Greener or Cheaper Goods: Economies of Scope in R&D Investments

Ana Espinola-Arredondo, Felix Munoz-Garcia, and John Strandholm

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Motivation

- Firms investments in cost-reducing R&D are large and increasing:
  - $625 billion in the US and $310 billion in the EU; OECD (2021).
- Environmental R&D (ER&D) has also increased:
  - Investments in low-carbon technologies reached $755 billion in 2021 (25% increase); Bloomberg.
- Both investments separately received attention, but firms' simultaneous choice of R&D and ER&D has been largely overlooked.
  - Most chemical companies recognize investing in both, Potters and Grassano (2019).

Motivation

- We allow for both investments, helping us:
  - Better understand firms' decisions.
  - Avoid potential regulatory mistakes (undertaxation).

Motivation

- Why not just analyze R&D and ER&D separately?
  - We could...
  - if their marginal benefits and costs were additively separable.
    - A larger investment in one didn't affect firms' incentives to invest in the other.
- But are they separable?

Motivation

- Benefits are likely not separable.
  - If a firm invests in R&D, it lowers its production costs, increasing pollution,
  - This triggers a more stringent emission fee,
  - ultimately increasing firms' incentives to invest in abatement.

Motivation

- Costs may not be separable either:
  - Waterless dying technologies in the textile industry, Heida (2014).
  - Innovations originally developed to reduce emissions can also be used to reduce costs.
  - We refer to them as "economies of scope" in investments:
    - Investing in multiple forms of R&D is less costly than separately investing in each of them.

Motivation

- We also allow for “diseconomies of scope” in investments:
    - Innovations developed to reduce emissions end up increasing costs.
    - Examples abound in firms’ green investments in the EU.

Motivation - Regulatory implications

- Ignoring firms' simultaneous investment decisions gives rise to an *undertaxation* problem.
- First, consider no economies of scope.
  - We show that R&D and ER&D are strategic complements...
    - leading to more investments in both.
    - but especially more investments in cost-reducing R&D.
  - Anticipating more production and pollution, the regulator sets a more stringent fee.
  - Ignoring the multiplicity of investments leads to lower-than-optimal fees.
- Second, allowing for economies of scope.

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- Second, allowing for economies of scope.
  - More investment in abatement.
  - The reg. can set less stringent fees...
  - Ameliorating undertaxation.

Literature-I

- We contribute to three branches:
- Firms' abatement decisions.
  - Poyago-Theotoky (2007), Montero (2011), Lambertini et al. (2017), and Strandholm et al. (2018, 2023), among others.
  - We allow for both investments, and how emission fees are affected.
  - Petrakis and Poyago-Theotoky (2002) study subsidies in a model with both types of investments, but assume an exogenous emission fee (no economies of scope).
- Cost-reducing R&D.

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  - Seminal article by d'Aspremont and Jacquemin (1988), followed by Kamien et al. (1992), and Matsumura et al. (2013).
  - We show that their results can underestimate firms' investment in R&D.

Literature-II

- Investing in abatement because of CSR reasons.
  - Baron (2001, 2008), Farzin (2003), and Calveras and Ganuza (2006), among others.
  - Alternative channel for green investment
    - Without having to rely on green consumers.
    - Even in the absence of environmental regulation.

Outline of the presentation

- Model
- Equilibrium behavior.
  - Unregulated oligopoly (benchmark).
  - Regulated oligopoly
- Comparing investments with and without regulation.

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  - First, invest in abatement; then, in R&D.
  - Is regulation more effective under sim. or seq. investments?

Model

- **Time structure:**
  - Stage 1. Every firm i chooses its investment in cost-reducing R&D, k_i, and ER&D, z_i.
  - Stage 2. The regulator responds with emission fee $t \geq 0$.
  - Stage 3. Firms compete à la Cournot.
- $n \geq 2$ firms facing inverse demand function $p(Q) = 1 - Q$, where $Q \geq 0$ denotes aggregate output.

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- $n \geq 2$ firms facing inverse demand function $p(Q) = 1 - Q$, where $Q \geq 0$ denotes aggregate output.
- Marginal cost, $c \in [0, 1]$, decreases to $c - k_i$.
- Emissions from firm i are $e = q_i - z_i$.

