The Environment and Directed Technical Change

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Introduction

- Growing concern that economic growth is not “sustainable” because of
    - Negative impact on the environment (pollution, global warming)
    - Depletion of natural resources (in particular, oil).
- Discussion among climate scientists focusing on effects of environmental change on health, conflict,... and on effect of environmental regulation.
- Economic analyses using computable general equilibrium models with exogenous technology (and climatological constraints; e.g., Nordhaus, 1994, 2002).
- Key issues for economic analyses: (1) economic costs and benefits of environmental policy; (2) costs of delaying intervention (3) role of discounting and risk aversion

Context

- Previous literature (with exogenous technological change) involves three different type of answers:

1. **Nordhaus approach:** intervention should be limited and gradual; small long-run growth costs.
2. **Stern/Al Gore approach:** intervention needs to be large, immediate and maintained permanently; large long-run growth costs.
3. **Greenpeace approach:** only way to avoid disaster is zero growth.

- Our paper: yet another approach.

Importance of Technology (1)

- All these approaches essentially ignore the essence of technological responses.
- Evidence that technological change and technology adoption respond to profit incentives
    - **Newell, Jaffe and Stavins (1999)**: energy prices on direction of technological change in air conditioning
    - **Popp (2002)**: relates energy prices and energy saving innovation

This paper

- Once directed technical change is factored in, a very different answer.
    1. Immediate and decisive intervention is necessary (in contrast to Nordhaus)
    2. Temporary intervention may be sufficient (in contrast to Stern/Al Gore)
    3. Two instruments, not one
- Therefore, more optimistic than all, and as proactive as any.

Why (1)

- Two sector model with “clean” and “dirty” inputs.
- Dirty inputs create environmental degradation.
- Researchers work to improve the technology depending on expected profits and “build on the shoulders of giants” in their sector.
- Policy interventions can redirect technical change towards clean technologies.
- **New important parameter:** elasticity of substitution between clean and dirty inputs
  → e.g., whether clean energy replaces fossil fuel (high elasticity) or whether producing components for clean cars uses fossil fuel (low elasticity)

Why (2)

- **Two key externalities:**
  1. *Environmental externality*: production of dirty inputs creates environmental degradation.
  2. *Knowledge externality*: advances in dirty (clean) inputs make their future use more profitable.

Why (3)

1. Immediate and decisive intervention is necessary (in contrast to Nordhaus)
   - → without intervention, innovation is directed towards dirty sectors; thus gap between clean and dirty technology widens; thus cost of intervention (reduced growth when clean technologies catch up with dirty ones) increases
2. Temporary intervention may be sufficient (in contrast to Stern/Al Gore)
   - → once government intervention has induced a technological lead in clean technologies, firms will spontaneously innovate in clean technologies (if clean and dirty inputs are sufficiently substitutes).
3. Two instruments, not one:
   - → optimal policy involves both a carbon tax and a subsidy to clean research to redirect innovation to green technologies
   - → too costly in terms of foregone short-run consumption to use carbon tax alone

Other factors—Exhaustible Resources

- Baseline model without exhaustible resources.
- Oil will likely become more expensive over the next 20 years.
- Directed technical change implies that this will also redirect innovations towards clean technologies.
- Environmental disaster can be avoided without government intervention
    - Because the market may reallocate research away from dirty technologies by itself
- Interestingly, structure of optimal environmental regulation fairly similar with exhaustible resources.

Other factors—Global Interactions

- Baseline model without global interactions.
- Do we need global coordination to avoid disasters?
- The answer is no again because of **directed technical change** (advances in the North will induce the South to also switch to clean technologies).
- But free trade may undermine this result by creating **pollution havens.**

Roadmap

1. **The basic model**
2. Environmental disaster and prevention
3. Optimal policy
4. Simple calibration
5. Exhaustible resource in the production of the dirty input
6. Two-country case
7. Conclusion

Model (1): production

- Infinite horizon in discrete time (suppress time dependence for now)
- Final good Y produced competitively with a clean intermediary input Y_c, and a dirty input Y_d

$$Y = \left(Y_c^{\frac{\varepsilon-1}{\varepsilon}} + Y_d^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

