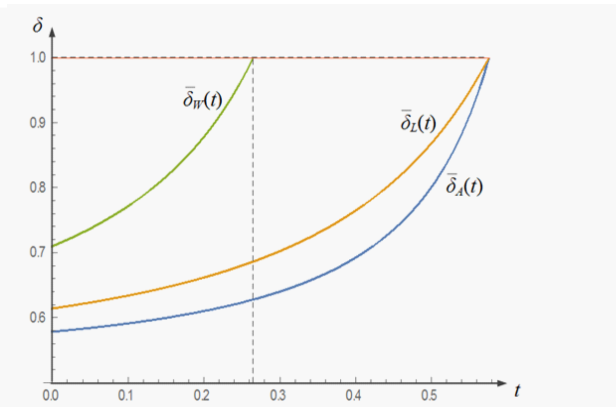

Fig 2b. $\overline{\delta}_W(t)$, $\overline{\delta}_L(t)$ and $\overline{\delta}_A(t)$ - High bribes.

4 Endogenous regulation

In this section, we introduce an environmental protection agency (EPA) and examine its impact at deterring collusion. The time structure of the game coincides with that in previous sections, but considers that the environmental agency sets emission fee $t \geq 0$ in the first stage.[11]

For tractability and to provide more precise comparisons, we hereafter focus on the setting with linear production costs, as examined in our ongoing example. Section 5 relaxes this context, allowing for nonlinear costs, product differentiation, several firms, and price competition.

When the regulator chooses emission fee t, she anticipates aggregate output and emissions. If Cournot competition unfolds, $\delta < \overline{\delta}_k(t)$, where $k = \{A, L, W\}$, every firm produces $q_i^C = \frac{1-c-t}{3}$, yielding aggregate output $Q^C(t) = 2q_i^C(t)$. In this context, the EPA sets an emission fee t that solves the following welfare-maximization problem

$$\max_{t \geq 0} \; W = CS + PS + T - Env \tag{5}$$

where $CS = \frac{(Q^C(t))^2}{2}$ denotes consumer surplus; $PS = 2\pi_i^C$ is producer surplus; $T = tQ^C(t)$ measures total tax collection, to make the emission fee revenue neutral; and $Env = d\left(Q^C(t)\right)^2$ is the environmental damage from pollution, where d represents pollution severity and $d \geq 1/2$ to guarantee positive emission fees. This welfare function follows that in Poyago-Theotoky (2007) and Lambertini et al. (2017), among others.

Lemma 4. *The regulator sets an emission fee $t^C = \frac{(1-c)(4d-1)}{2(1+2d)}$, which is unambiguously positive, increasing in pollution severity, d, but decreasing in marginal production cost, c.*

[11] An alternative timing where the EPA sets the emission fee in the third stage is uninteresting. In particular, the emission fee is more stringent when firms compete à la Cournot than when they collude to address a larger amount of pollution. In both settings, however, the EPA would induce the same aggregate socially optimal output.

As expected, the regulator sets a fee that becomes more stringent when pollution is more damaging (higher d). In contrast, when firms' costs increase (higher c) the regulator anticipates less aggregate output and emissions, requiring a less stringent fee.

The next proposition evaluates the minimal discount factor $\overline{\delta}_k(t)$ at the socially optimal fee t^C, obtaining $\overline{\delta}_k(t^C)$, along with cutoff $\overline{d}_{W,L}$; which are presented, for compactness, in the appendix.

Proposition 4. *Minimal discount factor $\overline{\delta}_k(t^C)$ is unambiguously increasing in c, d, ρ, and F, and its cross-partials satisfy $\frac{\partial \overline{\delta}_k(t^C)}{\partial \rho \partial c} > \frac{\partial \overline{\delta}_k(t^C)}{\partial \rho \partial d} > 0$ and $\frac{\partial \overline{\delta}_k(t^C)}{\partial F \partial c} > \frac{\partial \overline{\delta}_k(t^C)}{\partial F \partial d} > 0$ for every program $k = \{A, L, W\}$. In addition, $\overline{\delta}_W(t^C) \geq \overline{\delta}_L(t^C) \geq \overline{\delta}_A(t^C)$ for all $d \leq \overline{d}_{W,L}$, but $\overline{\delta}_L(t^C) > \overline{\delta}_W(t^C) \geq \overline{\delta}_A(t^C)$ otherwise.*

Technically, a marginal increase in c gives rise to two effects on $\overline{\delta}_A(t^C)$: (i) a direct effect, since c increases $\overline{\delta}_A(t)$ at a generic fee t, as shown in Proposition 1; and (ii) an indirect effect, since an increase in c leads the EPA to set a less stringent fee t^C, see Lemma 4, which, in turn, decreases $\overline{\delta}_A(t^C)$. The direct effect dominates, yielding an overall positive effect, implying that higher costs hinder collusion, as found in Proposition 4 and summarized in Table I. However, the presence of emission fees ameliorates the effect of c at deterring collusion.

Changes in other parameters give rise to direct or indirect effects alone. An increase in the expected fine, ρF, only entails a direct effect, but does not impact the emission fee t^C, thus not bringing indirect effects on collusion. As a consequence, the overall effect is positive, implying that collusion is hindered; as shown in Proposition 4 where we found that $\overline{\delta}_A(t^C)$ increases in both ρ and F. In contrast, an increase in pollution severity, d, gives rise to a positive indirect effect, via a more stringent fee t^C, without affecting the minimal discount factor, $\overline{\delta}_A(t)$. In this case, the overall effect is also positive, thus hindering collusion. A similar argument applies to the direct, indirect, and overall effects of $\overline{\delta}_L(t^C)$ and $\overline{\delta}_W(t^C)$, both exhibiting the same signs as those presented in Table I.

	Direct effect	Indirect effect	Overall effect on $\overline{\delta}_A(t^C)$
Higher c	+	−	+
Higher ρ	+	N/A	+
Higher F	+	N/A	+
Higher d	N/A	+	+

Table I. Direct and indirect effects on $\overline{\delta}_A(t^C)$.

We next evaluate how production costs and pollution severity interact with emission fees to influence antitrust effectiveness. Under exogenous emission fees, an increase in c and t gives rise to the same effect in $\frac{\partial \overline{\delta}_k(t)}{\partial \rho}$, implying that both are equally effective at preventing collusion. However, under endogenous emission fees, our above results show that an increase in c yields a larger effect on $\frac{\partial \overline{\delta}_k(t)}{\partial \rho}$ than d, i.e., $\frac{\partial \overline{\delta}_k(t^C)}{\partial \rho \partial c} > \frac{\partial \overline{\delta}_k(t^C)}{\partial \rho \partial d} > 0$, since more severe pollution induces a less-than-proportional increase in the emission fee t. Intuitively, higher costs not only affect profits structurally, even in the absence of emission fees, but also through a change in t. In contrast, an increase in pollution intensity only affects profits via emission fees, making the former more useful at boosting the effectiveness of competition policy than the latter.

Comparison. Figure 3a depicts minimal discount factors $\overline{\delta}_A(t^C)$, $\overline{\delta}_L(t^C)$, and $\overline{\delta}_W(t^C)$, considering the same parameter values as in figure 2a, with pollution severity, d, on the horizontal axis, where $d \geq 1/2$ by definition. As in section 3.4, where $\overline{\delta}_W(t)$ was more sensitive to increases in t than its counterpart under leniency programs, $\overline{\delta}_L(t)$, now $\overline{\delta}_W(t^C)$ is more affected by severe pollution than $\overline{\delta}_L(t^C)$ is. As a consequence, $\overline{\delta}_L(t^C) \geq \overline{\delta}_W(t^C)$ when pollution severity is low (condition $d \leq \overline{d}_{W,L}$ in Proposition 4 becomes $d < 0.61$ in the figure), but the opposite ranking holds for higher values of d; implying that $\overline{\delta}_W(t^C) > \overline{\delta}_L(t^C) > \overline{\delta}_A(t^C)$ holds for most pollution severities.

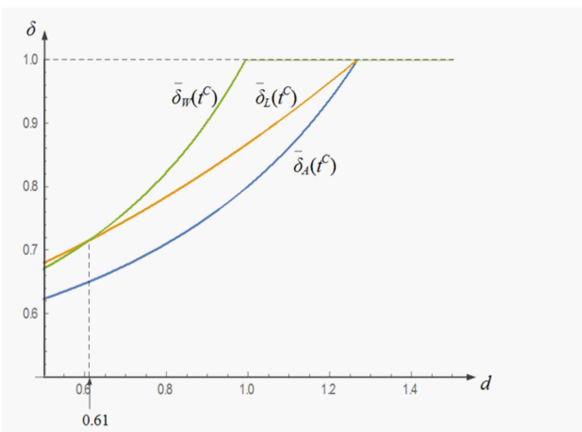

Fig 3a. $\overline{\delta}_k(t^C)$ as a function of d.

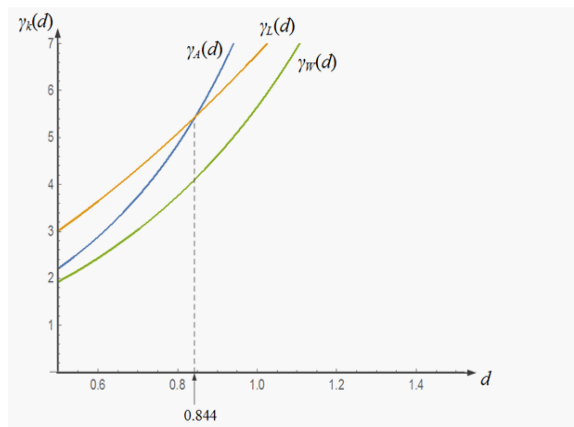

Fig 3b. $\gamma_k(d)$ as a function of d.

Figure 3b illustrates the derivative $\gamma_A(d) \equiv \frac{\partial \overline{\delta}_A(t^C)}{\partial \rho}$ considering the same parameters as previous figures. Since $\gamma_A(d)$ increases in d, it indicates that more severe pollution (higher d) induces the EPA to set a more stringent emission fee, t^C, making competition policy more effective at deterring collusion. Graphically, the slope of $\gamma_A(d)$ captures the "boosting" effect that more stringent emission fees have on competition policy. A similar argument applies to the derivatives $\gamma_L(d) \equiv \frac{\partial \overline{\delta}_L(t^C)}{\partial \rho}$ and $\gamma_W(d) \equiv \frac{\partial \overline{\delta}_W(t^C)}{\partial \rho}$, which are also increasing in d; as shown in Proposition 4.

While figure 3a indicates that whistleblower programs are the most effective at limiting collusion for most environmental damages, d, figure 3b shows that the boosting effect of emission fees is more significant with audits than with the other programs when pollution is severe.

4.1 Emission fees inducing collusion?

If the EPA anticipates that collusion will ensue in subsequent stages, $\delta \geq \overline{\delta}_A(t)$, it solves problem (5) evaluated at aggregate output $Q^M(t) = \frac{1-c-t}{2}$, obtaining an emission fee $t^M = \frac{(1-c)(2d-1)}{1+2d}$, which is positive given that $d \geq 1/2$ by definition. Since $\overline{\delta}_A(t)$ is increasing in t, and fees satisfy $t^C > t^M$, we find that $\overline{\delta}_A(t^C) > \overline{\delta}_A(t^M)$, giving rise to three regions, depicted in figure 4: (i) when $\delta < \overline{\delta}_A(t^M)$, collusion does not arise in equilibrium regardless of whether the regulator sets emission fee t^C or t^M; (ii) when $\overline{\delta}_A(t^M) \leq \delta \leq \overline{\delta}_A(t^C)$, collusion cannot be sustained if the regulator sets emission fee t^C, but can be supported if she sets t^M; and (iii) otherwise, collusion can arise with emission fee t^C and t^M.

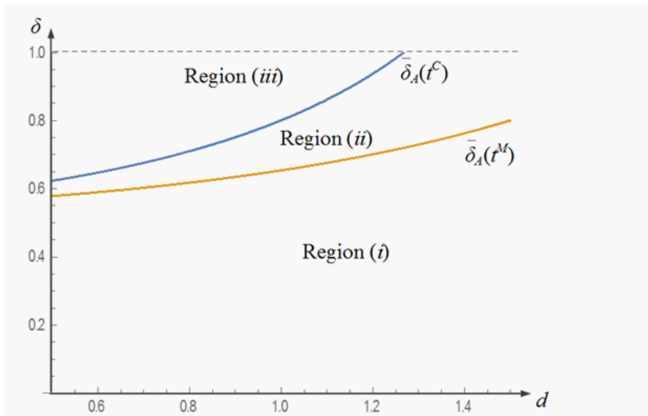

Fig. 4. $\overline{\delta}_A(t^M)$ and $\overline{\delta}_A(t^C)$.

Therefore, emission fees induce no changes in firm's collusive behavior when discounting is relatively low or high, as shown in regions (i) and (iii). For intermediate discounting, however, setting the stringent fee t^C prevents collusion whereas the lower fee t^M facilitates it.

In region (ii), the EPA can induce collusion, which sounds as "good news" since it reduces aggregate output and emissions; or prevent collusion, which seems "bad news" because firms produce larger emissions. However, collusion in this region only arises after fee t^M, leading firms to produce the first-best aggregate output $Q^M(t^M) = \frac{1-c}{1+2d}$, which coincides with that emerging after setting fee t^C and deterring collusion, $Q^C(t^C)$, thus yielding the same welfare level with both fees. In summary, the EPA sets emission fee t^C in regions (i) and (ii), and fee t^M only in region (iii).[12]

4.2 Welfare comparisons

As discussed above, in region (i), firms compete regardless of the emission fee. Therefore, if the EPA (incorrectly) sets emission fee t^M instead of t^C, where $t^M < t^C$, regulation would be too lax, yielding a socially excessive level of pollution. Formally, we measure this inefficiency (regulatory

[12] Other emission fees are suboptimal. To see this point, consider, for instance, a fee $t' \neq t^M \neq t^C$. Starting from t^C, a fee t' satisfying $t^C > t' > t^M$, implies that $\overline{\delta}_A(t') < \overline{\delta}_A(t^C)$, thus expanding region (iii), which facilitates collusion. However, anticipating collusion, fee t' is not welfare maximizing; instead, fee t^M is. A similar argument applies if the EPA sets a fee $t'' > t^C$, entailing that $\overline{\delta}_A(t'') > \overline{\delta}_A(t^C)$, hindering collusion. Conditional on competition ensuing in this industry, fee t^C is welfare maximizing, while t'' is not.

error) with

$$\Delta W^C \equiv W^C(t^C) - W^C(t^M),$$

where $W^C(\cdot)$ indicates that firms compete. Similarly, in region (iii), firms collude regardless of the emission fee. Hence, if the EPA sets fee t^C instead of t^M, environmental policy would be too stringent, giving rise to an inefficiency

$$\Delta W^M \equiv W^M(t^M) - W^M(t^C),$$

where $W^M(\cdot)$ denotes that firms collude. Finally, in region (ii), firms do not collude when facing fee t^C but do when facing t^M. Therefore, the welfare change from the EPA setting fee t^M instead of t^C is $\Delta W^{C,M} \equiv W^C(t^C) - W^M(t^M)$. The next corollary examines these three inefficiencies.

Corollary 1. *Inefficiency* $\Delta W^C = \frac{2d^2(1-c)^2}{9(1+2d)}$ *is unambiguously positive and increasing in pollution severity, d. Inefficiency* $\Delta W^M = \frac{(1-c)^2}{32(1+2d)}$ *is also positive, but decreasing in pollution severity, d; and* $\Delta W^{C,M}$ *is nil for all parameter values.*

Intuitively, the inefficiency from setting a too lax fee, ΔW^C, increases as pollution becomes more severe; while that arising from a too stringent fee, ΔW^M, decreases in this severity. Finally, welfare levels $W^C(t^C)$ and $W^M(t^M)$ coincide, indicating that the EPA seeks to induce the same aggregate socially optimal output in both market structures, $Q^C(t^C) = Q^M(t^M) = \frac{1-c}{1+2d}$, thus yielding the same welfare level.

5 Extensions

We now examine how our above results are affected by changes in the modeling assumptions, allowing for convex production costs, product differentiation, more than two firms, and for firms competing in prices.

5.1 Allowing for non-linear costs

Consider that every firm faces non-linear production costs,

$$C(q_i) = cq_i + \frac{\beta}{2}q_i^2,$$

where $\beta \geq 0$ measures the extent of convexity. In this context, marginal costs are $c + \beta q_i$, implying that when $\beta = 0$, marginal costs are constant, as in previous sections; otherwise, they are increasing in output (i.e., firms suffer from diseconomies of scale).

Appendix 2 identifies equilibrium conditions to sustain collusion under audits, leniency, and whistleblower programs. For compactness, we next focus on how convexity, as captured by parameter β, affects our previous results.[13]

[13] For simplicity, we consider that $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, as in previous sections; and that expected penalties from

Under no competition policy, collusion can be sustained if

$$\delta \geq \overline{\delta}(\beta) \equiv \frac{(3+\beta)^2}{17+2\beta(6+\beta)},$$

which originates at $\overline{\delta}(0) = \frac{9}{17}$ when costs are linear, $\beta = 0$, and decreases in β, indicating that firms have more incentives to collude when facing convex costs (i.e., collusion ameliorates diseconomies of scale). As in the linear cost setting, $\overline{\delta}(\beta)$ is unaffected by the emission fee, t.

When the CA uses audits to deter collusion, Appendix 2 shows that it can be supported if $\delta \geq \overline{\delta}_A(\beta, t)$, where $\overline{\delta}_A(\beta, t)$ coincides with that in Example 3 when costs are linear, $\overline{\delta}_A(0, t) = \overline{\delta}_A(t)$, satisfies $\overline{\delta}_A(\beta, t) \in (0, 1)$ and $\overline{\delta}_A(\beta, t) \geq \overline{\delta}(\beta)$. In addition, $\overline{\delta}_A(\beta, t)$ exhibits similar comparative statics as $\overline{\delta}_A(t)$, increasing in t, ρ, and F. A similar argument applies under leniency and whistleblower programs, $\overline{\delta}_L(\beta, t)$ and $\overline{\delta}_W(\beta, t)$; as reported in Appendix 2.

Emission fees. The EPA sets an emission fee t to maximize social welfare, as in problem (5), but evaluated at $Q^C(t) = \frac{2(1-c-t)}{3+\beta}$ since equilibrium output is $q_i^C(t) = \frac{1-c-t}{3+\beta}$ in this context. Differentiating with respect to t, yields

$$t^C(\beta) = \frac{(1-c)(4d-1)}{2(1+2d)+\beta}.$$

This fee coincides with that in the baseline model when $\beta = 0$, since $t^C(0) = \frac{(1-c)(4d-1)}{2(1+2d)}$; but decreases in cost convexity, β. Intuitively, a marginal increase in the emission fee t produces a larger reduction in aggregate output under convex than linear costs, that is, $\frac{\partial Q^C(t)}{\partial t \partial \beta} = \frac{2}{(3+\beta)^2} > 0$, making the fee, essentially, more effective at curbing pollution. As a consequence, the regulator can set a less stringent fee when β increases.[14]

More convex costs (higher β) give rise to a direct and indirect effect on the minimal discount factor $\overline{\delta}_A(\beta, t)$ evaluated at the equilibrium fee $t^C(\beta)$, similar to those discussed in section 4 and Table I. As shown in Appendix 2, an increase in β yields the total derivative

$$\frac{d\overline{\delta}_A(\beta, t^C(\beta))}{d\beta} = \underbrace{\frac{\partial \overline{\delta}_A(\beta, t^C(\beta))}{\partial \beta}}_{+ \text{ Direct effect}} + \underbrace{\underbrace{\frac{\partial \overline{\delta}_A(\beta, t)}{\partial t}}_{+} \underbrace{\frac{\partial t^C(\beta)}{\partial \beta}}_{-}}_{- \text{ Indirect effect}}$$

On one hand, more convex costs lower the stringency of the emission fee $t^C(\beta)$, which decreases $\overline{\delta}_A(\beta, t)$, facilitating collusion (i.e., negative indirect effect). On the other hand, convex costs also reduce firms' profits from continuing their collusion, as captured by the right-hand side of equation (2), thus hindering collusive practices (i.e., positive direct effect). To identify which effect

collusion are non-negligible, $\rho F > \frac{(1-c-t)^2}{(3+\beta)^3(4+\beta)(8+3\beta)}$. This lower bound on ρF originates at $\rho F > \frac{(1-c-t)^2}{864}$ when $\beta = 0$ and decreases in β, thus becoming less demanding when firms' costs are more convex.

