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ORIGINAL ARTICLE

Measuring regulatory errors from environmental policy uncertainty

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Abstract

We examine an environmental policy which may be revisited by a new administration. We allow for pollution to be persistent over time and for uncertainty in next period's environmental policy. When pollution is non-persistent, we show that regulatory uncertainty is inconsequential for output, pollution, or emission fees. However, when pollution is persistent, we find that a more likely reelection of a stringent administration has the unintended (positive) consequence of reducing current pollution. We also measure the inefficiencies stemming from ignoring pollution persistence and from policy uncertainty, identifying in which contexts they are severe or negligible.

Keywords Environmental policy · Pollution persistence · Policy uncertainty · Inefficiencies

JEL Classification L13 · L51 · Q58

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1 Introduction

Environmental regulation usually faces the threat of potential changes in future administrations. In March 2018, for instance, the Environmental Protection Agency (EPA) announced it will ease car fuel-efficiency rules previously put in place under Obama's administration. Other examples include Australia, where Prime Minister Scott Morrison stated in 2018 that he did not plan to fully implement the National Energy Guarantee of the previous administration, see The Guardian (2018, September 7th); and the increasing opposition that Canadian Prime Minister, Justin Trudeau, faced to change his carbon pricing policy, Bloomberg (2018, July 20th). More recently, President Biden approved the Willow drilling project in Alaska in March 2023, after announcing no more oil or gas drilling in June 2021.

In the above examples, the risk of changes in future environmental guidelines generated a policy uncertainty, affecting both firms and regulators. This risk introduces a significant challenge in the design of emission fees that can lead some regulators to simply ignore uncertainty in their decision process, yielding inefficiencies. Our paper evaluates these inefficiencies, identifying in which cases they are small, thus being justified for regulators to overlook policy uncertainty, and in which settings they are large.

Our model considers a polluting industry with several firms where, in the first period, the regulator sets an emission fee and firms respond choosing their output level. In the second period, the regulator remains in office with some probability, or a different regulator takes office. Under both regulators, firms respond choosing their second-period output levels. For generality, we allow regulators to exhibit different environmental concerns, and a share of first-period pollution to persist into the second period.

As a benchmark, we first analyze the case in which pollution is non-persistent, showing that first-period production does not affect the stringency of second-period fees, ultimately not changing second-period profits. As a consequence, firms' output decisions in each period can be treated as separate, and coincide across periods. A same argument applies to the regulator's setting of emission fees. Therefore, when pollution is non-persistent, regulatory uncertainty is inconsequential for output, pollution, or emission fees, because intertemporal effects are absent.

However, when pollution is persistent, first-period output decisions need to account for their effect in next period's fee, making it more stringent. In particular, we show that this output can be expressed as a linear combination of two output levels: (i) that arising when the regulator remains in office with certainty, and (ii) that emerging when a different regulator takes office. Comparing (i) and (ii), we find that the output level in (i) exceeds that in (ii) if the current administration holds less concerns for environmental damages than a (potential) new administration. Intuitively, firms anticipate that second-period emission fees become more stringent due to pollution persistence, increasing their current pollution.

Therefore, these results entail that if a future administration is more environmentally concerned, firms increase their current pollution taking advantage of the more lenient current policy. This output shift has been observed in some industries, with firms increasing their production when they anticipate a strengthening of environmental policy; see Lemoine (2017) for evidence of increased emissions in the US coal industry.

Firms' weight to (i) is, essentially, identical to the probability of reelection, simplifying firms' output decisions. Similarly, the regulator's setting of first-period emission fees can be expressed as a linear combination of the fee she would set when remaining in power with certainty and that when not being reelected. In addition, this weight can also be approximated by the probability of reelection, thus providing a simple rule of thumb in an otherwise complex regulatory problem.

We evaluate the inefficiencies stemming from regulators ignoring pollution persistence or policy uncertainty. We find that, when pollution persistence is ignored, more inefficiencies are generated when the industry is concentrated, the regulator is less concerned about environmental damage, and production costs are low. Otherwise, ignoring the persistence of pollution yields negligible inefficiencies, facilitating the regulator's task. Similarly, when the regulator ignores policy uncertainty (i.e., she may not be reelected), an inefficiency arises, which increases when the industry is concentrated, and costs are low. However, this inefficiency is ameliorated when regulators become more similar in their environmental concerns. Therefore, government agencies can ignore policy uncertainty when the market is highly competitive, production costs are high, and current and future administrations share similar views about the environment.

Related literature. A large body of empirical literature analyzes the negative effect of uncertainty in future policies on firm-level capital investment; see, for instance, Aizenman and Marion (1993), Stein and Stone (2014), Gulen and Ion (2015), Bontempi (2015), and Lim and Yurukoglu (2018). Some papers specifically study policy uncertainty in the energy industry, such as Meyer and Koefoed (2003), which considers wind promotion policy in Denmark; Agnolucci (2006), which examines the Renewable Energy Act in Germany; Wiser et al. (2007), which studies tax incen- tives in the US wind energy sector; Barradale (2010), which investigates the federal production tax credit in the US wind industry; and Fabrizio (2013), which examines state-level Renewable Portfo- lio Standard policies in the US electric utility industry. Overall, these papers empirically find that policy uncertainty—often measured as an index, following Baker et al. (2013)[1]—negatively affects investment decisions in renewable energy projects. In contrast, we theoretically examine emission fees and pollution levels, isolating the inefficiencies originating from policy uncertainty alone and that stemming from ignoring pollution persistence, identifying under which industry conditions these inefficiencies are large or negligible.

