Technology Adoption and Productivity Growth During the Industrial Revolution: Evidence from France

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Motivation

Diffusion of innovation across firms is key for economic growth

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Puzzling patterns when major new technologies arise:

1. Technology diffusion is often slow (Griliches 1957, Mansfield 1961, Rosenberg 1976)
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   - Yet, technology adoption can boost firm-level productivity (Bloom et al. 2013, Bloom et al. 2018, Giorcelli 2019)

2. Data do not show major *aggregate* productivity gains when breakthrough innovations (e.g., IT and electricity) spread across firms
   - "You can see the computer age everywhere but in the productivity statistics." (Solow 1987)

Technology Adoption and Productivity Distribution

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- Natural lens to study aggregate effects of technology adoption: Firm productivity distribution (e.g. Syverson 2011)
- But this approach is challenging to implement:
  - Data on the use of specific technology are rare
  - Old and new technologies often co-exist within the same sector or even firms
  - Productivity distributions under old and new technology are not independent

Challenges and Common Approaches

- To address empirical challenges, some papers use RCT-s (Bloom et al. 2013, Atkin et al. 2017, Bruhn et al. 2018, Hardy and McCasland 2019)
    - Advantage: clean identification
    - Disadvantage: limited sample size and short time horizon

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- This paper: bypass typical limitations by studying a unique historical setting:
- Adoption of mechanized cotton spinning technology in France
  - Breakthrough innovation
  - Allows us to isolate productivity distribution of adopters
  - Results can shed light on the two motivating puzzles

Historical Setting

Mechanized cotton spinning in France

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Mechanized cotton spinning in France

- Invented in Britain. Led to huge productivity improvements
  - Old technology: handspinning in *home production*
  - New technology (spinning jenny) required *firm production*

⇒ Factory-based production emerged

old technology (home)

new tech. (firm-based)

What we do

Construct novel firm-level dataset from historical French surveys in 1800 and 1840

- Main sector: Mechanized Cotton Spinning
  - Switch from home to firm production
  - *By definition* all cotton "firms" use the new technology

  ⇒ Isolate the entire firm productivity distribution for adopters of the *new technology*

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Construct novel firm-level dataset from historical French surveys in 1800 and 1840

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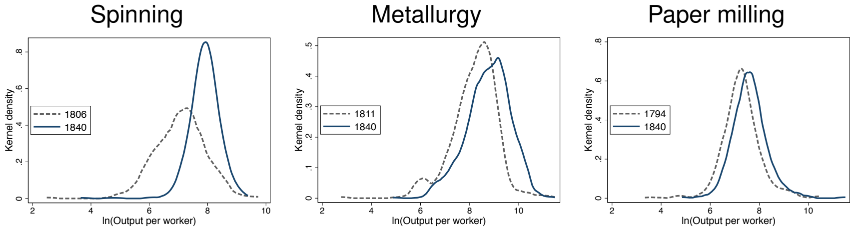
- Comparison sectors: Metallurgy and Paper Milling
  - Production already organized in firms in 1800 (high-fixed-cost machinery and water power)
  - ⇒ Productivity distribution reflects a mix of older and newer vintages in a process of *gradual technology upgrading*

⇒ Study evolution of firm productivity distributions

Main Finding: Lower tail bias of productivity growth in cotton spinning



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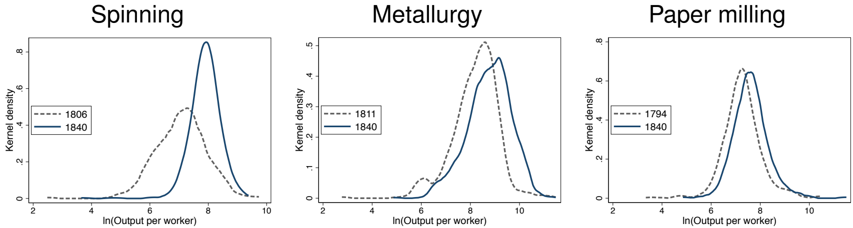

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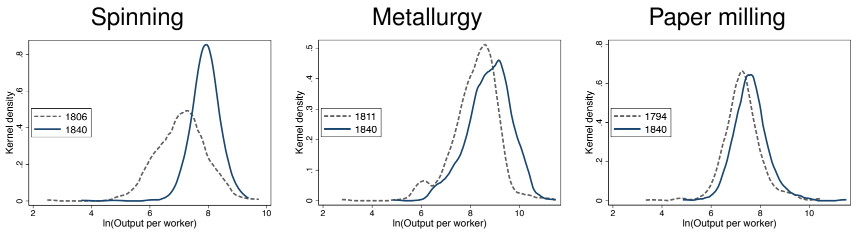

