Lost in Transition: Financial Barriers to Green Growth

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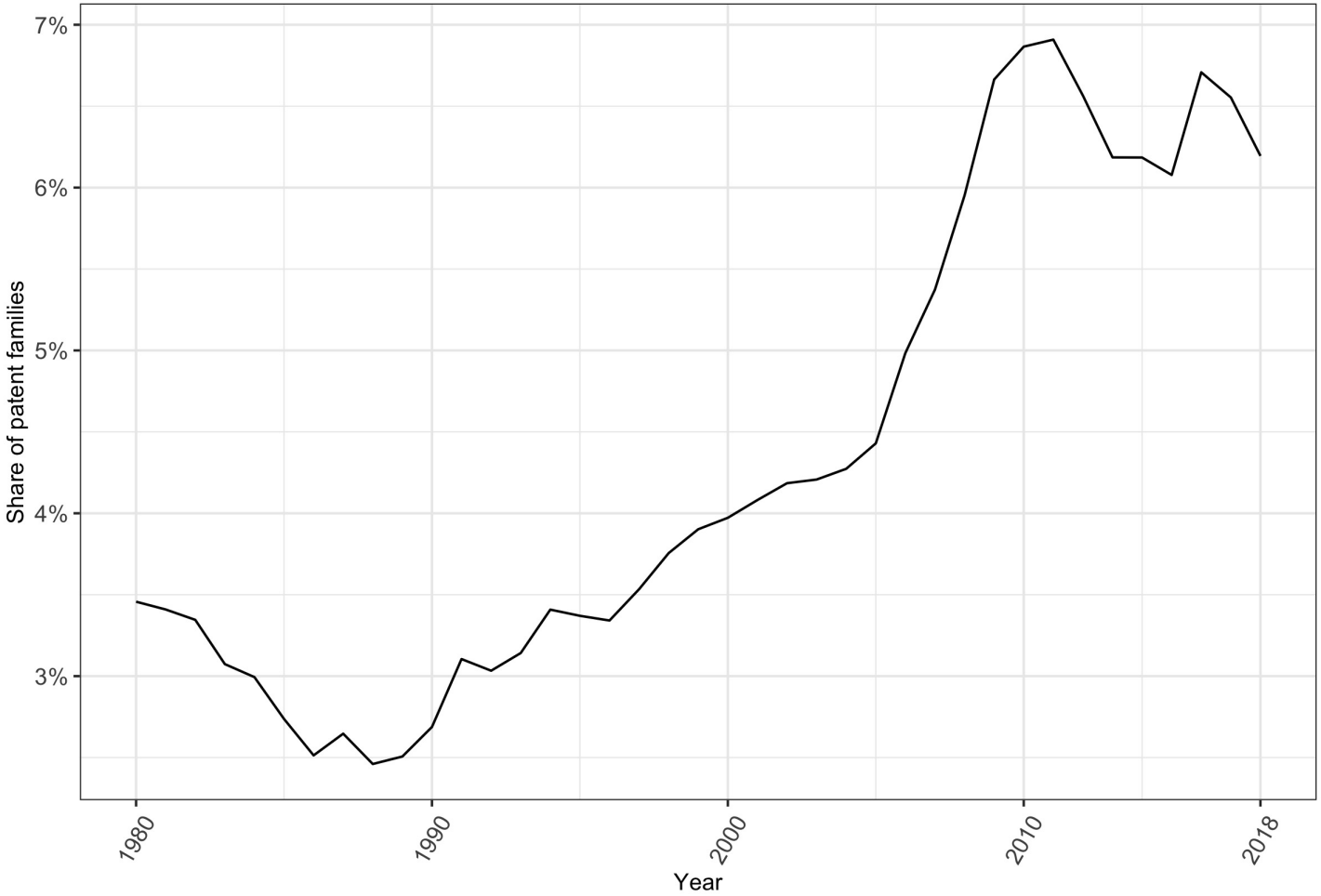
Motivation



Note: Patent families that are classified under the 'Y02' class by the Cooperative Patent Classification scheme are considered as 'clean' innovations. The y-axis denotes the share of clean patent families in all patent families

This paper

How do financial disruptions affect the transition to a new technology?

Two parts:

1. Evidence on the relationship between finance and green innovation
2. Theory: financial crisis during transition to new (green) technology

This paper: empirical analysis

Causal evidence on relationship between credit tightness and green patents

- Effect of tight credit during global financial crisis on green innovation
- Exposure to tight credit only reduces green patents
- This effect is concentrated in small and young firms
- Green patents are predominantly awarded to small and young firms

This paper: theory

Economy where firms can produce goods with clean and dirty technology

- Directed innovation and endogenous growth through creative destruction
- Firms successful innovation history determines their innovation costs

Policy change increases the relative profitability of green innovation

- Young firms have an endogenous competitive advantage in green tech
- But they are also financially constraint: tightening hurts green transition
- Stuck in transition despite no intrinsic difference dirty/green innovation

Empirical Analysis

Empirical strategy

Effect of exposure to Global Financial Crisis on green and non-green innovation

- Measure green and non-green innovation through patent classifications
- Exposure to the global financial crisis from firm-bank links
- Assume firms' innovation propensity orthogonal to bank identity
- Today: German data on exposure to Commerzbank from Huber (2018)
  - Commerzbank incurred large trading losses in U.S.' subprime market
  - Huber: balance tests, effect on employment, investments, overall patents

Data

Firm-level data:

- Balance sheet and income statement for German firms from Dafne (Orbis)
- Merged with data on bank relationships from Creditreform
- Firms in non-financial and public sectors with full coverage for 2007-2012
- Focus on innovative firms: at least one patent in PATSTAT $\Rightarrow$ 601 firms

Patent-level data for the 80 main patent offices:

- BvD code to match with firms, and IPC codes to classify green patents
- Green patents coded using OECD classification (Hascic and Migotto 2015)
  - Green patents relate to environmental management, water-related adaption technologies, biodiversity and ecosystem health, climate-change mitigation

Estimation equation

Calculate fraction of relationship banks that was Commerzbank branch in 2006:

$$CB_i = \frac{\text{number of relationships with Commerzbank branches}_i}{\text{total number of bank relationships}_i}$$

