# Licensing resource exploitation with endogenous and privately known reserves

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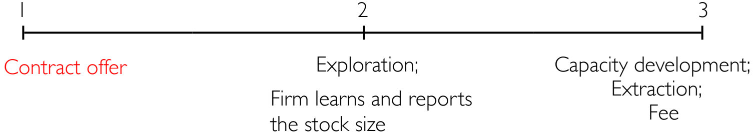
# Motivation & problem

- Economic growth and climate change mitigation require large quantities of raw materials from nonrenewable sources.
- Current reserves of critical metals are limited, spurring exploration.
- Exploration effort is often unobservable to the owner.
- Results of exploration (discovered deposits and their sizes) remain private information to the firm.

**Problem**

How should the owner design resource pricing mechanisms when the firm takes unobservable exploration actions and has incentives to lie about discovered stock?


# Model

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# Model

1 — Contract offer

2 — Exploration;

Firm learns and reports the stock size

3 — Capacity development;
Extraction;
Fee

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2. Firm chooses exploration effort, learns, and reports stock size (the owner cannot observe the exploration effort or the discovered resource stock).

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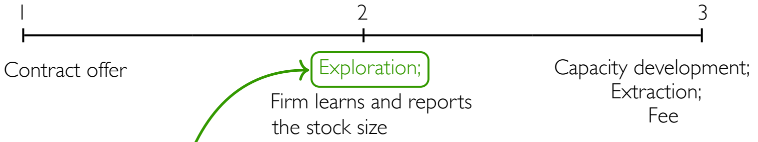
# Information asymmetries

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hidden action

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1 — 2 — 3

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1: Contract offer

Contract $(q(x), T(x))$

2: Exploration with effort $y$;

Firm learns and reports the stock size $x$

3: Capacity development $q$;
Extraction;
Fee $T$

### Adverse selection problem

How should the owner design resource pricing mechanisms when the firm takes unobservable exploration actions and has incentives to lie about discovered stock?

*Firm/agent:* the expected exploration profit with the fee $T$

$$D(y)\ \mathbb{E}[\ \pi(q(x);x)\ - T(x)\ ] - \ z\ y$$

1 | 2 | 3
--- | --- | ---
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*Firm/agent:* the expected exploration profit with the fee $T$

$$\boxed{D(y)}\,\mathbb{E}[\,\pi(q(x);x)\; - T(x)\,] - \; z\,y$$

the discovery probability

$$\boxed{D'(y) > 0, \quad D''(y) < 0, \quad D(0) = 0 \quad \text{and} \quad D(y) \in (0,1) \text{ for all } y > 0}$$

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unit cost of exploration

1 | 2 | 3

Contract offer

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How should the owner design resource pricing mechanisms when the firm takes unobservable exploration actions and has incentives to lie about discovered stock?

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$$D(y)\,\mathbb{E}[\,\boxed{\pi(q(x);x)} - T(x)\,] - z\,y$$

The resource profit from capacity development and extraction has a unique maximum with respect to $q \geq 0$

$$\boxed{\pi(0;x) = 0, \quad \pi_x > 0, \quad \pi_{qx} > 0, \quad \pi_{qq} < 0, \quad \pi_q(0;x) = 0 \text{ for some } x}$$

| 1 | 2 | 3 |
|---|---|---|
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## Adverse selection problem

How should the owner design resource pricing mechanisms when the firm takes unobservable exploration actions and has incentives to lie about discovered stock?

*Firm/agent:* the expected exploration profit with the fee $T$

$$D(y)\ \mathbb{E}[\ \pi(q(x);x)\ - T(x)\ ] -\ z\,y$$

*Owner/principal* maximizes expected revenues:

$$\max_{\{q(x),T(x)\}} D(y)\ \mathbb{E}[\ T(x)\ ]$$

# Feasibility constraints

Limited liability type constraint (the firm can always claim bankruptcy after the exploration and discovery and obtain zero resource profit by doing so):

$$\pi(q(x); x) - T(x) \geq 0 \quad \text{for all} \quad x \in [0, \bar{x}]. \tag{LL}$$

The contract must provide incentives for reporting the true discovery; the incentive compatibility constraint:

$$\pi(q(x); x) - T(x) \geq \pi(q(\hat{x}); x) - T(\hat{x}) \quad \text{for all} \quad (x, \hat{x}) \in [0, \bar{x}]^2. \tag{IC}$$

The (unobservable) exploration effort chosen by the firm maximizes the expected exploration profit, that is,

$$y = \arg\max_{\hat{y}} \{D(\hat{y})\, \mathbb{E}[\, \pi(q(x); x) - T(x)\, ] - z\, \hat{y}\}. \tag{EC}$$

# The baseline: no license fee

Without the license fee

$$D(y)\ \mathbb{E}[\ \pi(q(x);x)\ \cancel{-T(x)}\ ] - z\,y,$$

there is an optimal extraction capacity $q^{\mathrm{wot}}(x)$

$$q^{\mathrm{wot}}(x) = \begin{cases} 0, & x \leq x^{\mathrm{wot}}, \\ \text{the solution to } \pi_q(q;x) = 0, & x > x^{\mathrm{wot}}, \end{cases}$$

A reserve cut-off $x^{\mathrm{wot}}$ is defined as the largest discovery for which optimal capacity is zero. Capacity is zero for $x \leq x^{\mathrm{wot}}$ and positive for $x > x^{\mathrm{wot}}$.