[14] Otherwise, $t^C(\beta)$ exhibits the same comparative statics as t^C in the main body of the paper, namely, decreasing in c, but increasing in d.

dominates, figure 5a depicts minimal discount factor $\overline{\delta}_A(\beta, t^C(\beta))$ considering the same parameter values as figure 3a and $\beta = 1/2$. Discount factor $\overline{\delta}_A(\beta, t^C(\beta))$ shifts upwards relative to figure 3a, where $\beta = 0$, implying that the direct positive effect dominates, ultimately hindering collusion. A similar argument applies to leniency and whistleblower programs where, as shown in figure 5a, $\overline{\delta}_L(\beta, t^C(\beta))$ and $\overline{\delta}_W(\beta, t^C(\beta))$ also shift upwards relative to figure 3a.[15]

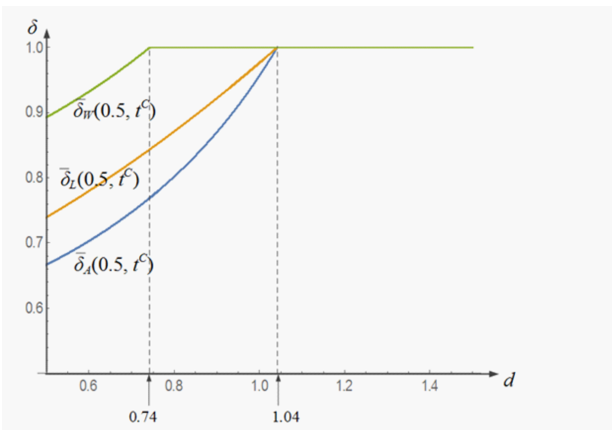

Fig. 5a. $\overline{\delta}_k(\beta, t^C)$ as a function of d.

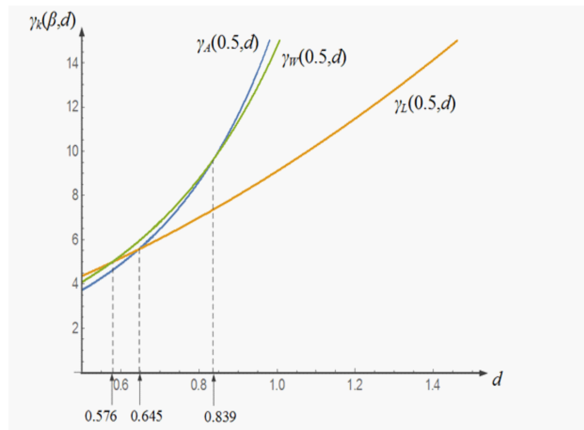

Fig. 5b. $\gamma_k(\beta, d)$ as a function of d.

Figure 5b evaluates the derivative $\gamma_k(\beta, d) \equiv \frac{\partial \overline{\delta}_L(\beta, t^C(\beta))}{\partial \rho}$ at the equilibrium fee $t^C(\beta)$ found above. This figure is analogous to figure 3b, but considers $\beta = 1/2$, to compare our results against those under linear costs. Relative to figure 3b, $\gamma_k(\beta, d)$, shifts upwards as firms experience more convex costs (higher β), implying that the boosting effect of emission fees is emphasized by cost convexities. In summary, while firms have stronger incentives to collude when their costs are convex than linear (to ameliorate diseconomies of scale), the presence of environmental regulation makes competition policy more effective at deterring collusion.

Economies of scale. Our model also applies to settings where firms face concave cost functions, $\beta < 0$, thus benefiting from economies of scale.[16] In this context, more significant economies of scale (i.e., more negative β) yields similar results as a reduction in β in our above discussion, namely, $\overline{\delta}(\beta)$ decreases, thus facilitating collusion. A similar argument applies to $\overline{\delta}_A(\beta, t^C(\beta))$, $\overline{\delta}_L(\beta, t^C(\beta))$, and $\overline{\delta}_W(\beta, t^C(\beta))$. Likewise, the booster becomes smaller when economies of scale are more significant, i.e., $\gamma_A(\beta, d)$, $\gamma_L(\beta, d)$, and $\gamma_W(\beta, d)$ decrease as β is more negative. Intuitively, these findings go in the opposite direction as those above: while firms have less incentives to collude when they benefit from economies of scale than otherwise, the presence of emission fees make competition policy less effective at deterring collusion. In consequence, collusive practices in

[15] Figure 5a considers low bribes, $B = \frac{1}{1{,}000}$, as in figure 2a. Allowing for high bribes, $B = \frac{1}{200}$, as in figure 2b, produces a downward shift in $\overline{\delta}_W(\beta, t^C(\beta))$, while leaving $\overline{\delta}_A(\beta, t^C(\beta))$ and $\overline{\delta}_L(\beta, t^C(\beta))$ unaffected.

[16] To ensure that output is bounded, we need economies of scale to not be excessive, specifically, $\beta > -3$.

industries with strong economies of scale, while uncommon, may become harder to monitor and prosecute when firms are being regulated by the EPA.

5.2 Allowing for product differentiation

Consider the same setting as in sections 3-4, but with inverse demand function $p(q_i, q_j) = 1 - q_i - \gamma q_j$, where $\gamma \in [0, 1]$ denotes product substitutability, that is, when $\gamma = 0$ goods are completely differentiated, while when $\gamma = 1$ they become homogeneous, as in previous sections. Appendix 3 shows output and minimal discount factors sustaining collusion, while here we focus on the role of parameter γ.

Under no competition policy, collusion is supported when

$$\delta \geq \overline{\delta}(\gamma) \equiv \frac{(2+\gamma)^2}{8+\gamma(8+\gamma)},$$

which increases in γ, and reaches its maximum at $\overline{\delta}(1) = \frac{9}{17}$ when products are homogeneous. Consequently, when products become more differentiated (lower γ), cutoff $\overline{\delta}(\gamma)$ decreases, implying that collusion is facilitated. This is a well-known result: when goods are more differentiated, every firm has less incentives to deviate from the collusive agreement, since its sales are less impacted by its rival's output. As a consequence, collusion can be sustained under larger parameter conditions.

The following lemma identifies how the minimal discount factors sustaining collusion are affected by parameter γ.

Lemma 5. *Cutoff $\overline{\delta}_A(\gamma, t)$ increases in γ if and only if $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{\gamma^2}{2(2+\gamma)}$, cutoff $\overline{\delta}_L(\gamma, t)$ unambiguously increases in γ, and cutoff $\overline{\delta}_W(\gamma, t)$ increases in γ if and only if $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{1}{2(2+\gamma)}$. In addition, $\overline{\delta}_k(\gamma, t)$ coincides with $\overline{\delta}_k(t)$ in Propositions 1-3 when $\gamma = 1$ for every program $k = \{A, L, W\}$; increases in t, c, ρ, and F; and the derivatives $\frac{\partial \overline{\delta}_k(\gamma,t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_k(\gamma,t)}{\partial F}$ are increasing in t.*

When expected penalties are sufficiently low, cutoffs in every program, $\overline{\delta}_k(\gamma, t)$, are increasing in γ. Alternatively, more differentiated goods (lower γ) decreases these cutoffs, facilitating collusion. When expected penalties are relatively high, however, more differentiated goods hinder collusion under audits and whistleblower programs, but still facilitate it under leniency programs. Intuitively, the "collusion-destruction" effect of rewards is ameliorated when firms sell differentiated products, ultimately facilitating collusion. This does not occur with the other two programs, where higher expected penalties make deviation more attractive under differentiated products.

In addition, $\overline{\delta}_k(\gamma, t)$ exhibits similar comparative statics as $\overline{\delta}_k(t)$, increasing in t, c, ρ, and F; and the "booster" effects are still positive, since $\frac{\partial \overline{\delta}_k(\gamma,t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_k(\gamma,t)}{\partial F}$ increase when emission fee t becomes more stringent.

Emission fees. The regulator sets an emission fee t to maximize social welfare, as in problem

(5), which in this context yields

$$t^C(\gamma) = \frac{(1-c)(4d-1)}{4d+1+\gamma}.$$

This fee coincides with that in the baseline model when products are homogeneous, $\gamma = 1$, but increases as goods become more differentiated (lower γ). As under convex costs, a marginal increase in the emission fee t produces a larger reduction in aggregate output when goods are homogeneous than differentiated, that is, $\frac{\partial Q^C(t)}{\partial t \partial \gamma} = \frac{2}{(2+\gamma)^2} > 0$, making the fee more effective at curbing pollution. As a consequence, a less stringent fee is required when γ increases or, alternatively, a lower fee is needed when goods are more differentiated.

We next disentangle the direct and indirect effect of more homogeneous goods (higher γ) on the minimal discount factor $\overline{\delta}_A(\gamma, t)$ evaluated at the equilibrium fee $t^C(\gamma)$,

$$\frac{d\overline{\delta}_A(\gamma, t^C(\gamma))}{d\gamma} = \underbrace{\frac{\partial\overline{\delta}_A(\gamma, t^C(\gamma))}{\partial\gamma}}_{+ \text{ or } - \text{ Direct effect}} + \underbrace{\underbrace{\frac{\partial\overline{\delta}_A(\gamma, t)}{\partial t}}_{+}\underbrace{\frac{\partial t^C(\gamma)}{\partial\gamma}}_{-}}_{- \text{ Indirect effect}}.$$

As shown above, fee $t^C(\gamma)$ is decreasing in γ and, as found in Lemma 5, $\overline{\delta}_A(\gamma, t)$ increases in fee t, yielding a negative indirect effect. Intuitively, this indicates that more homogeneous goods facilitate collusion or, alternatively, more differentiated products hinder collusion. The sign of the direct effect is, however, ambiguous. As shown in Lemma 5, it is negative when expected penalties are relatively high, reinforcing the indirect effect, making the overall effect unambiguously negative, and facilitating collusion. In this case, more differentiated goods hinder collusion. In contrast, when expected penalties are low, the direct effect becomes positive, potentially exceeding the indirect negative effect, leading to an overall positive effect. A similar argument applies under leniency and whistleblower programs.

5.3 Allowing for more firms

We now consider $m \geq 2$ firms in the industry. Appendix 4 identifies equilibrium output, profits, and the minimal discount factors sustaining collusion, while here we analyze how more firms (higher m) affects the sustainability of collusion.

Under no competition policy, collusion is supported when

$$\delta \geq \overline{\delta}(m) \equiv \frac{(m+1)^2}{m(m+6)+1},$$

which satisfies $\overline{\delta}(m) \in [0, 1]$, originates at $\overline{\delta}(2) = \frac{9}{17}$ when $m = 2$, increases in m, and approaches 1 when $m \to +\infty$. This is a well-known result, namely, as more firms are active in the industry, collusion is more difficult to be sustained. As in section 3.1, $\overline{\delta}(m)$ is not a function of t, implying that, in the absence of competition policy, collusion incentives are unaffected by the emission fee.

When the CA uses audits, Appendix 4 shows that collusion can be supported if

$$\delta \geq \overline{\delta}_A(m,t) \equiv \frac{(m^2-1)^2\,(1-c-t)^2}{(m-1)^2\,(1-c-t)^2\,[m(m+6)+1] - 16m^2(m+1)^2\rho F},$$

where $\overline{\delta}_A(m,t)$ exhibits similar comparative statics as that in Example 3, namely, $\overline{\delta}_A(m,t) \geq \overline{\delta}_A(m)$ under all parameter values; increasing in t, c, ρ, and F; and its derivatives $\frac{\partial \overline{\delta}_A(m,t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_A(m,t)}{\partial F}$ are unambiguously increasing in the stringency of the emission fee, t. A similar argument applies to the other programs, $\overline{\delta}_L(m,t)$ and $\overline{\delta}_W(m,t)$, presented for compactness in Appendix 4.

Regarding the comparative statics of $\overline{\delta}_A(m,t)$ with respect to m (direct effect), our results go in line with those in the previous extension, finding that $\overline{\delta}_A(m,t)$ increases in m if and only if $\rho F < \frac{(m-1)^4(1-c-t)^2}{8m(m+1)^3}$, with this condition being more demanding than the initial assumption $\rho F < \pi^M(t) - \pi^C(t) = \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$. Therefore, the direct effect of m on $\overline{\delta}_A(m,t)$ is positive, hindering collusion, if the expected penalty ρF is relatively low; but becomes negative, facilitating collusion, otherwise. Similar conditions on the expected penalty apply to the leniency and whistleblower programs, as reported in Appendix 4.

Emission fees. The regulator sets an emission fee t to maximize welfare, as in problem (5), yielding

$$t^C(m) = \frac{(1-c)(2dm-1)}{m(1+2d)}$$

which is positive since $d \geq 1/2$ by definition. This fee coincides with that in Lemma 4 when $m = 2$ firms, $t^C(2) = \frac{(1-c)(4d-1)}{2(1+2d)}$, and becomes more stringent when more firms are active (higher m). Therefore, the indirect effect of m on $\overline{\delta}_A(m,t)$, via the emission fee, is unambiguously positive, i.e., $\frac{\partial \overline{\delta}_A(m,t)}{\partial t}\frac{\partial t^C(m)}{\partial m} > 0$ since both terms are positive, ultimately hindering collusion. Overall, considering the direct and indirect effect of m, we obtain

$$\frac{d\overline{\delta}_A(m,t^C(m))}{dm} = \underbrace{\frac{\partial \overline{\delta}_A(m,t^C(m))}{\partial m}}_{+\text{ or }-\text{ Direct effect}} + \underbrace{\underbrace{\frac{\partial \overline{\delta}_A(m,t)}{\partial t}}_{+}\underbrace{\frac{\partial t^C(m)}{\partial m}}_{+}}_{+\text{ Indirect effect}}.$$

implying that, when the direct effect is positive, which occurs when expected fines are relatively low, the direct and indirect effect reinforce each other. In this context, a more competitive industry (higher m) produces an overall increase in $\overline{\delta}_A(m,t^C(m))$, hindering collusion. A similar argument applies when the direct effect is negative, but small, still yielding a positive overall effect. When the direct effect is negative and large in absolute value, however, which occurs when expected fines are high, the negative direct effect may dominate, implying that a more competitive market (higher m) facilitates collusion.

5.4 Allowing for price competition

If firms compete in prices (à la Bertrand), collusion can be sustained under no competition policy if equation (1) holds, which in this context implies that $\delta \geq \overline{\delta}^B(t) \equiv \frac{1}{2}$, where superscript B denotes Bertrand competition. This result coincides with that in standard models with firms competing in prices, and confirms our finding in section 3.1, namely, firms' incentives to collude are unaffected by the presence of emission fees, t.

Appendix 5 identifies conditions sustaining collusion with audits alone, $\delta \geq \overline{\delta}_A^B(t) \equiv \frac{(1-c-t)^2}{2(1-c-t)^2-8\rho F}$, showing that it exhibits the same properties as that when firms compete in quantities. In particular, we confirm that $\overline{\delta}_A^B(t)$ is increasing in t, c, ρ, and F; and its first-order derivatives $\frac{\partial \overline{\delta}_A^B(t)}{\partial \rho}$ and $\frac{\partial \overline{\delta}_A^B(t)}{\partial F}$ are both increasing in the stringency of emission fee t, indicating that environmental regulation makes competition policy more effective.

A similar argument applies to leniency programs, where $\delta \geq \overline{\delta}_L^B(t) \equiv \frac{(1-c-t)^2+2(R+4\rho F)}{2\left[(1-c-t)^2+R\right]}$, and to whistleblower programs, $\delta \geq \overline{\delta}_W^B(t) \equiv \frac{(1-c-t)^2}{2\left[(1-c-t)^2-4(nB+\rho F)\right]}$; thus going in line with our previous results. Both minimal discount factors are increasing in competition policy variables (such as R, n, and B) and the marginal effect of these policies is emphasized by the stringency of emission fee, t.

Emission fees. The regulator solves problem (5), which in this context yields an equilibrium emission fee $t^B = \frac{2d(1-c)}{1+2d}$ (see Appendix 5 for more details). This fee exhibits the same comparative statics as that under quantity competition, namely, increasing in pollution severity, d, but decreasing in cost, c. Comparing this fee against that under Cournot competition, t^C, we find that $t^B > t^C$ for all parameter values. Intuitively, the regulator anticipates more aggregate output and emissions under Bertrand than Cournot competition, requiring a more stringent fee.

For illustration purposes, figure 6a depicts $\overline{\delta}_A^B(t^B)$, $\overline{\delta}_L^B(t^B)$, and $\overline{\delta}_W^B(t^B)$ evaluated at the equilibrium fee t^B found above and considering, for consistency, the same parameter values as in figure 3a (low bribes). Like with output competition, the figure shows that $\overline{\delta}_k^B(t^B)$ increases in d for every program $k = \{A, L, W\}$ and that leniency programs more effectively deter collusion than whistleblower or audit programs, $\overline{\delta}_L^B(t^B) > \overline{\delta}_W^B(t^B) > \overline{\delta}_A^B(t^B)$. In addition, comparing figures 3a and 6a, cutoffs satisfy $\overline{\delta}_k^B(t^B) < \overline{\delta}_k(t^C)$ for every program k, implying that collusion can be sustained under larger conditions when firms compete in prices than quantities, which holds for all values of d.

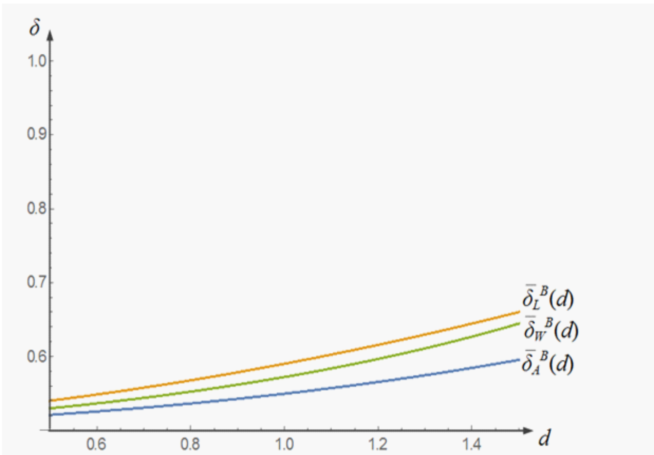

Fig. 6a - Discount factors $\overline{\delta}_k^B(t^B)$.

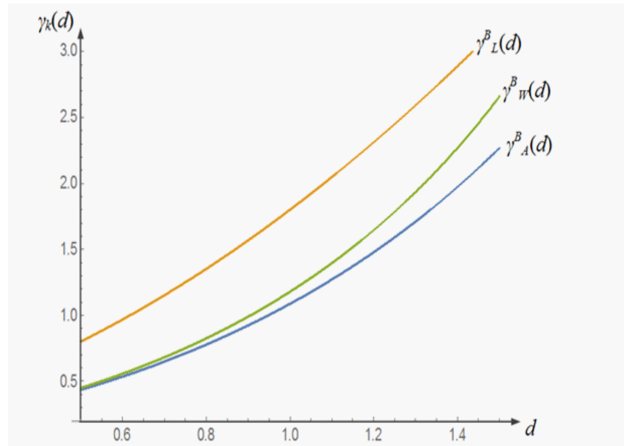

Fig 6b - Booster effects, $\gamma_k^B(d)$.

Figure 6b illustrates the booster effects, $\gamma_k^B(d) \equiv \frac{\partial \overline{\delta}_k^B(t^B)}{\partial \rho}$ evaluated at the equilibrium fee t^B found above. Like in figure 3b under output competition, boosters are increasing in pollution severity, d, implying that, as emission fees become more stringent, competition policy (e.g., increasing the expected fine, ρF) is more effective at deterring collusion. The boosting effect is, however, generally smaller when firms compete in prices than quantities, $\gamma_k^B(d) < \gamma_k(d)$ for all values of d.

6 Discussion

Production costs and emission fees. Our results show that, when taking emission fees as given, their effect on collusive behavior is identical to a cost increase, i.e., c and t increase $\overline{\delta}_k(t)$ by the same amount. When emission fees are endogenous, however, we find that an increase in pollution severity, d, is no longer symmetric to that arising from a cost increase. This is due to the presence of direct and indirect effects on $\overline{\delta}_k(t)$ when evaluated at the equilibrium emission fee. While more severe pollution only gives rise to indirect effects (i.e., a more stringent fee hinders collusion), an increase in production costs induces a positive direct and a negative indirect effect: the former arising regardless of whether the industry is regulated, the latter stemming from a less stringent fee. This result is consistent across our four extensions, implying that it holds when production costs are linear and convex, firms sell homogeneous and heterogeneous products, two or more firms compete in the industry, and competition is in quantities or prices.