- For $j \in \{c, d\}$, input Y_j produced with labor L_j and a continuum of machines x_{ji}:

$$Y_j = L_j^{1-\alpha} \int_0^1 A_{ji}^{1-\alpha} x_{ji}^{\alpha} di$$

- Machines produced **monopolistically** using the final good

Model (2): consumption

- Constant mass 1 of infinitely lived representative consumers with intertemporal utility:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u\left(C_t, S_t\right)$$

where u increasing and concave, with

$$\lim_{S \to 0} u\left(C, S\right) = -\infty; \frac{\partial u}{\partial S}\left(C, \bar{S}\right) = 0$$

Model (3): environment

- Production of dirty input depletes environmental stock S:

$$S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t \quad \text{if} \quad S \in (0, \bar{S}) . \tag{1}$$

- Reflecting at the upper bound $\bar{S}$ ($< \infty$): baseline (unpolluted) level of environmental quality.
- Absorbing at the lower bound $S = 0$.
- $\delta > 0$: rate of "environmental regeneration" (measures amount of pollution that can be absorbed without extreme adverse consequences)
- S is general quality of environment, inversely related to CO2 concentration (what we do below for calibration).

Model (4): innovation

- At the beginning of every period scientists (of mass $s = 1$) work either to innovate in the clean or the dirty sector.
- Given sector choice, each randomly allocated to one machine in their target sector.
- Every scientist has a probability η_j of success (without congestion).
    - if successful, proportional improvement in quality by $\gamma > 0$ and the scientist gets monopoly right for one period, thus

$$A_{jit} = (1 + \gamma) A_{jit-1};$$

    - if not successful, no improvement and monopoly rights in that machine randomly allocated to an entrepreneur who uses technology

$$A_{jit} = A_{jit-1}.$$

    - simplifying assumption, so that markups equalized across sectors (mimicking structure in continuous time models).

Model (5): innovation (continued)

- Therefore, law of motion of quality of input in sector $j \in \{c, d\}$ is:

$$A_{jt} = \left(1 + \gamma\eta_j s_{jt}\right) A_{jt-1}$$

- **Note:** knowledge externality; "building on the shoulders of giants," but importantly "giants in the same sector"
    - Intuition: Fuel technology improvements do not directly facilitate discovery of alternative energy sources

Assumption

A_{d0} sufficiently higher than A_{c0}.

- Capturing the fact that currently fossil-fuel technologies are more advanced than alternative energy/clean technologies.

Laissez-faire equilibrium: direction of innovation

- Scientists choose the sector with higher expected profits Π_{jt}:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \quad \underbrace{\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}}_{\text{price effect}} \quad \underbrace{\frac{L_{ct}}{L_{dt}}}_{\text{market size effect}} \quad \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\text{direct productivity effect}}$$

  - The direct productivity effect pushes towards innovation in the more advanced sector
  - The price effect towards the less advanced, price effect stronger when ε smaller
  - The market size effect towards the more advanced when $\varepsilon > 1$ and the less advanced when $\varepsilon < 1$ (market size effect itself results from combination between relative productivity and price effects)

Laissez-faire equilibrium (continued)

- Use equilibrium machine demands and prices in terms of technology levels (state variables) and let $\varphi \equiv (1-\alpha)(1-\varepsilon)$:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \left(\frac{1+\gamma\eta_c s_{ct}}{1+\gamma\eta_d s_{dt}} \right)^{-\varphi-1} \left(\frac{A_{ct-1}}{A_{dt-1}} \right)^{-\varphi}.$$

- Implications: innovation in relatively advanced sector if $\varepsilon > 1$, and in the backward one if $\varepsilon < 1$

Laissez-faire equilibrium production levels

- Equilibrium input production levels

$$\begin{aligned} Y_d &= \frac{1}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{\alpha+\varphi}{\varphi}}} A_c^{\alpha+\varphi} A_d; \\ Y &= \frac{A_c A_d}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{1}{\varphi}}} \end{aligned}$$