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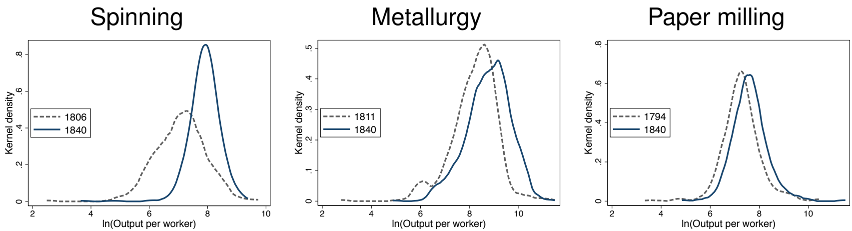

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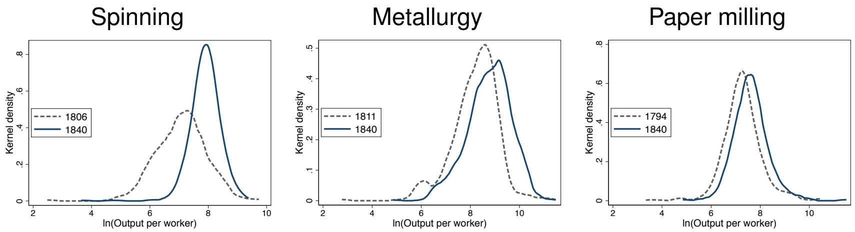

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4. Comparison sectors: Whole distribution shifts right

Qregs Firm Size

Most Likely Mechanism: Re-organizing production

- Mechanization in spinning required the re-orginization of the production process: emergence of the "fully-evolved factory" (Chapman 1974)
  - Flow production: Machines and equipment arranged so that goods could be produced continuously
  - Larger firm scale, finer division of labor, and larger concentration of capital

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- Running factories meant developing solutions to multiple challenges (Pollard 1965)
  - "The cotton mill, in other words, had to be invented as well as the spinning machinery per se." (Allen, 2009)

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- Running factories meant developing solutions to multiple challenges (Pollard 1965)
  - "The cotton mill, in other words, had to be invented as well as the spinning machinery per se." (Allen, 2009)
- Progress made via a process of trial and error

Empirical evidence for learning

A set of results that are consistent with the proposed mechanism:

1. Firm survival rates much lower in cotton spinning Results
2. Exiting firms particularly unproductive in cotton spinning Results
3. Younger firms *more* productive in cotton spinning in 1800, but not later and not in metallurgy Results
4. Spatial diffusion of knowledge? Cotton firms closer to high-productivity firms are themselves more productive

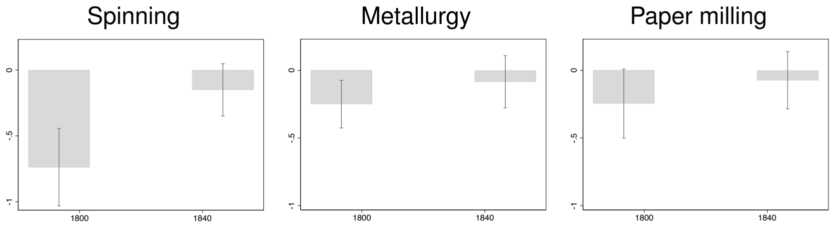
How does Knowledge Diffuse?

- Proposed mechanism: Firms learn from each other by observing successful experimenters
- Test for spatial diffusion of knowledge from 'frontier' firms

$$ln(Y/L)_i = \beta_0 + \beta_1 ln(dist^{p90})_i + \epsilon_i$$

- $dist^{p90}$ is log distance to closest firm with productivity in the 90th percentile

Importance of Proximity to High-Productivity Firms



Standardized beta coefficient on distance to most productive firms

⇒ Strongest in cotton spinning in 1800 – the sector & period where firms were conducting most experimentation