Model

- Total investment cost is

$$C(k_i, z_i) = \frac{1}{2}\gamma k_i^2 + \frac{1}{2}\alpha z_i^2 - \lambda k_i z_i,$$

  where γ and α denote the efficiency in R&D and ER&D, respectively.
- Marginal costs: $C_{k_i} = \gamma k_i - \lambda z_i$ and $C_{z_i} = \alpha z_i - \lambda k_i$.
- Special cases:

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- Special cases:
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  - If $z_i = 0$, total cost collapses to $\frac{1}{2}\gamma k_i^2$ [Traditional R&D models].

Model

- Economies of scope:
  - If $\lambda = 0$, total costs in R&D and ER&D are independent.
  - If $\lambda > 0$ ($\lambda < 0$) economies (diseconomies) of scope arise.
- Assumption I (γ and α are high enough, $\gamma, \alpha \geq \frac{2n^2}{(n+1)^2}$)
- Assumption II ($\lambda < \overline{\lambda} \equiv \frac{\sqrt{\alpha(\gamma(n+1)^2 - 2n)}}{(n+1)}$ is not excessive).

Benchmark - No regulation

Unregulated Oligopoly

Benchmark - No regulation

- **Last stage:**
  - Every firm i takes $(k_1, ..., k_n)$ and $(z_1, ..., z_n)$ as given, and solves
    $$\max_{q_i \geq 0} \ (1 - q_i + Q_{-i})q_i - (c - k_i)q_i$$
    where $Q_{-i} = \sum_{j \neq i} q_j$.
  - Cournot model with n cost-asymmetric firms:
    - The investment profile $(k_1, \ldots, k_n)$ can entail a different net production cost $c - k_i$ for each firm i.

Benchmark - No regulation

- **Lemma 1 (summary)**
  - Equilibrium output is $q_i^{NR} = \frac{1-c+nk_i-K_{-i}}{n+1}$, which increases in k_i, but decreases in c, n, and $K_{-i} = \sum_{j\neq i} k_j$;
- Therefore every firm's output increases in its cost advantage, either because:
  - its own R&D investment k_i is higher, or
  - its rivals' investment K_{-i} is lower.

Benchmark - No regulation

- **First stage:**
  - In the first stage, each firm i anticipates profit $\pi_i^{NR} = (q_i^{NR})^2$ and solves

$$\max_{k_i, z_i \geq 0} \quad \frac{(1 - c + nk_i - K_{-i})^2}{(n+1)^2} - \left(\frac{1}{2}\gamma k_i^2 + \frac{1}{2}\alpha z_i^2 - \lambda k_i z_i \right).$$

    Differentiating with respect to k_i, yields best response function

$$k_i(K_{-i}) = \frac{2n(1-c) + \lambda(n+1)^2 z_i}{\gamma + n[(\gamma - 2)n + 2\gamma]} - \frac{2n}{\gamma + n[(\gamma - 2)n + 2\gamma]} K_{-i}.$$

- Because of Assumption I, $k_i(K_{-i})$ originates in the positive quadrant and decreases in K_{-i} (strategic substitutes).

Benchmark - No regulation

- **First stage:**
- Special cases:
  - When $\lambda = 0$, this best response function simplifies to

$$k_i(K_{-i}) = \frac{2n(1-c)}{\gamma + n[(\gamma-2)n + 2\gamma]} - \frac{2n}{\gamma + n[(\gamma-2)n + 2\gamma]} K_{-i},$$

    meaning that abatement decisions, z_i, do not affect R&D investment.
  - When $\lambda > 0$, however, $k_i(K_{-i})$ shifts upward, without changing its slope:
    - Firms have stronger incentives to invest in R&D, but its strategic substitutability is unaffected.

- What about abatement?

Benchmark - No regulation

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- What about abatement?
  - Differentiating with respect to z_i, yields $z_i = \frac{\lambda}{\alpha} k_i$.

Benchmark - No regulation

- **Lemma 2 (summary)**
- When $\lambda \leq 0$, corner solution where $z_i^{NR} = 0$ and $k_i^{NR} > 0$.
  - As in the models where firms can only invest in abatement.
  - No abatement without regulation.
- When $\lambda > 0$, we find an interior solution:

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  - $z_i^{NR} = \frac{2(1-c)\lambda n}{(n+1)^2(\alpha\gamma-\lambda^2)-2\alpha n}$ and $k_i^{NR} = \frac{2\alpha(1-c)n}{(n+1)^2(\alpha\gamma-\lambda^2)-2\alpha n}$, both positive.

