Technological Stickiness: Switching and Entry in the Long Transition from Water to Steam Power

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Motivation

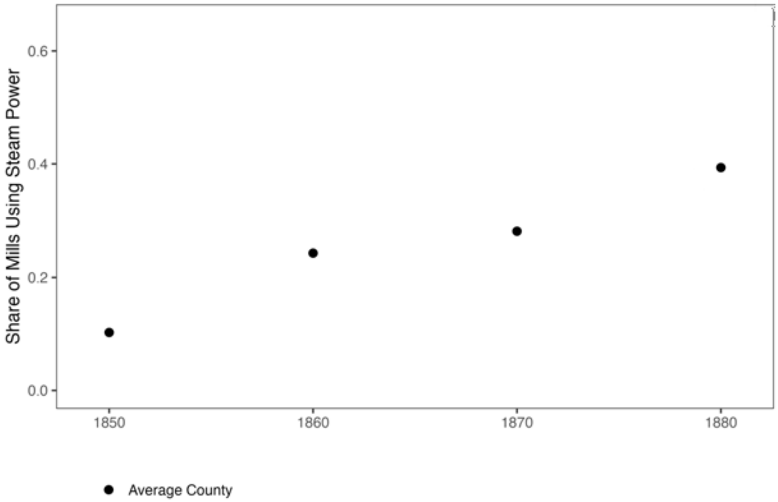
Technological innovations drive growth, but widespread adoption can be protracted

→ Long periods with coexistence of new and old technology (David, 1990)

Case in point: Transition from water to steam power in 19th century US manufacturing

- Steam offers freedom of location, scalability, all-year reliability, ...
- Yet, 100 years before peak adoption

Steam Use in Lumber and Flour Milling



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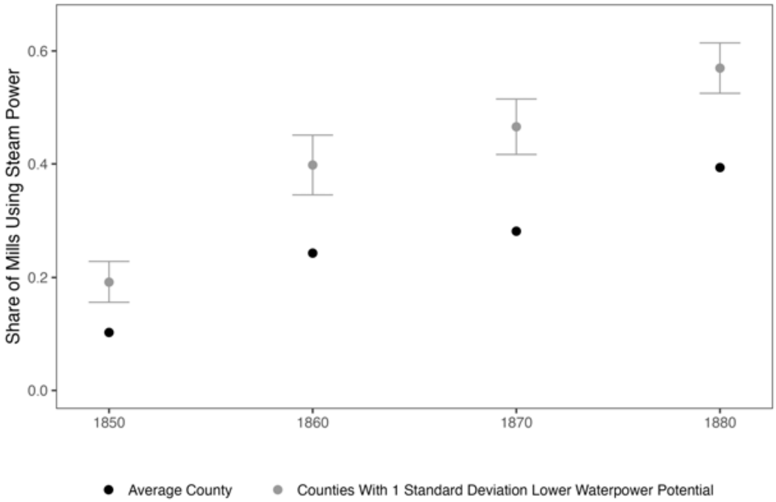
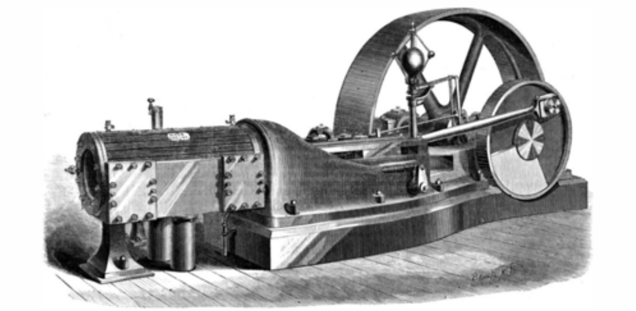


Water vs Steam: Static

- Steam has many advantages over water power
  - fewer locational constraints, easier to scale, not seasonal,...
- But benefits even larger in places that previously did not have access to mechanical power