Maps Placebo Robustness

Robustness to Alternative Mechanisms

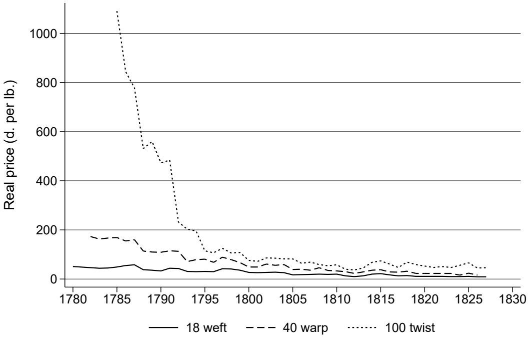
1. Economy-wide effects unlikely to drive pattern in cotton: Different pattern observed across comparison sectors
2. Firm size
   - Focusing on firms with at least 10 workers
     - ★ Productivity distributions & Quantile regressions
   - Controlling for total number of workers
3. Pattern robust to controlling for capital deepening
4. Accounting for market integration
   - Market access & Region FE & Maps
5. Other shocks specific to cotton spinning
   - Napoleonic blockade: Spitting sample into firms in Northern vs. Southern regions
6. Robustness to data construction choices
   - Using prices not adjusted for quality
   - Using TFP

Conclusion

- What does this setting teach us more generally about technology diffusion?
  - Slow technology adoption
    - ★ Firms face high initial uncertainty about their efficiency in operating new technology
    - ⇒ There may be a strategic incentive to delay adoption until tacit knowledge about efficient firm organization has diffused
  - Why do aggregate efficiency gains take time to materialize?
    - ★ Early adopters experiment with organization of production, and many of them will operate the new technology inefficiently
    - ⇒ The promised benefits of the new technology may materialize relatively slowly for the average firm

- Important role for organizational innovations in driving productivity growth during the IR

Cotton Yarn Prices – Britain



Source: Harley (1998)

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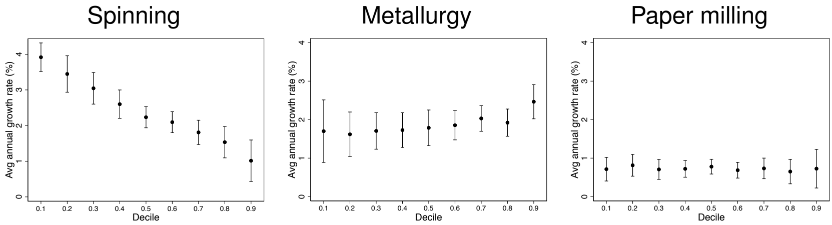
Quantile regressions



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Evolution of Firm Size

Sector	year	(1) mean	(2) sd	(3) median	(4) 10perc	(5) 90perc	(6) N
Cotton Spinning	1806	63	(101)	30	4	150	372
	1840	112	(148)	72	28	210	528
Metallurgy	1811	20	(23)	11	4	46	457
	1840	57	(114)	22	7	135	839
Paper Milling	1794	13	(19)	11	5	23	550
	1840	43	(58)	19	5	112	348

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Firm Survival Rates Lower in Cotton Spinning

	Spinning 1806-1840	Metallurgy 1811-1840	Paper Milling 1794-1840
Firm survival rate	7%	34%	9%
Number of firms	389	477	593
Restricted sample survival rate	6.5%	49%	20%
Number of firms	93	303	218

Notes: "Firm survival rate" is defined as the percentage of firms from the initial period that survive into the later period based on matching either on owner name or local matching. "Restricted sample survival rate" adjusts for the fact that different sectors have single firm communes to a varying degree. It is based on the subset of firms located in communes that have only one firm in the initial period and that either do not show up in the 1840 data or they show up with still only one firm.

- Some early adopters will be too unproductive to survive $\Rightarrow$ exit market

Linking firms
Back to Talk

Exiting firms in 1800 are less productive than surviving firms

Dependent variable	(1) log(Y/L)	(2) log L	(3) Log Y	N
Spinning (exit = 1)	-0.506***	-1.043***	-1.548***	340
	(0.153)	(0.221)	(0.258)	
Metallurgy (exit = 1)	-0.139	-0.439***	-0.578***	457
	(0.087)	(0.089)	(0.097)	
Paper milling (exit = 1)	-0.179	-0.151	-0.331*	520
	(0.150)	(0.131)	(0.172)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- Pattern is particularly strong in cotton spinning
- Consistent with large organizational challenges and low initial guidance in switching to factory-based cotton spinning.

