Non-Renewable Resources, Extraction Technology, and Endogenous Growth

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Motivation

- "Future will not be limited by sheer availability of important materials" (Nordhaus, 1974). Data
- Tiny fraction of resources in the Earth's crust are in *reserves* (= economically recoverable at current technology).
- Innovation in extraction technology turns mineral deposits into reserves. Data
- Traditional growth models with non-renewable resources only consider technological change in resource efficiency.
- Typical predictions from these models not in line with empirical evidence. (Krautkraemer, 1998; Livernois, 2009)

Contribution

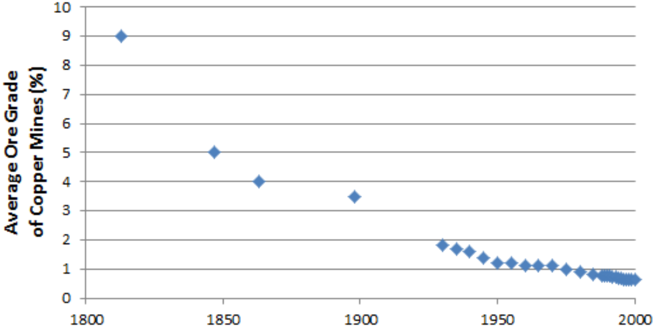
- Theory of technological change in resource extraction in an endogenous growth model.
- Analytically solvable model that breaks down complex investment problem into a static one.
- First to study the interaction between geology and technological change, and its effects on price, resource intensity, and aggregate output.
- Accommodate historical trends: constant growth rate of extraction, non-increasing real resource prices.

Related Literature

Key Take-aways

- Offsetting interaction between geology and technology leads to constant marginal cost of resource production.
- The extractive sector only features constant returns to scale.
  - Firms can only use the flow of new technology.
  - Technology is grade specific, deposits are depleted.
- A higher crustal abundance leads to a lower resource price, a higher resource intensity, and higher aggregate output growth.

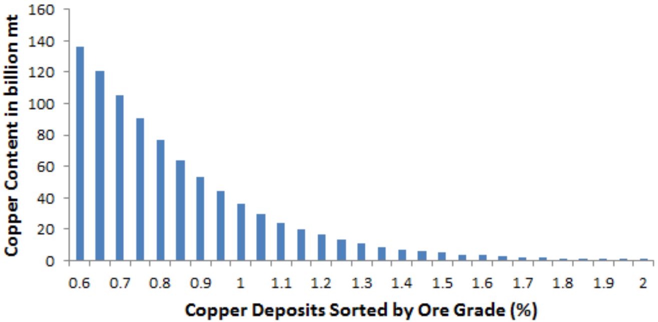
Technological change overcomes depletion



Average Ores Grades of Copper Mines Worldwide, 1800-2000.
Source: Gerst (2008)

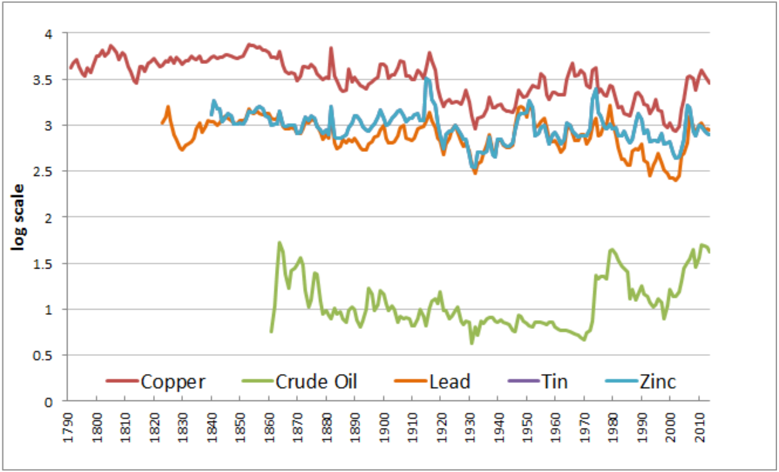
Example of U.S. Copper Mining
Example of Crude Oil