- Recall that $\varphi \equiv (1-\alpha)(1-\varepsilon)$.
- In particular, given the assumption that A_{d0} sufficiently higher than A_{c0}, Y_d will always grow without bound under laissez-faire
  - If $\varepsilon > 1$, then all scientists directed at dirty technologies, thus $g_{Y_d} \rightarrow \gamma\eta_d$
  - If $\varepsilon < 1$, then both technologies advanced together, thus $g_{Y_d} \rightarrow \gamma\eta_c\eta_d / (\eta_c + \eta_d)$

Roadmap

1. The basic model
2. **Environmental disaster and prevention**
3. Optimal policy
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5. Exhaustible resource in the production of the dirty input
6. Two-country case
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Environmental disaster

- An environmental "**disaster**" occurs if S_t reaches 0 in finite time.

Proposition

Disaster.

The laissez-faire equilibrium always leads to an environmental disaster, and sooner when $\varepsilon > 1$ *than when* $\varepsilon < 1$.

Proposition

The role of policy.

1. *when the two inputs are strong substitutes* ($\varepsilon > 1/\left(1-\alpha\right)$) *and* $\bar{S}$ *is sufficiently high, a temporary clean research subsidy will prevent an environmental disaster;*
2. *in contrast, when the two inputs are complements or weak substitute* ($\varepsilon < 1/\left(1-\alpha\right)$)*, a temporary clean research subsidy cannot prevent an environmental disaster.*

Sketch of proof

- Look at effect of a temporary clean research subsidy
- Key role: redirecting technical change; innovation can be redirected towards clean technology
- If $\varepsilon < 1$, temporary policy is not very effective; innovation will revert to previous pattern and long-run growth of dirty input remains $\gamma\eta_c\eta_d / (\eta_c + \eta_d)$
- If $\varepsilon > 1$, then subsequent to an extended period of taxation, innovation will remain in clean technology
- Is this sufficient to prevent an environmental disaster?

Sketch of proof (continued)

- Even with innovation only in the clean sector, production of dirty inputs may increase
    - *on the one hand:* innovation in clean technology reduces labor allocated to dirty input $\Rightarrow Y_d \downarrow$
    - *on the other hand*: innovation in clean technology makes final good cheaper an input to production of dirty input $\Rightarrow Y_d \uparrow$
    - which of these two effects dominates, will depend upon ε.
- With clean research subsidy (because $\varepsilon > 1$ and thus $\varphi < 0$):

$$Y_d = \frac{1}{\left(A_c^{\varphi} + A_d^{\varphi}\right)^{\frac{\alpha+\varphi}{\varphi}}} A_c^{\alpha+\varphi} A_d \rightarrow A_c^{\alpha+\varphi}$$

- If $\alpha + \varphi > 0$ or $\varepsilon < 1/(1-\alpha)$, then second effect dominates, and long run growth rate of dirty input is positive equal to $(1+\gamma\eta_c)^{\alpha+\varphi} - 1$
- If $\alpha + \varphi < 0$ or $\varepsilon > 1/(1-\alpha)$, then first effect dominates, so that Y_d decreases over time.

Cost of intervention and delay

- Concentrate on strong substitutability case $(\varepsilon > 1/(1-\alpha))$
- While A_{ct} catches up with A_{dt}, growth is reduced.
- T: number of periods necessary for the economy under the policy intervention to reach the same level of output as it would have done within one period without intervention
- If intervention delayed, not only the environment gets further degraded, but also technology gap A_{dt-1}/A_{ct-1} increases, growth is reduced for a longer period.