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Younger firms systematically more productive in cotton spinning in 1806

Dependent variable: log(Y/L)

	(1)	(2)	(3)	(4)	(5)	(6)
Young firm	0.575***	0.374***	0.543***	0.493***	0.608***	0.534***
	(0.088)	(0.079)	(0.083)	(0.085)	(0.086)	(0.085)
(log) Yarn quality		0.673***				
		(0.074)				
Low-tech spindles			-0.626***			
			(0.087)			
High-tech spindles				0.481***		
				(0.086)		
(log) Workers					0.107***	
					(0.025)	
(log) Spindles per worker						0.336***
						(0.070)
R^2	0.11	0.32	0.20	0.18	0.14	0.17
N	340	323	340	340	340	340

Notes: Robust standard errors in parentheses. Low-tech spindles and high-tech spindles are binary indicators equal to 1 for firms are using the earliest (jenny) and latest (mule jenny) vintage of machinery respectively. 'Young' firm is a binary indicator for firms with below-median age. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- Younger firms have higher productivity in 1806
- Patterns in line with younger firms adopting (evolving) best practices of mill design
- Similar pattern does not hold in metallurgy or in 1840 in spinning

▸ 1840 ▸ Metallurgy ▸ Back to Talk

Productivity and firms' age profile, 1840 – cotton spinning

Dependent variable: log(Y/L)

	(1)	(2)	(3)	(4)	(5)
Entrant 1840	-0.053	-0.060	-0.072	-0.056	-0.116
	(0.099)	(0.099)	(0.100)	(0.099)	(0.098)
Water power		0.062			
		(0.050)			
Steam power			-0.093**		
			(0.047)		
Other power				0.172	
				(0.140)	
(log) Workers					-0.157***
					(0.028)
R^2	0.00	0.00	0.01	0.00	0.07
N	528	528	528	528	528

Notes: Robust standard errors in parentheses. Entrant 1840 is a binary indicator equal to 1 for firms that entered the market after 1806. Water power, steam power, and other (wind or animal) power are binary indicators equal to 1 for firms using the respective source of power. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- Entrant firms do not have higher productivity in 1840
- In 1840s, factory layout practices had already been established

▸ Metallurgy ▸ Back to Talk

Productivity and firms' age profile, 1811 – metallurgy

Dependent variable: log(Y/L)

	(1)	(2)
Young 1811	0.226*	0.101
	(0.118)	(0.117)
(log) Workers		-0.313***
		(0.051)
R^2	0.01	0.10
N	448	448

Notes: Robust standard errors in parentheses. Entrant 1811 is a binary indicator equal to 1 for firms that entered the market after 1788. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Productivity and firms' age profile, 1840 – metallurgy

Dependent variable: log(Y/L)

	(1)	(2)	(3)	(4)	(5)
Entrant 1840	-0.084	-0.029	-0.080	-0.078	-0.144**
	(0.077)	(0.077)	(0.078)	(0.077)	(0.065)
Water power		0.327***			
		(0.062)			
Steam power			-0.045		
			(0.076)		
Other power				-0.193**	
				(0.090)	
(log) Workers					-0.373***
					(0.027)
R^2	0.00	0.03	0.00	0.01	0.24
N	839	839	839	839	839

Notes: Robust standard errors. Entrant 1840 is a binary indicator equal to 1 for firms that entered the market after 1811. Water power, steam power, and other (wind or animal) power are binary indicators equal to 1 for firms using the respective source of power. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Linking

Two ways to link firms across time:

1. Match on owner name and location (commune)
2. Match firms that are the only active firm in the given sector in a commune – fairly common in the data.
   - Does 'local matching' identify the same firm? Likely – reliance on water-power.
   - Validate assumption: how frequently do communes with a single firm active in 1800 show up in 1840 with multiple firms? Very rarely (6%-8%)

Construct two measures of survival rates:

1. Baseline: the percentage of firms from the initial period that survive into the later period based on matching either on name or on location.
2. 'Restricted sample': examine survival on the subset of firms that are the only ones in their commune in 1800 and that commune either does not show up in 1840 or shows up with only one firm
   - Adjusts for differences across sectors in single-firm communes

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Additional specifications: Proximity regressions

- Baseline table ▸ Table
- Local density control ▸ Table
- Location fundamentals control ▸ Table
- Firms' age profile ▸ Table
- Placebo ▸ Table

▸ Back to Talk

Effect of distance - baseline specification

Dependent variable: log(Output per worker)