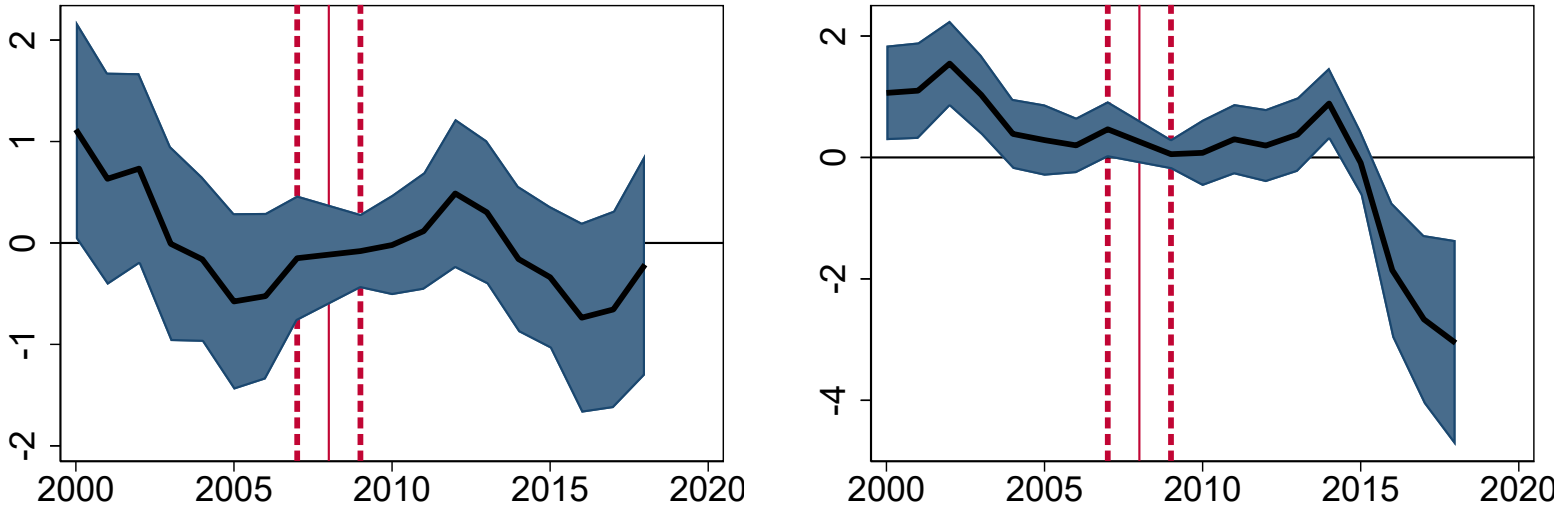
Difference-in-difference estimation using interaction of CB_i with year effects:

- Two outcomes: count of non-green patents, count of green patents

$$\mathbb{E}_t[y_{it}|CB_i, i, t] = exp(\gamma_t \mathbb{I}_t CB_i + \phi_i + \psi_t + \epsilon_{it})$$

- Pseudo-Poisson Maximum Likelihood: γ_t gives pct increase in patents
- Estimate the equation separately for young/old, small/large

Effect of financial tightness on patents over time

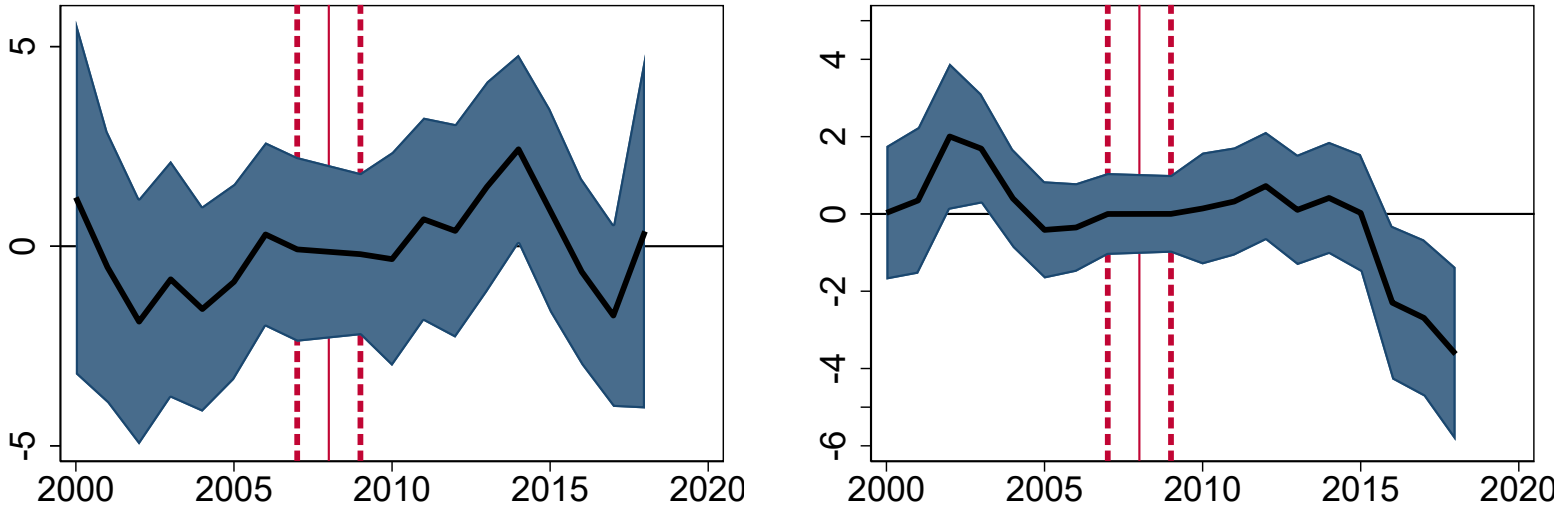


(a) Overall Patents

(b) Green Patents

The figure plots the effect of exposure to Commerzbank on patenting in the year on the horizontal axis. Estimates from PPML. Confidence bounds are at the 95% level using firm-clustered standard errors.