Emission fees enhancing competition policy. Our findings suggest that CAs may require fewer resources for monitoring and prosecuting colluding firms within industries facing emission fees, compared to unregulated markets. The mechanism behind this result is not pollution itself but rather the environmental policy in place. As environmental damage increases, so does fee stringency, which weakens cartel stability and strengthens competition policy's ability to deter collusion, even in scenarios where collusion might otherwise emerge in the absence of environmental oversight. Hence, our results provide a novel, unintended role to the EPA, namely, making competition policy more effective.

This "boosting" effect of emission fees is amplified in settings where firms face highly convex production costs, enabling CAs to further reduce monitoring efforts and reduced fines to firms cooperating with investigators. Conversely, when the production process benefits from economies of scale, our results indicate that competition policy must be more robust to effectively prevent collusion. A similar argument applies when products become more differentiated, where firms have stronger incentives to collude under no competition policy, but these incentives are hindered thanks to the interaction of emission fees and competition policy if expected penalties are high.

Political challenges of leniency programs. Leniency programs often face public opposition due to the perception that they reward firms that have previously exploited consumers. Our findings contribute to this debate by indicating that, in regulated industries, CAs can reduce leniency rewards and whistleblower compensations, which could make these programs less contentious and more politically sustainable.

Prioritizing antitrust efforts. Our results also offer guidance on prioritizing antitrust enforcement efforts, such as monitoring and investigating potential collusion, by suggesting a shift towards unregulated industries. In these contexts, while the probability of detection does reduce the likelihood of collusion, it is generally less effective without concurrent emission fees. This insight also applies to offering incentives for firms or employees assisting investigations within leniency or whistleblower programs, since these measures become less effective in the absence of emission fees. In summary, environmental regulation could allow the CA to reduce antitrust efforts in regulated markets and, instead, concentrate them in unregulated sectors.

Further research. Our model can be extended along several dimensions. First, one could model firms producing in different countries, each subject to different emission fees, but monitored by the CA of the country where both firms sell their products. Second, allowing for asymmetries in firm production costs could yield insightful results; under linear costs, such asymmetry might lead to corner solutions following collusion, where only the most efficient firm remains active, whereas nonlinear costs might sustain multiple active firms. Lastly, the EPA could be uninformed about production costs, setting fees based on expected costs, which can potentially affect collusive patterns.

7 Appendix

7.1 Appendix 1 - Linear production costs

Competition. When firms compete, every firm i chooses its output q_i to solve

$$\max_{q_i \geq 0} \pi_i(t) = (1 - q_i - q_j)q_i - (c+t)q_i$$

where $j \neq i$, and $t \geq 0$ denotes the per-unit emission fee. This problem yields the well-known output level $q_i^C(t) = \frac{1-c-t}{3}$, where superscript C denotes "competition," and profits $\pi^C(t) = \left(q_i^C(t)\right)^2$, which are decreasing in the stringency of the emission fee, t.

Collusion. When firms collude, they seek to maximize their joint profits, as follows

$$\max_{q_i, q_j \geq 0} \pi_i(t) + \pi_j(t).$$

yielding individual output $q_i^M(t) = \frac{1-c-t}{4}$, where superscript M represents that firms choose the monopoly output. In this context, profits are $\pi^M(t) = 2\left(q_i^M(t)\right)^2$, which are decreasing in t.

Deviation. When a firm unilaterally deviates from the collusive output $q_i^M(t)$, choosing $q_i^D(t) = \frac{3(1-c-t)}{8}$, where superscript D denotes deviation, it earns profits $\pi^D(t) = \left(q_i^D(t)\right)^2$, which are decreasing in t. As expected, profits in the above three scenarios satisfy $\pi^D(t) \geq \pi^M(t) \geq \pi^C(t)$.

No competition policy. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ in equation (1), yields

$$\left(\frac{3(1-c-t)}{8}\right)^2 - 2\left(\frac{1-c-t}{4}\right)^2 \leq \frac{\delta}{1-\delta}\left[2\left(\frac{1-c-t}{4}\right)^2 - \left(\frac{1-c-t}{3}\right)^2\right]$$

which simplifies to $\frac{(1-c-t)(17\delta-9)}{1-\delta} \geq 0$. Since $t < 1-c$ by definition, this inequality holds if $17\delta - 9 \geq 0$, or $\delta \geq \frac{9}{17}$.

Audits. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (2), and solving for δ, yields

$$\delta \geq \overline{\delta}_A(t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2 - 576\rho F}.$$

Cutoff $\overline{\delta}_A(t) > 0$ for all $\rho F < \frac{17(1-c-t)^2}{576}$, which holds since condition $\pi^M(t) - \rho F > \pi^C(t)$ implies $\rho F < \frac{(1-c-t)^2}{72}$, and $\frac{17(1-c-t)^2}{576} > \frac{(1-c-t)^2}{72}$. In addition, $\overline{\delta}_A(t) < 1$ for all $\rho F < \frac{(1-c-t)^2}{72}$, which holds by definition. Comparing cutoffs $\overline{\delta} \equiv \frac{9}{17}$ and $\overline{\delta}_A(t)$, we find that

$$\overline{\delta}_A(t) - \overline{\delta} = \frac{5,184\rho F}{289(1-c-t)^2 - 9,792\rho F},$$

which is positive for all $\rho F < \frac{17(1-c-t)^2}{576}$, which holds since $\rho F < \frac{(1-c-t)^2}{72}$ by definition.

In addition, the comparative statics of $\overline{\delta}_A(t)$ are the following: $\frac{\partial \overline{\delta}_A(t)}{\partial c} = \frac{\partial \overline{\delta}_A(t)}{\partial t} = \frac{10{,}368\rho F(1-c-t)}{\left[17(1-c-t)^2 - 576\rho F\right]^2} >$

0, $\frac{\partial \overline{\delta}_A(t)}{\partial \rho} = \frac{5{,}184F(1-c-t)^2}{\left[17(1-c-t)^2-576\rho F\right]^2} > 0$, and $\frac{\partial \overline{\delta}_A(t)}{\partial F} = \frac{5{,}184\rho(1-c-t)^2}{\left[17(1-c-t)^2-576\rho F\right]^2} > 0$; while its cross-partial derivative is $\frac{\partial^2 \overline{\delta}_A(t)}{\partial \rho \partial t} = \frac{10{,}368F(1-c-t)\left[17(1-c-t)^2+576\rho F\right]}{\left[17(1-c-t)^2-576\rho F\right]^3} > 0$ and, similarly, $\frac{\partial^2 \overline{\delta}_A(t)}{\partial F \partial t} = \frac{10{,}368\rho(1-c-t)\left[17(1-c-t)^2+576\rho F\right]}{\left[17(1-c-t)^2-576\rho F\right]^3} > 0$, because $\rho F < \frac{(1-c-t)^2}{72}$ by definition.

Leniency programs. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (3), yields

$$\delta \geq \overline{\delta}_L(t) \equiv \frac{9\left[(1-c-t)^2 + 64\left(R+\rho F\right)\right]}{17(1-c-t)^2 + 576R}.$$

The numerator of cutoff $\overline{\delta}_L(t)$ is positive for all $R > -\frac{(1-c-t)^2}{64} - \rho F \equiv R_1$, its denominator is positive for all $R > -\frac{17(1-c-t)^2}{576} \equiv R_2$. Comparing cutoffs R_1 and R_2, we can see that R_1 decreases in the expected fine, ρF, and satisfies $R_1 > R_2$ for all $\rho F < \frac{(1-c-t)^2}{72}$, which holds by definition. Therefore, $R_1 > R_2$ under all admissible parameters, entailing that condition $R > R_1$ is more demanding than $R > R_2$. However, condition $R > R_1$ must hold by assumption: since $R > -\rho F$ by definition, then $R > -\frac{(1-c-t)^2}{64} - \rho F$ as well, ultimately implying that $R > R_1$ is also satisfied. Furthermore, cutoff $\overline{\delta}_L(t)$ satisfies $\overline{\delta}_L(t) < 1$ when $\rho F < \frac{(1-c-t)^2}{72}$, which holds by definition.

Comparing cutoffs $\overline{\delta}_A(t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2-576\rho F}$ and $\overline{\delta}_L(t)$, we find that

$$\overline{\delta}_L(t) - \overline{\delta}_A(t) = \frac{4,608\left[(1-c-t)^2 - 72\rho F\right]\left(R+\rho F\right)}{\left[17(1-c-t)^2 + 576R\right]\left[17(1-c-t)^2 - 576\rho F\right]},$$

which is positive since: (i) the first term in the numerator is positive given that $\rho F < \frac{(1-c-t)^2}{72}$ by definition; (ii) the second term in the numerator is positive because $R > -\rho F$ by definition; (iii) the first term in the denominator is positive for all $R > -\frac{17(1-c-t)^2}{576} \equiv R_2$, but this condition is satisfied when $R > R_1$ holds, which is true as shown above; and (iv) the second term in the denominator is positive because $\rho F < \frac{17(1-c-t)^2}{576}$ holds given that $\rho F < \frac{(1-c-t)^2}{72}$ by definition. Therefore, $\overline{\delta}_L(t) \geq \overline{\delta}_A(t)$ for all admissible parameters. Since $\overline{\delta}_A(t) \geq \overline{\delta}$ from Proposition 1, we obtain the ranking $\overline{\delta}_L(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}$.

In addition, the comparative statics of $\overline{\delta}_L(t)$ are the following: $\frac{\partial \overline{\delta}_L(t)}{\partial c} = \frac{\partial \overline{\delta}_L(t)}{\partial t} = \frac{1{,}152(1-c-t)(8R+17\rho F)}{\left[17(1-c-t)^2+576R\right]^2} > 0$ since $R > -\rho F$ by definition; $\frac{\partial \overline{\delta}_L(t)}{\partial \rho} = \frac{576F}{17(1-c-t)^2+576R} > 0$ if and only if $R > -\frac{17(1-c-t)^2}{576} \equiv R_2$, but this condition is satisfied when $R > R_1$ holds, which is true for all admissible parameters, as shown above. By the same argument, $\frac{\partial \overline{\delta}_L(t)}{\partial F} = \frac{576\rho}{17(1-c-t)^2+576R}$ is also positive. Finally, $\frac{\partial \overline{\delta}_L(t)}{\partial R} = \frac{4{,}608\left[(1-c-t)^2-72\rho F\right]}{\left[17(1-c-t)^2+576R\right]^2} > 0$ since $\rho F < \frac{(1-c-t)^2}{72}$ by definition. The cross-partial derivatives of cutoff $\overline{\delta}_L(t)$ are $\frac{\partial^2 \overline{\delta}_L(t)}{\partial \rho \partial t} = \frac{19{,}584F(1-c-t)}{\left[17(1-c-t)^2+576R\right]^2} > 0$, $\frac{\partial^2 \overline{\delta}_L(t)}{\partial F \partial t} = \frac{19{,}584\rho(1-c-t)}{\left[17(1-c-t)^2+576R\right]^2} > 0$, and $\frac{\partial^2 \overline{\delta}_L(t)}{\partial R \partial t} = \frac{9{,}216(1-c-t)\left[17(1-c-t)^2-576R-2448\rho F\right]}{\left[17(1-c-t)^2+576R\right]^3}$, where the denominator is positive if and only if $R > -\frac{17(1-c-t)^2}{576} \equiv R_2$, but this condition is satisfied when $R > R_1$ holds, which is true for all admissible parameters, as shown above. Similarly, the numerator is positive if and only if $R > -\frac{17\left[(1-c-t)^2-144\rho F\right]}{576}$, which also holds because $R > R_2$. Therefore, $\frac{\partial^2 \overline{\delta}_L(t)}{\partial R \partial t} > 0$ for all admissible parameters.

Whistleblower programs. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (4), yields

$$\delta \geq \overline{\delta}_W(t) \equiv \frac{9(1-c-t)^2}{17\,(1-c-t)^2 - 576(\rho F + nB)}.$$

The numerator of cutoff $\overline{\delta}_W(t)$ is unambiguously positive, while its denominator is positive since $\rho F + nB < \frac{17(1-c-t)^2}{576}$, which holds given that $\rho F + nB < \frac{(1-c-t)^2}{72}$ by definition. Furthermore, cutoff $\overline{\delta}_W(t)$ satisfies $\overline{\delta}_W(t) < 1$ because $\rho F + nB < \frac{(1-c-t)^2}{72}$, which holds by definition; and satisfies

$$\overline{\delta}_W(t) - \overline{\delta}_A(t) = \frac{5,184nB(1-c-t)^2}{[17(1-c-t)^2 - 576(\rho F + nB)]\,[17(1-c-t)^2 - 576\rho F]},$$

which is positive since $\rho F + nB < \frac{(1-c-t)^2}{72}$ by definition, making both terms of the denominator unambiguously positive. Therefore, $\overline{\delta}_W(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}$. In addition, the difference $\overline{\delta}_W(t) - \overline{\delta}_A(t)$ increases in t since

$$\frac{\partial\left(\overline{\delta}_W(t) - \overline{\delta}_A(t)\right)}{\partial t} = \frac{10,368nB(1-c-t)\left[289(1-c-t)^4 - 331,776\rho F(\rho F + nB)\right]}{\{[17(1-c-t)^2 - 576(\rho F + nB)]\,[17(1-c-t)^2 - 576\rho F]\}^2}$$

which is positive since term $\left[289(1-c-t)^4 - 331,776\rho F(\rho F + nB)\right] > 0$ if and only if $\rho F + nB < \frac{289(1-c-t)^4}{331,776\rho F}$. Comparing this condition against the initial assumption $\rho F + nB < \frac{(1-c-t)^2}{72}$, we obtain that $\frac{289(1-c-t)^4}{331,776\rho F} > \frac{(1-c-t)^2}{72}$ simplifies to $\frac{289(1-c-t)^2}{4,608} > \rho F$, which is less stringent than the initial assumption $\rho F + nB < \frac{(1-c-t)^2}{72}$.

Comparing cutoffs $\overline{\delta}_W(t)$ and $\overline{\delta}_L(t)$, we find that $\overline{\delta}_W(t) \geq \overline{\delta}_L(t)$ for all

$$t \geq t_{W,L} \equiv (1-c) - \frac{24(\rho F + nB)(R + \rho F)}{\left[(8(R+\rho F) - 9nB)\,(\rho F + nB)\,(R + \rho F)\right]^{1/2}}.$$

In addition, the comparative statics of $\overline{\delta}_W(t)$ are the following: $\frac{\partial\overline{\delta}_W(t)}{\partial c} = \frac{\partial\overline{\delta}_W(t)}{\partial t} = \frac{10,368(1-c-t)(\rho F+nB)}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^2} > 0$, $\frac{\partial\overline{\delta}_W(t)}{\partial \rho} = \frac{5,184F(1-c-t)^2}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^2} > 0$, $\frac{\partial\overline{\delta}_W(t)}{\partial F} = \frac{5,184\rho(1-c-t)^2}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^2} > 0$, as well as $\frac{\partial\overline{\delta}_W(t)}{\partial n} = \frac{5,184B(1-c-t)^2}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^2} > 0$, and $\frac{\partial\overline{\delta}_W(t)}{\partial B} = \frac{5,184n(1-c-t)^2}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^2} > 0$. Finally, the cross-partial derivative of $\overline{\delta}_W(t)$ with respect to ρ and t is $\frac{\partial^2\overline{\delta}_W(t)}{\partial\rho\partial t} = \frac{10,368F(1-c-t)\left[17(1-c-t)^2+576(\rho F+nB)\right]}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^3} > 0$, where the denominator is positive because $\rho F + nB < \frac{17(1-c-t)^2}{576}$, which holds given that $\rho F + nB < \frac{(1-c-t)^2}{72}$ by definition. Similarly, $\frac{\partial^2\overline{\delta}_W(t)}{\partial F\partial t} = \frac{10,368\rho(1-c-t)\left[17(1-c-t)^2+576(\rho F+nB)\right]}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^3} > 0$, $\frac{\partial^2\overline{\delta}_W(t)}{\partial n\partial t} = \frac{10,368B(1-c-t)\left[17(1-c-t)^2+576(\rho F+nB)\right]}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^3} > 0$, and $\frac{\partial^2\overline{\delta}_W(t)}{\partial B\partial t} = \frac{10,368n(1-c-t)\left[17(1-c-t)^2+576(\rho F+nB)\right]}{\left[17(1-c-t)^2-576(\rho F+nB)\right]^3} > 0$.

7.2 Appendix 2 - Non-linear production costs

Competition. When firms compete, every firm i chooses q_i to solve

$$\max_{q_i \geq 0} \pi_i(t) = (1 - q_i - q_j)q_i - \left(cq_i + \frac{\beta}{2}q_i^2\right) - tq_i$$

yielding best response function $q_i(q_j) = \frac{1-c-t}{2+\beta} - \frac{1}{2+\beta}q_j$, which shifts downward and becomes flatter when costs become more convex (higher β). In a symmetric equilibrium, every firm produces output level $q_i^C(t) = \frac{1-c-t}{3+\beta}$, earning profits $\pi^C(t) = \frac{2+\beta}{2}\left(q_i^C(t)\right)^2$, which satisfy $\frac{\partial \pi^C(t)}{\partial t} = -\frac{(2+\beta)(1-c-t)}{(3+\beta)^2} < 0$ and $\frac{\partial \pi^C(t)}{\partial \beta} = -\frac{(1+\beta)(1-c-t)^2}{2(3+\beta)^3} < 0$.

Collusion. When firms collude, they seek to maximize their joint profits, as follows

$$\max_{q_i, q_j \geq 0} \pi_i(t) + \pi_j(t)$$

which yields $q_i^M(t) = q_j^M(t) = \frac{1-c-t}{4+\beta}$, earning profits $\pi^M(t) = \frac{(1-c-t)^2}{2(4+\beta)}$ for every firm i, which satisfy $\frac{\partial \pi^M(t)}{\partial t} = -\frac{1-c-t}{4+\beta} < 0$ and $\frac{\partial \pi^M(t)}{\partial \beta} = -\frac{(1-c-t)^2}{2(4+\beta)^2} < 0$.

Deviation. When a firm unilaterally deviates from the collusive output $q_i^M(t)$, choosing $q_i^D(t) = \frac{(3+\beta)(1-c-t)}{(2+\beta)(4+\beta)}$, earning profits $\pi^D(t) = \frac{(3+\beta)^2(1-c-t)^2}{2(2+\beta)(4+\beta)^2}$, which satisfy $\frac{\partial \pi^D(t)}{\partial t} = -\frac{(3+\beta)^2(1-c-t)}{(2+\beta)(4+\beta)^2} < 0$ and $\frac{\partial \pi^D(t)}{\partial \beta} = -\frac{(3+\beta)(1-c-t)^2[8+\beta(5+\beta)]}{2(2+\beta)^2(4+\beta)^3} < 0$. As expected, output levels and profits in the above three scenarios coincide with those in Appendix 1 when costs are linear, $\beta = 0$.

Comparing $\frac{\partial \pi^C(t)}{\partial t}$, $\frac{\partial \pi^M(t)}{\partial t}$, and $\frac{\partial \pi^D(t)}{\partial t}$, we find that $\frac{\partial \pi^C(t)}{\partial t} - \frac{\partial \pi^M(t)}{\partial t} = \frac{(1-c-t)}{(3+\beta)^2(4+\beta)} > 0$ and $\frac{\partial \pi_i^M(t)}{\partial t} - \frac{\partial \pi_i^D(t)}{\partial t} = \frac{(1-c-t)}{(2+\beta)(4+\beta)^2} > 0$, implying that $0 > \frac{\partial \pi^C(t)}{\partial t} > \frac{\partial \pi^M(t)}{\partial t} > \frac{\partial \pi^D(t)}{\partial t}$, thus being consistent with Lemma 2. As a result, $PG(t) = \pi^D(t) - \pi^M(t) = \frac{(1-c-t)^2}{2(2+\beta)(4+\beta)^2}$ with derivative $PG_t(t) = -\frac{1-c-t}{(2+\beta)(4+\beta)^2}$, and associated elasticity $\varepsilon_{PG,t} = \frac{PG_t(t)}{PG(t)}t = -\frac{2t}{1-c-t} < 0$. Similarly, $PL(t) = \pi^D(t) - \pi^C(t) = \frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2}$ with derivative $PL_t(t) = -\frac{[17+2\beta(6+\beta)](1-c-t)}{(2+\beta)(3+\beta)^2(4+\beta)^2}$, and associated elasticity $\varepsilon_{PL,t} = \frac{PL_t(t)}{PL(t)}t = -\frac{2t}{1-c-t} < 0$, implying that both elasticities coincide.