The theoretical literature analyzing how capital investment is affected by policy uncertainty is, however, relatively small, and mostly focuses on utility regulation, such as pricing or rate- of-return policies; see Rodrik (1991) and Dixit and Pindyck (1994). Similarly, another line in this field examines how utility incentives to invest in new plants are reduced by the uncertainty in future capital disallowances; which

[1] Baker et al. (2013) propose a policy uncertainty index as a weighted average of: (1) a count of newspaper articles containing key terms related to policy uncertainty (this is the element receiving the highest weight on the index);(2) the dollar impact of tax provisions set to expire in the near future (as a measure of uncertainty about future changes in the tax code); and (3) dispersion in economic forecasts of the CPI and government spending (as a proxy for uncertainty about fiscal and monetary policy).

has been recurrently observed even in regions needing additional electricity capacity, see Leonard et al. (1987), Joskow (1989), Kolbe and Tye (1991), and Lyon and Mayo (2005).

A different branch of the literature has examined how regulator's uncertainty about a firm's true cost induces this firm to act in a welfare improving manner; see Sappington (1986), Spiegel and Spulber (1994), and Armstrong and Sappington (2007); among others. Our paper considers that the source of uncertainty comes from the future reelection of the current regulator, or from a change in the regulator's environmental concern, also identifying a change in firms' behavior, potentially reducing pollution.

Finally, Lyon (1991), Gal-Or and Spiro (1992), Gilbert and Newbery (1994) and Lyon and Li (2004) theoretically examine how utility companies may reduce their investments when facing uncertainty about future price regulation, which responds to changes in the realization of the investment cost or demand. However, our setting does not consider changes in demand or costs, instead, we focus on the possibility of a change in the administration that could adjust previous policies.[2]

The next section presents our model, while Sect. 3 describes equilibrium behavior by firms and regulator, considering the setting of non-persistent pollution as a benchmark. Section 4 then evaluates the inefficiencies that arise from ignoring pollution persistence or policy uncertainty, identifying how they are affected by changes in the parameters. Section 5 examines robustness checks and Sect. 6 discusses the policy implications of our findings.

2 Model

Consider an industry with $n \geq 1$ firms competing à la Cournot, facing inverse demand function $p(Q) = 1 - Q$, where Q denotes aggregate output; and marginal production cost c satisfies $0 \leq c < 1$. Every unit of output generates one unit of emissions. The time structure of the complete- information game is the following:

1. **First period:**
   (a) In the first stage, the regulator in office, R_A, considering an environmental damage d_A to emissions, sets an emission fee f.
   (b) In the second stage, every firm i observes emission fee f and responds simultaneously and independently choosing its output level, x_i.
2. **Second period:**
   (a) In the third stage, R_A remains in office with probability $p \in [0, 1]$, still considering the same environmental damage d_A, and sets a second-period emission fee t_A. (We allow this emission fee to differ from f, as we show below.) With probability $1-p$, however, a new regulator takes office, R_B, with marginal environmental damage d_B. For generality, we allow for d_B to satisfy

[2] Svensson et al. (2009) analyze an optimization model considering different types of uncertainty, such as future energy prices or policy instruments, and examine investments decisions in energy efficiency. However, they do not consider evaluate the inefficiencies from ignoring pollution persistence or policy uncertainty.

$d_B > d_A$, $d_B < d_A$, or $d_B = d_A = d$. Regulator R_B sets the second-period emission fee t_B.
Alternatively, the change in environmental damage from d_A to d_B can be interpreted as that the same administration remains in office in both periods, but with probability p this administration keeps its environmental concerns unaffected ($d_A = d_B$), but with probability $1 - p$ it experiences a change in its environmental concerns ($d_A \neq d_B$).

(b) In the fourth stage, every firm i observes emission fee t_k, where $k = \{A, B\}$, and responds simultaneously and independently choosing its output level, q_i.

For simplicity, we assume no payoff discounting. Therefore, in the first period R_A considers social welfare function

$$W_1 \equiv CS_1 + PS_1 + T_1 - Env_1$$

where $CS_1 + PS_1 = \frac{1}{2}X^2 + [(1 - X)X - (c + f)X]$ is the sum of consumer and producer surplus, and $T_1 = fX$ denotes total tax collection in this period so emission fees are revenue neutral. $Env_1 \equiv d_A X^2$ represents the environmental damage from pollution, which is increasing and convex in aggregate emissions, X, and $d_A > 1/2$ to guarantee positive emission fees.[3] In the second period, R_k considers a similar social welfare function

$$W_2 \equiv CS_2 + PS_2 + T_{2,k} - Env_{2,k}$$

where $CS_2 + PS_2 = \frac{1}{2}Q^2 + [(1 - Q)Q - (c + t_k)Q]$ and $T_{2,k} = t_k Q$. However, environmental damages are, now, $Env_{2,k} \equiv d_k(\alpha X + Q)^2$, where $d_k > 1/2$ for all k. Parameter $\alpha \in [0, 1]$ denotes the persistence of first-period pollution, X, into the second period, and Q are the emissions generated during the second period. This environmental damage embodies different settings as special cases:

(i) if $\alpha = 0$, $Env_{2,k}$ collapses to $Env_{2,k} = d_k Q^2$, thus being symmetric to Env_1; (ii) if $\alpha > 0$, a share $1 - \alpha$ of first-period pollution is absorbed by nature while the remaining share, α, carries into the second period; and (iii) if $\alpha = 1$ all first-period pollution is still present in the second period (no natural absorption).

In the next section, we use backward induction to find the subgame perfect equilibrium of the game.

[3] Our setting considers linear demand and production costs, and convex environmental damages, which are standard assumptions in the literature analyzing environmental regulation in oligopolistic industries, such as Poyago-Theotoky (2007), Ouchida and Goto (2014), Lambertini et al. (2017), and Haruna and Goel (2018); among others.