Effect is concentrated in young, small firms

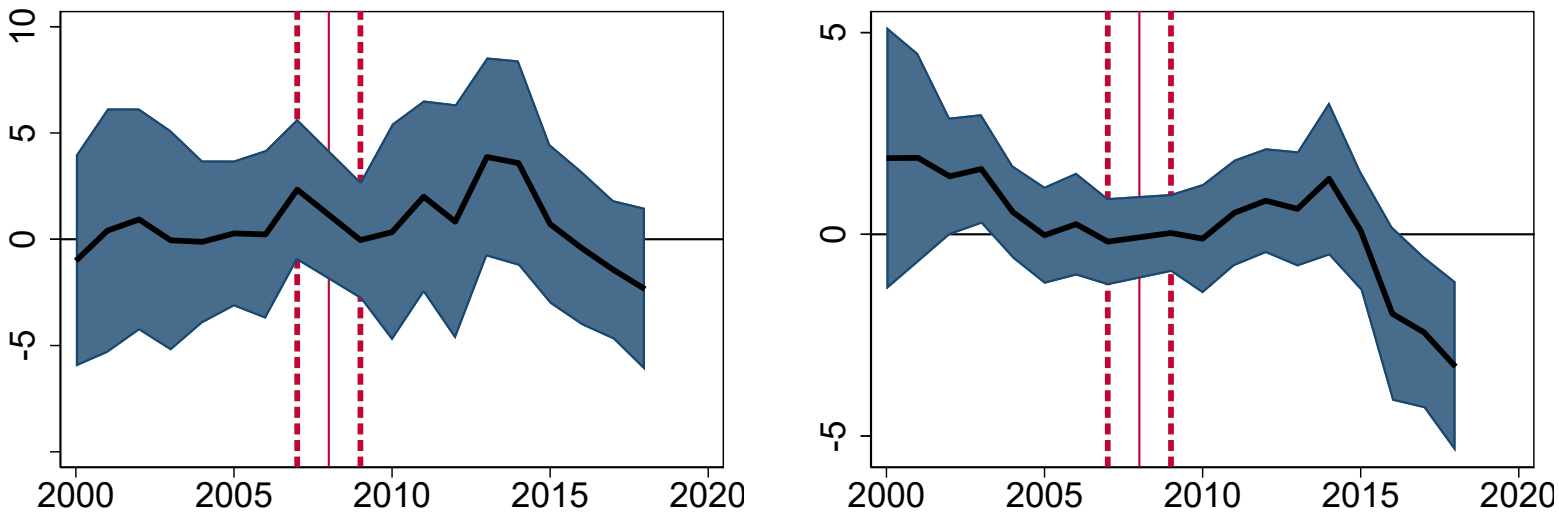


(c) Large Firms

(d) Small Firms

The figure plots the effect of exposure to Commerzbank on patenting in the year on the horizontal axis. Estimates from PPML. Confidence bounds are at the 95% level using firm-clustered standard errors.

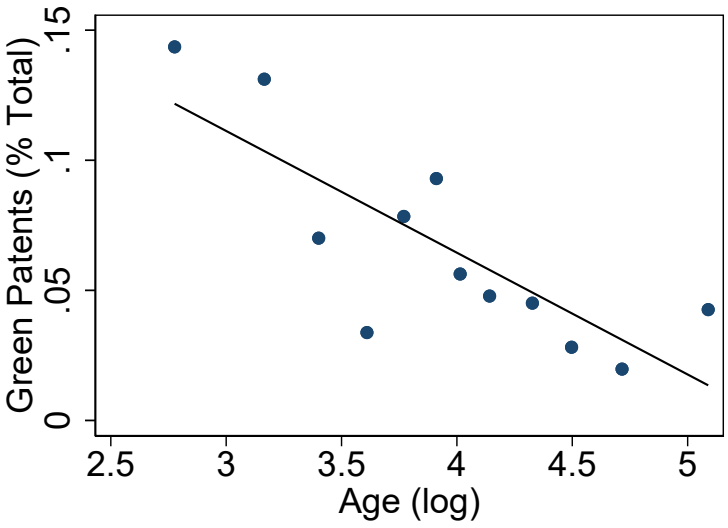
Effect is concentrated in young, small firms



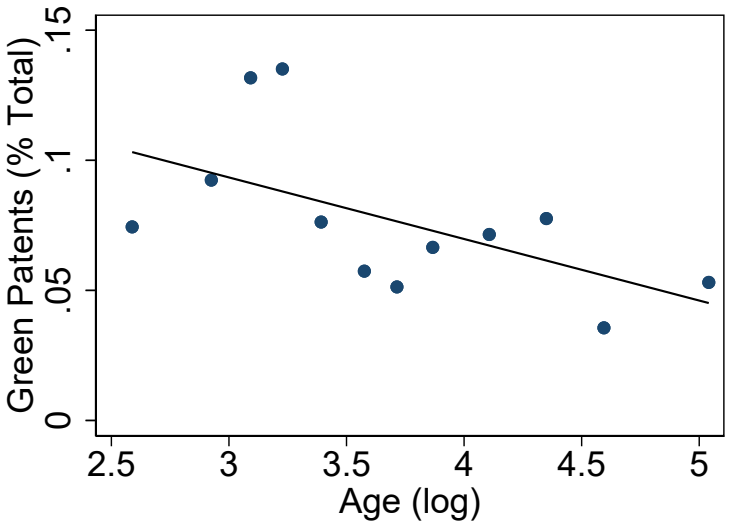
(e) Old Firms (f) Young Firms

The figure plots the effect of exposure to Commerzbank on patenting in the year on the horizontal axis. Estimates from PPML. Confidence bounds are at the 95% level using firm-clustered standard errors.

Young firms are green innovators



(g) 1990 to 2000

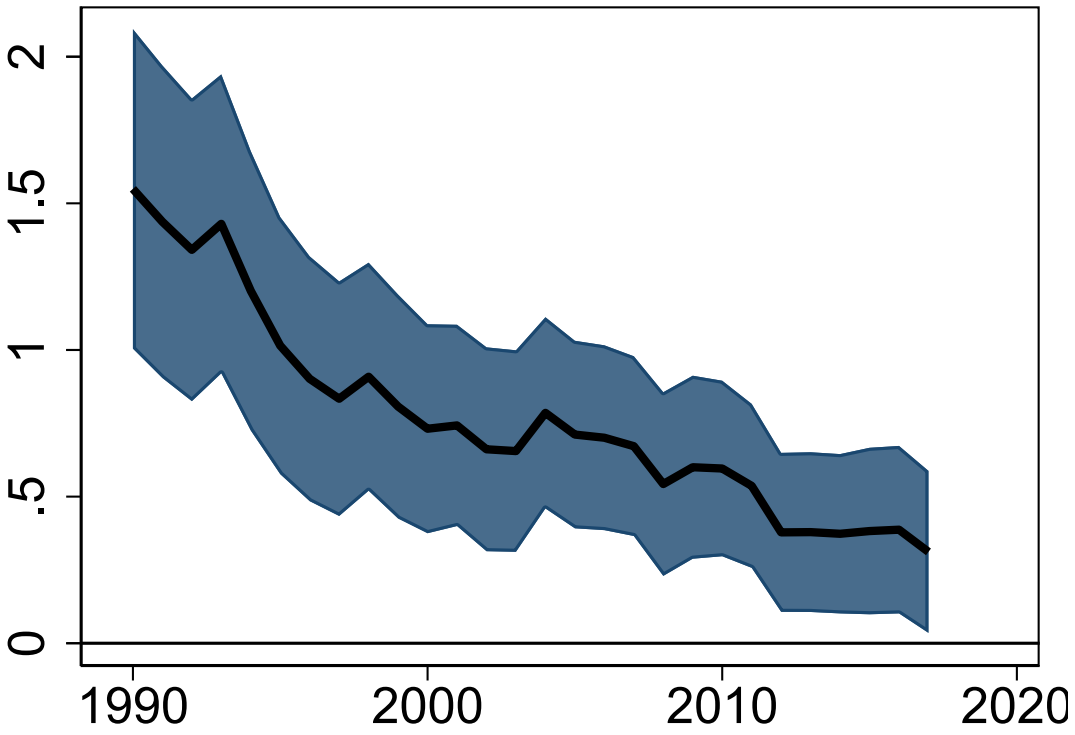


(h) Since 2010

The figure plots the binscatter on the relationship between age and the percentage of green patents.