No competition policy. Without competition policy, the sustainability condition is given by equation (1). Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (3), we find that collusion can be sustained if

$$\delta \geq \overline{\delta}(\beta) \equiv \frac{(3+\beta)^2}{17 + 2\beta(6+\beta)},$$

which is unambiguously positive; originates at $\overline{\delta}(0) = \frac{9}{17}$ when costs are linear; decreases in β since $\frac{\partial \overline{\delta}(\beta)}{\partial \beta} = -\frac{2(3+\beta)^2}{[17+2\beta(6+\beta)]^2} < 0$; and remains positive for all β since $\lim_{\beta \to +\infty} \overline{\delta}(\beta) = \frac{1}{2}$. As in the case of linear costs, this minimal discount factor is unaffected by environmental policy, t.

Audits. When the CA uses audits alone to deter collusion, firms have incentives to sustain collusion according to equation (4). In this context, the initial condition $\rho F < \pi^M(t) - \pi^C(t)$ becomes $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, which becomes more stringent as costs are more convex (i.e., the profit gain $\pi^M(t) - \pi^C(t)$ decreases in β since $\frac{\partial\left(\pi^M(t) - \pi^C(t)\right)}{\partial \beta} = -\frac{(11+3\beta)(1-c-t)^2}{2(3+\beta)^3(4+\beta)^2}$).

Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (2), yields

$$\delta \geq \overline{\delta}_A(\beta, t) \equiv \frac{(3+\beta)^2 (1-c-t)^2}{[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F},$$

which coincides with that in Appendix 1 when costs are linear, $\overline{\delta}_A(0,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2-576\rho F}$. In addition, cutoff $\overline{\delta}_A(\beta,t)$ is positive for all $\rho F < \frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, we obtain that $\frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2} - \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)} = \frac{(1-c-t)^2}{2(2+\beta)(4+\beta)} > 0$, implying that condition $\rho F < \frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2}$ is less demanding than the initial assumption, and thus being satisfied by definition. Cutoff $\overline{\delta}_A(\beta,t)$ also satisfies $\overline{\delta}_A(\beta,t) < 1$ for all $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, which coincides with the initial assumption on ρF.

Furthermore, cutoff $\overline{\delta}_A(\beta,t)$ increases in β if

$$\frac{\partial \overline{\delta}_A(\beta,t)}{\partial \beta} = \frac{2(3+\beta)(1-c-t)^2 \left[(3+\beta)^3(4+\beta)(8+3\beta)\rho F - (1-c-t)^2\right]}{\left[[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F\right]^2} > 0$$

which holds when $\rho F > \frac{(1-c-t)^2}{(3+\beta)^3(4+\beta)(8+3\beta)}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, we obtain that $\frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)} - \frac{(1-c-t)^2}{(3+\beta)^3(4+\beta)(8+3\beta)} = \frac{(2+\beta)(11+3\beta)(1-c-t)^2}{2(3+\beta)^3(4+\beta)(8+3\beta)} > 0$, implying that cutoff $\frac{(1-c-t)^2}{(3+\beta)^3(4+\beta)(8+3\beta)}$ is lower than $\frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$. Since this section focuses on non-negligible expected penalties, $\rho F > \frac{(1-c-t)^2}{(3+\beta)^3(4+\beta)(8+3\beta)}$, $\overline{\delta}_A(\beta,t)$ increases in β under all admissible parameters.

In addition, $\overline{\delta}_A(\beta,t)$ satisfies

$$\begin{aligned}
\frac{\partial \overline{\delta}_A(\beta,t)}{\partial t} &= \frac{4(2+\beta)(3+\beta)^4(4+\beta)^2(1-c-t)^2\rho F}{\left[[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F\right]^2} > 0,\\
\frac{\partial \overline{\delta}_A(\beta,t)}{\partial \rho} &= \frac{2(2+\beta)(3+\beta)^4(4+\beta)^2(1-c-t)^2 F}{\left[[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F\right]^2} > 0,\\
\frac{\partial \overline{\delta}_A(\beta,t)}{\partial F} &= \frac{2(2+\beta)(3+\beta)^4(4+\beta)^2(1-c-t)^2 \rho}{\left[[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F\right]^2} > 0,
\end{aligned}$$

and cross-partial derivatives are

$$\begin{aligned}
\frac{\partial \overline{\delta}_A(\beta,t)}{\partial \rho \partial t} &= \frac{4(2+\beta)(3+\beta)^4(4+\beta)^2(1-c-t) F \times A}{\left[2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F - [17+2\beta(6+\beta)](1-c-t)^2\right]^3} > 0, \text{ and}\\
\frac{\partial \overline{\delta}_A(\beta,t)}{\partial F \partial t} &= \frac{4(2+\beta)(3+\beta)^4(1-c-t)^2 \rho \times A}{\left[2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F - [17+2\beta(6+\beta)](1-c-t)^2\right]^3} > 0
\end{aligned}$$

where term $A \equiv [17 + 2\beta(6+\beta)](1-c-t)^2 + 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F > 0$. The denominator in both $\frac{\partial\overline{\delta}_A(\beta,t)}{\partial\rho\partial t}$ and $\frac{\partial\overline{\delta}_A(\beta,t)}{\partial F\partial t}$ is positive for all $\rho F < \frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)}$, we obtain that $\frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2} - \frac{(1-c-t)^2}{2(3+\beta)^2(4+\beta)} = \frac{(1-c-t)^2}{2(2+\beta)(4+\beta)^2} > 0$, meaning that the initial assumption is more demanding, so condition $\rho F < \frac{[17+2\beta(6+\beta)](1-c-t)^2}{2(2+\beta)(3+\beta)^2(4+\beta)^2}$ holds by definition; ultimately yielding that $\frac{\partial\overline{\delta}_A(\beta,t)}{\partial\rho\partial t}, \frac{\partial\overline{\delta}_A(\beta,t)}{\partial F\partial t} > 0$. Therefore, $\overline{\delta}_A(\beta,t)$ increases in t, ρ, and F; and the marginal effects of ρ and F at deterring collusion are emphasized by emission fee, t, as under linear costs in the main model.

Finally, comparing $\overline{\delta}_A(\beta,t)$ and $\overline{\delta}(\beta)$, we obtain that

$$\overline{\delta}_A(\beta,t) - \overline{\delta}(\beta) = \frac{(3+\beta)^2(1-c-t)^2}{[17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F} - \frac{(3+\beta)^2}{17+2\beta(6+\beta)}$$

which is positive if and only if $(1-c-t)^2[17+2\beta(6+\beta)] > [17+2\beta(6+\beta)](1-c-t)^2 - 2(2+\beta)(3+\beta)^2(4+\beta)^2\rho F$, that, after rearranging, yields $(2+\beta)(3+\beta)(4+\beta)\rho F > 0$, which holds for all admissible parameter values, entailing that $\overline{\delta}_A(\beta,t) > \overline{\delta}(\beta)$ holds.

The total derivative of $\overline{\delta}_A(\beta,t)$ evaluated at $t^C(\beta)$ with respect to β is

$$\frac{d\overline{\delta}_A(\beta,t^C(\beta))}{d\beta} = \underbrace{\frac{\partial\overline{\delta}_A(\beta,t^C(\beta))}{\partial\beta}}_{+\ \text{Direct effect}} + \underbrace{\underbrace{\frac{\partial\overline{\delta}_A(\beta,t)}{\partial t}}_{+}\underbrace{\frac{\partial t^C(\beta)}{\partial\beta}}_{-}}_{-\ \text{Indirect effect}}$$

where $\frac{\partial t^C(\beta)}{\partial\beta} < 0$ is shown in the main body of the paper, $\frac{\partial\overline{\delta}_A(\beta,t)}{\partial t} > 0$ and $\frac{\partial\overline{\delta}_A(\beta,t)}{\partial\beta} > 0$ as shown above.

Leniency programs. When the CA uses leniency programs, equation (3) provides the sustainability condition. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (5), yields

$$\delta \geq \overline{\delta}_L(\beta,t) \equiv \frac{(3+\beta)^2\left[D + 2(2+\beta)(4+\beta)^2(R+\rho F)\right]}{2R(2+\beta)(3+\beta)^2(4+\beta)^2 + D[17+2\beta(6+\beta)]}$$

where term $D \equiv (1-c-t)^2$. In the case of linear costs, $\beta = 0$, cutoff $\overline{\delta}_L(\beta,t)$ simplifies to $\overline{\delta}_L(0,t) \equiv \frac{9\left[(1-c-t)^2+64(R+\rho F)\right]}{17(1-c-t)^2+576R}$, which coincides with that in Appendix 1; but when costs are convex, cutoff $\overline{\delta}_L(\beta,t)$ decreases in β if

$$\frac{\partial\overline{\delta}_L(\beta,t)}{\partial\beta} = \frac{2D(3+\beta)\left[(4+\beta)\left[R(2+\beta)^2(4+\beta)(11+3\beta) + G\right] - D\right]}{\left[2R(2+\beta)(3+\beta)^2(4+\beta)^2 + D[17+2\beta(6+\beta)]\right]^2} < 0$$

where term $G \equiv \rho F\left[392 + \beta 565 + \beta\left(301 + 70\beta + 6\beta^2\right)\right]$, which holds if $R < \frac{D-(4+\beta)G}{(2+\beta)^2(4+\beta)^2(11+3\beta)}$.

Whistleblower programs. When the CA uses leniency programs, collusion can be sustained if equation (4) holds, which in this context yields

$$\delta \geq \overline{\delta}_W(\beta,t) \equiv \frac{(3+\beta)^2(1-c-t)^2}{17-34c+576nB-34t+17(c+t)^2-576\rho F+H}$$

where term

$$\begin{aligned} H \quad \equiv \quad & 2\beta^2\left[c^2-2c(1-t)+(1-t)^2-314(\rho F+nB)\right] \\ & +12\beta\left[c[c-2(1-t)]+(1-t)^2-80(\rho F+nB)\right] \\ & -2\beta^3(\rho F+nB)(101+16\beta+\beta^2). \end{aligned}$$

In the case of linear costs, $\beta = 0$, cutoff $\overline{\delta}_W(\beta,t)$ simplifies to $\overline{\delta}_W(0,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2-576(\rho F+nB)}$, which coincides with that in Appendix 1; but when costs are convex, cutoff $\overline{\delta}_W(\beta,t)$ decreases in β if

$$\frac{\partial\overline{\delta}_W(\beta,t)}{\partial\beta} = -\frac{2(3+\beta)(1-c-t)^2\left[c^2-(3+\beta)^2(4+\beta)(8+3\beta)nB-J\right]}{\left[17-34c+576nB-34t+17(c+t)^2-576\rho F+H\right]^2} < 0$$

where term $J \equiv 2c(1-t)+(1-t)^2-(3+\beta)^3(4+\beta)(8+3\beta)\rho F$.

7.3 Appendix 3 - Product differentiation

Competition. When firms compete, every firm i chooses q_i to solve

$$\max_{q_i\geq 0} \pi_i = (1-q_i-\gamma q_j)\,q_i-(c+t)\,q_i$$

yielding a best response function $q_i(q_j) = \frac{1-c-t}{2} - \frac{\gamma}{2}q_j$. Then, more differentiated goods (lower γ) have a flattening effect on the best response function, indicating that every firm becomes less affected by its rival's output decisions. In equilibrium, output is $q_i^C(\gamma,t) = \frac{1-c-t}{2+\gamma}$, which coincides with $q_i^C(t) = \frac{1-c-t}{3}$ in the main body of the paper when goods are homogeneous, $\gamma = 1$, but increases when goods are more differentiated (lower γ). In this setting, profits are $\pi_i^C(\gamma,t) = \frac{(1-c-t)^2}{(2+\gamma)^2} = \left(q_i^C(\gamma,t)\right)^2$, which collapse to $\pi_i^C(1,t) = \frac{(1-c-t)^2}{9}$ when goods are undifferentiated, $\gamma = 1$. In addition, a marginal increase in fee t produces $\frac{\partial\pi_i^C(\gamma,t)}{\partial t} = -\frac{2(1-c-t)}{(2+\gamma)^2} < 0$.

Collusion. When firms collude, they seek to maximize their joint profits, as follows

$$\max_{q_i,q_j\geq 0} \quad \pi_i(t)+\pi_j(t)$$

which yields output $q_i^M(\gamma,t) = q_j^M(\gamma,t) = \frac{1-c-t}{2(1+\gamma)}$ which coincides with that in section 3 when products are homogeneous, $q_i^M(1,t) = \frac{1-c-t}{4}$, but increase when products become more differentiated (lower γ). In this context, profits are $\pi_i^M(\gamma,t) = \frac{(1-c-t)^2}{4(1+\gamma)}$ for every firm i, which collapse to $\pi_i^M(1,t) = \frac{(1-c-t)^2}{8}$ when $\gamma = 1$, but increase when products become more differentiated (lower γ). In addition, a marginal increase in fee t produces $\frac{\partial\pi_i^M(\gamma,t)}{\partial t} = -\frac{1-c-t}{2(1+\gamma)^2} < 0$.

Deviation. When a firm unilaterally deviates from the collusive output $q_i^M(\gamma,t)$, it chooses

$q_i^D(\gamma,t) = \frac{(1-c-t)(2+\gamma)}{4(1+\gamma)}$, which simplifies to $q_i^D(1,t) = \frac{3(1-c-t)}{8}$ when $\gamma = 1$, earning profits $\pi_i^D(\gamma,t) = \frac{(1-c-t)^2(2+\gamma)^2}{16(1+\gamma)^2}$, which are decreasing in γ because $\frac{\partial \pi_i^D(\gamma,t)}{\partial \gamma} = -\frac{(1-c-t)^2(2+\gamma)}{8(1+\gamma)^3} < 0$, implying that profits increase when goods become more differentiated (lower γ). In addition, a marginal increase in fee t produces $\frac{\partial \pi_i^D(\gamma,t)}{\partial t} = -\frac{(2+\gamma)^2(1-c-t)}{8(1+\gamma)^2} < 0$.

Comparing $\frac{\partial \pi_i^C(\gamma,t)}{\partial t}$, $\frac{\partial \pi_i^M(\gamma,t)}{\partial t}$, and $\frac{\partial \pi_i^D(\gamma,t)}{\partial t}$, we find that $\frac{\partial \pi_i^C(\gamma,t)}{\partial t} - \frac{\partial \pi_i^M(\gamma,t)}{\partial t} = \frac{(2+\gamma)^2(1-c-t)}{8(1+\gamma)^2} > 0$ and $\frac{\partial \pi_i^M(\gamma,t)}{\partial t} - \frac{\partial \pi_i^D(\gamma,t)}{\partial t} = \frac{\gamma^2(1-c-t)}{8(1+\gamma)^2} > 0$, implying that $0 > \frac{\partial \pi_i^C(\gamma,t)}{\partial t} > \frac{\partial \pi_i^M(\gamma,t)}{\partial t} > \frac{\partial \pi_i^D(\gamma,t)}{\partial t}$, being consistent with Lemma 2. As a consequence, $PG(t) = \pi_i^D(\gamma,t) - \pi_i^M(\gamma,t) = \frac{\gamma^2(1-c-t)^2}{16(1+\gamma)^2}$ with derivative $PG_t(t) = -\frac{\gamma^2(1-c-t)}{8(1+\gamma)^2}$, and associated elasticity $\varepsilon_{PG,t} = \frac{PG_t(t)}{PG(t)}t = -\frac{2t}{1-c-t} < 0$. Similarly, $PL(t) = \pi_i^D(\gamma,t) - \pi_i^C(\gamma,t) = \frac{\gamma^2(1-c-t)^2[8+\gamma(8+\gamma)]}{16(1+\gamma)^2(2+\gamma)^2}$ with derivative $PL_t(t) = -\frac{\gamma^2(1-c-t)[8+\gamma(8+\gamma)]}{8(1+\gamma)^2(2+\gamma)^2}$, and associated elasticity $\varepsilon_{PL,t} = \frac{PL_t(t)}{PL(t)}t = -\frac{2t}{1-c-t} < 0$, entailing that both elasticities coincide.

No competition policy. Without competition policy, the sustainability condition is given by equation (1). Inserting profits $\pi_i^C(\gamma,t)$, $\pi_i^M(\gamma,t)$, and $\pi_i^D(\gamma,t)$ into equation (3), we find that collusion can be sustained if

$$\delta \geq \overline{\delta}(\gamma) \equiv \frac{(2+\gamma)^2}{8+\gamma(8+\gamma)},$$

which is unambiguously positive; originates at $\overline{\delta}(0) = \frac{1}{2}$ when products are completely differentiated, $\gamma = 0$; increases in parameter γ since $\frac{\partial \overline{\delta}(\gamma)}{\partial \gamma} = \frac{4\gamma(2+\gamma)}{[8+\gamma(8+\gamma)]^2} > 0$; and reaches its maximum at $\overline{\delta}(1) = \frac{9}{17}$ when products are homogeneous, $\gamma = 1$. Therefore, when products become more differentiated (lower γ), cutoff $\overline{\delta}(\gamma)$ decreases, implying that collusion is facilitated. Like in the case of homogeneous products, this minimal discount factor is unaffected by emission fee, t.

Proof of Lemma 5

Audits. When the CA uses audits alone to deter collusion, firms have incentives to sustain collusion according to equation (4). In this context, the initial condition $\rho F < \pi_i^M(\gamma,t) - \pi_i^C(\gamma,t)$ becomes $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$, which simplifies to the condition $\rho F < \frac{(1-c-t)^2}{72}$ when goods are undifferentiated, $\gamma = 1$, as in the main body of the paper. Otherwise, this condition is less demanding when goods become more differentiated (lower γ) since $\frac{\partial\left(\frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\right)}{\partial \gamma} = \frac{(1-c-t)^2\gamma[4+\gamma(2-\gamma)]}{4(1+\gamma)^2(2+\gamma)^3} > 0$.

Inserting profits $\pi_i^C(\gamma,t)$, $\pi_i^M(\gamma,t)$, and $\pi_i^D(\gamma,t)$ into equation (2), yields

$$\delta \geq \overline{\delta}_A(\gamma,t) \equiv \frac{(1-c-t)^2\gamma^2(2+\gamma)^2}{(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)] - 16\rho F(1+\gamma)^2(2+\gamma)^2},$$

which coincides with that in Appendix 1 when goods are homogeneous, $\overline{\delta}_A(1,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2-576\rho F}$. In addition, cutoff $\overline{\delta}_A(\gamma,t)$ satisfies

$$\frac{\partial \overline{\delta}_A(\gamma,t)}{\partial \gamma} = \frac{4(1-c-t)^2\gamma(2+\gamma)\left[(1-c-t)^2\gamma^4 - 8\rho F(1+\gamma)(2+\gamma)^3\right]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)] - 16\rho F(1+\gamma)^2(2+\gamma)^2\right]^2},$$

which is positive if the last term in the numerator is positive, which holds if $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{\gamma^2}{2(2+\gamma)}$.

Ratio $\frac{\gamma^2}{2(2+\gamma)} < 1$ for all admissible values of γ, implying that condition $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{\gamma^2}{2(2+\gamma)}$ is more demanding than the initial assumption, $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$. Therefore, when $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{\gamma^2}{2(2+\gamma)}$ holds, cutoff $\overline{\delta}_A(\gamma,t)$ increases in γ, entailing that collusion is facilitated when products are more differentiated (lower γ). In contrast, when $\frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2} > \rho F \geq \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{\gamma^2}{2(2+\gamma)}$ holds, cutoff $\overline{\delta}_A(\gamma,t)$ decreases in γ, implying that collusion is hindered when goods are more differentiated.

Furthermore, the comparative statics of cutoff $\overline{\delta}_A(\gamma,t)$ are

$$\begin{aligned}
\frac{\partial\overline{\delta}_A(\gamma,t)}{\partial c} &= \frac{\partial\overline{\delta}_A(\gamma,t)}{\partial t} = \frac{32\rho F(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\rho F(1+\gamma)^2(2+\gamma)^2\right]^2} > 0 \\
\frac{\partial\overline{\delta}_A(\gamma,t)}{\partial \rho} &= \frac{16F(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\rho F(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \text{ and} \\
\frac{\partial\overline{\delta}_A(\gamma,t)}{\partial F} &= \frac{16\rho(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\rho F(1+\gamma)^2(2+\gamma)^2\right]^2} > 0
\end{aligned}$$

and its cross-partial derivatives satisfy

$$\frac{\partial\overline{\delta}_A(\gamma,t)}{\partial t\partial\rho} = \frac{32F(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4 A}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\rho F(1+\gamma)^2(2+\gamma)^2\right]^3}$$

where term $A \equiv (1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16\rho F(1+\gamma)^2(2+\gamma)^2$, implying that the numerator is positive. The denominator is also positive for all $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{8+\gamma(8+\gamma)}{4(1+\gamma)}$, which holds since $\frac{8+\gamma(8+\gamma)}{4(1+\gamma)} > 1$ for all admissible values of γ, entailing that $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{8+\gamma(8+\gamma)}{4(1+\gamma)}$ is satisfied by the initial condition $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$. Similarly,

$$\frac{\partial\overline{\delta}_A(\gamma,t)}{\partial t\partial F} = \frac{32\rho(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4 A}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\rho F(1+\gamma)^2(2+\gamma)^2\right]^3}$$

which is also positive by the above discussion.