3 Equilibrium analysis

3.1 Second period

Fourth stage. In this stage, every firm i observes emission fee t_k (set by R_A or R_B), and chooses q_i to solve

$$\max_{q_i \geq 0}(1 - q_i - Q_{-i})q_i - (c + t_k)q_i \tag{1}$$

where $Q_{-i} = \sum_{j \neq i} q_j$ denotes aggregate output by firm i's rivals. This problem yields equilibrium output $q_i(t_k) = \frac{1-(c+t_k)}{n+1}$, which is positive for all$c < 1 - t_k$; and entails profits of$\pi_i(t_k) = \left(\frac{1-(c+t_k)}{n+1}\right)^2 = (q_i(t_k))^2$. As expected, output and profits are both decreasing in the production costs, c, the second-period emission fee, t_k, and in the number of firms,n.

Third stage. R_A is still in office with probability p or R_B is present with probability $1 - p$. Generally, regulator R_k is present in the second period, with environmental damage parameter d_k. This regulator considers the second-period social welfare W_2, and sets emission fee t_k. Alternatively, we can find the socially optimal output in this period, q_i^{SO}, and then identify the emission fee t_k that induces each firm to produce q_i^{SO} units. Following this approach, R_k first solves

$$\max_{q_i \geq 0} W_2 \equiv CS_2 + PS_2 + T_{2,k} - Env_{2,k}. \tag{2}$$

Differentiating with respect to q_i, yields the socially optimal output per firm, q_i^{SO}, as reported in the next lemma. (For simplicity, our analysis considers that environmental damages are not excessive, $d_k < \frac{1-c}{2\alpha X}$ as, otherwise, firms would be induced to shut down.)

Lemma 1. *The second-period socially optimal output per firm is* $q_i^{SO} = \frac{1-c-2d_k\alpha X}{n(1+2d_k)}$, *which is unambiguously decreasing in c, α, X, and* d_k*; and is positive for all parameter values.*

Proof relegated to the Appendix (see Sect. 7.3).

Intuitively, the regulator seeks to reduce output, thus curbing pollution, when emissions are more damaging (higher d_k) and when pollution is more persistent (higher α). If first-period pollution does not carry into the second period (because $\alpha = 0$, $X = 0$, or both), the regulator only needs to consider second-period output, Q, in the above problem, simplifying q_i^{SO} to $q_i^{SO} = \frac{1-c}{n(1+2d_k)}$. In this case, regulators in each period face independent (unrelated) output decisions.

Given the socially optimal output in Lemma 1, q_i^{SO}, and anticipating firms' output decision in $q_i(t_k)$, R_k finds the emission fee t_k that solves $q_i^{SO} = q_i(t_k)$, thus inducing every firm to produce q_i^{SO} units of output.

Lemma 2. *The second-period optimal emission fee is.*

$$t_k^* = \frac{2d_k[n(1-c) + (n+1)\alpha X]}{n(1+2d_k)}$$

which is positive and unambiguously increasing in α, X, d_k, *and n, but decreasing in* c.

Proof relegated to the Appendix (see Sect. 7.4).

Intuitively, as total pollution persistence increases, αX, marginal second-period environmental damage also increases, inducing the regulator to set a more stringent fee. A similar argument applies if pollution becomes more severe (higher d_k), increasing the damaging effect of both the pollution that persisted from the first period and that originated in the second period, driving the regulator to set a more stringent second-period fee.

Finally, a more competitive industry or lower production costs (higher n or lower c) induces a larger aggregate output in the absence of regulation, requiring more stringent fees to curb more emissions.

3.2 First period

As a benchmark, we first examine the case of no pollution persistence ($\alpha = 0$), showing that output and fees in each period are unaffected by regulatory uncertainty. Afterwards, we study how our results are affected by the introduction of pollution persistence.

3.2.1 First period: non-persistent pollution

Second stage. In this stage, every firm i anticipates the second-period emission fee, t_A^* with probability p and t_B^* with probability$1 - p$, as identified in Lemma 2. Inserting fee t_k^* evaluated at$\alpha = 0$, $t_k^* = \frac{(1-c)(2nd_k - 1)}{n(1+2d_k)}$, into its second-period profit yields $\pi_i(t_k^*) = \frac{2d_k(1-c)^2}{n(1+2d_k)^2}$

In this setting, every firm i choose its first-period output, x_i, to solve

$$\max_{x_i \geq 0} \underbrace{(1-X)x_i - (c+f)x_i}_{\text{First-period profits}} + \underbrace{p\pi_i(t_A^*) + (1-p)\pi_i(t_B^*)}_{\text{Expected second-period profits}} \tag{3}$$

where expected second-period profits are unaffected by first-period output, x_i or X, because pollution is non-persistent. Intuitively, every firm i's first-period production does not change the amount of second-period pollution, thus not affecting the stringency of second-period fees; which occurs *regardless* of the specific second-period regulator (R_A or R_B).

Differentiating (3) with respect to x_i, yields first-period production decisions that are symmetric to those in the second period, that is, $x_i(f) = \frac{1-(c+f)}{n+1}$, which is decreasing in the first-period fee, f, and positive for all $f \leq 1 - c$.

First stage. Following the same approach as in the third stage, R_A solves

$$\max_{x_i \geq 0} W_1 + \underbrace{pW_2(t_A^*) + (1-p)W_2(t_B^*)}_{\text{Expected second-period welfare}} \tag{4}$$

where, as above, expected second-period welfare is unaffected by first-period output decisions (i.e., it is not a function of X because pollution is non persistent). As a consequence, first-period output, X, only affects first-period welfare, which applies both when R_A remains in office and otherwise.

The next lemma identifies the socially optimal output and emission fee in this period, which are symmetric to those in the second period (Lemmas 1 and 2).