Costs of delay: calibration

- 1 period = 5 years
- $\alpha = 1/3$: share of capital
- $\eta_c = \eta_d = 0.1$, $\gamma = 1$: long-run growth 2% per year
- A_{c-1}, A_{d-1} to match Y_{c-1}, Y_{d-1} with 2002 - 2006 production of non fossil fuel, fossil fuel energy

The Cost of Delayed Intervention

(Values of T, in years, as a function of delay and ε)

delay (in years)\ ε	3	5	10
0	15	20	15
10	20	25	25
20	25	30	35
30	30	40	45

Undirected technical change

- Compare with a model where scientists randomly allocated across sectors so as to ensure equal growth in the qualities of clean and dirty machines, thus $g_{Y_d} \rightarrow \gamma\eta_c\eta_d / (\eta_c + \eta_d) < \gamma\eta_d$

Proposition

The role of directed technical change.
When $\varepsilon > 1/(1-\alpha)$*:*

1. *An environmental disaster under laissez-faire arises earlier with directed technical change than in the equivalent economy with undirected technical change.*
2. *However, a temporary clean research subsidy can prevent an environmental disaster with directed technical change, but not in the equivalent economy with undirected technical change.*

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Optimal environmental regulation

Proposition

Optimal environmental regulation.
The social planner can implement the social optimum through a tax on the use of the dirty input, a clean research subsidy and a subsidy for the use of all machines (all taxes/subsidies are financed lump sum).

1. *If* $\varepsilon > 1/(1-\alpha)$ *and the discount rate* ρ *is sufficiently small, then the optimal allocation involves all innovation switching to the clean technology in finite time. Optimal environmental regulation uses both a carbon tax,* τ_t*, and a subsidy to clean research,* q_t*, and both policies are temporary.*
2. *If* $\varepsilon < 1/(1-\alpha)$*, then the optimal carbon tax and/or the optimal clean research subsidy are permanent.*

- Parts 1 and 2 $\sim$ Us vs. Stern/Al Gore.

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Calibration: environmental quality

- Same as before +
- Relate S with the atmospheric concentration of carbon:
  1. Relate atmospheric concentration of carbon dioxide (ppm), C_{CO_2} to increase in temperature since preindustrial times (°C), Δ. Common approximation:
  $$\Delta \approx 3 \log_2 \left(C_{CO_2} / 280 \right).$$
  2. Choose a "disaster temperature" $\Delta_{disaster} = 9.2°\text{C}$ which corresponds to twice the temperature increase that would lead to the melting of the Greenland icesheet.
  3. Relate S to Δ through previous equation and:
  $$S = 280 \times 2^{\Delta_{disaster}/3} - \max \left\{ C_{CO_2}, 280 \right\}.$$
  so that $S = 0 \Leftrightarrow \Delta = \Delta_{disaster} = 9.2°\text{C}$
- ξ from the observed value of Y_d and the annual emission of CO_2 in 2002-2006
- δ such that only half of the amount of emitted carbon contributes to increasing C_{CO2}

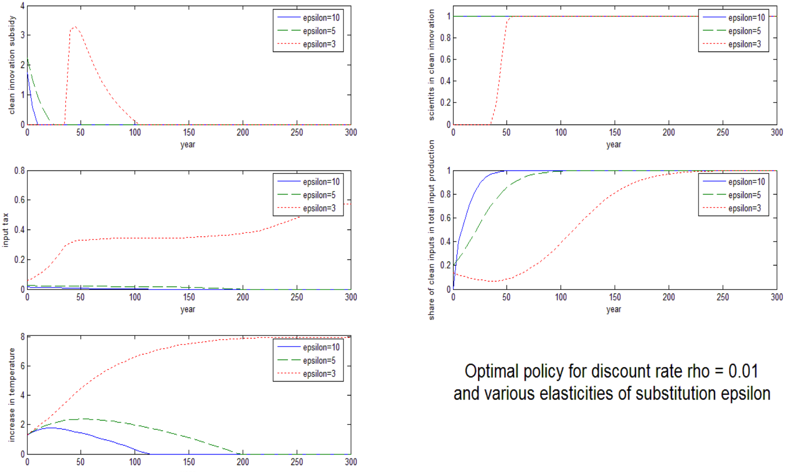
Calibration: utility

- Choose
$$u(C_t, S_t) = \frac{\left(\phi\left(S_t\right) C_t\right)^{1-\sigma}}{1-\sigma}.$$
With $\sigma = 2$. Same as previous literature.
$$\phi\left(S\right) = \frac{\left(\Delta_{disaster} - \Delta\left(S\right)\right)^{\lambda} - \lambda \Delta_{disaster}^{\lambda-1}\left(\Delta_{disaster} - \Delta\left(S\right)\right)}{\left(1-\lambda\right)\Delta_{disaster}^{\lambda}},$$
where ϕ is strictly increasing and concave in S.
- This defines a flexible family of continuous functions parameterized by λ, such that $\phi\left(0\right) = 0$
- Compute λ to match ϕ with the mapping between temperature and final output in Nordhaus' DICE 2007 model over the range of temperature increases up to 3.5°C.