Optimal effort equalizes expected marginal exploration revenue with unit exploration cost, provided expected profit is large enough, i.e., $y^{\mathrm{wot}}$ is the solution to

$$D'(y)\ \mathbb{E}\pi(q^{\mathrm{wot}}(x), x) = z,$$

when $D'(0)\mathbb{E}\pi(q^{\mathrm{wot}}(x), x) > z$.

# With the fee & asymmetries

*Owner/principal* maximizes expected revenues:

$$\max_{\{q(x),T(x)\}} D(y)\, \mathbb{E}[\, T(x) \,]$$

*Firm/agent's* the expected profit

$$D(y)\, \mathbb{E}[\, \pi(q(x);x) - T(x) \,] - z\, y$$

**Proposition**

The optimal extraction capacity $q^{\mathrm{t}}$ is smaller, i.e., $q^{\mathrm{t}} < q^{\mathrm{wot}}$.

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The reserve cut-off $x^{\mathrm{t}}$ is larger, i.e., $x^{\mathrm{t}} > x^{\mathrm{wot}}$.

The resource profit $\pi(q, x)$ satisfies
$\pi(0; x) = 0, \quad \pi_x > 0, \quad \pi_{qx} > 0, \;\; \pi_{qq} < 0, \;\; \pi_q(0; x) = 0$ for some $x$ and $\pi_{qqx} \geq 0, \;\; \pi_{qxx} \leq 0$ ( the last two are 'standard assumptions' and made to avoid bunching of the capacity $q$, especially, the solution to the so-called relaxed problem is monotone and thus feasible).

*On endogenous resources*: the known continuous probability density $g$ of the unknown stock size $x$ satisfies the inequality (denote the cumulative distribution with $G$)

$$\frac{\partial}{\partial x} \frac{1 - G(x)}{g(x)} \leq 0 \qquad \text{for all } x \in [x^{\text{wot}}, \bar{x}]$$

i.e., the increasing hazard rate must hold for big enough stocks.

*Owner/principal* maximizes expected revenues:

$$\max_{\{q(x),T(x)\}} D(y)\,\mathbb{E}[\,T(x)\,]$$

*Firm/agent* maximizes the expected profit

$$D(y)\,\mathbb{E}[\,\pi(q(x);x) - T(x)\,] - z\,y$$

**Proposition**

The optimal extraction capacity $q^{\mathrm{t}}$ is smaller, i.e., $q^{\mathrm{t}} < q^{\mathrm{wot}}$.

$$q^{\mathrm{t}} = \begin{cases} 0, & x \leq x^{\mathrm{t}}, \\ \text{the solution to } \pi_q(q;x) - \dfrac{1-G(x)}{g(x)}\pi_{qx}(q;x) = 0, & x > x^{\mathrm{t}}, \end{cases}$$

when $x^{\mathrm{t}} < \bar{x}$.

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**Proposition**

The optimal exploration effort $y^{\mathrm{t}}$ is smaller, i.e., $y^{\mathrm{t}} < y^{\mathrm{wot}}$.

$$y^{\mathrm{t}} = \begin{cases} 0, & D'(0)\mathbb{E}U \leq z, \\ \text{the solution to } D'(y)\mathbb{E}U = z, & D'(0)\mathbb{E}U > z. \end{cases}$$

The resource profit or the 'rent' left to the firm is defined as $U(x) := \pi(q(x); x) - T(x)$.

*Owner/principal* maximizes expected revenues:

$$\max_{\{q(x),T(x)\}} D(y)\ \mathbb{E}[\ T(x)\ ]$$

*Firm/agent's* the expected profit

$$D(y)\ \mathbb{E}[\ \pi(q(x);x) - T(x)\ ] - z\,y$$

**Proposition**

The optimal license fee is strictly increasing in the resource discovery

$$T(x) = \begin{cases} 0, & x \le x^{t}, \\ \pi(q^{t}(x);x) - \displaystyle\int_{x^{t}}^{x} \pi_x(q^{t}(s);s)\,\mathrm{d}s, & x > x^{t}, \end{cases}$$

and the expected profit (or rent $U(x) = \pi(q^{t}(x);x) - T(x)$) left for the firm is

$$\mathbb{E}U = \int_{x^{t}}^{\bar{x}} \pi_x(q^{t}(s);s)(1 - G(s))\,\mathrm{d}s.$$

*Owner/principal* maximizes expected revenues:

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*Firm/agent's* the expected profit

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- Tax schemes are non-neutral: no matter how royalties and rent taxes are designed, they will not deliver the same allocation as without them.
- The form of the tax scheme, can be as complicated as wanted and it can be made contingent on any observable (prices, costs, capacity, etc.) and unobservable characteristics (stock size and exploration effort). Any such design attempt fails, because the scheme cannot induce the correct allocation without breaking at least one of the feasibility constraints.

# Conclusion

- Reserve cut-off is larger With the license fee, the optimal mechanism requires discovered resources to be greater than without a mechanism to yield a new reserve for extraction (i.e., $x^{t} > x^{wot}$).
  - ➔ This means fewer discoveries qualify as reserves
- Optimal exploration effort is smaller With the license fee, the optimal mechanism induces less exploration (i.e., $y^{t} < y^{wot}$).
  - ➔ This means fewer discoveries are made
- Extraction capacity is smaller When a discovery does yield a reserve, the optimal mechanism induces the firm to build a smaller extraction capacity than without the license fee (i.e., $q^{t} < q^{wot}$).

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