	Spinning		Metallurgy		Paper milling	
	1806	1840	1811	1840	1794	1840
	(1)	(2)	(3)	(4)	(5)	(6)
Dist to p90 (1800)	-0.814***		-0.249***		-0.245*	
	(0.143)		(0.088)		(0.128)	
Dist to p90 (1840)		-0.176		-0.084		-0.073
		(0.106)		(0.097)		(0.106)
Department FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.56	0.15	0.37	0.27	0.29	0.42
N	290	471	377	746	456	312

Notes: Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Effect of distance - local density of production control

Dependent variable: log(Output per worker)

	Spinning		Metallurgy		Paper milling	
	1806	1840	1811	1840	1794	1840
	(1)	(2)	(3)	(4)	(5)	(6)
Dist to p90 (1800)	-0.743***		-0.245***		-0.210	
	(0.186)		(0.088)		(0.131)	
Dist to p90 (1840)		-0.147		-0.094		-0.064
		(0.115)		(0.092)		(0.114)
production density	0.019	0.008	0.004	-0.003	0.019	0.004
	(0.021)	(0.013)	(0.012)	(0.008)	(0.015)	(0.017)
Department FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.57	0.15	0.37	0.27	0.30	0.42
N	290	471	377	746	456	312

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Effect of distance - location fundamentals controls

Dependent variable: log(Output per worker)

	Spinning		Metallurgy		Paper milling	
	1806	1840	1811	1840	1794	1840
	(1)	(2)	(3)	(4)	(5)	(6)
Dist to p90 (1800)	-0.848***		-0.259***		-0.228*	
	(0.123)		(0.081)		(0.133)	
Dist to p90 (1840)		-0.192*		-0.090		-0.076
		(0.106)		(0.091)		(0.105)
access high stream flow	-0.085	0.253**	-0.038	0.243	-0.163	-0.032
	(0.304)	(0.118)	(0.160)	(0.216)	(0.250)	(0.306)
proximity to coal	0.007	-0.099	-0.248	0.074	0.159	-0.112
	(0.199)	(0.311)	(0.185)	(0.156)	(0.356)	(0.191)
share forest area	-1.307***	0.440	-0.172	-0.005	0.458	-0.273
	(0.482)	(0.299)	(0.302)	(0.388)	(0.502)	(0.803)
Department FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.58	0.16	0.38	0.28	0.30	0.42
N	290	471	369	746	456	312

Notes: Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.

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Effect of distance – testing for selection effects

Dependent variable: log(Output per worker)

	Spinning 1806				
	(1)	(2)	(3)	(4)	(5)
			Only firms entering before high productivity firms		
Dist to p90 (1800)	-0.791***	-0.845***	-0.439***	-0.393**	-0.481**
	(0.136)	(0.129)	(0.153)	(0.153)	(0.196)
Firm Age	-0.046	-0.203		-0.153	-0.388*
	(0.085)	(0.135)		(0.133)	(0.205)
Firm Age* Dist to p90 (1800)		0.237			0.365
		(0.203)			(0.258)
Department FE	Yes	Yes	Yes	Yes	Yes
R^2	0.56	0.57	0.66	0.66	0.67
N	284	284	176	176	176

Notes: Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Effect of distance - Placebo using timing

Dependent variable: log(Output per worker)

	Spinning 1806	Metallurgy 1811	Paper milling 1794
	(1)	(2)	(3)
Dist to p90 (1840)	-0.055	-0.245	0.083
	(0.237)	(0.161)	(0.129)
Department FE	Yes	Yes	Yes
R^2	0.55	0.30	0.22
N	321	415	507

Notes: Standard errors (clustered at the departmental level) in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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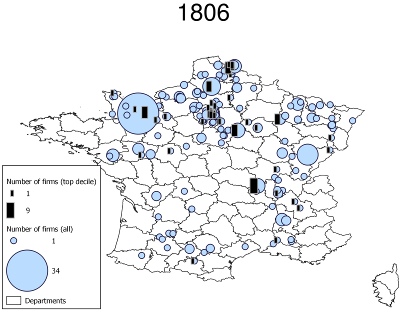
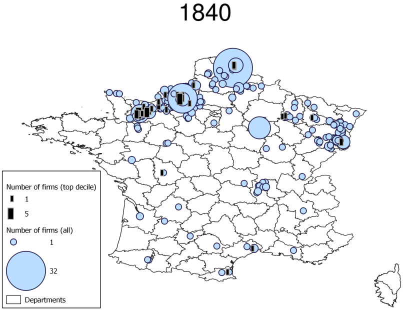
Distance to top decile: Cotton spinning