Static advantages can lead to gradual steam adoption given technical change



Water vs Steam: Dynamic

- Water powered mills depreciate slowly
  - You can go buy Central Milling Flour (est. 1867), 2 miles away
- But businesses churn: 10-year survival rate is about a fifth in our sample

Related Literature

1. Technology diffusion: Griliches (1957), Gerschenkron (1962); Jovanovic and Nyarko (1996), Comin and Hobijn (2010), Collard-Wexler & De Loecker (2015), Humlum (2021)
   - ⋆ Quantify role of switching costs
2. Creative destruction: Schumpeter (1947), Christensen (1997)
   - ⋆ Steam entrants crowd out of water incumbents
3. Water and steam power: Temin (1966); Chandler (1972); Hunter (1979); Atack (1979); Rosenberg and Trajtenberg (2004); Atack, Bateman, and Margo (2008); Chernoff (2021)
   - ⋆ Long panel to study switching and entry

Key Features of the Model

Estimate structural model of firm entry and steam adoption:

- Both steam and waterpowers exist in tandem:
  - One must be cheaper to purchase, the other cheaper to use
  - Use the firm size distribution $\Rightarrow$ steam is the low marginal cost technology
- Similar strategy to motivate:
  - Improvements in steam power over time
  - Differences in water costs over space

Quantify role of switching barriers in aggregate transition dynamics

$\Rightarrow$ Given entry, what makes firm-level barriers matter on aggregate?

Roadmap

Data

Facts

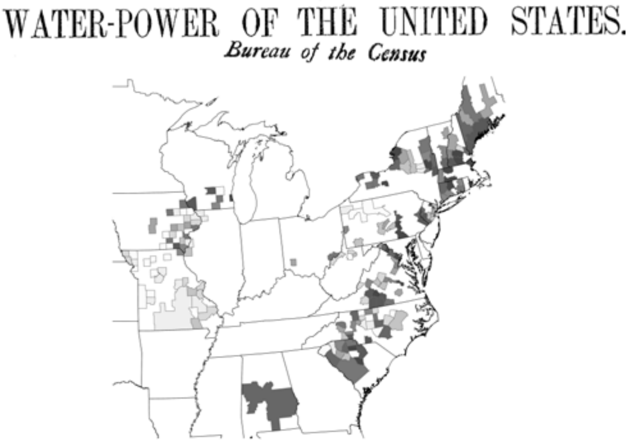
Reduced-Form Results

Water Power Potentials

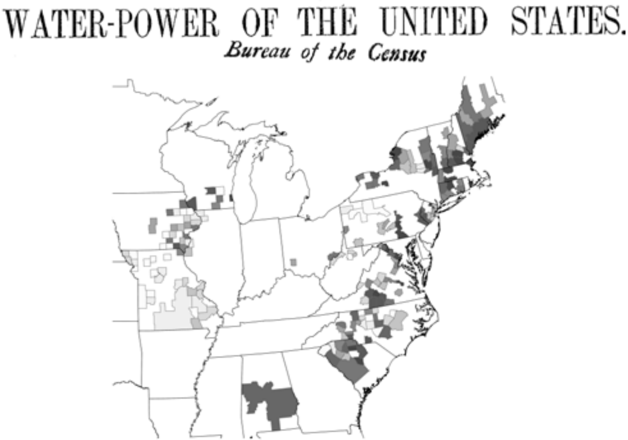
$$\text{TheoreticalWaterPower} = \underbrace{\text{FlowRate}}_{\substack{\text{Cubic Feet}\\ \text{Per Second}}} \times \underbrace{\text{FallHeight}}_{\text{Feet}} \times {}^{\substack{\text{Gravitational}\\ \text{Constant}}}$$

→ Flow and fall are complements in producing power

Historical Water Census



Historical Water Census



"describing privileges actually in use, and calling attention to locations where power could be advantageously developed" ▸ Bias

Modern Hydrographic Data (NHDPlusV2)

For each "flowline" (1 mile river segments):