Calibration: 2 important parameters

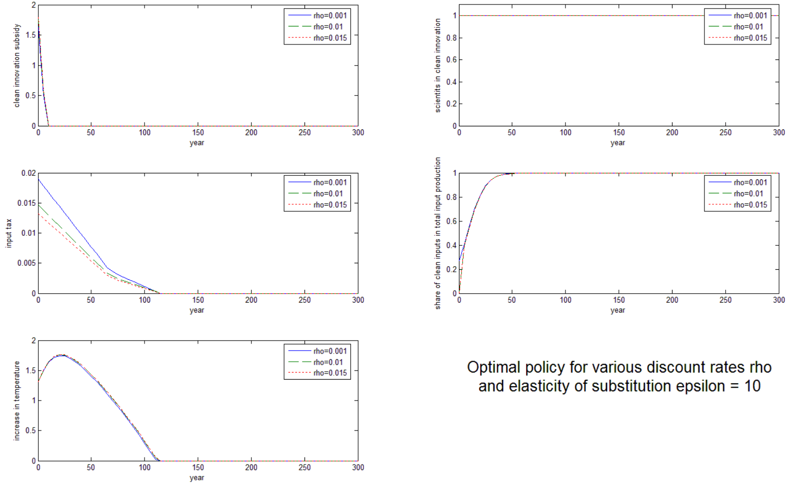
- Choose the elasticity of substitution between clean and dirty input as $\varepsilon = 3, 5, 10$ (low, moderate, high).
- Choose ρ, time discount rate (/year here) as $\rho = 0.001$ (Stern; discount factor$\simeq 0.999$), $\rho = 0.01$ (moderate; discount factor$\simeq 0.99$), and $\rho = 0.015$ (Nordhaus; discount factor$\simeq 0.985$).

Simulation: optimal policy for different values of ε



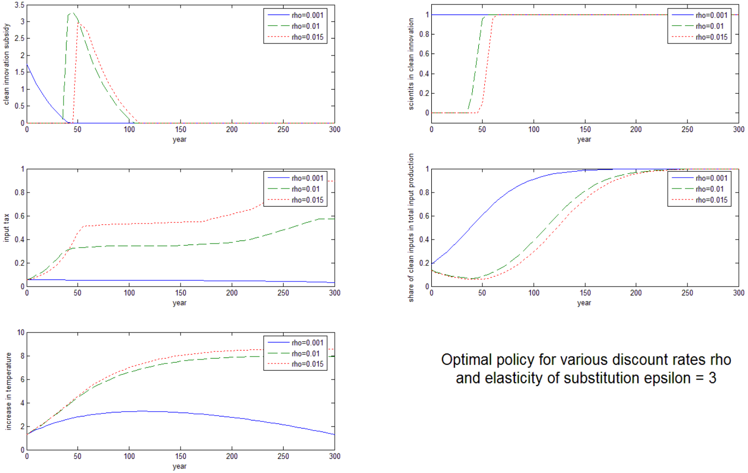
Optimal policy for discount rate rho = 0.01
and various elasticities of substitution epsilon

Simulation: optimal policy for different discount factors (1)



Optimal policy for various discount rates rho
and elasticity of substitution epsilon = 10

Simulation: optimal policy for different discount factors (2)



Optimal policy for various discount rates rho and elasticity of substitution epsilon = 3

Simulation: cost of delaying optimal policy implementation

Welfare costs of delayed intervention as functions of ε and ρ
(Percentage reductions in consumption relative to immediate optimal policy)