Lemma 3. *When pollution is non-persistent, first-period socially optimal output is* $x_i^{SO}(d_A) = \frac{1-c}{n(1+2d_A)}$, *which is unambiguously decreasing in* c, n, *and* d_A; *and is positive for all parameter values. The first-period optimal emission fee is* $f^* = \frac{(1-c)(2nd_A-1)}{n(1+2d_A)}$, *which is unambiguously positive, increasing in* d_A *and* n, *but decreasing in* c.

Proof relegated to the Appendix (see Sect. 7.5).

Overall, our results indicate that when pollution is non-persistent, $\alpha = 0$, regulatory uncertainty, $p \in (0, 1)$, does not affect firms' output decisions, pollution levels, or emission fees. Informally, non-persistent pollution "separates" both periods, yielding identical equilibrium outcomes in each period. Otherwise, intertemporal effects of first-period emissions arise, as we identify in the next section.

3.2.2 First period: Persistent pollution

Second stage. In this stage, every firm i chooses its first-period output, x_i, to solve

$$\max_{x_i \geq 0} \underbrace{(1-X)x_i - (c+f)x_i}_{\text{First-period profits}} + \underbrace{p\pi_i(t_A^*) + (1-p)\pi_i(t_B^*)}_{\text{Expected second-period profits}} \tag{5}$$

where, unlike in problem (3), second-period profits are now $\pi_i(t_k^*) = \frac{2d_k(1-c+\alpha X)(1-c-2d_k\alpha X)}{n(1+2d_k)^2}$, thus being unambiguously decreasing[4] in α and X. Intuitively, an increase in first-period output (and pollution) yields a more stringent second-period fee, decreasing profits regardless of the regulator in office.

Lemma 4 identifies first-period equilibrium output with uncertainty, $x_i^U(f, d_A)$, but for presentation purposes we first find that without uncertainty, $x_i^{NU}(f, d_A)$, when $p = 1$, as follows

$$x_i^{NU}(f, d_A) = \frac{(1-c)[n + 2d_A(2n + \alpha + 2(n-\alpha)d_A)] - n(1+2d_A)^2 f}{n\big[n + 1 + 4d_A\big(n + 1 + (n + 1 + 2\alpha^2)d_A\big)\big]}$$

4 In particular, $\pi_i(t_k^*)$ is decreasing in α and X if and only if $d_k > \frac{1-c}{2(1-c)+4\alpha X}$, which holds since $d_k > 1/2$ by definition.

while the expression of $x_i^{NU}(f, d_B)$, when $p = 0$, is symmetric, but evaluated at d_B. In addition, these output levels satisfy, for a given fee f,

$x_i^{NU}(f, d_A) \leq x_i^{NU}(f, d_B)$ if and only if $d_A \geq d_B$.

That is, firms anticipate more stringent second-period regulation from R_A than R_B since $d_A \geq d_B$, reducing their first-period output when R_A remains in office than otherwise. Intuitively, the persistence of first-period output triggers more stringent second-period fees from R_A than R_B, leading firms to choose a lower first-period output with the former than the latter, helping them lower their second-period tax burden.

Both $x_i^{NU}(f, d_A)$ and $x_i^{NU}(f, d_B)$ are unambiguously decreasing in fee f, but $x_i^{NU}(f, d_A)$ decreases more significantly than $x_i^{NU}(f, d_B)$ if and only if the environmental concerns of R_A are stronger than R_B's, i.e., $d_A \geq d_B$. As shown in Sect. 3.2.1, when $\alpha = 0$, these output levels simplify$x_i^{NU}(f, d_A) = x_i^{NU}(f, d_B) = \frac{1-c-f}{n+1}$. We next present first-period output with uncertainty as a linear combination of$x_i^{NU}(f, d_A)$ and $x_i^{NU}(f, d_B)$.

Lemma 4. *First-period output is* $x_i^U = \theta x_i^{NU}(f, d_A) + (1-\theta)x_i^{NU}(f, d_B)$, *where weight* θ*is.*

$$\theta \equiv \frac{p\left[n+1+4d_A\left(n+1+2\alpha^2 d_A\right)\right](1+2d_B)^2}{4d_A^2\left[n+1+2p\alpha^2+4d_B\left(n+1+2p\alpha^2+\left(n+1+2\alpha^2\right)d_B\right)\right]+(1+4d_A)A}$$

where $A \equiv n+1+4d_B\left[n+1+(n+1+2(1-p)\alpha^2)d_B\right]$. *Weight* θ *satisfies* $\theta = 1$ *when* $p = 1, \theta = 0$ *when* $p = 0$, *and* $\theta = p$ *when* $d_A = d_B$. *In addition, weight* θ *is: (i) unaffected by fee* f; *(ii) unambiguously increasing in* p *and* d_A; *(iii) unambiguously decreasing in* d_B; *and (iv) increasing in* α *if and only if* $d_A > d_B$.

Proof relegated to the Appendix (see Sect. 7.6).

Intuitively, weight θ measures firms' optimal output distribution as a function of the regulatory uncertainty. To understand this point, first note that, when no uncertainty exists about R_A staying in office, $p = 1$, firms just choose $\theta = 1$, yielding an output $x_i^{NU}(f, d_A)$. Similarly, when R_B takes office with certainty, $p = 0$, they choose $x_i^{NU}(f, d_B)$. More generally, firms choose a first-period output that is closer to that when R_A remains in office, $x_i^{NU}(f, d_A)$, thus increasing the weight θ, if: (i) the probability of R_A remaining in office increases (higher p); (ii) her environmental concern increases (higher d_A); and (iii) R_B's environmental concern decreases (lower d_B). In addition, if R_A exhibits stronger environmental concerns than R_B, $d_A > d_B$, weight θ increases if: (iv) a larger share of first-period pollution persists into the second period (higher α); and (v) fewer companies compete in the industry (lower n). This occurs because firms expect a more stringent expected fee in the second period, reducing their current production decisions to lower their second-period tax burden.