Leniency programs. When the CA uses leniency programs, equation (3) provides the sustainability condition. Inserting profits $\pi_i^C(\gamma,t)$, $\pi_i^M(\gamma,t)$, and $\pi_i^D(\gamma,t)$ into equation (3), yields

$$\delta \geq \overline{\delta}_L(\gamma,t) \equiv \frac{(2+\gamma)^2\left[(1-c-t)^2\gamma^2+16(R+\rho F)(1+\gamma)^2\right]}{(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2}$$

and in the case of homogeneous goods, $\gamma=1$, cutoff $\overline{\delta}_L(\gamma,t)$ simplifies to $\overline{\delta}_L(1,t) \equiv \frac{9\left[(1-c-t)^2+64(R+\rho F)\right]}{17(1-c-t)^2+576R}$, coinciding with that in Appendix 1. In addition, cutoff $\overline{\delta}_L(\gamma,t)$ satisfies

$$\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial\gamma} = \frac{4(1-c-t)^2\gamma(2+\gamma)\left[(1-c-t)^2\gamma^4-16R(1+\gamma)^2[4+\gamma(2-\gamma)]-8\rho F(1+\gamma)D\right]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2},$$

where term $D \equiv 16+\gamma\left[24+\gamma\left(8-\gamma\right)\right]$. This derivative is positive if the last term in the numerator is positive, which holds if $\rho F < -\frac{(1-c-t)^2\gamma^4+16R(1+\gamma)^2[4+\gamma(2-\gamma)]}{8(1+\gamma)D}$, which is not satisfied, meaning that $\overline{\delta}_L(\gamma,t)$ decreases in γ or, alternatively, more differentiated products hinder collusion.

Furthermore, the comparative statics of cutoff $\overline{\delta}_L(\gamma,t)$ are

$$\begin{aligned}
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial c} &= \frac{\partial\overline{\delta}_L(\gamma,t)}{\partial t} = \frac{32(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^2\left[4R(1+\gamma)+\rho F[8+\gamma(8+\gamma)]\right]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0 \\
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial \rho} &= \frac{16F(1+\gamma)^2(2+\gamma)^2}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \\
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial F} &= \frac{16\rho(1+\gamma)^2(2+\gamma)^2}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \text{ and} \\
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial R} &= \frac{64(1+\gamma)^3(2+\gamma)^2\left[(1-c-t)^2\gamma^2-4\rho F(1+\gamma)(2+\gamma)^2\right]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0
\end{aligned}$$

since $\rho F < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$ by definition. Its cross-partial derivatives satisfy

$$\begin{aligned}
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial t\partial \rho} &= \frac{32F(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^2[8+\gamma(8+\gamma)]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0 \text{ and} \\
\frac{\partial\overline{\delta}_L(\gamma,t)}{\partial t\partial F} &= \frac{32\rho(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^2[8+\gamma(8+\gamma)]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16R(1+\gamma)^2(2+\gamma)^2\right]^2} > 0
\end{aligned}$$

Whistleblower programs. In this context, the initial condition $\rho F + nB < \pi_i^M(\gamma,t) - \pi_i^C(\gamma,t)$ becomes $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$, which simplifies to the condition $\rho F + nB < \frac{(1-c-t)^2}{72}$ when goods are undifferentiated, $\gamma = 1$. When the CA uses whistleblower programs, collusion can be sustained if equation (4) holds, which in this context yields

$$\delta \geq \overline{\delta}_W(\gamma,t) \equiv \frac{(1-c-t)^2\gamma^2(2+\gamma)^2}{(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)] - 16\left(\rho F + nB\right)(1+\gamma)^2(2+\gamma)^2}$$

which is positive if the denominator is positive, which holds if $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{8+\gamma(8+\gamma)}{4(1+\gamma)}$. This condition is satisfied since $\frac{8+\gamma(8+\gamma)}{4(1+\gamma)} > 1$ for all admissible values of γ, implying that cutoff $\overline{\delta}_W(\gamma,t)$ is unambiguously positive given the initial condition $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$. In the case of homogenous goods, $\gamma = 1$, cutoff $\overline{\delta}_W(\gamma,t)$ simplifies to $\overline{\delta}_W(1,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2 - 576(\rho F + nB)}$, thus coinciding with that in Appendix 1. In addition, cutoff $\overline{\delta}_W(\gamma,t)$ satisfies

$$\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial\gamma} = \frac{4(1-c-t)^2\gamma(2+\gamma)\left[(1-c-t)^2\gamma^4 - 8\left(\rho F + nB\right)(1+\gamma)(2+\gamma)^3\right]}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)] - 16\left(\rho F + nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2},$$

which is positive if the last term in the numerator is positive, which holds if $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{1}{2(2+\gamma)}$. Ratio $\frac{1}{2(2+\gamma)} < 1$ for all admissible values of γ, implying that condition $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{1}{2(2+\gamma)}$ is more demanding than the initial assumption, $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}$. Therefore, when $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{1}{2(2+\gamma)}$ holds, cutoff $\overline{\delta}_W(\gamma,t)$ increases in γ, entailing that collusion is facilitated when products are more differentiated (lower γ). In contrast, when $\frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2} > \rho F + nB \geq \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{1}{2(2+\gamma)}$ holds, cutoff $\overline{\delta}_W(\gamma,t)$ decreases in γ, implying that collusion is hindered when goods are more differentiated.

Furthermore, the comparative statics of cutoff $\overline{\delta}_W(\gamma,t)$ are

$$\begin{aligned}
\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial c} &= \frac{\partial\overline{\delta}_W(\gamma,t)}{\partial t} = \frac{32(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4(\rho F+nB)}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2} > 0 \\
\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial \rho} &= \frac{16F(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \\
\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial F} &= \frac{16\rho(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \\
\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial n} &= \frac{16B(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2} > 0, \text{ and} \\
\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial B} &= \frac{16n(1-c-t)^2\gamma^2(1+\gamma)^2(2+\gamma)^4}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^2} > 0
\end{aligned}$$

and its cross-partial derivatives satisfy

$$\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial t\partial\rho} = \frac{32F(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4E}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^3}$$

where term $E \equiv (1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]+16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2$. The numerator is positive for all admissible parameters. The denominator is positive if and only if $\rho F + nB < \frac{(1-c-t)^2\gamma^2}{4(1+\gamma)(2+\gamma)^2}\frac{8+\gamma(8+\gamma)}{4(1+\gamma)}$. Term $\frac{8+\gamma(8+\gamma)}{4(1+\gamma)} > 1$ for all admissible parameters, implying that $\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial t\partial\rho} > 0$. Similarly,

$$\frac{\partial\overline{\delta}_W(\gamma,t)}{\partial t\partial F} = \frac{32\rho(1-c-t)\gamma^2(1+\gamma)^2(2+\gamma)^4E}{\left[(1-c-t)^2\gamma^2[8+\gamma(8+\gamma)]-16\left(\rho F+nB\right)(1+\gamma)^2(2+\gamma)^2\right]^3} > 0$$

which is also positive by the above discussion.

Emission fees. The regulator chooses an emission fee t that solves problem (5), where $CS = \frac{(1-c-t)^2(1+\gamma)}{(2+\gamma)^2}$, $PS = \frac{2(1-c-t)^2}{(2+\gamma)^2}$, $T = tQ^C = t\frac{2(1-c-t)}{(2+\gamma)}$, $Env = d(Q^C)^2 = \frac{4d(1-c-t)^2}{(2+\gamma)^2}$. Differentiating with respect to t, and solving, yields

$$t^C(\gamma) = \frac{(1-c)(4d-1)}{4d+1+\gamma}$$

which is positive since $d > \frac{1}{2}$ by definition, coincides with that in Lemma 2 when products are homogeneous, $\gamma = 0$, $t^C(0) = \frac{(1-c)(4d-1)}{4d+1}$, and satisfies $\frac{\partial t^C(\gamma)}{\partial\gamma} = -\frac{(1-c)(4d-1)}{(4d+1+\gamma)^2} < 0$, $\frac{\partial t^C(\gamma)}{\partial d} = \frac{4(1-c)(2+\gamma)}{(4d+1+\gamma)^2} > 0$, and $\frac{\partial t^C(\gamma)}{\partial c} = -\frac{4d-1}{4d+1+\gamma} < 0$.

7.4 Appendix 4 - Allowing for $m \geq 2$ firms

Competition. When firms compete, every firm i chooses q_i to solve

$$\max_{q_i \geq 0} \pi_i(t) = (1 - q_i - Q_{-i})q_i - (c+t)\,q_i$$

where $Q_{-i} = \sum_{j \neq i} q_j$ denotes the aggregate output from firm i's rivals. Differentiating with respect to q_i, we obtain best response function $q_i(q_j) = \frac{1-c-t}{2} - \frac{1}{2}Q_{-i}$. In a symmetric equilibrium, every firm produces output level $q_i^C(t) = \frac{1-c-t}{2+m}$, earning profits $\pi^C(t) = \left(q_i^C(t)\right)^2$, which are decreasing in t and m. In addition, a marginal increase in the stringency of emission fee t yields $\pi_t^C(t) = -\frac{2(1-c-t)}{(2+m)^2} < 0$.

Collusion. When firms collude, they seek to maximize their joint profits, as follows

$$\max_{q_i, q_j \geq 0} \pi_i(t) + \pi_j(t)$$

which yields $q_i^M(t) = q_j^M(t) = \frac{1-c-t}{2m}$, earning profits $\pi^M(t) = \frac{(1-c-t)^2}{4m}$ for every firm i, which are decreasing in t and m. In addition, a marginal increase in the stringency of emission fee t yields $\pi_t^M(t) = -\frac{1-c-t}{2m} < 0$.

Deviation. When a firm unilaterally deviates from the collusive output $q_i^M(t)$, choosing $q_i^D(t) = \frac{(m+1)(1-c-t)}{4m}$, which is decreasing in the number of firms, m, since $\frac{\partial q_i^D(t)}{\partial m} = -\frac{(1-c-t)^2}{4m^2} < 0$. In this context, the deviating firm earns profits $\pi^D(t) = \frac{(m+1)^2(1-c-t)^2}{16m^2} = \left(q_i^D(t)\right)^2$, which satisfy $\frac{\partial \pi^D(t)}{\partial m} = -\frac{(m+1)(1-c-t)^2}{8m^3} < 0$. As expected, output levels and profits in the above three scenarios coincide with those in Appendix 1 when only two firms are active in the industry, $m = 2$. In addition, a marginal increase in the stringency of emission fee t yields $\pi_t^D(t) = -\frac{(1-c-t)(m+1)^2}{8m^2} < 0$.

Comparing $\pi_t^C(t)$, $\pi_t^M(t)$, and $\pi_t^D(t)$, we find that $\pi_t^C(t) - \pi_t^M(t) = \frac{(4+m^2)(1-c-t)}{2m(2+m)^2} > 0$ and $\pi_t^M(t) - \pi_t^D(t) = \frac{(m-1)^2(1-c-t)}{8m^2} > 0$, implying that $0 > \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$, thus being consistent with Lemma 2. As a consequence, $PG(t) = \pi_i^D(t) - \pi_i^M(t) = \frac{(m-1)^2(1-c-t)^2}{16m^2}$ with derivative $PG_t(t) = -\frac{(m-1)^2(1-c-t)}{8m^2}$, and associated elasticity $\varepsilon_{PG,t} = \frac{PG_t(t)}{PG(t)}t = -\frac{2t}{1-c-t} < 0$. Similarly, $PL(t) = \pi_i^D(t) - \pi_i^C(t) = \frac{(2+m^2-m)(1-c-t)^2(2+m^2+7m)}{16m^2(2+m)^2}$ with derivative $PL_t(t) = -\frac{(2+m^2-m)(1-c-t)(2+m^2+7m)}{8m^2(2+m)^2}$, and associated elasticity $\varepsilon_{PL,t} = \frac{PL_t(t)}{PL(t)}t = -\frac{2t}{1-c-t} < 0$, entailing that both elasticities coincide.

No competition policy. Without competition policy, the sustainability condition is given by equation (1). Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (1), we find that collusion can be sustained if

$$\delta \geq \overline{\delta}(m) \equiv \frac{(m+1)^2}{m(m+6)+1},$$

which is unambiguously positive; originates at $\overline{\delta}(2) = \frac{9}{17}$ when only $m = 2$ firms are active; increases in m since $\frac{\partial \overline{\delta}(m)}{\partial m} = \frac{4(m^2-1)}{[m(m+6)+1]^2} > 0$; and approaches 1 since $\lim_{m \to +\infty} \overline{\delta}(m) = 1$. In addition, $\overline{\delta}(m) < 1$ since $(m+1)^2 < m(m+6)+1$ simplifies to $-4m < 0$, which is true for all admissible parameters, $m \geq 2$. As in the case of duopoly, this minimal discount factor is unaffected by environmental policy, t.

Audits. When the CA uses audits alone to deter collusion, firms have incentives to sustain collusion according to equation (4). In this context, the initial condition $\rho F < \pi^M(t) - \pi^C(t)$ becomes $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$.

Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (2), yields

$$\delta \geq \overline{\delta}_A(m,t) \equiv \frac{(m^2-1)^2(1-c-t)^2}{(m-1)^2(1-c-t)^2[m(m+6)+1] - 16m^2(m+1)^2\rho F},$$

which coincides with that in Appendix 1 when $m = 2$ firms, $\overline{\delta}_A(2,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2 - 576\rho F}$. In addition, cutoff $\overline{\delta}_A(m,t)$ is positive for all $\rho F < \frac{(m+1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$, we obtain that

$$\frac{(m+1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2} - \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2} = \frac{(1-c-t)^2[1+m[4+m(22+m(4+m))]]}{16m^2} > 0,$$

implying that condition $\rho F < \frac{(m+1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2}$ is less demanding than the initial assumption, and thus being satisfied by definition. Cutoff $\overline{\delta}_A(m,t)$ also satisfies $\overline{\delta}_A(m,t) < 1$ for all $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$, which coincides with the initial assumption on ρF.

Furthermore, cutoff $\overline{\delta}_A(m,t)$ increases in m if

$$\frac{\partial \overline{\delta}_A(m,t)}{\partial m} = \frac{(m^2-1)(1-c-t)^2\left[4(m-1)^4(1-c-t)^2 - 32m(m+1)^3\rho F\right]}{\left[(m-1)^2(1-c-t)^2[m(m+6)+1] - 16m^2(m+1)^2\rho F\right]^2} > 0$$

which holds when $\rho F < \frac{(m-1)^4(1-c-t)^2}{8m(m+1)^3}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(m+1)^2(1-c-t)^2}{4m(m+1)^2}$, we obtain that $\frac{(m-1)^4(1-c-t)^2}{8m(m+1)^3} - \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2} = \frac{(m-1)^2[m(m-4)-1](1-c-t)^2}{8m(m+1)^3}$, which is positive if $m(m-4) - 1 > 0$, which holds if and only if $m > 2 + \sqrt{5} \simeq 4.23$ firms. Therefore, when $m > 2 + \sqrt{5}$, condition $\rho F < \frac{(m-1)^4(1-c-t)^2}{8m(m+1)^3}$ is less demanding than the initial condition, implying that $\overline{\delta}_A(m,t)$ is unambiguously increasing in m. In contrast, when $m \leq 2 + \sqrt{5}$, condition $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$ is more demanding than the initial condition. In this case, if condition $\rho F < \frac{(m-1)^4(1-c-t)^2}{8m(m+1)^3}$ holds, $\overline{\delta}_A(m,t)$ is increasing in m; but otherwise, $\overline{\delta}_A(m,t)$ is decreasing in m.

In addition, $\overline{\delta}_A(m,t)$ satisfies

$$\frac{\partial \overline{\delta}_A(m,t)}{\partial t} = \frac{\partial \overline{\delta}_A(m,t)}{\partial c} = \frac{32\rho F(m-1)^2 m^2 (m+1)^4 (1-c-t)}{\left[(m-1)^2(1-c-t)^2[m(m+6)+1] - 16m^2(m+1)^2\rho F\right]^2} > 0,$$

$$\frac{\partial \overline{\delta}_A(m,t)}{\partial \rho} = \frac{16F(m-1)^2 m^2 (m+1)^4 (1-c-t)^2}{\left[(m-1)^2(1-c-t)^2[m(m+6)+1] - 16m^2(m+1)^2\rho F\right]^2} > 0,$$

$$\frac{\partial \overline{\delta}_A(m,t)}{\partial F} = \frac{16\rho(m-1)^2 m^2 (m+1)^4 (1-c-t)^2}{\left[(m-1)^2(1-c-t)^2[m(m+6)+1] - 16m^2(m+1)^2\rho F\right]^2} > 0,$$

and cross-partial derivatives are

$$\frac{\partial\overline{\delta}_A(m,t)}{\partial\rho\partial t} = \frac{32F(m-1)^2m^2(m+1)^4(1-c-t)A}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\rho F\right]^3} > 0, \text{ and}$$

$$\frac{\partial\overline{\delta}_A(m,t)}{\partial F\partial t} = \frac{32\rho(m-1)^2m^2(m+1)^4(1-c-t)A}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\rho F\right]^3} > 0$$

where term $A \equiv (m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]+16m(m+1)^2\rho F > 0$. The denominator in both $\frac{\partial\overline{\delta}_A(m,t)}{\partial\rho\partial t}$ and $\frac{\partial\overline{\delta}_A(m,t)}{\partial F\partial t}$ is positive for all $\rho F < \frac{(m+1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2}$. Comparing this condition on ρF against the initial assumption $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$, we obtain that the initial assumption is more demanding, so condition $\rho F < \frac{(m+1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2}$ holds by definition; ultimately yielding that $\frac{\partial\overline{\delta}_A(m,t)}{\partial\rho\partial t}, \frac{\partial\overline{\delta}_A(m,t)}{\partial F\partial t} > 0$. Therefore, $\overline{\delta}_A(m,t)$ increases in t, ρ, and F; and the marginal effects of ρ and F at deterring collusion are emphasized by emission fee, t, as under the duopoly in the main model.

Finally, comparing $\overline{\delta}_A(m,t)$ and $\overline{\delta}(m)$, we obtain that

$$\overline{\delta}_A(m,t)-\overline{\delta}(m) = \frac{(m^2-1)^2\left(1-c-t\right)^2}{(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\rho F} - \frac{(m+1)^2}{m(m+6)+1}$$

which is positive if and only if $\rho F < \frac{(m-1)(m^2-2)(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^3}$. Comparing this condition against the initial assumption $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$, we find that $\frac{(m-1)(m^2-2)(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^3} - \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2} = \frac{(1-c-t)^2\left[2+m(6+m(m(m^2+m-3)-7)\right]}{16m^2(m+1)^3} > 0$ since $m(m^2+m-3) > 7$ for all admissible values of $m \geq 2$. Therefore, the initial assumption is more demanding than $\rho F < \frac{(m-1)(m^2-2)(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^3}$, implying that cutoff $\overline{\delta}_A(m,t)$ satisfies $\overline{\delta}_A(m,t) \geq \overline{\delta}(m)$ holds for all admissible parameters.

Leniency programs. When the CA uses leniency programs, equation (3) provides the sustainability condition. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (3), yields

$$\delta \geq \overline{\delta}_L(m,t) \equiv \frac{(m+1)^2\left[(m-1)^2(1-c-t)^2+16m^2(R+\rho F)\right]}{(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R}$$

In the case of only two firms, $m=2$, cutoff $\overline{\delta}_L(m,t)$ simplifies to $\overline{\delta}_L(2,t) \equiv \frac{9\left[(1-c-t)^2+64(R+\rho F)\right]}{17(1-c-t)^2+576R}$, which coincides with that in Appendix 1. Otherwise, cutoff $\overline{\delta}_L(m,t)$ increases in β if

$$\frac{\partial\overline{\delta}_L(m,t)}{\partial m} = \frac{4(1-c-t)^2(m^2-1)\left[(1-c-t)^2(m-1)^4+8mD\right]}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} < 0$$

where term $D \equiv 2mR\left[m(m-4)-1\right]+\rho F\left[m[m(m-11)-5]-1\right]$. $\frac{\partial\overline{\delta}_L(m,t)}{\partial m} > 0$ holds if and only if $\rho F < \frac{(1-c-t)^2(m-1)^4+16m^2R[m(m-4)-1]}{8m[1-m(m(m-11)-5)]}$.