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  - Despite the absence of emission fees, investments lower each other's marginal costs.

Introducing Environmental Regulation

Introducing environmental regulation

- **Third stage:**
  - Observing the investment profile $(k_1, \ldots, k_n, z_1, \ldots, z_n)$ and emission fee t, every firm i solves

$$\max_{q_i \geq 0} (1 - q_i - Q_{-i})q_i - (c - k_i)q_i - t(q_i - z_i)$$

which yields output $q_i^R = \frac{1-c-t+nk_i-K_{-i}}{n+1}$, with associated profit $\pi_i^R = (q_i^R)^2 + tz_i$.

Introducing environmental regulation

- **Second stage:**
  - The regulator chooses t to maximize

$$\max_{t} \quad SW = CS(Q) + PS(Q) + T(Q) - ED(Q)$$

    where $CS(Q) = \frac{1}{2}Q^2$ denotes consumer surplus,
  - $PS(Q)$ represents aggregate profits net of taxes,
  - $T(Q) = t(Q - Z)$ denotes total tax collection, with Z denoting aggregate abatement, and
  - $ED(Q) = d(Q - Z)^2$ measures aggregate environmental damages, where $d > 1$ denotes pollution severity.
- Aggregate output is evaluated at $Q^R = nq_i^R$.
- The optimal emission fee is the following.

Introducing environmental regulation

- **Second stage:**
  - **Lemma 3.** The emission fee t is
    $$t(K, Z) = \frac{(2dn - 1)[K + n(1 - c)] - dn(n + 1)Z}{(2d + 1)n^2}$$
    which is increasing in environmental damage, d, and R&D, K, but decreasing in ER&D, Z, and marginal cost, c.
  - In addition, the fee is positive if and only if $d > d(n) \equiv \frac{(1-c)n+K}{2n[n(1-c-Z)+K-Z]}$, where cutoff $d(n)$ is increasing in c and Z, but decreasing in K.
- Increase in z_i lowers the stringency of $t(K, Z)$; positive externality.

Introducing environmental regulation

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- Increase in z_i lowers the stringency of $t(K,Z)$; positive externality.
- Increase in k_i increases this stringency; negative externality (novel in this literature).
- In addition, $t(K,Z)$ is separable in K and Z, $\frac{\partial^2 t(K,Z)}{\partial Z \partial K} = 0$, i.e., no cross effects.

Introducing environmental regulation

- **First stage:**
  - Anticipating fee $t(K, Z)$, every firm i solves

$$\max_{k_i, z_i > 0} \left(\frac{1 - c - t(K, Z) + nk_i - K_{-i}}{n+1} \right)^2 + t(K, Z) z_i - \left[\frac{1}{2}\gamma k_i^2 + \frac{1}{2}\alpha z_i^2 - \lambda (k_i z_i) \right]$$

- Differentiating with respect to k_i and z_i yields $k_i(z_i, Z_{-i})$ and $z_i(k_i, K_{-i})$.
  - Each form of investment is increasing in the other type, which holds even when $\lambda = 0$
  - k_i and z_i are, then, strategic complements.

Introducing environmental regulation

- k_i **and** z_i **are strategic complements.**
- *Intuition:*
- A larger abatement induces a less stringent emission fee,
  - allowing firms to invest more in R&D.
- Similarly, a larger investment in R&D triggers a more stringent emission fee,

Introducing environmental regulation

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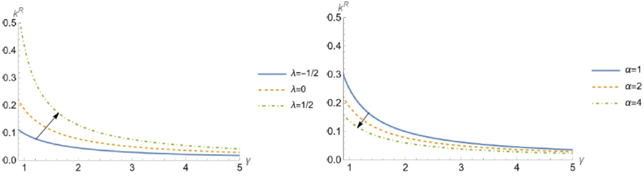
- This complementarity provides firms with more incentives to invest in both forms of R&D
    - than in models that consider a single type of investment, as we next show.