Young firms are green innovators (but less so over time)

$$\ln\left(\frac{\text{Green patents}_{ist}}{\text{Total patents}_{ist}}\right) = \alpha^t + \gamma_s^t - \beta^t \ln \text{Age}_{it} + \epsilon_{it}^t$$



The figure plots the annual estimates of β and robust 90% confidence bounds.

Theory

Model overview

Ingredients:

- Firms produce one or multiple products using green or dirty technology
- Dirty production negatively affects utility through climate $\rightarrow$ not today

  e.g. Nordhaus (1994, 2002, 2007), Stern (2007), Golosov, Hassler, Krussel, Tsyvinski (2014)
- Firms expand portfolio through innovation, directed to green and dirty

  e.g. Acemoglu, Akcigit, Hanley, Kerr (2016)
- R&D productivity depends on stock of past directed innovation

  e.g. Klette & Kortum (2004), Aghion, Dechezlepretre, Hemous, Martin, van Reenen (2016)
- Innovation comes at a financial costs, declines with firm's age/maturity

Household

- Household derives log-utility from consumption, supplies labor inelastically
- Continuum of goods j, firms i produce one or multiple of them
- Each product can be produced with a clean or dirty technology
- Patent grants firm i the right to produce j, with quality q_{ij}^h

$$\ln C = \int_0^1 \ln \left(\sum_{h \in \{d,c\}} \sum_{i \in I_j} q_{ij}^h \cdot y_{ij}^h \right) dj$$

- A patent enables production with a particular production technology, h
- Firms compete à la Bertrand: demand goes to firm with highest q_{ij}/p_{ij}

Production

Two production technologies: dirty and clean. Say firm i produces good j:

- Production with the clean technology only requires a labor input

$$y_{ij}^c = l_{ij}^c$$

- Dirty technology requires both a labor input and a fossil input

$$y_{ij}^d = (l_{ij}^d)^\eta \cdot (o_{ij})^{1-\eta} \qquad \Rightarrow \qquad o_{ij} = \left(\frac{\eta}{1-\eta}\frac{w}{p^o}\right) l_{ij}^d$$

$$\Rightarrow \qquad y_{ij}^d = \underbrace{\left(\frac{\eta-1}{\eta}\frac{p^o}{w}\right)^{-\eta}}_{(\tilde{p}^o)^{-1}} l_{ij}^d$$

- Minimum price a firm can charge is its marginal cost

$$mc_t^h = \begin{cases} w & \text{if } h = c \\ w \quad \times \quad \tilde{p}^o & \text{if } h = d \end{cases}$$

Static optimization

Producing firm i limit prices its closest competitor -i. Four possible markups:

- If the producer uses a green technology:
  - Competitor is green: $\mu^{cc} = q_{ij}/q_{-ij}$
  - Competitor is dirty: $\mu^{cd} = q_{ij}/q_{-ij} \times \tilde{p}^o$
- If the producer uses a dirty technology:
  - Competitor is dirty: $\mu^{cc} = q_{ij}/q_{-ij}$
  - Competitor is green: $\mu^{cd} = q_{ij}/q_{-ij} \times (\tilde{p}^o)^{-1}$
- Profits:

$$\pi^{h\hat{h}} = \left[1 - (\mu^{h\hat{h}})^{-1}\right] C$$

Innovation

Firms expand their product portfolio through directed innovation

- Improve random product's leading quality by λ
- Firms choose the Poisson arrival rate of clean and dirty technologies:

$$X_i^h = \phi^h \cdot (rd_i^h)^{\frac{1}{\psi}} \cdot (n_i^h)^{1-\frac{1}{\psi}}$$

Note that innovation costs decline in stock of products in directed technology:

- Reflects accumulated organization capital in larger firms. Evidence:
  - Firms' patenting direction has strong path dependence (Aghion et al. 2016)
  - Inventors mostly innovate in only dirty or green (Dugoua & Gerarden 2023)

Entry and Exit

Continuum of potential entrants that invest in green and dirty ideas

- Clean innovation technology:

$$e^c = \phi_e^c \cdot (rd^{ec})^{\frac{1}{\psi}}$$

- Dirty innovation technology:

$$e^d = \phi_e^d \cdot (rd^{ed})^{\frac{1}{\psi}}$$

Firms exit when they lose their final product through creative destruction

Creative destruction

A product is displaced at the rate of creative destruction:

$$\tau = \int_{\mathcal{M}} X_i^c \, di + \int_{\mathcal{M}} X_i^d \, di + e^c + e^c$$

- Sum of displacement due to incumbent innovation and entrant innovation
- Rate of creative destruction does not depend on incumbent's technology

Productivity growth:

$$g = (\lambda - 1) \cdot \tau$$

Financial frictions

Firms use external credit to finance a part of their R&D expenditures

- Firms incur a composite cost to hire R&D: $\tilde{r}(a_i)$
- This comprises interest expenditures, intermediation costs, credit rationing
- Firm state a_i is discrete, $a_i \in \mathcal{A}$, with $\tilde{r}(a_1) > \tilde{r}(a_2) > .. > \tilde{r}(a_{\|\mathcal{A}\|})$
- Firms are born as a_1 ("young")
- Flow to subsequent ages at a rate ν, until they reach absorbing state $\|\mathcal{A}\|$

Dynamic optimization

Incumbents choose innovation rates X_i^c, X_i^d to maximize expected firm value:

$$rV_t(J,a) - \dot{V}_t(\cdot) = \max_{X_i^c, X_i^d} \left\{ \begin{array}{c} \sum_{j \in J} \pi_t^{h_j h_j'} \\ \tau n^c \left[V_t(J \setminus \{ch'\}, a) - V_t(J,a) \right] + \\ \tau n^d \left[V_t(J \setminus \{dh'\}, a) - V_t(J,a) \right] + \\ \nu \left[V_t(J, a+1) - V_t(J,a) \right] + \\ X_i^c \left[V_t(J \cup_+ \{ch'\}, a)\alpha + V_t(J \cup_+ \{dh'\}, a)(1-\alpha) - V_t(J,a) \right] + \\ X_i^d \left[V_t(J \cup_+ \{dh'\}, a)\alpha + V_t(J \cup_+ \{ch'\}, a)(1-\alpha) - V_t(J,a) \right] - \\ w_t \tilde{r}(a)[(\phi^c)^{-\psi}(X^d)^{\psi}(n^d)^{-\frac{1}{\psi-1}} + (\phi^d)^{-\psi}(X^d)^{\psi}(n^d)^{-\frac{1}{\psi-1}}] \end{array} \right\}$$

Value is made up of:

- Instantaneous profits (per produced good)
- Change in value when loosing a good through creative destruction
- Change in value through increase in financial maturity
- Change in value when gaining a good through innovation

Dynamic optimization

Along the balanced growth path, optimal R&D gives innovation rates

$$X_i^h = \left(\phi_h^{\psi} \cdot \frac{\Pi^h}{\psi \cdot w \cdot \tilde{r}(a_i)} \right)^{\frac{1}{\psi - 1}} n_i^h$$

.