In addition, a more stringent fee leads firms to decrease $x_i^{NU}(f, d_A)$ and $x_i^{NU}(f, d_B)$, potentially in an asymmetric fashion. However, it does not alter the optimal weight between these output levels, θ, thus not affecting firms' risk distribution. Finally, when both regulators exhibit the same environ- mental concerns, $d_A = d_B$, the weight satisfies $\theta = p$ which, together with $x_i^{NU}(f, d_A) = x_i^{NU}(f, d_B)$, entails that $x_i^U = x_i^{NU}(f, d_A) = x_i^{NU}(f, d_B)$, implying that firms' decisions are unaffected by uncertainty.

Weight θ can be approximated at $p = 0$ by a first-order Taylor expansion $\theta(p) = \theta(0) + \frac{\partial\theta}{\partial p}\Big|_{p=0}(p-0)$, and since $\theta(0) = 0$, this expression simplifies to

$$\theta(p) = \frac{\left[1+n+4d_A\left(1+n+\left(1+n+2\alpha^2\right)d_A\right)\right](1+2d_B)^2}{\left[1+n+4d_B\left(1+n+\left(1+n+2\alpha^2\right)d_B\right)\right](1+2d_A)^2}p,$$

whose slope is exactly 1 when $d_A = d_B$, is larger than 1 when $d_A > d_B$, and smaller than 1 otherwise. Nonetheless, the slope is very close to 1, implying that weight $\theta(p)$ can be approximated by $\theta(p) = p$. Table A.1 in Appendix 1 evaluates weight $\theta(p)$ at a large set of parameter values, showing that it is, essentially, identical to p in all cases; and table A.2 identifies equilibrium first- and second-period output x_i^U and $q_i^{SO}\left(x_i^{SO,U}\right)$, and first- and second-period fees, f^U and $t(f^U)$.

Overall, this entails that x_i^U can be linearly approximated by $x_i^U = px_i^{NU}(f, d_A) + (1-p)x_i^{NU}(f, d_B)$, being increasing in p if and only if $x_i^{NU}(f, d_A) > x_i^{NU}(f, d_B)$, which holds if $d_A < d_B$; but x_i^U is decreasing in p if $d_A > d_B$. Intuitively, if a relatively stringent administration becomes more likely to remain in office (higher p), firms anticipate a more stringent future fee, which leads them to reduce first-period output. In other words, a more likely stringent future regulation induces firms to decrease their current pollution; as empirically shown in Hammar and Lofgren (2001), for the Swedish Sulphur Tax, and Elrod and Malik (2017), for the EPA's Cluster Rule.

First stage. In the first period, R_A solves

$$\max_{x_i \geq 0} W_1 + \underbrace{\left[pW_2(t_A^*) + (1-p)W_2(t_B^*)\right]}_{\text{Expected second-period welfare}}. \tag{6}$$

which yields the results in the next proposition. For compactness, we report the socially optimal output when R_A faces uncertainty, $x_i^{SO,U}$, as a linear combination of the corresponding output without uncertainty, $x_i^{SO,U}(d_A)$ when R_A remains in office and $x_i^{SO,U}(d_A, d_B)$ when she does not, where

$$x_i^{SO,NU}(d_A) = \frac{(1-c)\left[n^2+2nd_A(2n-\alpha)+4d_A^2(\alpha+n(n(1-\alpha)-\alpha))\right]}{n\left[n^2+2n^2d_A\left(3+\alpha^2\right)+4nd_A^2\left(3n+(3n-2)\alpha^2\right)+8d_A^3\left(n^2+(n-1)^2\alpha^2\right)\right]}$$

and

$$x_i^{SO,NU}(d_A, d_B) = \frac{(1-c)\left[n^2+2nd_B(2n-\alpha)+4d_B^2(\alpha+n(n(1-\alpha)-\alpha))\right]}{n\left[n^2+2n^2d_B\left(2+\alpha^2\right)+4nd_B^2\left(n+(3n-2)\alpha^2\right)+8d_B^3\alpha^2(n-1)^2+2n^2d_A(1+2d_B)^2\right]}$$

which coincide if $d_A = d_B$, but otherwise differ. Note that when $p = 1$, $x_i^{SO,NU}(d_A)$ is only a function of d_A; but when $p = 0$, $x_i^{SO,NU}(d_A, d_B)$ since R_A considers both d_A and d_B in the second period.

Proposition 1 *First-period socially optimal output is*

$$x_i^{SO,U} = \beta x_i^{SO,NU}(d_A) + (1-\beta) x_i^{SO,NU}(d_A, d_B)$$

where weight β is

$$\beta \equiv \frac{p\left[n^2 + 2n^2\left(3+\alpha^2\right)d_A + 4n\Psi d_A^2 + 8\left(n^2 + (n-1)^2\alpha^2\right)d_A^3\right](1+2d_B)^2}{\Delta + 4d_A^2\left[np\Psi + 2n\left(6n + (n-4p+5np)\alpha^2\right)d_B + 4nd_B^2\Psi + 8(n-1)^2(1-p)\alpha^2 d_B^3\right] + \eta}$$

where Δ, Ψ, and η, are defined in the appendix, for compactness. Weight β satisfies $\beta = 1$ when $p = 1$, $\beta = 1$ when $p = 1$, and $\beta = p$ when $d_A = d_B$. In addition, weight β is: (i) unambiguously increasing in p; (ii) unambiguously decreasing in d_B; and (iii) increasing in α and n if and only if $d_A > d_B$.

Proof relegated to the Appendix (see Sect. 7.7).