Geological Distribution of Copper



Grade-quantity distribution of copper. Source: Gerst (2008)

Non-renewable resource prices 1790-2014



Real prices of non-renewable resources in constant 1982-84 U.S. Dollar (logarithmic scale). Non-Renewable Resource Production & GDP

Model Setup

Following Acemoglu (2002), we consider an economy with a representative consumer that has constant relative risk aversion preferences:

$$\int_0^\infty \frac{C_t^{1-\theta} - 1}{1-\theta} e^{-\rho t} dt \ . \tag{1}$$

The variable C_t denotes the consumption of aggregate output at time t, ρ is the discount rate, and θ is the coefficient of relative risk aversion.

Model Setup

The budget constraint of the representative consumer is

$$C + I + M \leq Y \equiv \left[\gamma Z^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma) R^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \qquad (2)$$

where I is aggregate investment, M denotes aggregate R&D investment.

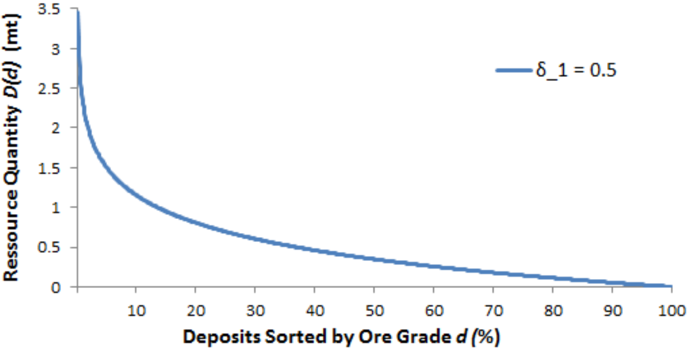
Aggregate output Y is produced from an intermediate good Z and a non-renewable resource R.

Parameter $\gamma \in (0, 1)$ indicates the importance of Z and R in aggregate production.

The elasticity of substitution is denoted by $\epsilon \in (0, \infty)$.

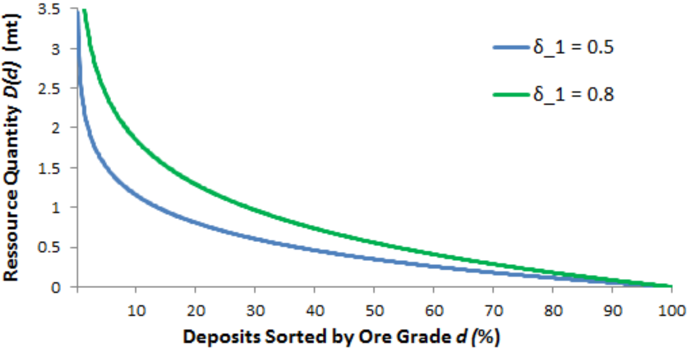
▸ Intermediate Goods Sector

Geology



Geological function: $D(d) = -\delta_1 \ln(d), \quad \delta_1 \in \mathbb{R}_+$

Geology



Geological function: $D(d) = -\delta_1 \ln(d), \quad \delta_1 \in \mathbb{R}_+$

Extractive firms

- Firms i extract the resource, R, from deposits of declining grades, d.
- Full knowledge about deposits and the geological distribution.
- Extraction cost infinitely high without grade specific technology.
- Firms invest M_R in terms of total output to develop grade specific extraction technology.
  - Makes deposits of lower grades extractable.
  - Firms claim ownership of the deposit and make it a reserve.
  - Extraction of resource at a constant operational cost.
- Extraction technology evolves according to: $\dot{N}_{Rt} = \eta_R M_{Rt}$.