- Π^h denotes the expected value of directing innovation to h

$$\Pi^c = \frac{1}{r - g + \tau} \left(\alpha \left[F\pi^{cc} + (1 - F)\pi^{cd} \right] + (1 - \alpha) \left[F\pi^{dc} + (1 - F)\pi^{dd} \right] \right)$$

$$\Pi^d = \frac{1}{r - g + \tau} \left((1 - \alpha) \left[F\pi^{cc} + (1 - F)\pi^{cd} \right] + \alpha \left[F\pi^{dc} + (1 - F)\pi^{dd} \right] \right)$$

where F is fraction of goods produced with green technologies

- Key result: innovation is proportional to n^h such that $x_i^h \equiv X_i^h / n_i^h = x^h(a_i)$

Creative destruction by incumbents

A product is displaced at the rate of creative destruction:

$$\tau = \int_{\mathcal{M}} X_i^c \, di + \int_{\mathcal{M}} X_i^d \, di + e^c + e^d$$

Inserting the optimal innovation rates:

$$\int_{\mathcal{M}} X_i^c \, di = \sum_{a \in \mathcal{A}} M^c(a) x^c(a) \qquad \int_{\mathcal{M}} X_i^d \, di = \sum_{a \in \mathcal{A}} M^d(a) x^d(a)$$

- $M^c(a)$: fraction of goods produced by maturity a firms using green tech
- $M^d(a)$: fraction of goods produced by maturity a firms using dirty tech

Equilibrium

State: measure of firms of age a that produces $\overline{n}^c$ clean and $\overline{n}^d$ dirty goods:

$$M_{n^c=\overline{n}^c, n^d=\overline{n}^d, a=\overline{a}}$$

Growth is determined by the share of products produced green:

$$F = \frac{\sum_{\overline{a}\in\mathcal{A}} \sum_{\overline{n}^c=1}^{\infty} \sum_{\overline{n}^d=1}^{\infty} M_{n^c=\overline{n}^c, n^d=\overline{n}^d, a=\overline{a}} \times \overline{n}^c}{\sum_{\overline{a}\in\mathcal{A}} \sum_{\overline{n}^c=0}^{\infty} \sum_{\overline{n}^d=0}^{\infty} M_{n^c=\overline{n}^c, n^d=\overline{n}^d, a=\overline{a}} \times (\overline{n}^c + \overline{n}^d)}$$

and the share of products produced green by firms of maturity a:

$$M^h(a) = \frac{\sum_{\overline{n}^c=1}^{\infty} \sum_{\overline{n}^d=1}^{\infty} M_{n^c=\overline{n}^c, n^d=\overline{n}^d, a} \times \overline{n}^h}{\sum_{\overline{a}\in\mathcal{A}} \sum_{\overline{n}^c=0}^{\infty} \sum_{\overline{n}^d=0}^{\infty} M_{n^c=\overline{n}^c, n^d=\overline{n}^d, a=\overline{a}} \times (\overline{n}^c + \overline{n}^d)}$$

▸ Balanced Growth Path Equilibrium ▸ Aggregate Variables ▸ Introducing climate

Finding the equilibrium

The change in the measure is given by:

$$
\begin{aligned}
\dot{M}_{n^c=\overline{n}^c,n^d=\overline{n}^d,a=\overline{a}} &= M_{n^c=\overline{n}^c+1,n^d=\overline{n}^d,a=\overline{a}}\tau^c(\overline{n}^c+1) + M_{n^c=\overline{n}^c,n^d=\overline{n}^d+1,a=\overline{a}}\tau^d(\overline{n}^d+1) \\
&+ M_{n^c=\overline{n}^c-1,n^d=\overline{n}^d,a=\overline{a}}\alpha x^c(\overline{a})(\overline{n}^c-1) + M_{n^c=\overline{n}^c-1,n^d=\overline{n}^d,a=\overline{a}}(1-\alpha)x^d(\overline{a})\overline{n}^d \\
&+ M_{n^c=\overline{n}^c,n^d=\overline{n}^d-1,a=\overline{a}}(1-\alpha)x^c(\overline{a})\overline{n}^c + M_{n^c=\overline{n}^c,n^d=\overline{n}^d-1,a=\overline{a}}\alpha x^d(\overline{a})(\overline{n}^d-1) \\
&+ \nu \cdot M_{n^c=\overline{n}^c,n^d=\overline{n}^d,a=\overline{a}-1} - \nu M_{n^c=\overline{n}^c,n^d=\overline{n}^d,a=\overline{a}} \\
&- \left((x^d(\overline{a})+\tau^d(\overline{a}))n^d - (x^d+\tau^d)\overline{n}^c\right) M_{n^c=\overline{n}^c,n^d=\overline{n}^d,a=\overline{a}}
\end{aligned}
$$

Steady state has constant measure of firms of all states:

$$\dot{M}_{n^c=\overline{n}^c,n^d=\overline{n}^d,a=\overline{a}} = 0 \qquad \forall \quad \overline{n}^c, \overline{n}^d, \overline{a}$$

Solution: define transition matrix T that has $(n^{max})^2 \cdot \|\mathcal{A}\| \times (n^{max})^2 \cdot \|\mathcal{A}\|$

$$\dot{M} = T \times M + E \quad \Rightarrow \quad M = -(T)^{-1}E$$

Financial Crises and Green Transitions

Transitioning to a green economy

Initial steady state: F is low $\rightarrow$ most goods produced with dirty technology