1. Estimates natural water flow, independent of dams and industrial activity
   - Geological model based on local rainfall, evaporation, flow transfers, etc.
2. Reports elevation change

Modern Water Power

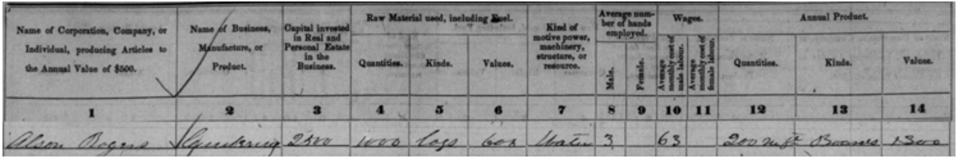
Flow Rate

Fall Height

▸ Agreement for Common Sites

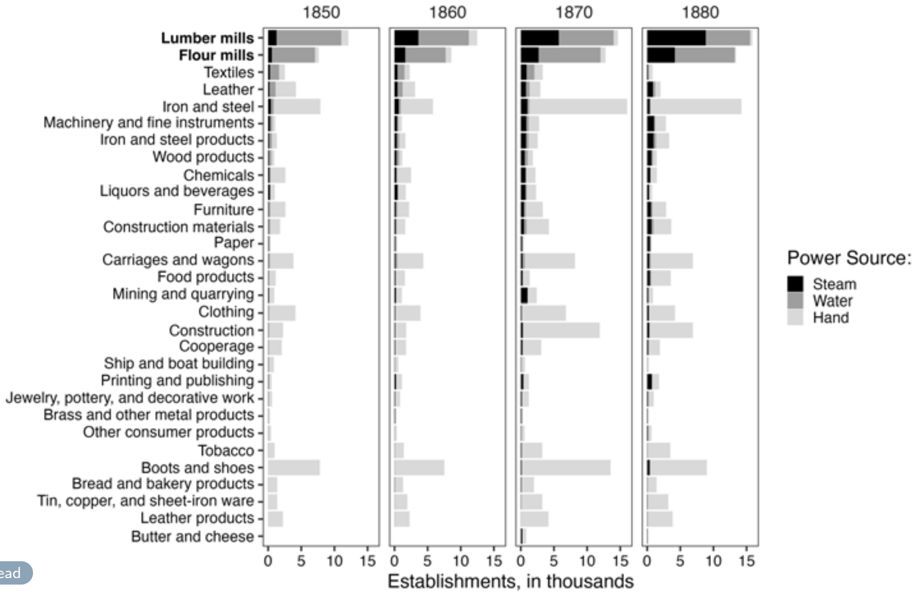
Establishment-Level Census of Manufactures

Figure: Alson Rogers' Lumber Mill in 1850



Name of Corporation, Company, or Individual, producing Articles to the Annual Value of $500.	Name of Business, Manufacture, or Product.	Capital invested in Real and Personal Estate in the Business.	Raw Material used, including Fuel.			Kind of motive power, machinery, structure, or resource.	Average number of hands employed.		Wages.		Annual Product.		
			Quantities.	Kinds.	Values.		Male.	Female.	Average monthly cost of male labour.	Average monthly cost of female labour.	Quantities.	Kinds.	Values.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Alson Rogers	[illegible]	2500	1000	Logs	600	Water	3		63		200 m ft	Boards	1300