Furthermore, the comparative statics of cutoff $\overline{\delta}_L(m,t)$ are

$$\begin{aligned}
\frac{\partial\overline{\delta}_L(m,t)}{\partial c} &= \frac{\partial\overline{\delta}_L(m,t)}{\partial t} = \frac{32m^2(m^2-1)^2(1-c-t)\left[4mR+\rho F[m(m+6)+1]\right]}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0 \\
\frac{\partial\overline{\delta}_L(m,t)}{\partial \rho} &= \frac{16Fm^2(m+1)^2}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0, \\
\frac{\partial\overline{\delta}_L(m,t)}{\partial F} &= \frac{16\rho m^2(m+1)^2}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0, \text{ and} \\
\frac{\partial\overline{\delta}_L(m,t)}{\partial R} &= \frac{64m^3(m+1)^2\left[(m-1)^2(1-c-t)^2-4m\rho F(m+1)^2\right]}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0
\end{aligned}$$

since $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$ by definition. Its cross-partial derivatives satisfy

$$\begin{aligned}
\frac{\partial\overline{\delta}_L(m,t)}{\partial t \partial \rho} &= \frac{32Fm^2(m^2-1)^2\left[m(m+6)+1\right](1-c-t)}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0 \text{ and} \\
\frac{\partial\overline{\delta}_L(m,t)}{\partial t \partial F} &= \frac{32\rho m^2(m^2-1)^2\left[m(m+6)+1\right](1-c-t)}{\left[(m-1)^2(1-c-t)^2\left[m(m+6)+1\right]+16m^2(m+1)^2R\right]^2} > 0.
\end{aligned}$$

Whistleblower programs. When the CA uses leniency programs, collusion can be sustained if equation (4) holds, which in this context yields

$$\delta \geq \overline{\delta}_W(m,t) \equiv \frac{(m^2-1)^2(1-c-t)^2}{(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)}$$

In the case of two firms, $m=2$, cutoff $\overline{\delta}_W(m,t)$ simplifies to $\overline{\delta}_W(2,t) \equiv \frac{9(1-c-t)^2}{17(1-c-t)^2-576(\rho F+nB)}$, which coincides with that in Appendix 1; but otherwise it satisfies

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial m} = \frac{4(m^2-1)^2(1-c-t)^2 J}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0$$

where term $J \equiv (m-1)^4(1-c-t)^2-8m(m+1)^3\left(\rho F+nB\right)$. Then, the derivative $\frac{\partial\overline{\delta}_W(m,t)}{\partial m}$ is positive if term J is positive, which holds if $\rho F+nB < \frac{(m+1)^4(1-c-t)^2}{8m(m+1)^3}$. Furthermore, the comparative statics of cutoff $\overline{\delta}_W(m,t)$ are

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial c} = \frac{\partial\overline{\delta}_W(m,t)}{\partial t} = \frac{32m^2(m-1)^2(m+1)^4(1-c-t)\left(\rho F+nB\right)}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0$$

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial \rho} = \frac{16Fm^2(m-1)^2(m+1)^4(1-c-t)^2}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0,$$

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial F} = \frac{16\rho m^2(m-1)^2(m+1)^4(1-c-t)^2}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0,$$

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial n} = \frac{16Bm^2(m-1)^2(m+1)^4(1-c-t)^2}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0, \text{ and}$$

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial B} = \frac{16nm^2(m-1)^2(m+1)^4(1-c-t)^2}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^2} > 0.$$

and its cross-partial derivatives satisfy

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial t\partial \rho} = \frac{32Fm^2(m-1)^2(m+1)^4(1-c-t)H}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^3} > 0 \text{ and}$$

$$\frac{\partial\overline{\delta}_W(m,t)}{\partial t\partial F} = \frac{32\rho m^2(m-1)^2(m+1)^4(1-c-t)H}{\left[(m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]-16m^2(m+1)^2\left(\rho F+nB\right)\right]^3} > 0$$

where term $H \equiv (m-1)^2\left(1-c-t\right)^2\left[m(m+6)+1\right]+16m^2(m+1)^2\left(\rho F+nB\right) > 0$, and the denominator is positive for all $\rho F+nB < \frac{(m-1)^2(1-c-t)^2[m(m+6)+1]}{16m^2(m+1)^2}$. As shown in the section of audits above, this condition is less demanding than the initial assumption $\rho F < \frac{(m-1)^2(1-c-t)^2}{4m(m+1)^2}$, which implies that both cross-partial derivatives are unambiguously positive.

Emission fees. The regulator chooses an emission fee t that solves problem (5), where $CS = \frac{m^2(1-c-t)^2}{2(m+1)^2}$, $PS = \frac{m(1-c-t)^2}{(m+1)^2}$, $T = t\frac{m(1-c-t)}{m+1}$, $Env = d(Q^C)^2 = \frac{dm(1-c-t)^2}{(m+1)^2}$. Differentiating with respect to t, and solving, yields

$$t^C(m) = \frac{(1-c)(2dm-1)}{m(1+2d)}$$

which is positive if $d > \frac{1}{2m}$, which holds since $d > \frac{1}{2}$ by definition. In addition, this fee coincides with that in Lemma 2 when $m = 2$ firms, $t^C(2) = \frac{(1-c)(4d-1)}{2(1+2d)}$, and satisfies $\frac{\partial t^C(m)}{\partial m} = \frac{(1-c)}{m^2(1+2d)} > 0$, $\frac{\partial t^C(m)}{\partial d} = \frac{2(1-c)(m+1)}{m(1+2d)^2} > 0$, and $\frac{\partial t^C(m)}{\partial c} = -\frac{2dm-1}{m(1+2d)} < 0$.

7.5 Appendix 5 - Price competition

If firms compete in prices (à la Bertrand), every firm i sets its price equal to marginal costs after taxes, $c+t$, earning zero profits, $\pi^C(t)=0$. If, instead, firms collude, they both set monopoly price $p^M=\frac{1+c+t}{2}$, earning a profit $\pi^M(t)=\frac{(1-c-t)^2}{8}$. Finally, if firm i unilaterally deviates from the collusive price, setting a deviating price $p^D=p^M-\varepsilon$, where $\varepsilon\to 0$, it captures all the market, earning profit $\pi^D(t)=\frac{(1-c-t)^2}{4}$. As under output competition, profits satisfy $\pi_\iota^D(t)\geq\pi_\iota^M(t)\geq\pi_\iota^C(t)$, which holds for all parameter values.

In addition, a marginal increase in emission fee t produces $\pi_t^C(t)=0$, $\pi_t^M(t)=\frac{1-c-t}{4}$, and $\pi_t^D(t)=\frac{1-c-t}{2}$, entailing that $\pi_t^C(t)-\pi_t^M(t)=\frac{1-c-t}{4}>0$ and $\pi_t^M(t)-\pi_t^D(t)=\frac{1-c-t}{4}>0$. Therefore, $0>\pi_t^C(t)>\pi_t^M(t)>\pi_t^D(t)$ holds, thus being consistent with Lemma 2. As a consequence, $PG(t)=\pi_i^D(t)-\pi_i^M(t)=\frac{(1-c-t)^2}{8}$ with derivative $PG_t(t)=-\frac{1-c-t}{4}$, and associated elasticity $\varepsilon_{PG,t}=\frac{PG_t(t)}{PG(t)}t=-\frac{2t}{1-c-t}<0$. Similarly, $PL(t)=\pi_i^D(t)-\pi_i^C(t)=\frac{(1-c-t)^2}{4}$ with derivative $PL_t(t)=-\frac{1-c-t}{2}$, and associated elasticity $\varepsilon_{PL,t}=\frac{PL_t(t)}{PL(t)}t=-\frac{2t}{1-c-t}<0$, entailing that both elasticities coincide.

No competition policy. Inserting profits $\pi^C(t)$, $\pi^M(t)$, and $\pi^D(t)$ into equation (1), we find that collusion can be sustained in the absence of competition policy if and only if $\delta\geq\overline{\delta}^B\equiv\frac{1}{2}$, which is unaffected by the stringency of the emission fee.

Audits. When allowing for audits, recall that the latter must not be too large, as otherwise it would deter collusion, i.e., we need $\pi^M(t)-\rho F>\pi^C(t)$; which in this context yields $\rho F<\frac{(1-c-t)^2}{8}$. Using equation (2) in this context, we obtain that collusion can be supported if and only if

$$\delta\geq\overline{\delta}_A^B(t)\equiv\frac{(1-c-t)^2}{2(1-c-t)^2-8\rho F}.$$

Cutoff $\overline{\delta}_A^B(t)\equiv\frac{(1-c-t)^2}{2(1-c-t)^2-8\rho F}>0$ for all $\rho F<\frac{(1-c-t)^2}{4}$, which holds since condition $\pi^M(t)-\rho F>\pi^C(t)$ implies $\rho F<\frac{(1-c-t)^2}{8}$, and $\frac{(1-c-t)^2}{4}>\frac{(1-c-t)^2}{8}$. In addition, $\overline{\delta}_A^B(t)<1$ for all $\rho F<\frac{(1-c-t)^2}{8}$, which holds by definition.

Comparing cutoffs $\overline{\delta}^B=\frac{1}{2}$ and $\overline{\delta}_A^B$, we find that $\overline{\delta}_A^B-\overline{\delta}^B=\frac{2\rho F}{(1-c-t)^2-4\rho F}$, which is positive for all $\rho F<\frac{(1-c-t)^2}{4}$, which holds since $\rho F<\frac{(1-c-t)^2}{8}$ by definition. Therefore, for all parameter values for which $\overline{\delta}_A^B(t)<1$, we can guarantee that $\overline{\delta}_A^B(t)>\overline{\delta}^B$.

In addition, the comparative statics of $\overline{\delta}_A^B(t)$ are the following: $\frac{\partial\overline{\delta}_A^B(t)}{\partial t}=\frac{\partial\overline{\delta}_A^B(t)}{\partial c}=\frac{4\rho F(1-c-t)}{\left[(1-c-t)^2-4\rho F\right]^2}>0$, $\frac{\partial\overline{\delta}_A^B(t)}{\partial\rho}=\frac{2F(1-c-t)^2}{\left[(1-c-t)^2-4\rho F\right]^2}>0$, and $\frac{\partial\overline{\delta}_A^B(t)}{\partial F}=\frac{2\rho(1-c-t)^2}{\left[(1-c-t)^2-4\rho F\right]^2}>0$; while its cross-partial derivative is $\frac{\partial^2\overline{\delta}_A^B(t)}{\partial\rho\partial t}=\frac{4F(1-c-t)\left[(1-c-t)^2+4\rho F\right]}{\left[(1-c-t)^2-4\rho F\right]^3}>0$ and, similarly, $\frac{\partial^2\overline{\delta}_A^B(t)}{\partial F\partial t}=\frac{4\rho(1-c-t)\left[(1-c-t)^2+4\rho F\right]}{\left[(1-c-t)^2-4\rho F\right]^3}>0$, because $\rho F<\frac{(1-c-t)^2}{8}$ by definition.

Leniency programs. Inserting profits $\pi^C(t)=0$, $\pi^M(t)=\frac{(1-c-t)^2}{8}$, and $\pi^D(t)=\frac{(1-c-t)^2}{4}$ into equation (3), yields that

$$\delta \geq \bar{\delta}_L^B(t) \equiv \frac{(1-c-t)^2 + 2(R+4\rho F)}{2\left[(1-c-t)^2 + R\right]}.$$

The numerator of cutoff $\bar{\delta}_L^B(t)$ is positive for all $R > -\frac{(1-c-t)^2}{2} - 4\rho F \equiv R_1^B$, its denominator is positive for all $R > -(1-c-t)^2 \equiv R_2^B$. Comparing cutoffs R_1^B and R_2^B, we can see that R_1^B decreases in the expected fine, ρF, while R_2^B is unaffected, and satisfy $R_1^B > R_2^B$ for all $\rho F < \frac{(1-c-t)^2}{8}$, which holds by the initial assumption. Therefore, $R_1^B > R_2^B$ under all admissible parameters, entailing that condition $R > R_1^B$ is more demanding than $R > R_1^B$. However, condition $R > R_1^B$ must hold by assumption: since $R > -\rho F$ by definition, then $R > -4\rho F$ as well, ultimately implying that $R > R_1^B$ is also satisfied. Furthermore, cutoff $\bar{\delta}_L^B(t)$ satisfies $\bar{\delta}_L^B(t) < 1$ when $\rho F < \frac{(1-c-t)^2}{8}$, which holds by definition.

Comparing cutoffs $\bar{\delta}_A^B(t) \equiv \frac{(1-c-t)^2}{2(1-c-t)^2 - 8\rho F}$ and $\bar{\delta}_L^B(t)$, we find that

$$\bar{\delta}_L^B(t) - \bar{\delta}_A^B(t) = \frac{\left[(1-c-t)^2 - 8\rho F\right](R+4\rho F)}{2\left[(1-c-t)^2 + R\right]\left[(1-c-t)^2 - 4\rho F\right]},$$

which is positive since: (i) the first term in the numerator is positive given that $\rho F < \frac{(1-c-t)^2}{8}$ by definition; (ii) the second term in the numerator is positive because $R > -\rho F$ by definition; (iii) the first term in the denominator is positive for all $R > -(1-c-t)^2 \equiv R_2^B$, but this condition is satisfied when $R > R_1^B$ holds, which holds as shown above; and (iv) the second term in the denominator is positive because $\rho F < \frac{(1-c-t)^2}{4}$ holds given that $\rho F < \frac{(1-c-t)^2}{8}$ by definition. Therefore, $\bar{\delta}_L^B(t) \geq \bar{\delta}_A^B(t)$ for all admissible parameters. Since $\bar{\delta}_A^B(t) \geq \bar{\delta}$, we obtain the ranking $\bar{\delta}_L^B(t) \geq \bar{\delta}_A^B(t) \geq \bar{\delta}^B$.

In addition, the comparative statics of $\bar{\delta}_L^B(t)$ are the following: $\frac{\partial \bar{\delta}_L^B(t)}{\partial t} = \frac{\partial \bar{\delta}_L^B(t)}{\partial c} = \frac{(1-c-t)(R+8\rho F)}{\left[(1-c-t)^2+R\right]^2} > 0$ since $R > -\rho F$ by definition; $\frac{\partial \bar{\delta}_L^B(t)}{\partial \rho} = \frac{4F}{(1-c-t)^2+R} > 0$ if and only if $R > -(1-c-t)^2 \equiv R_2^B$., but this condition is satisfied when $R > R_1^B$ holds, which is true for all admissible parameters, as shown above. By the same argument, $\frac{\partial \bar{\delta}_L^B(t)}{\partial F} = \frac{4\rho}{(1-c-t)^2+R}$ is also positive. Finally, $\frac{\partial \bar{\delta}_L^B(t)}{\partial R} = \frac{(1-c-t)^2 - 8\rho F}{2\left[(1-c-t)^2+R\right]^2} > 0$ since $\rho F < \frac{(1-c-t)^2}{8}$ by definition. The cross-partial derivatives of cutoff $\bar{\delta}_L^B(t)$ are $\frac{\partial^2 \bar{\delta}_L^B(t)}{\partial \rho \partial t} = \frac{8F(1-c-t)}{\left[(1-c-t)^2+R\right]^2} > 0$, $\frac{\partial^2 \bar{\delta}_L^B(t)}{\partial F \partial t} = \frac{8\rho(1-c-t)}{\left[(1-c-t)^2+R\right]^2} > 0$, and $\frac{\partial^2 \bar{\delta}_L^B(t)}{\partial R \partial t} = \frac{(1-c-t)\left[(1-c-t)^2+R-16\rho F\right]}{\left[(1-c-t)^2+R\right]^3}$, where the denominator is positive if and only if $R > -(1-c-t)^2 \equiv R_2^B$, but this condition is satisfied when $R > R_1^B$ holds, which is true for all admissible parameters, as shown above. Similarly, the numerator is positive if and only if $R > -(1-c-t)^2 - 16\rho F$, which also holds because $R > R_2^B$. Therefore, $\frac{\partial^2 \bar{\delta}_L^B(t)}{\partial R \partial t} > 0$ for all admissible parameters.

Whistleblower programs. Inserting profits $\pi^C(t) = 0$, $\pi^M(t) = \frac{(1-c-t)^2}{8}$, and $\pi^D(t) = \frac{(1-c-t)^2}{4}$ into equation (4), yields

$$\delta \geq \overline{\delta}_W^B(t) \equiv \frac{(1-c-t)^2}{2\left[(1-c-t)^2 - 4(nB+\rho F)\right]}.$$

The numerator of cutoff $\overline{\delta}_W^B(t)$ is unambiguously positive, while its denominator is positive since $\rho F + nB < \frac{(1-c-t)^2}{4}$, which holds given that $\rho F + nB < \frac{(1-c-t)^2}{8}$ by definition. Furthermore, cutoff $\overline{\delta}_W^B(t)$ satisfies $\overline{\delta}_W^B(t) < 1$ because $\rho F + nB < \frac{(1-c-t)^2}{8}$, which holds by definition; and satisfies

$$\overline{\delta}_W^B(t) - \overline{\delta}_A^B(t) = \frac{2nB(1-c-t)^2}{[(1-c-t)^2 - 4(\rho F + nB)]\,[(1-c-t)^2 - 4\rho F]},$$

which is positive since $\rho F + nB < \frac{(1-c-t)^2}{8}$ by definition, making both terms of the denominator unambiguously positive. Similarly, comparing $\overline{\delta}_W^B(t)$ and $\overline{\delta}_L^B(t)$, we obtain that $\overline{\delta}_L^B(t) \geq \overline{\delta}_W^B(t)$ if and only if $t \leq t_{W,L}^B \equiv (1-c) - \frac{2\sqrt{2}[(\rho F+nB)(R+4\rho F)[4(\rho F-nB)+R]]^{1/2}}{4(\rho F-nB)+R}$. In summary, we find that the complete ranking of cutoffs is $\overline{\delta}_L^B(t) \geq \overline{\delta}_W^B(t) \geq \overline{\delta}_A^B(t) \geq \overline{\delta}^B$ when t satisfies $t \leq t_{W,L}^B$; but $\overline{\delta}_W^B(t) > \overline{\delta}_L^B(t) \geq \overline{\delta}_A^B(t) \geq \overline{\delta}^B$ otherwise.

In addition, the comparative statics of $\overline{\delta}_W^B(t)$ are the following: $\frac{\partial \overline{\delta}_W^B(t)}{\partial t} = \frac{\partial \overline{\delta}_W^B(t)}{\partial c} = \frac{4(1-c-t)(\rho F+nB)}{\left[(1-c-t)^2-4(nB+\rho F)\right]^2} > 0$, $\frac{\partial \overline{\delta}_W^B(t)}{\partial \rho} = \frac{2F(1-c-t)^2}{\left[(1-c-t)^2-4(nB+\rho F)\right]^2} > 0$, $\frac{\partial \overline{\delta}_W^B(t)}{\partial F} = \frac{2\rho(1-c-t)^2}{2\left[(1-c-t)^2-4(nB+\rho F)\right]^2} > 0$, $\frac{\partial \overline{\delta}_W^B(t)}{\partial n} = \frac{2B(1-c-t)^2}{\left[(1-c-t)^2-4(nB+\rho F)\right]^2} > 0$, and $\frac{\partial \overline{\delta}_W^B(t)}{\partial B} = \frac{2n(1-c-t)^2}{\left[(1-c-t)^2-4(nB+\rho F)\right]^2} > 0$. Finally, the cross-partial derivatives of $\overline{\delta}_W^B(t)$ are $\frac{\partial^2 \overline{\delta}_W^B(t)}{\partial \rho \partial t} = \frac{4F(1-c-t)\left[(1-c-t)^2+4(nB+\rho F)\right]}{\left[(1-c-t)^2-4(nB+\rho F)\right]^3} > 0$, where the denominator is positive because $\rho F + nB < \frac{(1-c-t)^2}{4}$, which holds given that $\rho F + nB < \frac{(1-c-t)^2}{8}$ by definition. Similarly, $\frac{\partial^2 \overline{\delta}_W^B(t)}{\partial F \partial t} = \frac{4\rho(1-c-t)\left[(1-c-t)^2+4(nB+\rho F)\right]}{\left[(1-c-t)^2-4(nB+\rho F)\right]^3} > 0$, $\frac{\partial^2 \overline{\delta}_W^B(t)}{\partial n \partial t} = \frac{4B(1-c-t)\left[(1-c-t)^2+4(nB+\rho F)\right]}{\left[(1-c-t)^2-4(nB+\rho F)\right]^3} > 0$, and $\frac{\partial^2 \overline{\delta}_W^B(t)}{\partial B \partial t} = \frac{4k(1-c-t)\left[(1-c-t)^2+4(nB+\rho F)\right]}{\left[(1-c-t)^2-4(nB+\rho F)\right]^3} > 0$.