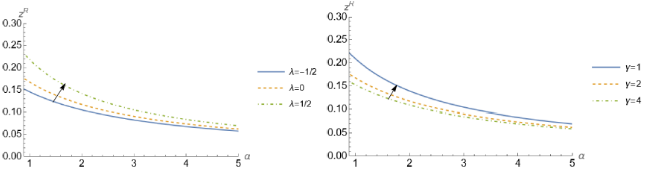
Introducing environmental regulation

- Equilibrium k^R and z^R.



(a) Equilibrium R&D k^R at different levels of λ. (b) Equilibrium R&D k^R at different levels of α.

Figure 1: Comparative statics for equilibrium R&D k^R.



(a) Equilibrium ER&D z^R at different levels of λ. (b) Equilibrium ER&D z^R at different levels of γ.

Figure 2: Comparative statics for equilibrium ER&D z^R.

Introducing environmental regulation

- *The Equilibrium emission fee is*

$$t^R = \frac{1}{C}(1-c)\left[\begin{array}{c} 2d^2n^3(2\alpha\gamma + \gamma - 2\lambda(\lambda+1)) \\ -dn(\gamma(1-2\alpha(n-1)n+n) \\ +2\lambda((\lambda+1)(n-1)n-1)) \\ -\lambda - n^2(\alpha\gamma - \lambda^2)] \end{array}\right]$$

When $\gamma \longrightarrow \infty$*, the equilibrium emission fee simplifies to* $\overline{t}^R = \frac{(1-c)[d(2dn^2-n-1)+\alpha(2d+1)n(2dn-1)]}{n[\alpha(2d+1)^2n+d(2d+1)n(n+2)+d]}$*, and when* $\alpha \longrightarrow \infty$*, the fee becomes* $t^R = \frac{(1-c)\gamma(2d+1)n^2(2dn-1)}{(2d+1)n[n(\gamma n(2d+1)-2)+2]-2}$.

Introducing environmental regulation

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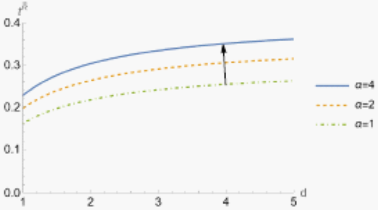
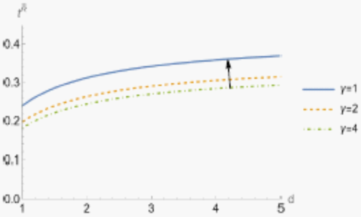
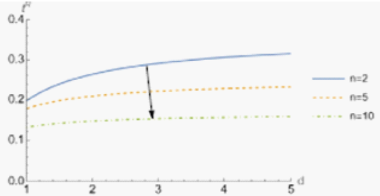


(a) Equilibrium fee t^R at different levels of α.



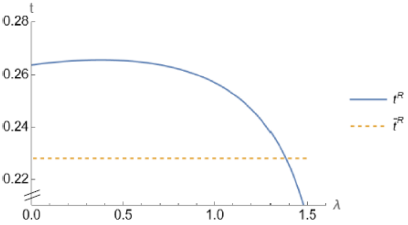
(b) Equilibrium fee t^R at different levels of γ.



(c) Equilibrium fee t^R at different levels of n.

Introducing environmental regulation

- **Effect of regulation:**



where $\bar{t}^R = \lim_{\gamma \to +\infty} t^R$, and coincides with that in PT (2007).

-
    - Undertaxation for most values of λ.
    - Ameliorated when the market is more competitive, pollution is not severe, and investments are more expensive.

Introducing environmental regulation

- **Effect of regulation:**
  - Increases abatement, $z^R > z^{NR}$.
  - Decreases R&D, $k^R < k^{NR}$
- This happens regardless of eco. of scope, λ.
- It is emphasized when investments are more costly (higher γ or α).