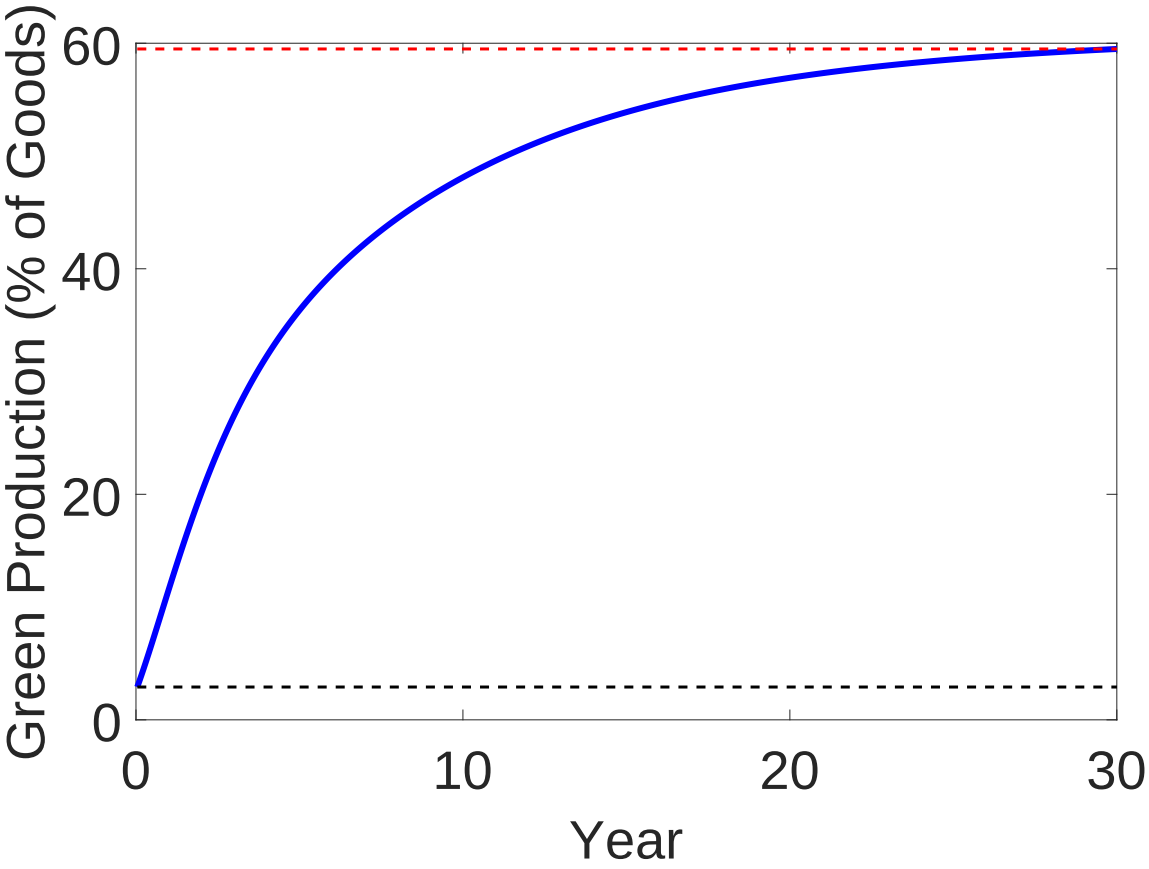
- This means that green innovation capacity is initially low

$$\int_{\mathcal{M}} X_i^c di = \sum_{a \in \mathcal{A}} M^c(a) x^c(a)$$

- Transition: increase in $\tilde{p}^o$ stimulates green innovation (from λ^{-1} to λ)
- Entrants/young firms: initially responsible for a large share of green growth
- Financial crisis slows the transition to high-green (F) economy
- Model is not quantified yet

Transition: % goods produced with green technology

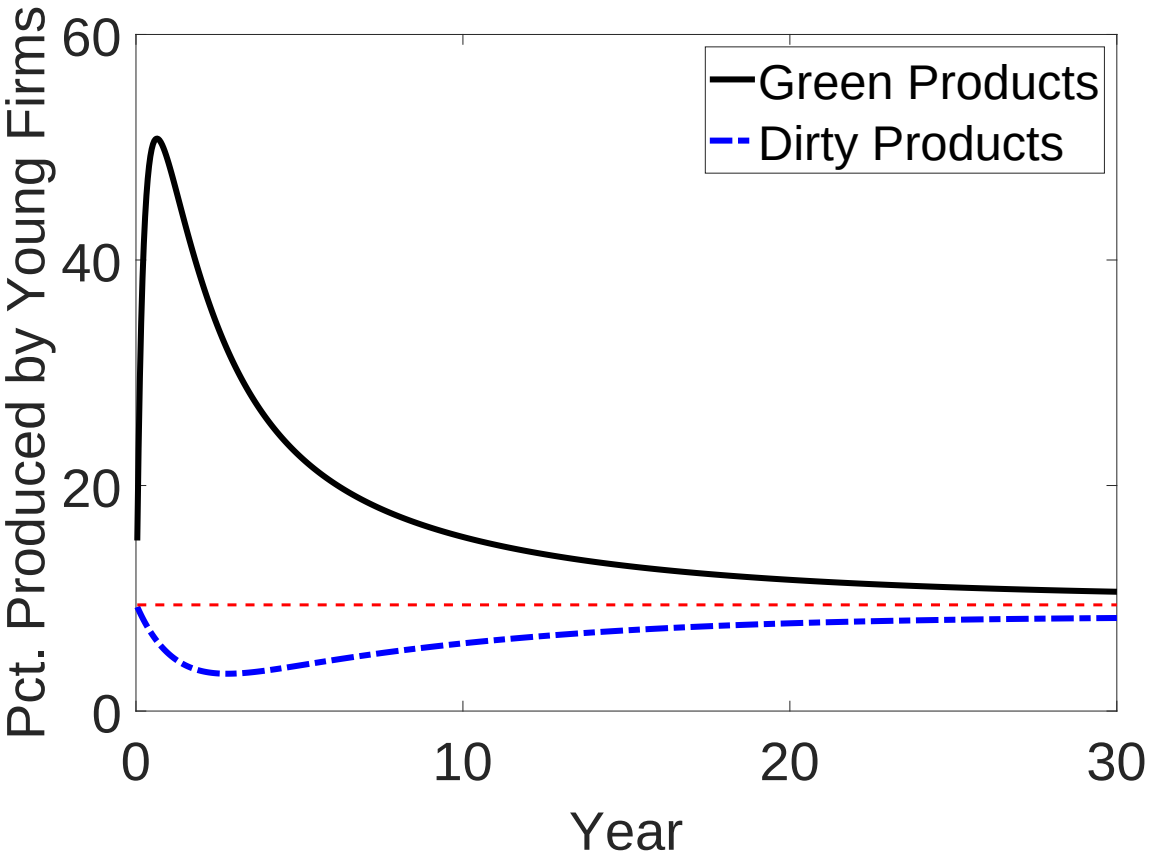
At time 0: increase in cost of dirty production $\tilde{p}^o$ to stimulate green entry