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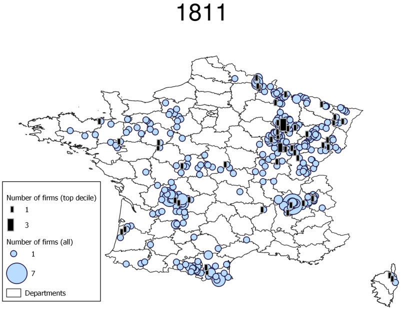
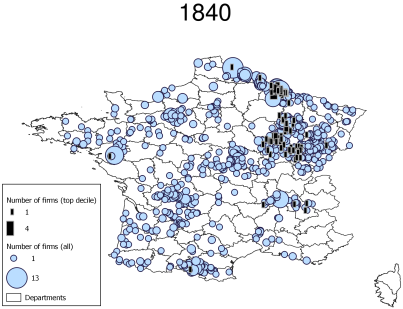
Distance to Top Decile: Metallurgy





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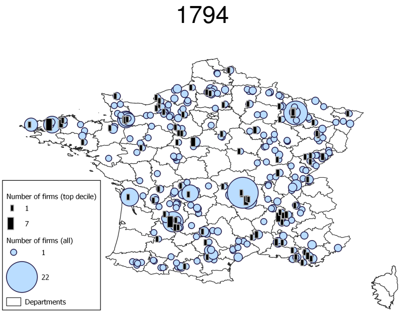
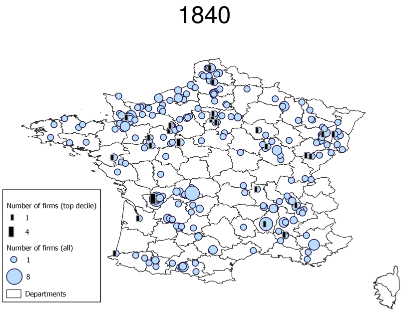
Distance to Top Decile: Paper Milling





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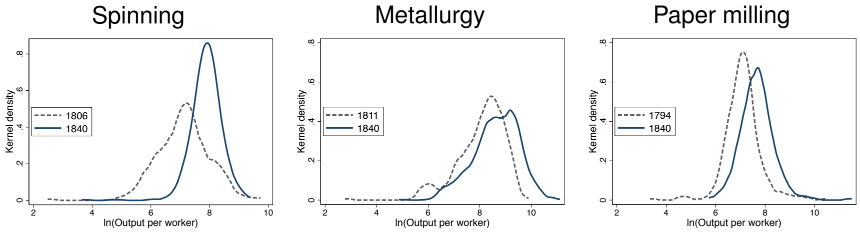
Productivity growth concentrated at different parts of the distribution – firms with at least 10 workers



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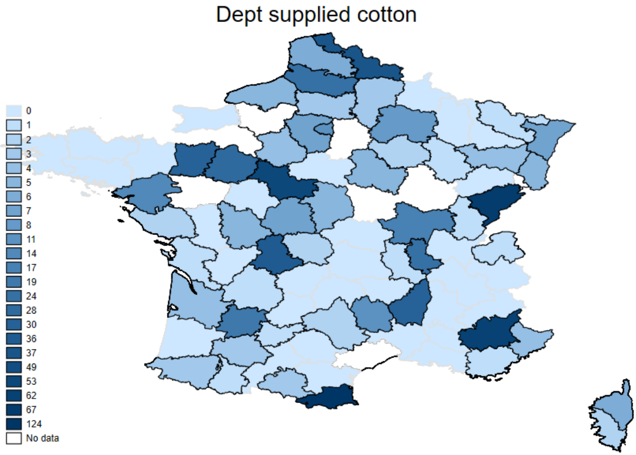
Cotton spinning already had a high degree of market integration