Comparison with models assuming separable investments

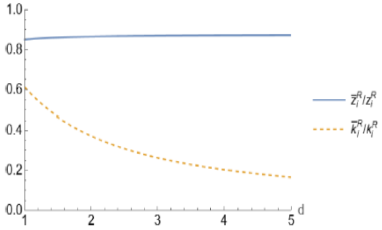
Introducing environmental regulation

- **Investment ratios:**
  - Let $\overline{z}^R = \lim_{\gamma \to +\infty} z^R$, as in Poyago-Theotoky (2007); and $\overline{k}^R = \lim_{\alpha \to +\infty} k^R$, as in standard R&D models.
  - Then, define investment ratios

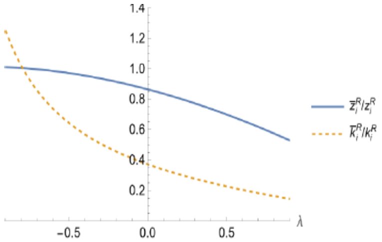
$$\frac{\overline{z}^R}{z^R} \quad \text{and} \quad \frac{\overline{k}^R}{k^R}.$$

- *Interpretation:*
  - If close to 1, we are "not losing much" by assuming separable investments
    - We could consider $\overline{z}^R$ and $\overline{k}^R$ to design policy, instead of z^R and k^R.
  - If lower than 1, we are underestimating investments.
  - If higher than 1, we are overestimating investments.

Introducing environmental regulation



(a) Ratios $\overline{z}_i^R/z_i^R$ and $\overline{k}_i^R/k_i^R$ as a function of d.



(b) Ratios $\overline{z}_i^R/z_i^R$ and $\overline{k}_i^R/k_i^R$ as a function of λ.

Extension: Sequential investment decisions

Sequential investments - No regulation

- **Third stage.** Output decisions coincide with Lemma 1.
- **Second stage.** R&D decisions, taking abatement $(z_1, ..., z_n)$ as given:
    - $k_i^{NR,Seq}(z_i) = \frac{2(1-c)n+(n+1)^2\lambda z_i}{\gamma(n+1)^2-2n}$, which is positive and increasing in z_i and λ.
- Therefore, when either abatement is nil, $z_i = 0$, or economies of scope are absent, $\lambda = 0$...
    - R&D investment simplifies to $k_i^{NR,Seq}(0) = \frac{2(1-c)n}{\gamma(n+1)^2-2n}$, coinciding with Lemma 2.
- However, when both abatement and economies of scope are positive, $z_i > 0$ and $\lambda > 0$,

Sequential investments - No regulation

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- However, when both abatement and economies of scope are positive, $z_i > 0$ and $\lambda > 0$,
  - Every firm benefits from lower marginal costs in its traditional R&D,
  - responding by increasing this investment.

Sequential investments - No regulation

- **First stage.** Anticipating $k_i^{NR,Seq}(z_i)$, every firm solves

$$\max_{z_i \geq 0} \frac{\left(1-c+k_i^{NR,Seq}(z_i)\right)^2}{(n+1)^2} - \left(\frac{1}{2}\gamma\left(k_i^{NR,Seq}(z_i)\right)^2 + \frac{1}{2}\alpha z_i^2 - \lambda\left(k_i^{NR,Seq}(z_i)\right)z_i\right).$$

  yielding the first-order condition

$$\underbrace{\frac{\partial k_i^{NR,Seq}(z_i)}{\partial z_i}}_{(+,\text{ Strategic effect})} \underbrace{\left[\frac{2\left(1-c+k_i^{NR,Seq}(z_i)\right)}{(n+1)^2} - \left(\gamma k_i^{NR,Seq}(z_i) - \lambda z_i\right)\right]}_{(-)}$$

$$+\alpha z_i - \lambda k_i^{NR,Seq}(z_i) = 0,$$

- Relative to sim., seq. decisions give rise to a new strategic effect.

Sequential investments - No regulation

- **First stage.**
- *Simultaneous setting*:
  - An increase in abatement lowers R&D costs if $\lambda > 0$;
  - helping firms increase their R&D investments which, in turn, reduces abatement costs;
  - Positive "*feedback*" effect.
- *Sequential investments*: break this feedback.

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  - An increase in abatement still lowers R&D costs, inducing more R&D investments, but...
  - an increase in R&D does not affect abatement costs because abatement decisions are now taken as given in the second stage.
  - Hence, $z_i^{NR,Seq} < z_i^{NR}$.