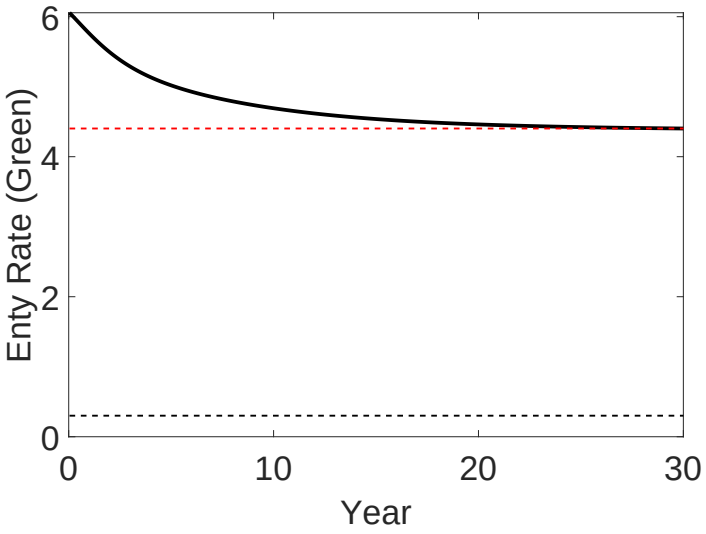
$$\dot{F} = \sum_{a \in \mathcal{A}} M^c(a) x^c(a) - \sum_{a \in \mathcal{A}} M^d(a) x^d(a) + e^c - e^d$$

Transition: % produced by young firms

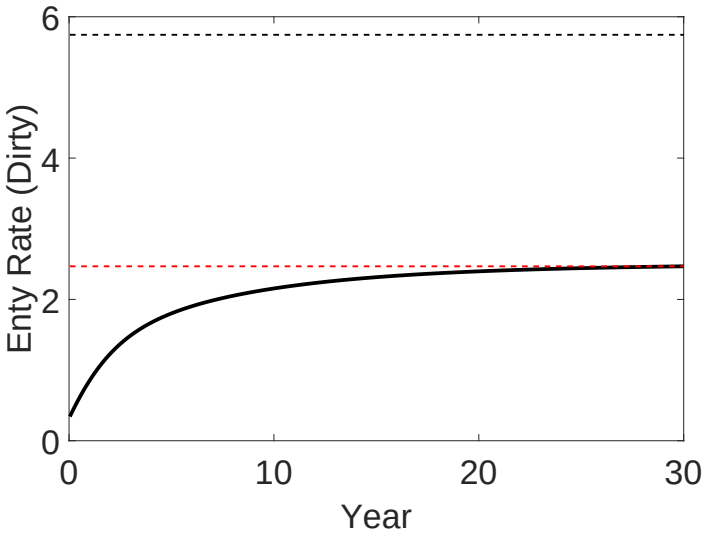
At time *0*: increase in cost of dirty production $\tilde{p}^o$ to stimulate green entry



Transition

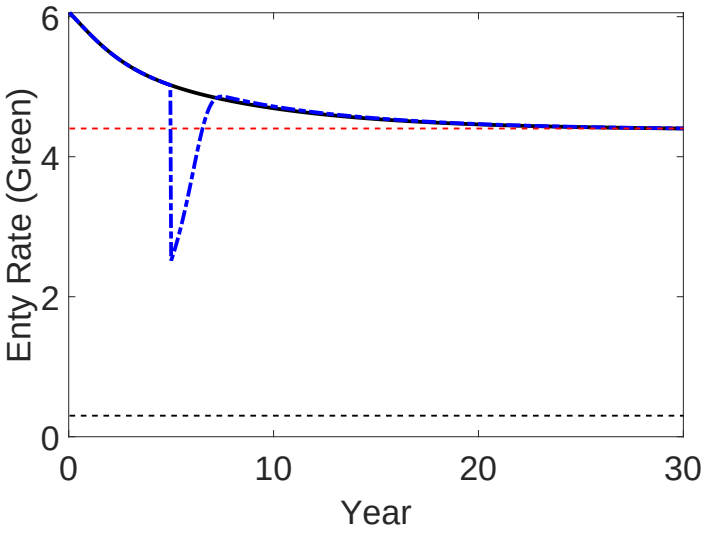


(a) Green Entry



(b) Dirty Entry

Transition



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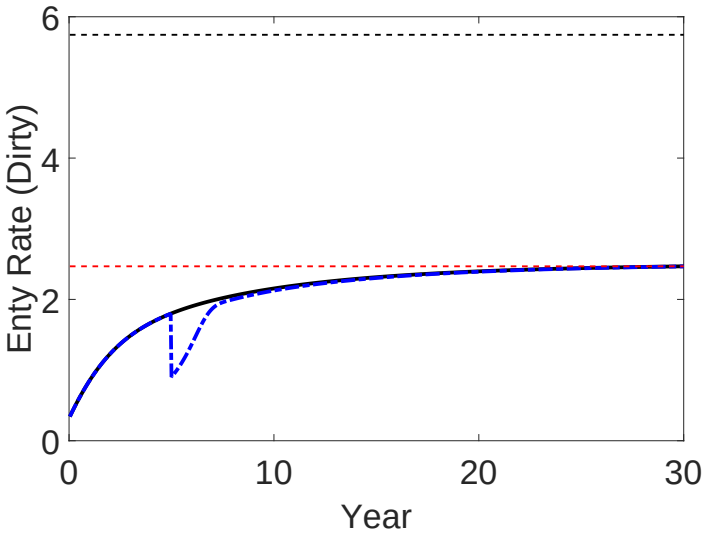
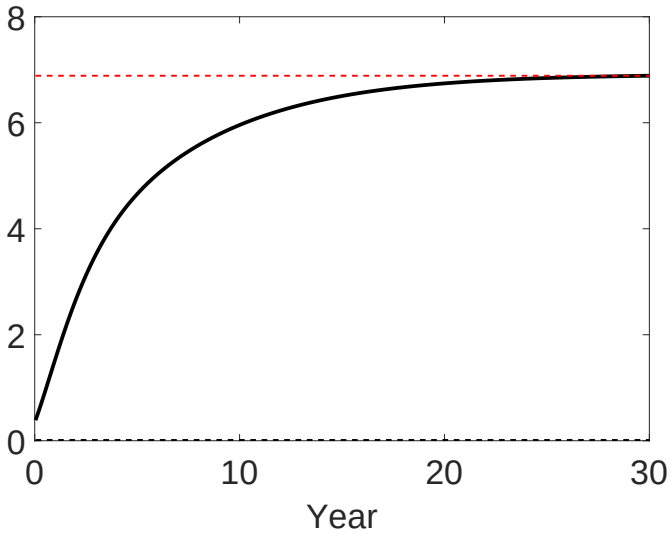
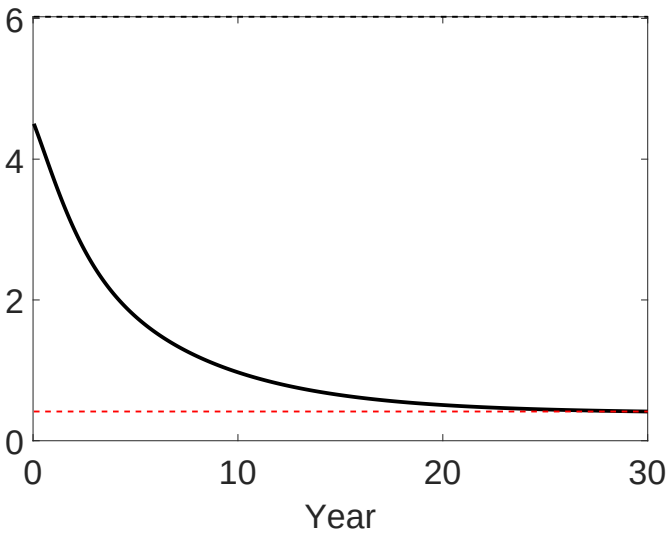