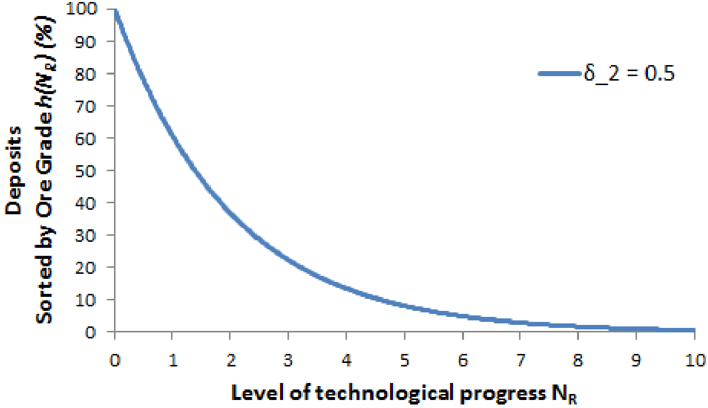
Extractive firms

- Technology is grade specific, benefits diffuse within one period.
- Extraction firms maximize current profits when making their technology investment decision.

$$\max_R p_R R - \phi_{N_R} R - M_R \ , \tag{3}$$

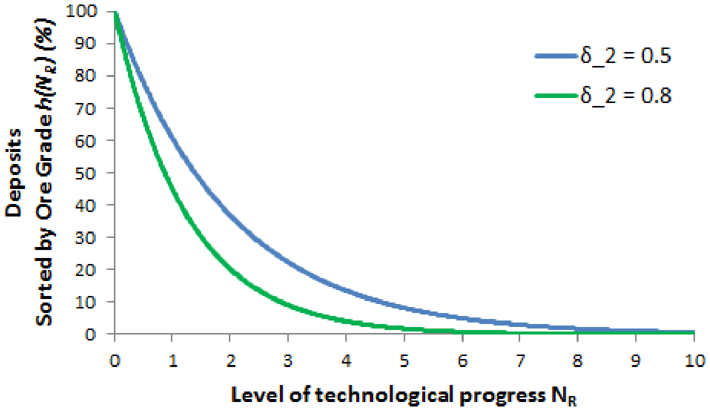
- Firms invest as soon as R&D cost can be paid for by revenues.
- Firms take resource price, p_R, as given.
- Innovation driven by non-replicable factor of production (see Desmet & Rossi-Hansberg, 2012)

Extraction technology and extractable deposits



Extraction technology function: $h(N_R) = e^{-\delta_2 N_{Rt}}, \ \delta_2 \in \mathbb{R}_+$

Extraction technology and extractable deposits



Extraction technology function: $h(N_R) = e^{-\delta_2 N_{Rt}}, \ \delta_2 \in \mathbb{R}_+$

Extractive firms

- Each firm's economically extractable reserves evolves:

$$\dot{S}_t = X_t - R_t \ , \qquad S_t \geq 0, X_t \geq 0, R_t \geq 0 \ , \tag{4}$$

- The production function of each firm is equal to:

$$R_t = X_t - \dot{S}_t \ . \tag{5}$$

Offsetting Effects of Geology and Technology

Proposition 1

The marginal return on extraction technology, $\dot{N}$, in terms of new reserves X is constant.

$$X_t = \frac{\partial D(h(N_{R_t}))}{\partial t} = \delta_1 \delta_2 \dot{N}_{Rt} = \delta_1 \delta_2 \eta_R M_R \ . \qquad (6)$$

- Exponentially increasing quantities in the geological function...
- ...are offset by decreasing returns in terms of grades in the technology function.

Extraction firms face constant R&D cost in converting one resource unit from a deposit into a new reserve.

Proposition 2

Resource Price

Proposition 3

The resource price is constant. Its level depends negatively on:

(i) the crustal concentration of the non-renewable resource,

(ii) the effect of R&D investment in terms of lower ore grades.

$$p_{Rt} = \frac{1}{\eta_R \delta_1 \delta_2} .$$

- The resource price equals marginal production costs due to perfect competition.