ε	10			5			3		
ρ	0.001	0.01	0.015	0.001	0.01	0.015	0.001	0.01	0.01
10 years	9.00	5.99	2.31	5.64	0.63	0.05	3.10	0.05	0.04
20 years	14.62	8.31	2.36	9.49	0.71	0.11	5.51	0.13	0.11
30 years	18.55	8.88	2.43	12.5	0.82	0.21	7.81	0.26	0.21

Simulation: cost of using only carbon tax

Welfare costs of relying solely on the carbon tax as functions of ε and ρ

(Percentage reductions in consumption relative to optimal policy)

ε	10			5			3		
ρ	0.001	0.01	0.015	0.001	0.01	0.015	0.001	0.01	0.015
Cost	0.92	1.33	1.55	1.38	2.10	4.35	1.57	3.49	2.84

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Exhaustible resources

- Polluting activities (CO2 emissions) often use an exhaustible resource (most importantly, oil).
- Implications for evolution of production and direction of research.
- Questions:
    - Does this make environmental disaster less likely? *Yes.*
    - Does it change the structure of optimal environmental regulation? *No.*

Model

- Dirty input produced with some exhaustible resource R:

$$Y_d = R^{\alpha_2} L_d^{1-\alpha} \int_0^1 A_{di}^{1-\alpha_1} x_{di}^{\alpha_1} di,$$

with $\alpha_1 + \alpha_2 = \alpha$.

- The resource stock Q_t evolves according to

$$Q_{t+1} = Q_t - R_t$$

- Extracting 1 unit of resource costs $c(Q_t)$ (with $c' \leq 0$).
- As Q_t decreases, producing the dirty input becomes increasingly costly.
- Consequently, production of dirty input will decrease over time.

Direction of innovation

- Ratio of expected profits from innovation in clean versus dirty is modified to:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \text{constant} \times \frac{\eta_c c(Q_t)^{\alpha_2(\varepsilon-1)}}{\eta_d} \frac{(1+\gamma\eta_c s_{ct})^{-\varphi-1}}{(1+\gamma\eta_d s_{dt})^{-\varphi_1-1}} \frac{A_{ct-1}^{-\varphi}}{A_{dt-1}^{-\varphi_1}},$$

  where $\varphi_1 \equiv (1-\alpha_1)(1-\varepsilon)$

- Provided that $\varepsilon > 1$, increasing cost of extraction helps switching towards clean innovation (again price effect vs market size effect).

Environmental disaster in the laissez-faire equilibrium

Proposition

1. *When the two inputs are substitutes ($\varepsilon > 1$), innovation in the long-run will be directed towards the clean sector only and the economy will grow at a rate $\gamma\eta_c$. Provided that $\bar{S}$ is sufficiently high, an environmental disaster is avoided under laissez-faire.*
2. *When the two inputs are complements ($\varepsilon < 1$), economic growth is not sustainable in the long-run.*

- When the two inputs are substitutes, the increase in the cost of dirty input production due to depletion of exhaustible resources creates enough incentives for research to switch to clean technologies.
- This prevents an environmental disaster provided that initial environmental stock is large enough.
- When two inputs are complements, resource stock is depleted in finite time, since one cannot dispense with dirty input production

Optimal environmental regulation

- How does optimal environmental regulation look like with exhaustible resources?
- *Answer:* generally similar to that without exhaustible resources, but also a resource tax so that the exhaustible resource does not get depleted completely.

Proposition

The social planner can implement the social optimum through a tax on the use of the dirty input, a subsidy on clean research, a subsidy on the use of all machines and a resource tax (all taxes/subsidies are imposed as a lump sum way to the corresponding agents). The resource tax must be maintained forever.

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Global interactions

- Consider a world where both North and South contribute to global environment (global environment externalities)
- South imitates technologies invented in the North (knowledge externality)
- **Main idea:** once environmental regulation in the North increases the relative technology of the clean sector, this may induce a switch in imitation and production patterns in the South.
  - → Q1: is this enough to avoid environmental disaster?
  - → Q2: how does international trade affect environmental externalities and interact with knowledge externalities?