Power Use By Sector



Geographic Spread

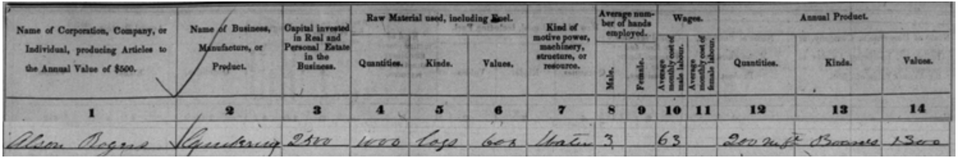
Panel of Lumber and Grist mills

Link establishments over time based on names, location, and industry

1. Hand-link mills 1850-1880
2. Validate against machine-learning model
3. Validate links in historical society pages

Establishment-Level Census of Manufactures

Figure: The Rogers' Lumber Mill in 1850 & 1880



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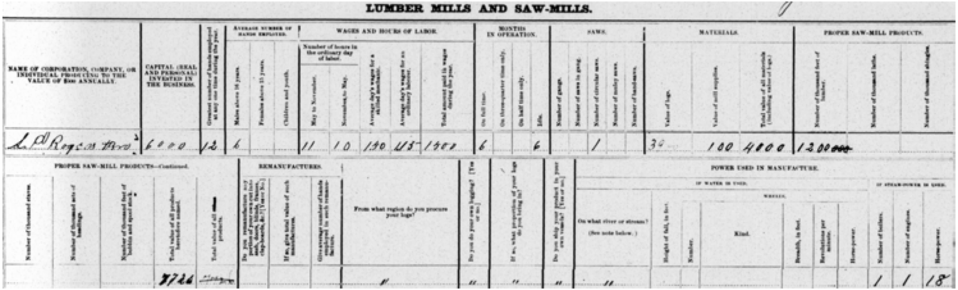

LUMBER MILLS AND SAW-MILLS.

Name of corporation, company, or individual producing to the value of $500 annually.	Capital (real and personal) invested in the business.	Greatest number of hands employed at any one time during the year.	Average number of hands employed: Males above 16 years.	Females above 15 years.	Children and youth.	Wages and hours of labor: Number of hours in the ordinary day of labor: May to November.	November to May.	Average day's wages for a skilled mechanic.	Average day's wages for an ordinary laborer.	Total amount paid in wages during the year.	Months in operation: On full time.	On three-quarter time only.	On half time only.	Idle.	Saws: Number of gangs.	Number of saws in gang.	Number of circular saws.	Number of muley saws.	Number of bandsaws.	Materials: Value of logs.	Value of mill supplies.	Total value of all materials (including value of logs).	Proper saw-mill products: Number of thousand feet of lumber.	Number of thousand laths.	Number of thousand shingles.
L. P. Rogers & Bros.	6000	12	6			11	10	1.50	1.15	1500	6			6			1			30	100	4800	1200		

Proper saw-mill products—Continued: Number of thousand staves.	Number of thousand sets of headings.	Number of thousand feet of bobbin and spool stock.	Total value of all products hereinbefore named.	Total value of all products.	Remanufactures: Do you remanufacture any portion of your own products into sash, doors, blinds, flume, clapboards, &c.? [Yes or No.]	If so, give total value of such manufactures.	Give average number of hands employed in such remanufacture.	From what region do you procure your logs?	Do you do your own logging? [Yes or no.]	If so, what proportion of your logs do you bring in?	Do you ship your product in your own vessels? [Yes or no.]	Power used in manufacture: If water is used: On what river or stream? (See note below.)	Height of fall, in feet.	Wheels: Number.	Kind.	Breadth, in feet.	Revolutions per minute.	Horse-power.	If steam-power is used: Number of boilers.	Number of engines.	Horse-power.
			7726	[illegible]				″	″	″	″	″							1	1	18

Roadmap

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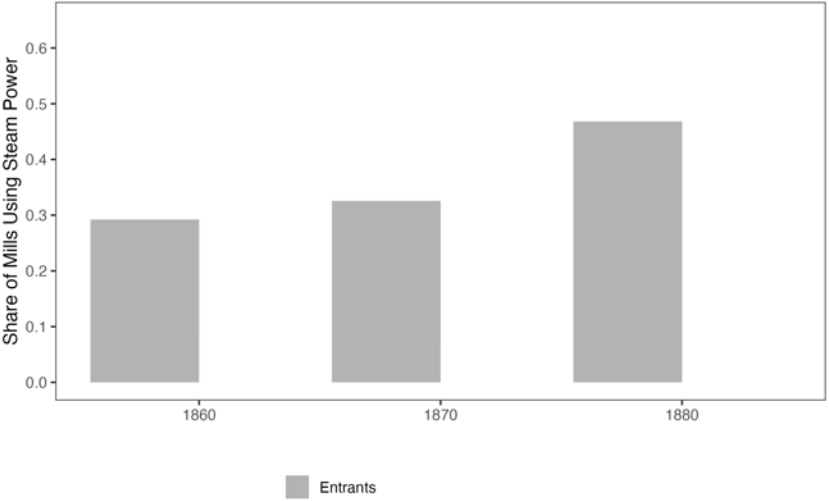
Facts