Resource Intensity

Proposition 4

The resource intensity (ratio of resource consumption to aggregate output) is constant.

It is positively affected by:

(i) the crustal concentration of the non-renewable resource,

(ii) the effect of R&D investment in terms of lower ore grades.

$$\frac{R}{Y} = \left[(1-\gamma)\eta_R \delta_1 \delta_2\right]^{\varepsilon} \ .$$

- The elasticity of substitution ϵ has a strong negative impact on the resource intensity.

Growth Rate of the Economy

Proposition 5

The growth rate on the balanced growth path is constant and given by:

$$g = \theta^{-1}\left(\beta\eta_Z L\left[\gamma^{-\epsilon} - \left(\frac{1-\gamma}{\gamma}\right)^{\epsilon}\left(\frac{1}{\eta_R\delta_1\delta_2}\right)^{1-\epsilon}\right]^{\frac{1}{1-\varepsilon}\frac{1}{\beta}} - \rho\right).$$

It is positively affected by:

(i) the crustal concentration of the non-renewable resource,

(ii) the effect of R&D investment in terms of lower ore grades.

Technological change

Proposition 6

Technology in the intermediate goods sector grows at rate g.

Technology in the extractive sector grows proportional to output:

$$\dot{N}_R = (\delta_1\delta_2)^{\varepsilon-1}(1-\gamma)^{\varepsilon}\eta_R Y \ .$$

- Extractive firms can only use the *flow* of new technology,...
- ...while intermediate good firms can use the entire *stock* of technology.

Conclusion

- Introducing innovation in extraction technology helps accommodating long-run trends in resource markets.
- Offsetting interaction between geology and technology leads to constant marginal cost of resource production.
- A higher crustal abundance leads to a lower resource price, a higher resource intensity, and higher aggregate output growth.

Non-renewable resources practically infinite.

	Reserves/ Annual production (Years)	**Crustal mass/ Annual production** (Years)
Aluminium	133	9,400,000,000
Copper	39	93,000,000
Gold	20	27,800,000
Coal	144	} 1,400,000 (Oil, Unconventional oil)
Oil	40	
Unconventional oil	34	
Natural gas	2,100	

Availability of non-renewable resources in years of production at the current production rate.

Sources: U.S. Geological Survey (2011), Perman et al. (2003), Nordhaus (1974), International Energy Agency (2010), Federal Institute for Geosciences and Natural Resources (2010), Littke and Welte (1992). Note: Data for the crustal mass of conventional oil, gas and coal includes all organic carbon in the earth's crust.

Definitions Return

Definitions

Reserves: "That part ... which could be economically extracted or produced at the time of determination."

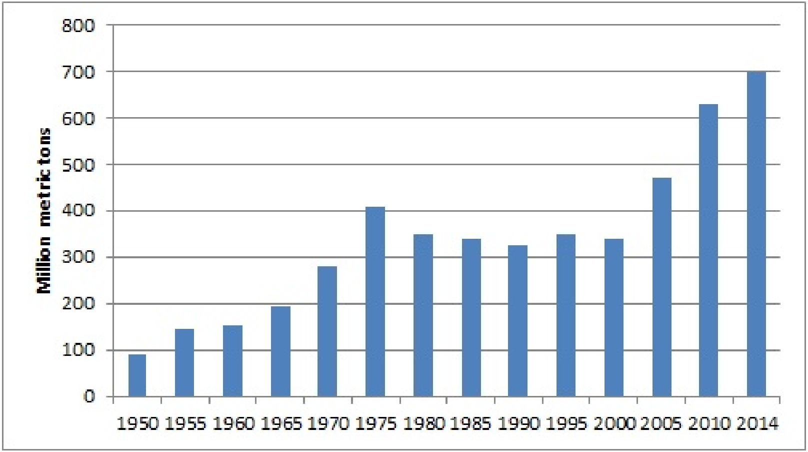
Resources: "A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible ."