Model: No international trade

- Two countries: North (N), identical to the economy studied so far, and that the South (S) imitating Northern technologies.
- Environmental externality (global):

$$S_{t+1} = -\xi \left(Y_{dt}^{N} + Y_{dt}^{S} \right) + (1+\delta) S_t \text{ for } S \in (0, \bar{S}).$$

Imitation in the South

- In South, scientists choose a sector to imitate, then are randomly allocated to a machine within the sector, they succeed to imitate the North with probability κ_j (no congestion)
    - if successful, they become monopolists for one period using $A_{jit}^S = A_{jit}^N$
    - for sectors without successful imitation, monopoly rights randomly allocated to an entrepreneur using $A_{jit}^S = A_{jit-1}^S$
- Therefore, law of motion of Southern productivity:

$$A_{jt}^S = \left(1 - \kappa_j s_{jt}^S\right) A_{jt-1}^S + \kappa_j s_{jt}^S A_{jt}^N.$$

Direction of innovation

- Ratio of expected profits from imitation in the two sectors in the South

$$\frac{\Pi_{ct}^{S}}{\Pi_{dt}^{S}} = \frac{\kappa_c (p_{ct}^{S})^{\frac{1}{1-\alpha}} L_{ct}^{S} A_{ct}^{N}}{\kappa_d (p_{dt}^{S})^{\frac{1}{1-\alpha}} L_{dt}^{S} A_{dt}^{N}}$$

- Inducing clean technology advances in the North eventually induces the South to switch to cleaner technologies
- For $\varepsilon > 1/(1-\alpha)$, temporary policy in North only is sufficient to avoid global disaster.

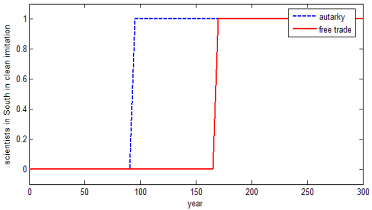
Free trade

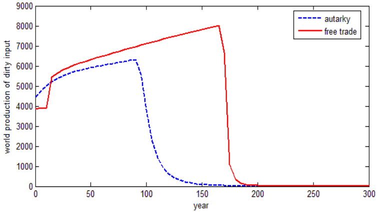
- If free trade between North and South, then environmental regulation in the North creates a "**pollution haven**" in the South
  - South has a comparative advantage in dirty input production whenever

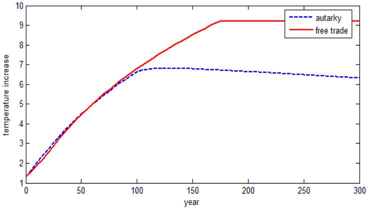
$$\frac{A_d^S}{A_c^S} > \frac{A_d^N}{\left(1+\tau^N\right)^{\frac{1}{1-\alpha}} A_c^N}$$

- Illustrative simulation:
  - North identical to baseline case when $\varepsilon = 5$, all research in clean, input tax as the optimal input tax of baseline case with $\rho = 0.01$
  - South: $L^S = 3$, $A_{d-1}^S = (0.33).A_{d-1}^N$ and $A_{c-1}^S = (0.1).A_{c-1}^S$, and $\kappa_c = \kappa_d = 0.1$.
  - Whenever multiple equilibria, pick up the equilibrium where most scientists in South imitate in clean

Illustrative simulation: comparing free-trade and autarky







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Policy implications: Factoring in endogenous directed technical change calls for...

- **Acting now**, even with Nordhaus' discount rate for reasonable degree of substitutability between clean and dirty inputs
- **Using two instruments, not one**: carbon tax and subsidy to clean innovation, not just the former
- **Developed countries acting as technological leaders and diffusers worldwide**
- **Do not rule out using the threat of carbon tariffs to prevent Pollution Haven Effect**

Future work

- More quantitative work to evaluate elasticity of substitution and therefore importance of endogenous and directed technical change.
- More systematic analysis of interactions between international trade and global environmental externalities.
- Introduce uncertainty (about the likelihood of environmental disaster, possibility of advances in clean technology, etc.).