Reduced-Form Results

Fact 1: Entrants More Likely to Use Steam



▸ Owner characteristics ▸ Alternative Stories

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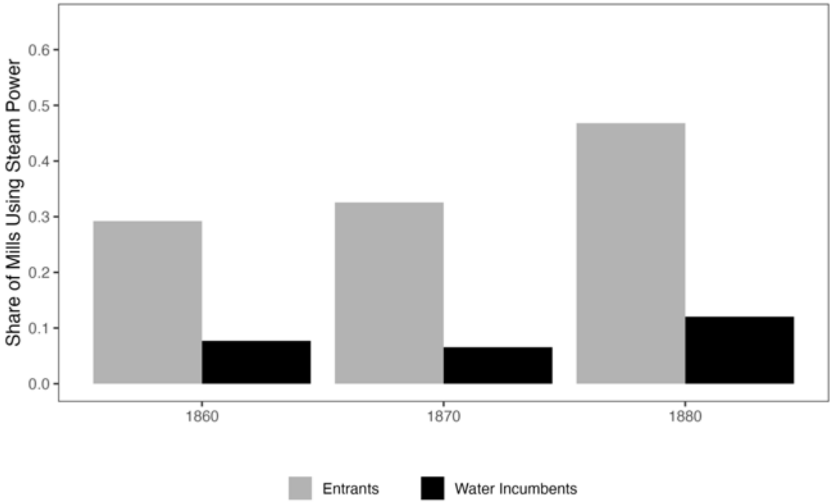


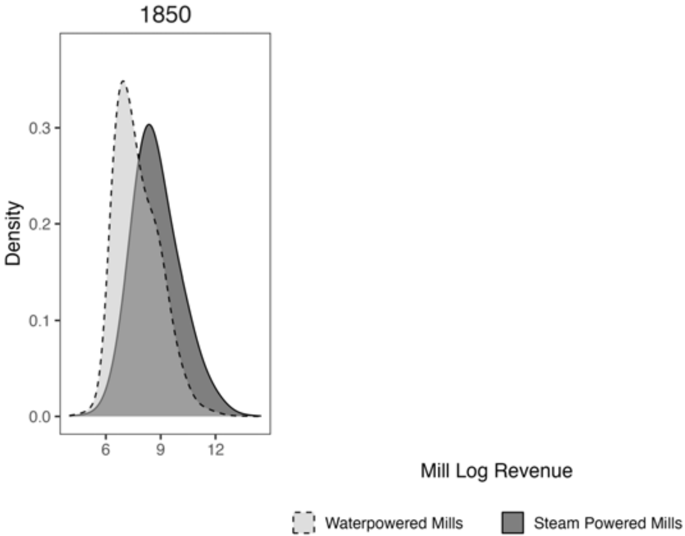
▸ Owner characteristics ▸ Alternative Stories