(b) Dirty Entry

Transition

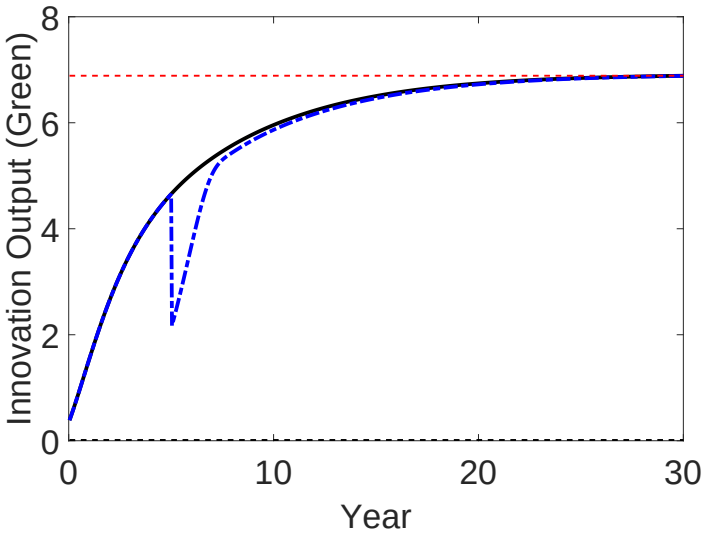


(a) Green Incumbent Patents



(b) Dirty Incumbent Patents

Transition



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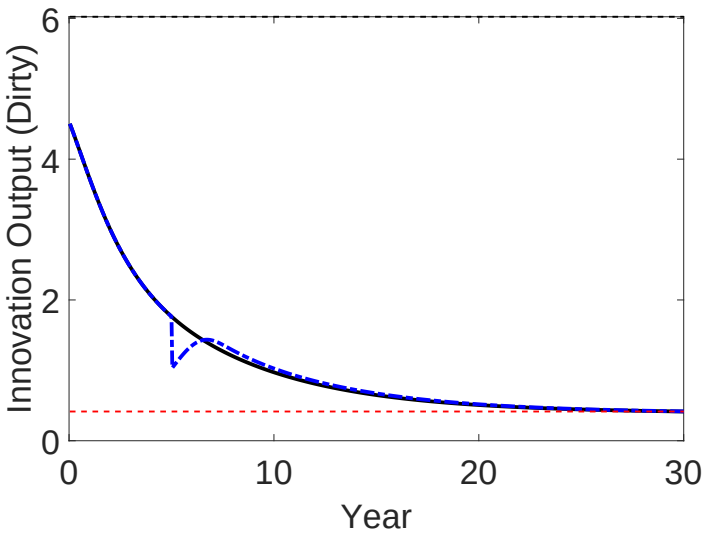
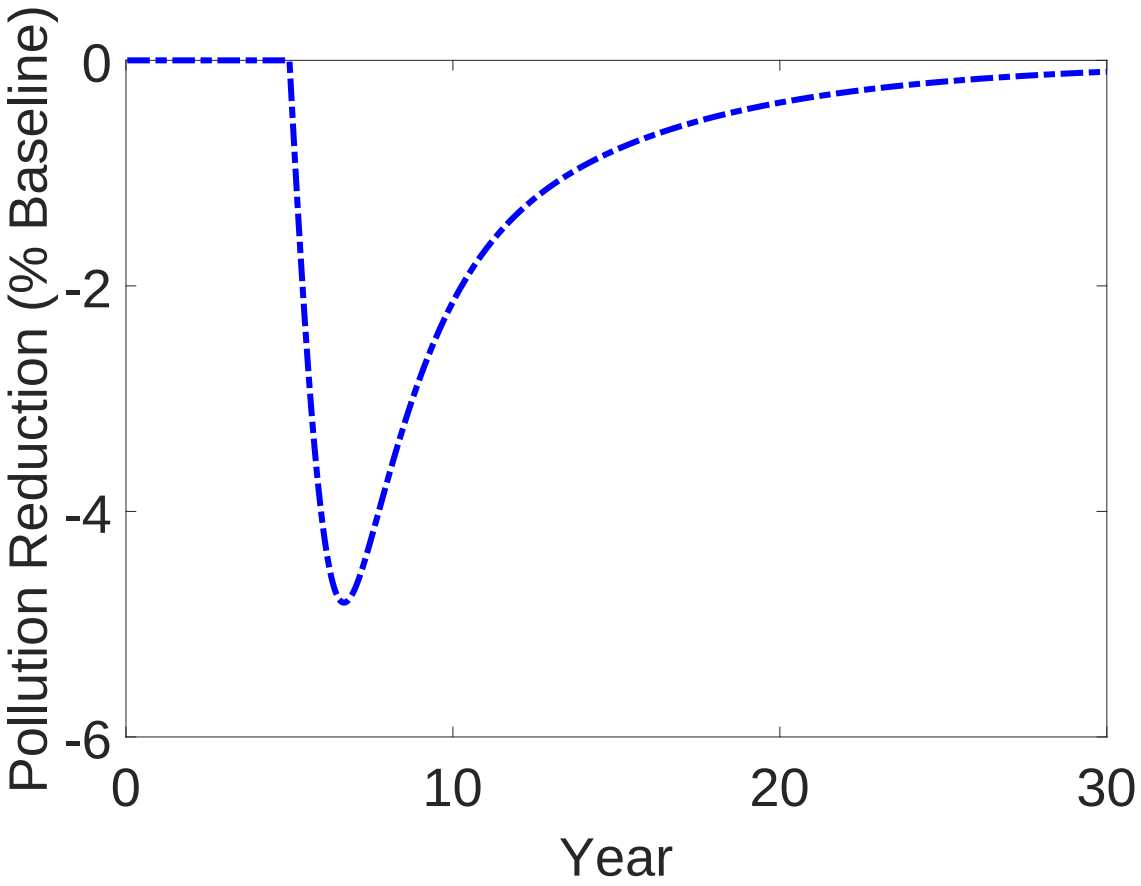


(b) Dirty Incumbent Patents

Transition



Conclusion

- Green patenting slowed down after the Global Financial Crisis
- Micro evidence: credit supply affected green innovation for young firms
- Framework with directed technological change and financial constraints
- Endogenous negative effect of financial crisis on technological transition
- Policy implication: crises more costly during young-firm led transitions
    - Optimal credit subsidies, interaction with R&D subsidies, carbon tax ..

Appendix