Number of districts to which each department supplied cotton



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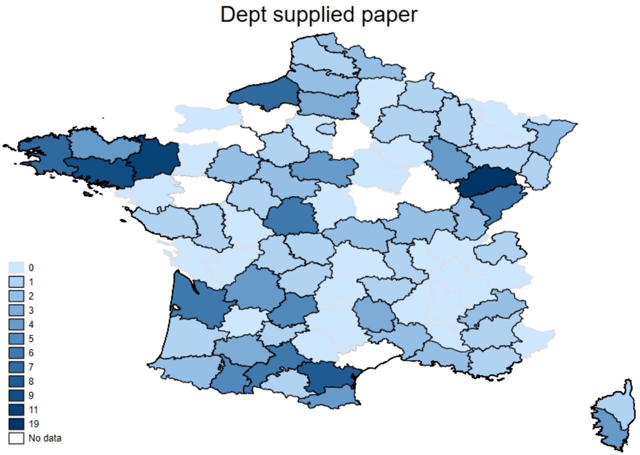
Metallurgy had lower market integration than cotton spinning

Number of districts to which each department supplied metal



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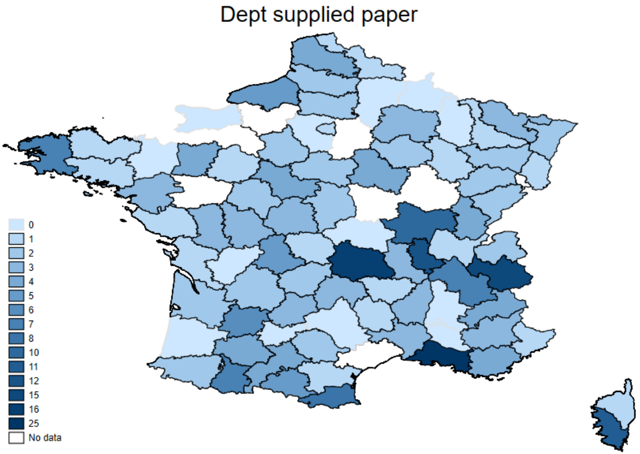
Paper milling had lower market integration than cotton spinning

Number of districts to which each department supplied paper



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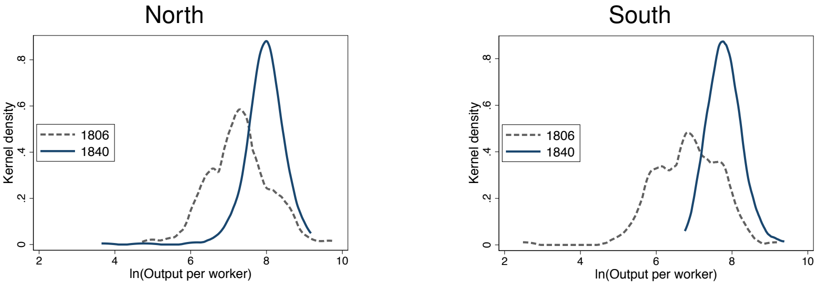
Spinning: Productivity growth in the 'North' and 'South' of France



Notes: Northern communes are those located in above-median latitude. Southern communes are those located in below-median latitude.

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Productivity growth concentrated at different parts of the distribution – firms with at least 10 workers

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Average	At the following quantiles:					N
		0.1	0.25	0.5	0.75	0.9	
Spinning (1806-1840)	2.261***	3.917***	3.191***	2.179***	1.612***	0.309	777
	(0.177)	(0.227)	(0.258)	(0.170)	(0.240)	(0.292)	
Metallurgy (1811-1840)	1.990***	1.751**	1.578***	1.523***	2.029***	1.845***	905
	(0.235)	(0.759)	(0.405)	(0.275)	(0.235)	(0.243)	
Paper milling (1794-1840)	1.245***	1.024***	1.086***	1.186***	1.434***	1.289***	507
	(0.136)	(0.225)	(0.162)	(0.121)	(0.159)	(0.274)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Productivity growth concentrated at different parts of the distribution – controlling for number of workers

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Average	At the following quantiles:					N
		0.1	0.25	0.5	0.75	0.9	
Spinning (1806-1840)	2.427***	3.941***	3.427***	2.292***	1.836***	0.974***	868
	(0.162)	(0.231)	(0.243)	(0.165)	(0.185)	(0.304)	
Number workers	-0.006	-0.073	-0.072	-0.048	-0.169**	-0.257**	
	(0.063)	(0.092)	(0.090)	(0.058)	(0.071)	(0.115)	
Metallurgy (1811-1840)	2.852***	3.296***	2.539***	2.552***	2.916***	2.507***	1296
	(0.177)	(0.438)	(0.275)	(0.214)	(0.184)	(0.202)	
Number workers	-1.219***	-1.338***	-1.183***	-1.193***	-1.105***	-1.066***	
	(0.082)	(0.143)	(0.093)	(0.099)	(0.081)	(0.083)	
Paper milling (1794-1840)	0.808***	0.744***	0.627***	0.780***	0.955***	1.505***	868
	(0.125)	(0.139)	(0.157)	(0.112)	(0.161)	(0.188)	
Number workers	-0.100*	0.206***	0.111	-0.002	-0.124*	-0.432***	
	(0.060)	(0.066)	(0.073)	(0.046)	(0.073)	(0.051)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Productivity growth concentrated at different parts of the distribution – capital deepening