Fact 2: Business Churn

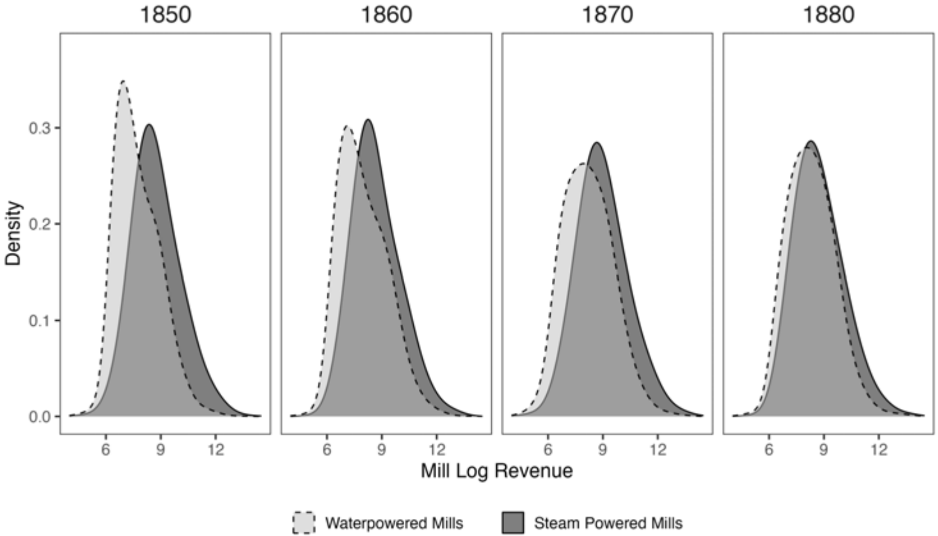
Table: Survival Rate

	By Initial Output				By Initial Power Source	
Year	Q1	Q2	Q3	Q4	Water	Steam
1850-1860	0.178	0.220	0.222	0.247	0.223	0.163
1860-1870	0.181	0.206	0.220	0.240	0.229	0.165
1870-1880	0.202	0.231	0.253	0.275	0.256	0.207