Intuitively, R_A assigns weight β in a similar fashion as firms assign weight θ. In particular, she induces output $x_i^{SO,NU}(d_A)$ when she remains in office with certainty, $p = 1$; but output $x_i^{SO,NU}(d_A, d_B)$ when R_B takes office for sure, $p = 0$. When both regulators have the same environmental concerns, $d_A = d_B$, R_A chooses $x_i^{SO,NU}(d_A)$ with a weight equal to her probability of remaining in office and $x_i^{SO,NU}(d_B)$ otherwise. Table A.1 (in Appendix 1) shows that, like weight θ in Lemma 4, weight β is also extremely close to probability p, and this property is robust to different parameter combinations. Therefore, R_A only needs to account for her chances of reelection when setting emission fees.

The following proposition identifies the emission fee f^U that induces firms to choose $x_i^{SO,U}$ in equilibrium. As in Proposition 1, we present this fee as a linear combination of the fee when R_A remains in office with certainty, $f^{NU}(d_A)$, which solves $x_i^{SO,NU}(d_A) = x_i^{NU}\left(f, d_A\right)$; and that when R_B takes office with certainty, $f^{NU}(d_A, d_B)$, which solves $x_i^{SO,NU}(d_A, d_B) = x_i^{NU}\left(f, d_B\right)$.

Proposition 2 *Regulator $R_A$sets first-period emission fee.*

$$f^U = \gamma f^{NU}(d_A) + (1-\gamma) f^{NU}(d_A, d_B),$$

where weight γ is defined, for compactness, in the appendix, and satisfies $\gamma = 1$ when $p = 1$, and $\gamma = 0$ when $p = 0$.

Proof relegated to the Appendix (see Sect. 7.8).

As weight θ in Lemma 4, which could be approximated by a first-order Taylor expansion, weight γ is extremely close to p. Table A.1 illustrates this property, confirming that it holds for a wide range of parameter combinations.

4 Examining inefficiencies

In this section, we evaluate inefficiencies, either stemming from pollution persistence or uncertainty.

4.1 Pollution persistence inefficiency, *PPI*

In the absence of uncertainty, $p = 1$, the difference between first-period pollution when emissions are non-persistent and persistent is

$$PPI = x_i^{SO,U}(\alpha = 0,\ p = 1) - x_i^{SO,U}(\alpha > 0,\ p = 1)$$

where $x_i^{SO,U}(\alpha = 0,\ p = 1) = \frac{1-c}{n(1+2d_A)}$ from Lemma 3. The expression of $x_i^{SO,U}(\alpha > 0,\ p = 1)$, which is evaluated at $p = 1$, coincides with $x_i^{SO,NU}(d_A)$. To see this point, recall that, as shown in Proposition 1, weight β collapses to $\beta = 1$ when $p = 1$, and $x_i^{SO,U} = \beta x_i^{SO,NU}(d_A) + (1-\beta)x_i^{SO,NU}(d_A, d_B)$, ultimately entailing that $x_i^{SO,U}(\alpha > 0,\ p = 1) = x_i^{SO,NU}(d_A)$, where

$$x_i^{SO,NU}(d_A) = \frac{(1-c)\left[n^2 + 2nd_A(2n-\alpha) + 4d_A^2(\alpha + n(n(1-\alpha)-\alpha))\right]}{n\left[n^2 + 2n^2 d_A\left(3+\alpha^2\right) + 4nd_A^2\left(3n + (3n-2)\alpha^2\right) + 8d_A^3\left(n^2 + (n-1)^2\alpha^2\right)\right]}$$

This inefficiency satisfies $PPI > 0$ for all admissible values because the emission fee is less stringent when pollution is non-persistent than otherwise, allowing for a socially excessive pollution in equilibrium. Therefore, if R_A chooses $x_i^{SO,U}(\alpha = 0,\ p = 1)$, where she should have selected $x_i^{SO,U}(\alpha > 0,\ p = 1)$, she gives rise to the inefficiency measured by PPI. Informally, PPI could be understood as the "regulatory error" from ignoring pollution persistence when setting first-period fees.

The comparative statics of PPI are highly non-linear, not allowing for explicit results, so we next rely on numerical simulations. Figure 1a plots PPI as a function of n, considering $d_A = 0.6$, $\alpha = 0.1$, and $c = 0$ as a benchmark. PPI decreases in n, indicating that, as the industry becomes more competitive, regulatory authorities can ignore pollution persistence under larger conditions, without generating large inefficiencies. The figure also illustrates how PPI is affected by an increase in d_A to $d_A = 1$ and to $d_A = 1.5$, producing a downward shift in PPI, but only when few firms compete. When the industry is very competitive (high n), increases in d_A essentially yield no changes in PPI.

Figure 1b evaluates PPI at more intense pollution persistence (α increases from $\alpha = 0.1$ to $\alpha = 0.2$ and to $\alpha = 0.4$). PPI shifts upwards, which holds for all n, indicating that the regulatory error from ignoring pollution persistence becomes more acute when pollution is more persistent.

In contrast, Fig. 1c plots PPI considering higher costs (c increases from $c = 0$ to $c = 1/4$ and to $c = 1/2$), suggesting that inefficiencies decrease when output becomes