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Average	At the following quantiles:					N
		0.1	0.25	0.5	0.75	0.9	
Spinning (1806-1840)	1.960***	3.555***	2.930***	1.966***	1.254***	0.755***	868
	(0.167)	(0.267)	(0.247)	(0.178)	(0.190)	(0.281)	
K/L	0.522***	0.374***	0.467***	0.389***	0.379***	0.542***	
	(0.075)	(0.082)	(0.085)	(0.068)	(0.090)	(0.141)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

- In 1800, key technology adopted in cotton spinning and no major technological changes until 1840 $\Longrightarrow$ but learning about efficient organization of factory-based production

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Productivity growth concentrated at different parts of the distribution – controlling for market access

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Average	At the following quantiles:					N
		0.1	0.25	0.5	0.75	0.9	
Spinning (1806-1840)	2.444***	3.978***	3.028***	2.170***	1.697***	1.251***	844
	(0.157)	(0.221)	(0.203)	(0.158)	(0.167)	(0.313)	
Market access	0.349***	0.401***	0.397***	0.229***	0.279***	0.483***	
	(0.095)	(0.138)	(0.097)	(0.075)	(0.104)	(0.186)	
Metallurgy (1811-1840)	1.951***	1.438***	1.687***	1.881***	2.161***	2.488***	1242
	(0.189)	(0.431)	(0.287)	(0.232)	(0.213)	(0.248)	
Market access	0.136	0.979**	0.190	-0.378	-0.114	-0.421*	
	(0.198)	(0.431)	(0.409)	(0.320)	(0.142)	(0.236)	
Paper milling (1794-1840)	0.710***	0.735***	0.685***	0.759***	0.743***	0.409	853
	(0.110)	(0.164)	(0.135)	(0.098)	(0.136)	(0.259)	
Market access	0.680***	0.209	0.314	0.433**	0.537*	1.775***	
	(0.187)	(0.205)	(0.271)	(0.171)	(0.307)	(0.664)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Productivity growth concentrated at different parts of the distribution – controlling for region FE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Average	At the following quantiles:					N
		0.1	0.25	0.5	0.75	0.9	
Spinning (1806-1840)	2.028***	2.941***	2.352***	1.982***	1.943***	1.659***	844
	(0.158)	(0.455)	(0.208)	(0.168)	(0.218)	(0.191)	
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	
Metallurgy (1811-1840)	1.766***	2.012***	1.317***	1.781***	1.838***	1.786***	1243
	(0.181)	(0.211)	(0.273)	(0.158)	(0.139)	(0.214)	
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	
Paper milling (1794-1840)	0.785***	0.928***	0.827***	0.730***	0.614***	0.664***	853
	(0.118)	(0.099)	(0.132)	(0.098)	(0.120)	(0.106)	
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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Productivity growth concentrated at different parts of the distribution – prices not quality-adjusted and TFP

	(1) Average	(2)	(3)	(4)	(5)	(6)	(7) N
		At the following quantiles:					
		0.1	0.25	0.5	0.75	0.9	
PANEL A: Baseline							
Spinning (1806-1840)	2.420***	3.917***	3.293***	2.234***	1.651***	1.014***	868
	(0.154)	(0.204)	(0.229)	(0.151)	(0.167)	(0.297)	
PANEL B: Using prices not quality-adjusted							
Spinning (1806-1840)	2.373***	3.381***	2.828***	2.105***	1.829***	1.628***	868
	(0.138)	(0.285)	(0.199)	(0.193)	(0.160)	(0.188)	
PANEL C: Using TFP							
Spinning (1806-1840)	2.845***	3.233***	3.107***	2.834***	2.647***	2.317***	868
	(0.050)	(0.080)	(0.072)	(0.056)	(0.083)	(0.072)	

Notes: Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

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