Sequential investments - No regulation

- **First stage.**
- **Proposition 2.** In the sequential-investment game without regulation, equilibrium investments satisfy:
  - If $\lambda = 0$, equilibrium abatement is $z_i^{NR,Seq} = 0$, yielding an equilibrium R&D of $k_i^{NR,Seq} = \frac{2(1-c)n}{\gamma(n+1)^2-2n}$.
  - If $\lambda > 0$, equilibrium abatement is $z_i^{NR,Seq} = \frac{2\lambda(1-c)\left[n^2(\gamma-2)+\gamma(2n+1)\right]}{D}$, yielding an equilibrium R&D of $k_i^{NR,Seq} = \frac{2(1-c)[nD+\lambda^2(n+1)^2(n^2(\gamma-2)+\gamma(2n+1))]}{D[(n+1)^2\gamma-2n]}$.
- Role of sequential investments?

Sequential investments - No regulation

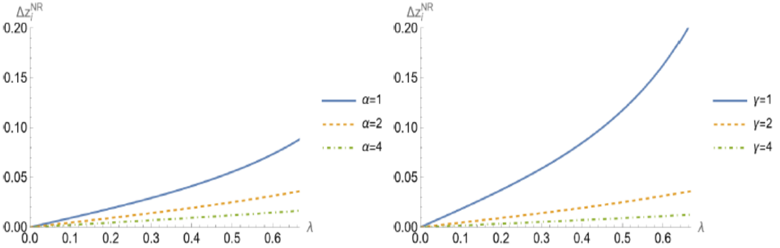
- **Measuring the effect of sequential investments.**
- Abatement differential

$$\Delta z_i^{NR} \equiv z_i^{NR} - z_i^{NR,Seq},$$

  - where z_i^{NR} from Lemma 2 and $z_i^{NR,Seq}$ in Proposition 2.
- When $\Delta z_i^{NR} > 0$, firms invest more in abatement when their R&D decisions are sim than seq;
  - the opposite applies when $\Delta z_i^{NR} < 0$.

Sequential investments - No regulation

- When $\lambda = 0$, abatement coincides, $\Delta z_i^{NR} = 0$.
- When $\lambda > 0$, abatement is larger under sim, $\Delta z_i^{NR} > 0$ (feedback effect).



(a) Differential Δz_i^{NR} at different values of α. (b) Differential Δz_i^{NR} at different values of γ.

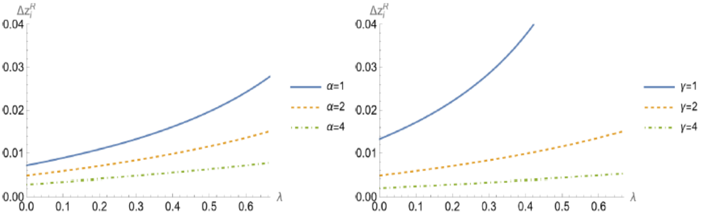
Figure 8: Differential Δz_i^{NR} over a range of λ.

Sequential investments - Regulation

- Similar approach with regulation, but:
- The strategic effect can now be positive or negative.
- *Interpretation*:
  - As under no reg., no feedback effect: less incentives to invest in z_i relative to sim.
  - Reg. gives rise to a second effect: investing in z_i to lower emissions, yielding less stringent fee.
  - Under simultaneous investments, firms face strategic uncertainty about the $(k_1, ..., k_n)$ profile.
  - Under sequential investments, they can anticipate this profile, investing more in z_i to lower production costs.
- If feedback effect dominates, firms would invest less under seq. than sim.

Sequential investments - Regulation

- Abatement differential $\Delta z_i^R \equiv z_i^R - z_i^{R,Seq}$.
    - Feedback effect dominates, $z_i^R > z_i^{R,Seq}$.
    - Even if $\lambda = 0$, unlike without regulation.
    - Increasing in λ, but decreasing in α and γ.



(a) Differential Δz_i^R at different values of α.

(b) Differential Δz_i^R at different values of γ.

Figure 9: Differential Δz_i^R over a range of λ.

Sequential investments - Regulation

- **Simultaneous vs. Sequential Fees**
  - Because $z_i^R > z_i^{R,Seq}$, fees respond in opposite direction, $t^{R,Seq} < t^R$.
  - Then, seq. investments emphasize undertaxation problems, $t^{R,Seq} - \bar{t}^R > t^R - \bar{t}^R$.