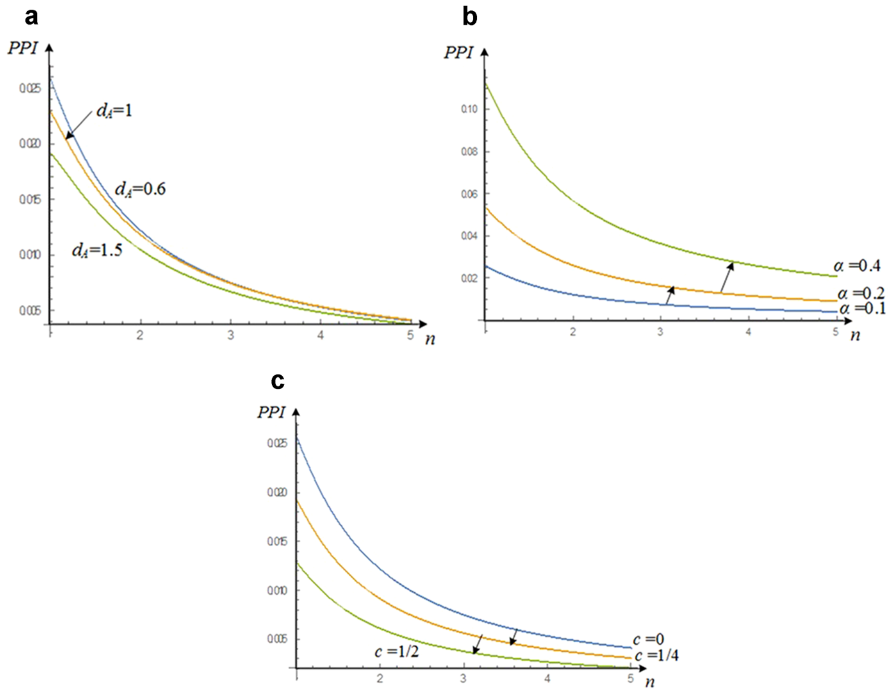

Fig. 1 **a** PPI at different values of d_A. **b** PPI at different values of α. **c** PPI at different values of c

more costly. This happens because, when c increases, firms produce few units of output (and emissions), both when the regulator considers and ignores pollution persistence.

Overall, PPI is relatively large when the industry is concentrated (low n), regulators exhibit less environmental concerns (low d_A), pollution is persistent (high α), and production costs are low (low c). In these contexts, our results indicate that it is critical for regulators to consider pollution persistence when setting emission fees. Otherwise, they can ignore such persistence, simplifying their task, as they would produce negligible inefficiencies.

4.2 Policy uncertainty inefficiency, *PUI*.

For a given pollution persistence, $\alpha = 1$, we now measure the inefficiencies arising from uncertainty alone. (Recall that when $\alpha = 0$, first-period output simplifies to that in Sect. 3.2.1, $x_i^U = \frac{1-c-f}{n+1}$, which is unaffected by p. To evaluate uncertainty effects, we then must fix pollution persistence at $\alpha > 0$.) Hence, the inefficiency stemming from policy uncertainty is

$$PUI = x_i^{SO,U}(\alpha = 1,\ p \in (0,1)) - x_i^{SO,U}(\alpha = 1,\ p = 1)$$

where $x_i^{SO,U}(\alpha = 1,\ p \in (0,\ 1))$ was identified in Proposition 1, but evaluated at $\alpha = 1$. The expression of $x_i^{SO,U}(\alpha = 1,\ p = 1)$ coincides with $x_i^{SO,NU}(d_A)$, as reported in Sect. 4.1, but evaluated at $\alpha = 1$.

Intuitively, this inefficiency captures the regulatory error arising from ignoring the policy un- certainty, as if R_A incorrectly assumed that she stays in office in the second period, choosing $x_i^{SO,U}(\alpha = 1,\ p = 1)$, instead of selecting $x_i^{SO,U}(\alpha = 1,\ p \in (0,\ 1))$. When $PUI > 0$, a regulator ignoring future uncertainty induces a socially insufficient output (and pollution), while when $PUI < 0$ she induces a socially excessive output.

The expression of PUI is also highly non-linear but, as expected, satisfies $PUI = 0$ when R_A suffers from no uncertainty, i.e., $p = 1$ or $d_A = d_B$; $PUI > 0$ when $d_A > d_B$;, but $PUI < 0$ otherwise. For comparison purposes, Fig. 2a evaluates PUI at the same parameter values as PPI in Fig. 1a, allowing for different probabilities ($p = 1/4$, $p = 1/2$, and $p = 3/4$). Graphically, PUI shifts downward as p increases, indicating that, as R_A is more certain to stay in office, the inefficiency she produces from ignoring uncertainty is attenuated. Figure 2b considers different values of d_A, for a given $d_B = 0.5$, showing that, as R_A and R_B become more asymmetric in their environmental concerns, PUI shifts upwards. Intuitively, R_A induces a socially insufficient output (setting too lax emission fees) from ignoring uncertainty: the expectation of a future "anti-environmentalist" in office is addressed by R_A by setting more stringent

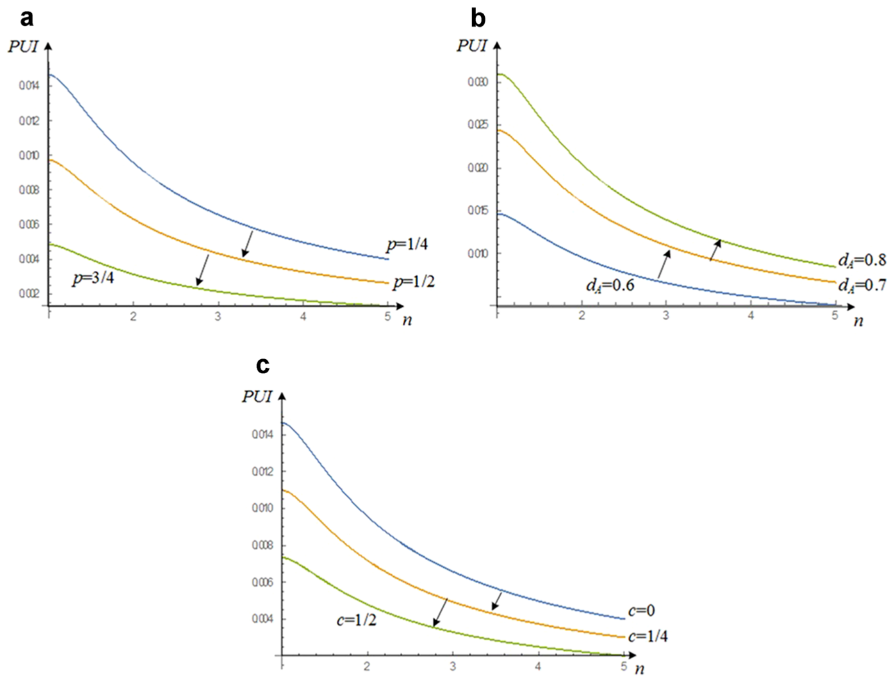

Fig. 2 **a** PUI at different values of p. **b** PUI at differen tvalues of d_A. **c** PUI at different values of c

fees during her administration. Ignoring this expectation generates more inefficiencies when R_A cares more about the environment, relative to R_B, as such concern would require more stringent emission fees while she is in office.