Other occurrences: "Materials that are too low grade or for other reasons are not considered potentially economic."

"... the boundary between subeconomic and other occurrences ... is obviously uncertain..."

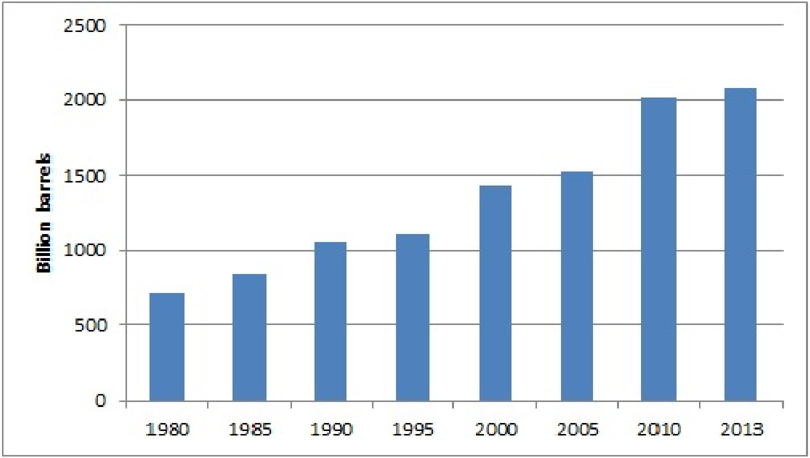
Source: US-Geological Survey, 2011, p. 193-4. Return

Evolution of Copper Reserves



The Evolution of World Copper Reserves, 1950 - 2014 (Sources: Tilton & Lagos, 2007; USGS, 2011, 2015).

Historical Evolution of Crude Oil Reserves



Historical evolution of world reserves of crude oil (Source: British Petroleum, 2015).

Return

Related Literature

- Seminal Hotelling (1931) model: fixed stock of non-renewable resource, increasing price, decreasing production.
- Empirical evidence that depletion has been offset by improvements in technology (Barnett and Morse (1963); Perry (1999))
- Availability of non-renewable resources is a function of technological progress (Nordhaus, 1974).
- Hotelling model with a backstop technology (Heal, 1976).
- Hotelling model with stepwise investment in techniques that extend the resource stock (Fourgeaud et al, 1982).

Related Literature

Exogenous technological progress in the extraction technology:

- Slade (1982): U-shaped relative price curve, depletion effect, decreasing extraction in the long run
- Cynthia-Lin and Wagner (2007): Constant relative price, ever growing extraction, exogenous technology development

Endogenous growth model with technological progress in the extraction technology (Tahvonen and Salo, 2001)

- Transition from non-renewable to renewable energy resource.
- Learning-by-doing approach of technological progress.
- Decreasing prices and increasing production of non-renewable energy over some time.
- Hart (2009): Prices grow at the growth rate of total output, consumption is constant.

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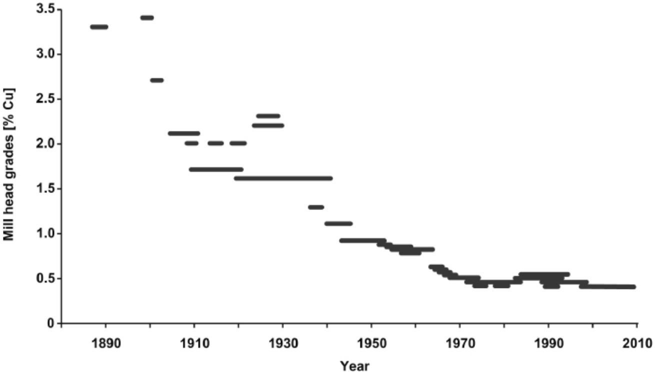
Technological change overcomes depletion