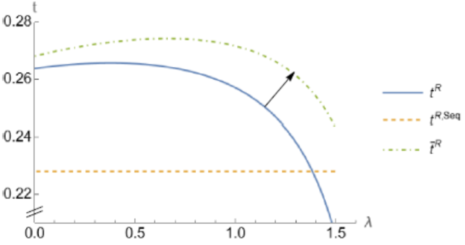


Figure 10: Equilibrium fees $t^{R,Seq}$, t^R, and $\bar{t}^R$ over a range of λ.

Sequential investments - Regulation

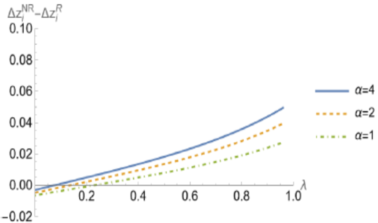
- **Is regulation more effective with sim. or seq. investments?**
- Consider $\Delta z_i^{NR} - \Delta z_i^{R}$, or after rearranging,

$$\left(z_i^{R,Seq} - z_i^{NR,Seq}\right) - \left(z_i^{R} - z_i^{NR}\right).$$

- If positive, regulation would provide firms with stronger incentives to increase z_i under seq. than sim. investments.
- If negative, the opposite ranking applies.

Sequential investments - Regulation

- **Is regulation more effective with sim. or seq. investments?**
- Positive differential, meaning regulation is more effective with seq. investments.
- Strategic uncertainty attenuates the feedback effect.



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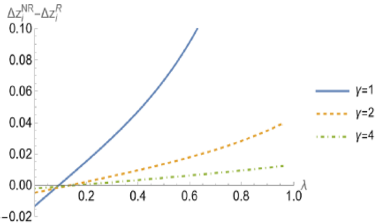

(b) Differential $\Delta z_i^{NR} - \Delta z_i^{R}$ at different values of γ.

Figure 11: Differentials $\Delta z_i^{NR} - \Delta z_i^{R}$ over a range of λ.

Discussion

Discussion

- **Three externalities**

1. In the absence of reg. and economies of scope.
   - An increase in k_i makes firm i more competitive.
   - #1: Negative externality on its rivals.

Still without reg., but allow introduce economies of scope.

2. An increase in abatement z_i helps firm i to lower its R&D costs.

- The firm can, then, invest more in k_i.
- #2: Emphasizing the above negative externality.

Discussion

- **Three externalities**

3. Now introduce regulation.
   - An increase in z_i lowers the stringency of t.
   - #3: Positive externality on its rivals.

- The literature only considers #3,

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Discussion

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- The literature only considers #3,
    - but the presence of #1 and #2 can lead regulators to...
    - underestimate k_i,
    - anticipate less pollution, and
    - undertax.

Discussion

- **Undertaxation.**
- It arises even in the absence of economies of scope, $\lambda = 0$.
  - In that setting, #2 does not exist, but #1 still gives rise to higher k_i, output, and pollution than in traditional models.
  - The regulator, then, responds with a fee that is too lax.
- When economies of scope are present, #2 arises.
  - Leading firms to invest more in both, but specially in abatement.
  - This attenuates the magnitude of undertaxation.

Discussion

- *Practitioners:* When is undertaxation the largest?
    - When pollution is severe, cost of R&D or ER&D is low, or when industry is less competitive.
    - Otherwise, ignoring the multiplicity of investments generates small inefficiencies.

Discussion

- **Sequential investments.**
- Under no reg., a positive feedback effect arises under sim. investments.
  - It helps firms lower their abatement costs.
- In a sequential setting, this feedback effect is broken.
  - R&D investments do not lower abatement costs.
  - Investing more in abatement under sim. than seq. ("abatement differential").

Discussion

- Introducing regulation:
  - Attenuates the abatement differential.
  - But this differential is still positive.
  - This implies that emission fee should be more stringent than under simultaneous investments.
  - Emphasizing the undertaxation problem.

Further research

- Firms coordinating their investment decisions.
  - Their k_i's, their z_i's, or both.
  - Helping at internalizing the above three externalities.
- Asymmetric economies of scope across firms.
  - λ_i and λ_j, but it would make results more untractable.
- Allowing for investments to generate spillover effects across firms:
  - R&D investments, $c - k_i - \beta K_{-i}$, where $\beta \geq 0$.
  - ER&D investments, $e_i = q_i - z_i - \beta_E Z_{-i}$, where $\beta_E \geq 0$.

Thank you!