Finally, Fig. 2c illustrates that PUI shifts downwards as firms' production cost increases (higher c). Overall, PUI is relatively large when the industry is concentrated (low n), regulators exhibit distinct environmental concerns (d_A is higher than d_B), and production costs are low (low c). Otherwise, R_A can ignore policy uncertainty and yet generate little or no inefficiencies.

5 Robustness checks

For completeness, Appendix 2 examines how our equilibrium results are separately affected when:

(i) firms' costs are convex in output instead of linear; and (ii) when products are heterogeneous instead of homogenous.

In particular, we consider that every firm i's production costs are cq_i^2, where we first find equilibrium output and fees in the second stage of the game, and then the same outcomes in the first stage. Results are, generally, less tractable than with linear costs and equilibrium output is lower (see Appendix 2 for more technical details). Nonetheless, weights θ, β, and γ are still linearly approximated by the probability of reelection, p. In addition, these weights still satisfy the properties identified in Lemma 4 and Proposition 1–2, namely, that they become one when $p = 1$, they become nil when $p = 0$, and exactly coincide with p when environmental concerns satisfy $d_A = d_B$. Table A.3 in Appendix 2 reports these three weights evaluated at the same vectors of parameter values as table A.1, for comparison purposes, showing that their values are essentially unaffected, and still coincide with probability p up to 3–4 decimal positions.

A similar argument applies when we allow for product differentiation, considering inverse demand function $p(q_i, Q_{-i}) = 1 - q_i - \lambda Q_{-i}$, where $\lambda \in [0, 1]$ represents the degree of product homogeneity, as in Singh and Vives (1984). When $\lambda = 1$ goods are homogeneous, when $1 > \lambda > 0$ they are differentiated, and when $\lambda = 0$ products are unrelated. Equilibrium results in this context are also highly non-linear but coincide with findings in previous sections when products are homogeneous, $\lambda = 1$. Nonetheless, weights θ, β, and γ are still linearly approximated by probability p; as reported in Table A.4. As a consequence, our finding about these weights being essentially identical to probability p is robust to these changes in the model specification.

6 Discussion

Regulatory challenges. Our paper analyzes a common regulatory context, where a share of pollution is time persistent and there is uncertainty about future administrations. The interaction of pollution persistence and policy uncertainty makes the regulator's job challenging, with many equilibrium results being highly non-linear.

Given these challenges, some regulators may choose to simply opt for ignoring pollution persistence or policy uncertainty.

We measure the regulatory inefficiencies that arise from ignoring each of these features (PPI and PUI, respectively). We show that both PPI and PUI are relatively large when the industry is concentrated (low n) and production costs are low (low c). However, PPI is large when the regulator's concern for environmental damage is relatively low, while PUI is small. Therefore, when the regulator assigns little importance to the environment, ignoring policy uncertainty generates less inefficiencies than overlooking pollution persistence. The opposite result arises when the regulator assigns a high value to environmental damages. Hence, it is more critical to consider pollution persistence when d_A is low, but policy uncertainty otherwise.

Regulatory opportunities. While socially optimal regulation in our setting may seem challenging at first glance, our equilibrium results highlight that emission fees follow a relatively simple "rule of thumb": fees are just a weighted average of the emission fee that the regulator would set if she stayed in office with certainty in the next period and that if a new administration took office with certainty. Interestingly, the weight on these emission fees can be linearly approximated with the probability of staying in office, p; being essentially unaffected by the number of firms in the industry, or the regulator's environmental concerns.

In other words, only uncertainty matters when finding the relative weights on the emission fees that regulator A would set in two extremely certain events (A remains in power or B takes office); further facilitating the regulator's task of setting first-period emission fees. Alternatively, one may think that, while some regulators may be tempted to ignore pollution persistence or policy uncertainty to simplify their job, it is actually unnecessary because the rule of thumb described above is tractable enough to apply, yielding socially optimal output (and pollution) levels, giving rise to no inefficiencies.

Further research. Our model can be extended along different dimensions. First, we consider that pollution persistence and damages are unrelated (α and d_k), but a more complex setting could allow for them to be positively correlated. Similarly, we could consider that the probability of reelection is a function of the first-period emission fee, potentially decreasing, if firms lobby against stringent environmental policies. Furthermore, one can test how our equilibrium results, particularly that of weight θ being linearly approximated by $\theta(p) = p$, are affected if firms are cost asymmetric. Another extension could consider firms strategically choosing how much of their first-period production to sell during that period, and how much to store with the intention of selling it in the second period. While their output still generates pollution during the first period, entailing the payment of emission fees, the stored output would only provide a revenue for firms once it is sold in the second period. Finally, we assume that firms cannot adapt their production process by investing in green technology, but one could consider an interim stage in which firms invest in abatement after observing emission fees.

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Author contributions All authors equally contributed to the development of the model, calculations, writing of results, and reviewing of the paper.

Declarations

Competing interests The authors declare no competing interests.

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