Comparison against output competition. Under no competition policy, we find that $\overline{\delta}^B \equiv \frac{1}{2} < \frac{9}{17} \equiv \overline{\delta}$, indicating that collusion can be supported under larger conditions when firms compete in prices than quantities.

Under audits, we find that $\overline{\delta}_A^B(t) \equiv \frac{(1-c-t)^2}{2(1-c-t)^2-8\rho F} < \frac{9(1-c-t)^2}{17(1-c-t)^2-576\rho F} \equiv \overline{\delta}_A(t)$ holds if and only if $\rho F > -\frac{(1-c-t)^2}{504}$, which holds for all admissible parameters. Similarly, under leniency programs, we have that

$$\overline{\delta}_L^B(t) \equiv \frac{(1-c-t)^2 + 2(R+4\rho F)}{2\left[(1-c-t)^2 + R\right]} < \frac{9\left[(1-c-t)^2 + 9R + 64\rho F\right]}{17(1-c-t)^2 + 81R} \equiv \overline{\delta}_L(t)$$

holds if and only if $R > \widetilde{R} \equiv -\frac{(1-c-t)^2[(1-c-t)^2+1{,}016\rho F]}{65(1-c-t)^2+504\rho F}$, where cutoff $\widetilde{R} < 0$ for all admissible parameters (but recall that R can be positive or negative). Comparing condition $R > \widetilde{R}$ against the initial assumption $R > -\rho F$, we obtain that inequality $-\rho F > \widetilde{R}$ simplifies to $\rho F\left[951(1-c-t)^2 - \rho F\right] > -(1-c-t)^2$, which holds for all admissible parameters. Therefore, condition $R > \widetilde{R}$ is satisfied by the initial assumption $R > -\rho F$, implying that $\overline{\delta}_L^B(t) < \overline{\delta}_L(t)$.

Finally, under whistleblower programs, we find that

$$\overline{\delta}_W^B(t) \equiv \frac{(1-c-t)^2}{2\left[(1-c-t)^2 - 4(nB+\rho F)\right]} < \frac{9(1-c-t)^2}{17\,(1-c-t)^2 - 576(\rho F + nB)} \equiv \overline{\delta}_W(t)$$

is satisfied if and only if $\rho F > -\frac{(1-c-t)^2 + 9{,}720nB}{9{,}720nB}$, which holds for all admissible parameters, entailing that $\overline{\delta}_W^B(t) < \overline{\delta}_W(t)$. In summary, $\overline{\delta}_k^B(t)$ satisfies $\overline{\delta}_k^B(t) < \overline{\delta}_k(t)$ for every $k = \{A, L, W\}$.

Emission fees. The regulator solves problem (5), anticipating an aggregate output $Q^B = 1-c-t$, which yields $CS = \frac{(1-c-t)^2}{2}$, $PS = 0$, $T = t(1-c-t)$, and $Env = d(1-c-t)^2$. Differentiating social welfare with respect to t, and solving for t, yields an emission fee under Bertrand competition of

$$t^B = \frac{2d(1-c)}{1+2d},$$

which satisfies $\frac{\partial t^B}{\partial d} = \frac{2(1-c)}{(1+2d)^2} > 0$ and $\frac{\partial t^B}{\partial c} = -\frac{2d}{1+2d} < 0$. Comparing this fee against that under Cournot competition, $t^C = \frac{(1-c)(4d-1)}{2(1+2d)}$, we obtain that $t^B - t^C = \frac{1-c}{2(1+2d)} > 0$, implying that t^B is more stringent than t^C. Intuitively, the regulator anticipates a larger aggregate output and emissions under Bertrand than Cournot competition, requiring a more stringent fee.

7.6 *Proof of Lemma 1*

We first identify first-order conditions under Cournot and collusion. We use these conditions later when evaluating the derivative of each profit with respect to fee t.

Cournot competition. Every firm i chooses its own output q_i to solve

$$\max_{q_i}\, p(Q(t))q_i - C(q_i) - tq_i,$$

where $Q(t) \equiv q_i(t) + q_j(t)$. Taking first order conditions with respect to q_i, we obtain

$$p'(Q^C(t))q_i + p(Q(t)) - C'(q_i) - t = 0.$$

Evaluating firm i's profit in the equilibrium output $q_i^C(t)$ and $q_j^C(t)$, we have that $\pi^C(t) = p(Q^C(t))q_i^C(t) - C(q_i^C(t)) - tq_i^C(t)$ and its derivative with respect to t, $\frac{\partial \pi^C(t)}{\partial t} \equiv \pi_t^C(t)$, is

$$p'(Q^C(t))\frac{\partial Q^C(t)}{\partial t}q_i^C(t) + p(Q^C(t))\frac{\partial q_i^C(t)}{\partial t} - C'(q_i^C(t))\frac{\partial q_i^C(t)}{\partial t} - q_i^C(t) - t\frac{\partial q_i^C(t)}{\partial t}$$

or alternatively

$$p'(Q^C(t))\frac{\partial q_i^C(t)}{\partial t}q_i^C(t) + p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t}q_i^C(t) + p(Q^C(t))\frac{\partial q_i^C(t)}{\partial t}$$
$$-C'(q_i^C(t))\frac{\partial q_i^C(t)}{\partial t} - q_i^C(t) - t\frac{\partial q_i^C(t)}{\partial t}$$

Rearranging, we obtain that

$$\frac{\partial q_i^C(t)}{\partial t}\left[p'(Q^C(t))q_i^C(t)+p(Q^C(t))-C'(q_i^C(t))-t\right]+p'(Q(t))\frac{\partial q_j^C(t)}{\partial t}q_i^C(t)-q_i^C(t)$$

and since $p'(Q^C(t))q_i + p(Q^C(t)) - C'(q_i) - t = 0$ from the above first-order conditions under Cournot, the above equation simplifies to $p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t}q_i^C(t) - q_i^C(t)$, and further reduces to

$$\pi_t^C(t) = q_i^C(t)\left[p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t} - 1\right] \tag{A1}$$

which is negative if and only if $p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t} < 1$.

Collusion. If, conditional on firm j choosing the collusive output $q_j^M(t)$, firm i chooses q_i to maximize joint profits, $\pi^M(t) + \pi_j^M(t)$, we obtain the following

$$\begin{aligned}
\frac{\partial\left(\pi^M(t)+\pi_j^M(t)\right)}{\partial q_i} &= p'(q_i(t)+q_j^M(t))q_i^M(t)+p(q_i(t)+q_j^M(t))-C'(q_i^M(t))-t+p'(q_i(t)+q_j^M(t))q_j^M(t)\\
&= p'(q_i(t)+q_j^M(t))(q_i^M(t)+q_j^M(t))+p(q_i(t)+q_j^M(t))-C'(q_i^M(t))-t\\
&= p'(Q^M(t))Q^M(t)+p(Q^M(t))-C'(q_i^M(t))-t=0.
\end{aligned}$$

Hence, a marginal increase in t yields the following effect on individual profit, $\frac{\partial \pi^M(t)}{\partial t} \equiv \pi_t^M(t)$,

$$\begin{aligned}
&p'(Q^M(t))\frac{\partial q_i^M(t)}{\partial t}q_i^M(t)+p'(Q^M(t))\frac{\partial q_j^M(t)}{\partial t}q_i^C(t)+p(Q^M(t))\frac{\partial q_i^M(t)}{\partial t}\\
&-C'(q_i^M(t))\frac{\partial q_i^M(t)}{\partial t}-q_i^M(t)-t\frac{\partial q_i^M(t)}{\partial t}.
\end{aligned}$$

Rearranging and invoking symmetry, $\frac{\partial q_i^M(t)}{\partial t} = \frac{\partial q_j^M(t)}{\partial t}$, yields

$$\frac{\partial q_i^M(t)}{\partial t}\left[2p'(Q^M(t))q_i^M(t)+p(Q^M(t))-C'(q_i^M(t))-t\right]-q_i^M(t)$$

and, given that $q_i^M(t) = q_j^M(t)$ in equilibrium, aggregate output is $Q^M(t) = 2q_i^M(t)$, helping us rewrite the above result as

$$\frac{\partial q_i^M(t)}{\partial t}\left[p'(Q^M(t))Q^M(t)+p(Q^M(t))-C'(q_i^M(t))-t\right]-q_i^M(t)$$

Finally, using $p'(Q^M(t))Q^M(t) + p(Q^M(t)) - C'(q_i^M(t)) - t = 0$ from the above first-order condition under collusion, the above equation simplifies to

$$\pi_t^M(t) = -q_i^M(t) < 0 \tag{A2}$$

which is unambiguously negative.

Comparing A1 and A2, $0 > \pi_t^C(t) > \pi_t^M(t)$ holds if and only if $q_i^C(t)\left[p'(Q^M(t))\frac{\partial q_j^C(t)}{\partial t} - 1\right] > -q_i^M(t)$ or, after rearranging,

$$p'(Q^M(t))\frac{\partial q_j^C(t)}{\partial t} > \frac{q_i^C(t) - q_i^M(t)}{q_i^C(t)}.$$

7.7 *Proof of Lemma 2*

First, we identify first-order conditions in the case of deviation. Second, we use them to evaluate the derivative of deviation profits with respect to fee t and, finally, compare the sensitivity of profits to fee t across settings (Cournot, collusion, and deviation) using Lemma 1.

Deviation. When firm j produces the collusive output $q_j^M(t)$, but firm i optimally deviates to maximize its individual profits, it solves

$$\max_{q_i \geq 0} \; p(q_i(t) + q_j^M(t))q_i - C(q_i) - tq_i$$

Taking first order condition with respect to q_i yields

$$p'(q_i(t) + q_j^M(t))q_i(t) + p(q_i(t) + q_j^M(t)) - C'(q_i(t)) - t = 0$$

Then, firm i's profits in equilibrium are $\pi_t^D(t) = p(q_i^D(t) + q_j^M(t))q_i^D - C(q_i^D) - tq_i^D$. Hence, a marginal increase in t yields a change in profits $\frac{\partial \pi^D(t)}{\partial t} \equiv \pi_t^D(t)$, that is,

$$\begin{aligned}
&p'(q_i^D(t) + q_j^M(t))\frac{\partial q_i^D(t)}{\partial t}q_i^D(t) + p'(q_i^D(t) + q_j^M(t))\frac{\partial q_j^M(t)}{\partial t}q_i^D(t) + \\
&p(q_i^D(t) + q_j^M(t))\frac{\partial q_i^D(t)}{\partial t} - C'(q_i^D(t))\frac{\partial q_i^D(t)}{\partial t} - q_i^D(t) - t\frac{\partial q_i^D(t)}{\partial t}.
\end{aligned}$$

Rearranging yields

$$\begin{aligned}
&\frac{\partial q_i^D(t)}{\partial t}\left[p'(q_i^D(t) + q_j^M(t))q_i^D(t) + p(q_i^D(t) + q_j^M(t)) - C'(q_i^D(t)) - t\right] \\
&+p'(q_i^D(t) + q_j^M(t))\frac{\partial q_j^M(t)}{\partial t}q_i^D(t) - q_i^D(t).
\end{aligned}$$

Since $p'(q_i^D(t) + q_j^M(t))q_i(t) + p(q_i^D(t) + q_j^M(t)) - C'(q_i^D(t)) - t = 0$ from the above first-order condition, this equation simplifies to

$$\frac{\partial q_j^M(t)}{\partial t}p'(q_i^D(t) + q_j^M(t))q_i^D(t) - q_i^D(t).$$

Finally, since $q_i^D(t) + q_j^M(t) = Q^D(t)$, this equation further reduces to

$$\pi_t^D(t) = q_i^D(t)\left[p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} - 1\right] \tag{A3}$$

which is negative if and only if $p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} < 1$.

Comparison. Using the results from derivatives $\pi_t^C(t)$, $\pi_t^M(t)$, and $\pi_t^D(t)$ (see equations A1-A3), we can now compare them. There are six possible rankings between these three derivatives, which we separately examine next:

Case 1. $0 > \pi_t^C(t) > \pi_t^M(t) > \pi_t^D(t)$. Because $0 > \pi_t^C(t) > \pi_t^M(t)$ holds by definition (from Lemma 1), we only need to check the last inequality in Case 1, $\pi_t^M(t) > \pi_t^D(t)$. This entails $0 > -q_i^M(t) > q_i^D\left[p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} - 1\right]$, which multiplying by $\frac{-1}{q_i^M(t)}$ yields $1 < \frac{q_i^D(t)}{q_i^M(t)}\left[1 - p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t}\right]$. After rearranging, we obtain

$$p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} > \frac{q_i^M(t) - q_i^D(t)}{q_i^D(t)}.$$

Since $p'(Q(t)) < 0$ and $\frac{\partial q_j^M(t)}{\partial t} < 0$, the left-hand side of this inequality is unambiguously positive. In contrast, since $q_i^M(t) < q_i^D(t)$, the right-hand side is unambiguously negative, implying that the above inequality always holds.

Case 2. $0 > \pi_t^C(t) > \pi_t^D(t) > \pi_t^M(t)$. This case entails $\pi_t^C(t) > \pi_t^D(t)$ and $\pi_t^D(t) > \pi_t^M(t)$. The latter is the opposite of Case 1, that is, $p'(Q^D(t))\frac{\partial q_i^M(t)}{\partial t} < \frac{q_i^M(t) - q_i^D(t)}{q_i^D(t)}$. This inequality, however, cannot hold since, as shown in Case 1, the right-hand side is unambiguously negative. Then, we do not need to check the former inequality, implying that Case 2 cannot hold.

Case 3. $0 > \pi_t^M(t) > \pi_t^D(t) > \pi_t^C(t)$. This case entails that $\pi_t^M(t) > \pi_t^C(t)$, which is incompatible with the initial condition $\pi_t^C(t) > \pi_t^M(t)$ in Lemma 1, so it cannot hold.

Case 4. $0 > \pi_t^D(t) > \pi_t^M(t) > \pi_t^C(t)$. This case cannot hold either since $\pi_t^M(t) > \pi_t^C(t)$ is incompatible with the initial condition $\pi_t^C(t) > \pi_t^M(t)$ in Lemma 1.

Case 5. $0 > \pi_t^D(t) > \pi_t^C(t) > \pi_t^M(t)$. This case implies that $\pi_t^D(t) > \pi_t^C(t)$ and $\pi_t^C(t) > \pi_t^M(t)$. The latter holds by definition (Lemma 1), so we only need to examine the former inequality, $\pi_t^D(t) > \pi_t^C(t)$. This inequality entails $q_i^D(t)\left[p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} - 1\right] > q_i^C(t)\left[p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t} - 1\right]$. After rearranging, yields

$$p'(Q^C(t))\frac{\partial q_j^C(t)}{\partial t} < p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t}\frac{q_i^D(t)}{q_i^C(t)} - \frac{q_i^D(t) - q_i^C(t)}{q_i^D(t)}.$$

Comparing the right-hand side of this inequality against that in Lemma 1, $\frac{q_i^C(t) - q_i^M(t)}{q_i^C(t)}$, we obtain that

$$p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t}\frac{q_i^D(t)}{q_i^C(t)} - \frac{q_i^D(t) - q_i^C(t)}{q_i^D(t)} < \frac{q_i^C(t) - q_i^M(t)}{q_i^C(t)}$$

which simplifies to $p'(Q^D(t))\frac{\partial q_j^M(t)}{\partial t} < \frac{q_i^D(t)-q_i^M(t)}{q_i^D(t)}$. If this condition holds, Case 5 cannot be sustained.

Case 6. $0 > \pi_t^M(t) > \pi_t^C(t) > \pi_t^D(t)$. This case cannot hold either since $\pi_t^M(t) > \pi_t^C(t)$ is incompatible with the initial condition $\pi_t^C(t) > \pi_t^M(t)$ in Lemma 1.

7.8 *Proof of Lemma 3*

Rearranging equation (1), and solving for δ, yields $\delta \geq \overline{\delta}(t) \equiv \frac{\pi^D(t)-\pi^M(t)}{\pi^D(t)-\pi^C(t)} = \frac{PG(t)}{PL(t)}$. Cutoff $\overline{\delta}(t) > 0$ since $\pi^D(t) \geq \pi^M(t)$ and $\pi^D(t) \geq \pi^C(t)$ by assumption; and satisfies $\overline{\delta}(t) < 1$ since $\pi^D(t) - \pi^M(t) < \pi^D(t) - \pi^C(t)$ simplifies to $\pi^M(t) > \pi^C(t)$, which holds by definition.

Differentiating cutoff $\overline{\delta}(t)$ with respect to t, we obtain that $\frac{\partial \overline{\delta}(t)}{\partial t} = \frac{PG_t(t)PL(t)-PL_t(t)PG(t)}{PL(t)^2} \geq 0$ if and only if $\frac{PG_t(t)}{PG(t)} \geq \frac{PL_t(t)}{PL(t)}$. This inequality can be rewritten as $\frac{PG_t(t)}{PL_t(t)} \geq \frac{PG(t)}{PL(t)}$, where the left-hand side is larger than 1 since $0 > PG_t(t) > PL_t(t)$, and the right-hand side is smaller than 1 given that $\overline{\delta}(t) \equiv \frac{PG(t)}{PL(t)} \in (0,1)$ as shown above. Therefore, $\frac{\partial \overline{\delta}(t)}{\partial t} > 0$ under all admissible conditions.

7.9 *Proof of Proposition 1*

Rearranging equation (2), and solving for δ, yields $\delta \geq \overline{\delta}_A(t) \equiv \frac{\pi^D(t)-\pi^M(t)}{\pi_t^D(t)-\pi^C(t)-\rho F} = \frac{PG(t)}{PL(t)-\rho F}$. Cutoff $\overline{\delta}_A(t) > 0$ since $\pi^D(t) \geq \pi^M(t)$ and $\pi^D(t) - \pi^C(t) \geq \rho F$ because $\pi^M(t) - \pi^C(t) \geq \rho F$ by assumption; and satisfies $\overline{\delta}_A(t) < 1$ since $\pi^D(t) - \pi^M(t) < \pi^D(t) - \pi^C(t) - \rho F$ simplifies to $\pi^M(t) - \pi^C(t) \geq \rho F$, which holds by definition. In addition, $\overline{\delta}_A(t) \geq \overline{\delta}(t)$ by comparing equations (1) and (2), and $\rho F > 0$ by assumption.

Differentiating $\overline{\delta}_A(t)$ with respect to t, we find that $\frac{\partial \overline{\delta}_A(t)}{\partial t} = \frac{PG_t(t)[PL(t)-\rho F]-PL_t(t)PG(t)}{[PL(t)-\rho F]^2}$, which is positive if and only if $\frac{PG_t(t)}{PL_t(t)} \geq \frac{PG(t)}{PL(t)-\rho F}$. This condition holds since the left-hand side is larger than 1 because $0 > PG_t(t) > PL_t(t)$, as shown in Lemma 3, and the right-hand side is smaller than 1 given that $\overline{\delta}_A(t) \in (0,1)$ as shown above.