Historical Development of Mining of Various Grades of Copper in the U.S. Source: Scholz and Wellmer (2012)

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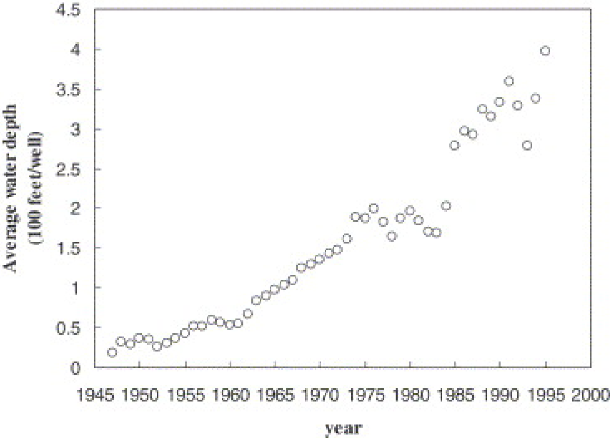
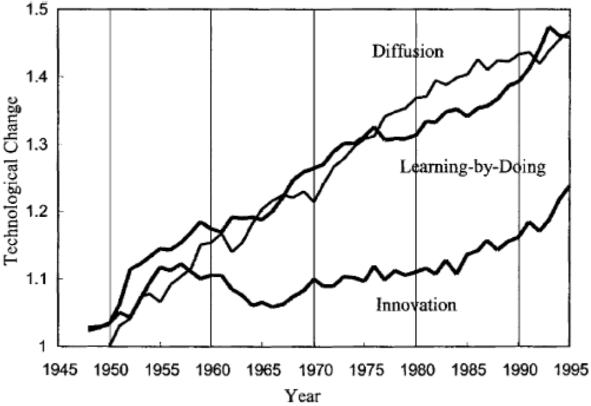
Technological change in oil extraction



Average Water Depth of Wells Drilled in the Gulf of Mexico
(Managi et al, 2004)

Technological change in oil extraction



Decomposition of total factor productivity in Mexican offshore oil production (Managi et al, 2004).

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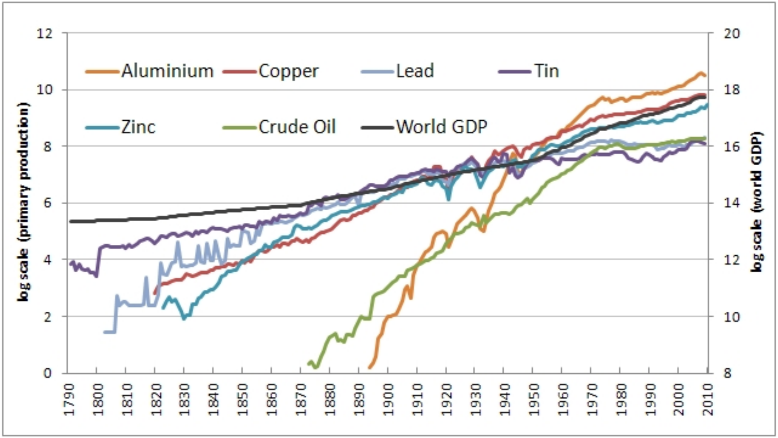
World Non-Renewable Resource Production and World GDP



World primary production of non-renewable resources and world GDP (secondary x-axis) (logarithmic scale).

Return

Intermediate goods sector

- The sector uses expanding varieties of machines to produce an intermediate good.
- Machines depreciate fully after use during one period.
- Firms buy machines from technology firms.
- Technology firms are in monopolistic competition as they hold patent on each machine variety.
- The variety of machines expands through R&D expenditure in terms of aggregate output.

Return

Stock Management

Proposition 2

Firms' resource extraction R equals their new reserves due to R&D:

$$R_t = X_t.$$

- Firms face constant R&D costs of converting deposits to reserves.
- Typical stock management result without uncertainty.

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