Furthermore, $\frac{\partial \overline{\delta}_A(t)}{\partial \rho} = \frac{F \times PG(t)}{[PL(t)-\rho F]^2} > 0$ and $\frac{\partial \overline{\delta}_A(t)}{\partial F} = \frac{\rho \times PG(t)}{[PL(t)-\rho F]^2} > 0$ since $\pi^D(t) > \pi^M(t)$ by definition. Finally, the cross-partial derivative is $\frac{\partial^2 \overline{\delta}_A(t)}{\partial \rho \partial t} = \frac{FPG_t(t)[PL(t)-\rho F]^2 - 2FPG(t)PL_t(t)[PL(t)-\rho F]}{[PL(t)-\rho F]^4}$, where the numerator is positive if

$$F \times PG_t(t)\,[PL(t) - \rho F]^2 > 2F \times PG(t)PL_t(t)\,[PL(t) - \rho F]$$

or, after rearranging, $\frac{PG_t(t)}{PL_t(t)} > \frac{2PG(t)}{PL(t)-\rho F}$, or $\frac{PG_t(t)}{PG(t)}t > \frac{2PL_t(t)}{PL(t)-\rho F}t$. Using the expressions of elasticities, this inequality yields $\varepsilon_{PG,t} \geq \frac{2PL_t(t)}{PL(t)-\rho F}t$, where the right-hand side can be alternatively written as $\frac{2PL_t(t)}{PL(t)-\rho F}t = 2\varepsilon_{PL,t}\left(1 + \frac{\rho F}{PL(t)-\rho F}\right)$. Therefore, $\frac{\partial^2 \overline{\delta}_A(t)}{\partial \rho \partial t} > 0$ if and only if $\varepsilon_{PG,t} \geq 2\varepsilon_{PL,t}\left(1 + \frac{\rho F}{PL(t)-\rho F}\right)$, where $2\varepsilon_{PL,t}\left(1 + \frac{\rho F}{PL(t)-\rho F}\right) < \varepsilon_{PL,t} < 0$, implying that initial condition

$0 > \varepsilon_{PG,t} \geq \varepsilon_{PL,t}$ is more demanding than $\varepsilon_{PG,t} \geq 2\varepsilon_{PL,t}\left(1+\frac{\rho F}{PL(t)-\rho F}\right)$. Hence, $\frac{\partial^2 \overline{\delta}_A(t)}{\partial\rho\partial t} > 0$ holds for all admissible parameters.

7.10 *Proof of Proposition 2*

Rearranging equation (3), and solving for δ, we find that $\delta \geq \overline{\delta}_L(t) \equiv \frac{PG(t)+R+\rho F}{PL(t)+R}$. Cutoff $\overline{\delta}_L(t) > 0$ since $PL(t) \geq \rho F$ and $R > -\rho F$, implying that $PL(t) \geq R$ and the denominator is positive. Similarly, $PG(t) \geq 0$ and $R > -\rho F$, entailing that the numerator is positive. In addition, $\overline{\delta}_L(t) < 1$ since $PG(t) + R + \rho F < PL(t) + R$ simplifies to $\pi^M(t) - \pi^C(t) \geq \rho F$, which holds by definition. In addition, $\overline{\delta}_L(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}(t)$ by comparing equations (1)-(3).

Differentiating cutoff $\overline{\delta}_L(t)$ with respect to t, we find that

$$\frac{\partial\overline{\delta}_L(t)}{\partial t} = \frac{PG_t(t)\left[PL(t)+R\right] - PL_t(t)\left[PG(t)+R+\rho F\right]}{\left[PL(t)+R\right]^2}$$

which is positive if and only if $PG_t(t)\left[PL(t)+R\right] > PL_t(t)\left[PG(t)+R+\rho F\right]$. Dividing both sides by $PL_t(t)$, yields $\frac{PG_t(t)}{PL_t(t)} \geq \frac{PG(t)+R+\rho F}{PL(t)+R} \equiv \overline{\delta}_L(t)$. This condition holds since the left-hand side is larger than 1 because $0 > PG_t(t) > PL_t(t)$, as shown in Lemma 3, while the right-hand side is smaller than 1 given that $\overline{\delta}_L(t) \in (0,1)$ as shown above. Therefore, $\frac{\partial\overline{\delta}_L(t)}{\partial t} > 0$ under all conditions.

Furthermore, $\frac{\partial\overline{\delta}_L(t)}{\partial\rho} = \frac{F}{PL(t)+R}$, $\frac{\partial\overline{\delta}_L(t)}{\partial F} = \frac{\rho}{PL(t)+R} > 0$, and $\frac{\partial\overline{\delta}_L(t)}{\partial R} = \frac{PL(t)-PG(t)-\rho F}{[PL(t)+R]^2} > 0$ since $\rho F < PL(t) - PG(t)$ by definition. The cross-partial derivatives are

$$\frac{\partial^2\overline{\delta}_L(t)}{\partial\rho\partial t} = \frac{-PL_t(t)F}{\left[PL(t)+R\right]^2} \quad \text{and} \quad \frac{\partial^2\overline{\delta}_L(t)}{\partial F\partial t} = \frac{-PL_t(t)\rho}{\left[PL(t)+R\right]^2}$$

which are both positive since $PL_t(t) < 0$ holds by definition.

7.11 *Proof of Proposition 3*

Rearranging equation (4), and solving for δ, we find that $\delta \geq \overline{\delta}_W(t) \equiv \frac{PG(t)}{PL(t)-(\rho F+nB)}$. Cutoff $\overline{\delta}_W(t) > 0$ since $PG(t) > 0$ and $PL(t) - PG(t) > \rho F + nB$ by definition; and satisfies $\overline{\delta}_W(t) < 1$ since $PG(t) < PL(t)-(\rho F+nB)$ simplifies to $PL(t)-PG(t) > \rho F+nB$, which holds by assumption. In addition, $\overline{\delta}_W(t) \geq \overline{\delta}_A(t) \geq \overline{\delta}(t)$ by comparing equations (1)-(4). Comparing $\overline{\delta}_W(t)$ and $\overline{\delta}_L(t) \equiv \frac{PG(t)+R+\rho F}{PL(t)+R}$, however, we find that $\overline{\delta}_W(t) > \overline{\delta}_L(t)$ if and only if $nB > \frac{[PL(t)-PG(t)-\rho F](\rho F+R)}{PG(t)+\rho F+R}$.

Differentiating cutoff $\overline{\delta}_W(t)$ with respect to t, we find that

$$\frac{\partial\overline{\delta}_W(t)}{\partial t} = \frac{PG_t(t)\left[PL(t)-(\rho F+nB)\right] - PL_t(t)PG(t)}{\left[PL(t)-(\rho F+nB)\right]^2}$$

which is positive if and only if $PG_t(t)\left[PL(t)-(\rho F+nB)\right] > PL_t(t)PG(t)$. Multiplying both sides by t and dividing by $PL_t(t)$, yields $\frac{PG_t(t)}{PL_t(t)} \geq \frac{PG(t)}{PL(t)-(\rho F+nB)} \equiv \overline{\delta}_W(t)$. The left-hand side of this inequality is larger than 1 since $0 > PG_t(t) > PL_t(t)$, as shown in Lemma 3, while the right-hand side is smaller than 1 given that $\overline{\delta}_W(t) \in (0,1)$ as shown above. Therefore, $\frac{\partial\overline{\delta}_W(t)}{\partial t} > 0$ holds under all conditions.

Furthermore, $\frac{\partial \overline{\delta}_W(t)}{\partial \rho} = \frac{PG(t)F}{[PL(t)-(\rho F+nB)]^2} > 0$, $\frac{\partial \overline{\delta}_W(t)}{\partial F} = \frac{PG(t)\rho}{[PL(t)-(\rho F+nB)]^2} > 0$, $\frac{\partial \overline{\delta}_W(t)}{\partial n} = \frac{PG(t)B}{[PL(t)-(\rho F+nB)]^2} > 0$, and $\frac{\partial \overline{\delta}_W(t)}{\partial B} = \frac{PG(t)n}{[PL(t)-(\rho F+nB)]^2} > 0$, and the cross-partial derivative is

$$\begin{aligned}\frac{\partial^2 \overline{\delta}_W(t)}{\partial \rho \partial t} &= \frac{PG_t(t)F\left[PL(t)-(\rho F+nB)\right]^2 - 2\left[PL(t)-(\rho F+nB)\right]PL_t(t)PG(t)F}{\left[PL(t)-(\rho F+nB)\right]^4} \\ &= \frac{F\left[PG_t(t)\left[PL(t)-(\rho F+nB)\right]-2PL_t(t)PG(t)\right]}{\left[PL(t)-(\rho F+nB)\right]^3}\end{aligned}$$

which is positive if and only if $PG_t(t)\left[PL(t)-(\rho F+nB)\right] > 2PL_t(t)PG(t)$. Dividing both sides by $PL_t(t)$ and rearranging, yields $\frac{PG_t(t)}{PL_t(t)} \geq \frac{2PG(t)}{PL(t)-(\rho F+nB)} = 2\overline{\delta}_W(t)$. While the left-hand side of this inequality is larger than 1 since $0 > PG_t(t) > PL_t(t)$, the right-hand side may be also larger than 1, implying that the inequality does not necessarily hold. Rearranging this inequality, we obtain $\frac{PG_t(t)}{PG(t)} > \frac{2PL_t(t)}{PL(t)-(\rho F+nB)}$. Multiplying both sides by t and using elasticities, yields $\varepsilon_{PG,t} \geq 2\varepsilon_{PL,t}\left(1+\frac{\rho F+nB}{PL(t)-\rho F-nB}\right)$, where $2\varepsilon_{PL,t}\left(1+\frac{\rho F+nB}{PL(t)-\rho F-nB}\right)$ satisfies $2\varepsilon_{PL,t}\left(1+\frac{\rho F+nB}{PL(t)-\rho F-nB}\right) < \varepsilon_{PL,t} < 0$, implying that initial condition $0 > \varepsilon_{PG,t} \geq \varepsilon_{PL,t}$ is more demanding than $\varepsilon_{PG,t} \geq 2\varepsilon_{PL,t}\left(1+\frac{\rho F+nB}{PL(t)-\rho F-nB}\right)$. Hence, $\frac{\partial^2 \overline{\delta}_W(t)}{\partial \rho \partial t} > 0$ holds for all admissible parameters. A similar argument applies to $\frac{\partial^2 \overline{\delta}_W(t)}{\partial F \partial t}$.

7.12 *Proof of Lemma 4*

The regulator considers welfare function $W = \frac{(Q^C)^2}{2} + \left[(1-Q^C)Q^C - (c+t)Q^C\right] + tQ^C - d(Q^C)^2$, where $Q^C = \frac{2(1-c-t)}{3}$. Differentiating with respect to fee t, yields

$$\frac{2[1-c(4d-1)+4d(1-c)-2t]}{9} = 0$$

and, after solving for t, we obtain that $t^C = \frac{(1-c)(4d-1)}{2(1+2d)}$. This emission fee is unambiguously positive since $d \geq \frac{1}{2}$ by definition, increasing in d since $\frac{\partial t^C}{\partial d} = \frac{3(1-c)}{(1+2d)^2} > 0$, but decreasing in c because $\frac{\partial t^C}{\partial c} = -\frac{4d-1}{2(1+2d)} < 0$.

7.13 *Proof of Proposition 4*

Inserting fee t^C into $\overline{\delta}_A(t)$, yields $\overline{\delta}_A(t^C) = \frac{9(1-c)^2}{17(1-c)^2-256(1+2d)^2\rho F}$, which satisfies $\overline{\delta}_A(t^C) > 0$ if its denominator is positive, which occurs when $\rho F < \frac{17(1-c)^2}{256(1+2d)^2}$. In addition, the comparative statics of cutoff $\overline{\delta}_A(t^C)$ are $\frac{\partial \overline{\delta}_A(t^C)}{\partial c} = \frac{4{,}608(1-c)(1+2d)^2\rho F}{[17(1-c)^2-256(1+2d)^2\rho F]^2} > 0$, $\frac{\partial \overline{\delta}_A(t^C)}{\partial d} = \frac{9{,}216(1-c)^2(1+2d)\rho F}{[17(1-c)^2-256(1+2d)^2\rho F]^2} > 0$, $\frac{\partial \overline{\delta}_A(t^C)}{\partial \rho} = \frac{2{,}304(1-c)^2(1+2d)^2 F}{[17(1-c)^2-256(1+2d)^2\rho F]^2} > 0$, and $\frac{\partial \overline{\delta}_A(t^C)}{\partial F} = \frac{2{,}304(1-c)^2(1+2d)^2\rho}{[17(1-c)^2-256(1+2d)^2\rho F]^2} > 0$. Furthermore, the cross-partial derivatives $\frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial c} = \frac{4{,}608(1-c)(1+2d)^2 F[17(1-c)^2+256(1+2d)^2\rho F]}{[17(1-c)^2-256(1+2d)^2\rho F]^3} > 0$, $\frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial d} = \frac{9{,}216(1-c)^2(1+2d)F[17(1-c)^2+256(1+2d)^2\rho F]}{[17(1-c)^2-256(1+2d)^2\rho F]^3} > 0$, where the difference $\frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial c} - \frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial d} = \frac{4{,}608(1-c)(1+2d)[2(c+d)-1]F[17(1-c)^2}{[17(1-c)^2-256(1+2d)^2\rho F}$ 0 since $d \geq \frac{1}{2}$ by definition, implying that $\frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial c} > \frac{\partial \overline{\delta}_A(t^C)}{\partial \rho \partial d}$ for all admissible parameter values. A symmetric result holds for $\frac{\partial \bar{\delta}_A(t^C)}{\partial F \partial c}$ and $\frac{\partial \bar{\delta}_A(t^C)}{\partial F \partial d}$.

Similarly, inserting fee t^C into $\bar{\delta}_L(t)$, yields $\bar{\delta}_L(t^C) = \frac{9[1-c(2-c)]+256(1+2d)^2(R+\rho F)}{17(1-c)^2+256(1+2d)^2 R}$, which satisfies $\bar{\delta}_L(t^C) > 0$ since both its numerator and denominator are positive since $1-c(2-c) > 0$ for all admissible values of c. The comparative statics of cutoff $\bar{\delta}_L(t^C)$ are $\frac{\partial \bar{\delta}_L(t^C)}{\partial c} = \frac{4{,}608(1-c)(1+2d)^2(16R+17\rho F)}{[17(1-c)^2+256(1+2d)^2 R]^2} > 0$, $\frac{\partial \bar{\delta}_L(t^C)}{\partial d} = \frac{1024(1-c)^2(1+2d)(8R+17\rho F)}{[17(1-c)^2+256(1+2d)^2 R]^2} > 0$, $\frac{\partial \bar{\delta}_L(t^C)}{\partial \rho} = \frac{256(1+2d)^2 F}{17(1-c)^2+256(1+2d)^2 R} > 0$, and $\frac{\partial \bar{\delta}_L(t^C)}{\partial F} = \frac{256(1+2d)^2 \rho}{17(1-c)^2+256(1+2d)^2 R} > 0$. Furthermore, the cross-partial derivatives $\frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial c} = \frac{8{,}704(1-c)(1+2d)^2 F}{[17(1-c)^2+256(1+2d)^2 R]^2} > 0$, $\frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial d} = \frac{17{,}408(1-c)^2(1+2d)F}{[17(1-c)^2+256(1+2d)^2 R]^2} > 0$, where the difference $\frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial c} - \frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial d} = \frac{8{,}704(1-c)(1+2d)[2(c+d)-1]F}{[17(1-c)^2+256(1+2d)^2 R]^2} > 0$ since $d \geq \frac{1}{2}$ by definition, implying that $\frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial c} > \frac{\partial \bar{\delta}_L(t^C)}{\partial \rho \partial d}$ for all admissible parameter values.

Finally, inserting fee t^C into $\bar{\delta}_W(t)$, yields $\bar{\delta}_W(t^C) = \frac{9(1-c)^2}{17(1-c)^2-256(1+2d)^2(\rho F+nB)}$, which satisfies $\bar{\delta}_W(t^C) > 0$ if $\rho F + nB < \frac{17(1-c)^2}{256(1+2d)^2}$, which holds since $\rho F + nB < \frac{(1-c-t)^2}{72}$ by definition. Furthermore, the comparative statics of cutoff $\bar{\delta}_W(t^C)$ are $\frac{\partial \bar{\delta}_W(t^C)}{\partial c} = \frac{4{,}608(1-c)(1+2d)^2(\rho F+nB)}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^2} > 0$, $\frac{\partial \bar{\delta}_W(t^C)}{\partial d} = \frac{9{,}216(1-c)^2(1+2d)(\rho F+nB)}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^2} > 0$, $\frac{\partial \bar{\delta}_W(t^C)}{\partial \rho} = \frac{2{,}304(1-c)^2(1+2d)^2 F}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^2} > 0$, and $\frac{\partial \bar{\delta}_W(t^C)}{\partial F} = \frac{2{,}304(1-c)^2(1+2d)^2 \rho}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^2} > 0$. Furthermore, the cross-partial derivatives $\frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial c} = \frac{4{,}608(1-c)(1+2d)^2 F[17(1-c)^2+256(1+2d)^2(\rho F+nB)]}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^3} > 0$, $\frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial d} = \frac{9{,}216(1-c)^2(1+2d)F[17(1-c)^2+256(1+2d)^2(\rho F+nB)]}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^3} > 0$, where the difference $\frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial c} - \frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial d} = \frac{4{,}608(1-c)(1+2d)[2(c+d)-1]F[17(1-c)^2+256(1+2d)^2(\rho F+nB)]}{[17(1-c)^2-256(1+2d)^2(\rho F+nB)]^3} > 0$ since $d \geq \frac{1}{2}$ by definition, implying that $\frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial c} > \frac{\partial \bar{\delta}_W(t^C)}{\partial \rho \partial d}$ for all admissible parameter values.

Comparisons. Comparing $\bar{\delta}_L(t^C)$ and $\bar{\delta}_A(t^C)$, we know that $\bar{\delta}_L(t) \geq \bar{\delta}_A(t)$ for every fee t from Proposition 2, entailing that $\bar{\delta}_L(t^C) \geq \bar{\delta}_A(t^C)$ when evaluated at fee t^C. When comparing $\bar{\delta}_W(t^C)$ and $\bar{\delta}_L(t^C)$, we know from Proposition 3 that $\bar{\delta}_W(t) \geq \bar{\delta}_L(t)$ holds if and only if $t \geq t_{W,L}$. Inserting fee t^C in this inequality, we obtain that $t^C \geq t_{W,L}$ holds if and only if

$$d \leq \bar{d}_{W,L} \equiv \frac{(1-c)[8(R+\rho F) - 9nB]}{32\left[(8(R+\rho F) - 9nB)(R+\rho F)(nB+\rho F)\right]^{1/2}} - \frac{1}{2},$$

implying that $\bar{\delta}_W(t^C) \geq \bar{\delta}_L(t^C)$ if $d \leq \bar{d}_{W,L}$, which yields the complete ranking $\bar{\delta}_W(t^C) \geq \bar{\delta}_L(t) \geq \bar{\delta}_A(t)$. If, instead, d satisfies $d > \bar{d}_{W,L}$, then $t^C < t_{W,L}$, entailing that $\bar{\delta}_W(t^C) < \bar{\delta}_L(t^C)$, and yielding the complete ranking $\bar{\delta}_L(t^C) > \bar{\delta}_W(t) \geq \bar{\delta}_A(t)$.

7.14 *Proof of Corollary 1*

Aggregate output under competition is $Q^C(t) = 2q_i^C(t) = \frac{2(1-c-t)}{3}$ and that under collusion is $Q^M(t) = 2q_i^M(t) = \frac{2(1-c-t)}{4}$. Then, $Q^C(t^C) = Q^M(t^M) = \frac{1-c}{1+2d}$, while evaluating $Q^C(t)$ at t^M yields $Q^C(t^M) = \frac{(1-c)(3+2d)}{3(1+2d)}$, and evaluating $Q^M(t)$ at t^C, we obtain $Q^M(t^C) = \frac{3(1-c)}{4(1+2d)}$. Therefore, welfare $W^C(t^C) = W^M(t^M) = \frac{(1-c)^2}{2(1+2d)}$, while $W^C(t^M) = \frac{(1-c)^2(9-4d^2)}{18(1+2d)}$ and $W^M(t^C) = \frac{15(1-c)^2}{32(1+2d)}$. As a consequence, inefficiencies are

$$
\begin{aligned}
\Delta W^C &\equiv W^C(t^C) - W^C(t^M) = \frac{(1-c)^2}{2(1+2d)} - \frac{(1-c)^2(9-4d^2)}{18(1+2d)} = \frac{2d^2(1-c)^2}{9(1+2d)}, \text{ and} \\
\Delta W^M &\equiv W^M(t^M) - W^M(t^C) = \frac{(1-c)^2}{2(1+2d)} - \frac{15(1-c)^2}{32(1+2d)} = \frac{(1-c)^2}{32(1+2d)}
\end{aligned}
$$

whereas $\Delta W^{C,M} \equiv W^C(t^C) - W^M(t^M) = 0$ since $W^C(t^C) = W^M(t^M) = \frac{(1-c)^2}{2(1+2d)}$. In addition, ΔW^C satisfies $\Delta W^C > 0$ for all admissible parameters and increases in d since $\frac{\partial(\Delta W^C)}{\partial d} = \frac{4d(1-c)^2(1+d)}{9(1+2d)^2} > 0$. Inefficiency ΔW^M is also positive for all parameter values, but is decreasing in d since $\frac{\partial(\Delta W^M)}{\partial d} = -\frac{(1-c)^2}{16(1+2d)^2} < 0$.

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