Fact 3: Steam Plants are Larger

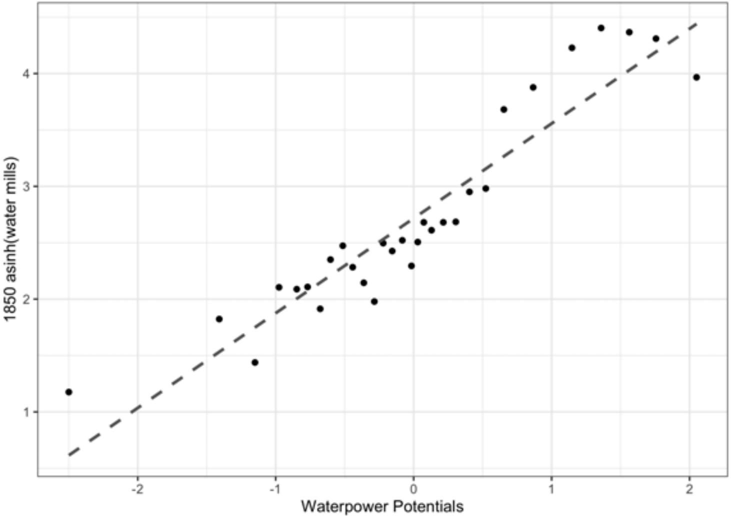


Fact 4: Steam Diffuses to Smaller Plants Over Time

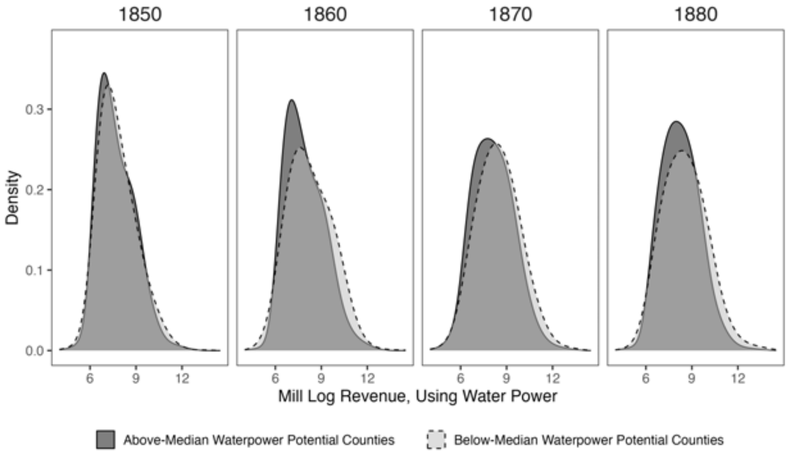


▸ Within-County

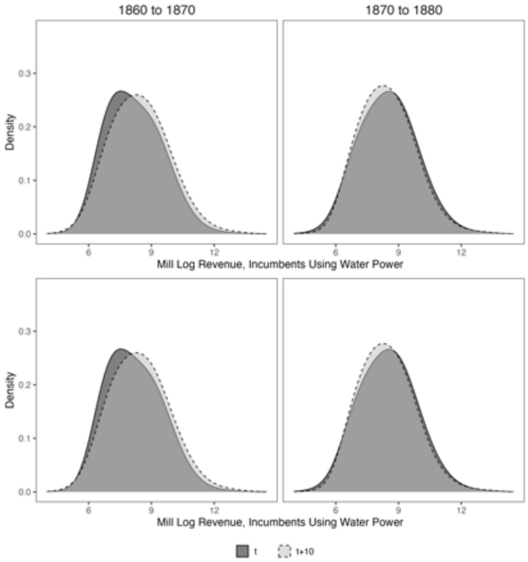
Fact 5: (Potential) Waterpower leads to (Actual) Waterpower



Stylized Fact 5b: Potential waterpower doesn't lead to larger mills



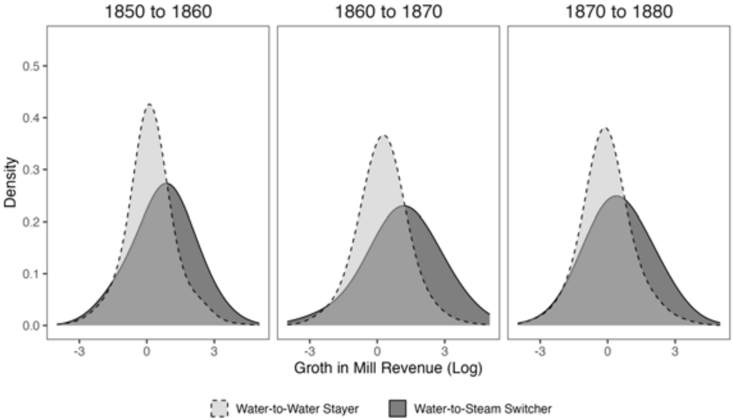
Stylized Fact 1b: Water Incumbents don't "grow" faster than entrants



▸ Back

Stylized Fact 1c: Water-to-Steam Switchers Grow

Figure: Mill Size by Past Switching Choice



Back

Linking to the Population Census

	Mean Value	Uses Steam			
	(1)	(2)	(3)	(4)	(5)
Immigrant	0.069	0.076			0.075
	[0.253]	(0.015)			(0.015)
Age, in years	44.7		-0.0018		-0.0016
	[13.3]		(0.0002)		(0.0002)
Professional Miller	0.395			0.041	0.035
	[0.489]			(0.006)	(0.006)
# Mills	30,777	30,777	30,777	30,777	30,777
Mean of Dependent Variable		0.203	0.203	0.203	0.203

Translating Stylized Facts to Model Assumptions

Stylized Fact

1. Business churn
2. Entrants use more steam
3. Steam users are larger
4. Steam diffuses to smaller plants
5. Water potential $\rightarrow$ Water use

Model Assumption

1. Fixed costs of operating
2. Fixed costs of switching
3. Fixed costs of adoption
4. Falling fixed costs of adoption
5. Heterogeneous fixed costs of waterpower over space

Comparative Statics

Lower waterpower $\rightarrow$

1. Faster steam adoption
   - especially of entrants
2. Faster growth
   - especially of entrants
3. Unclear: if incumbents are crowded out
   - option value of steam power vs. market stealing of steam entrants

Roadmap

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Identification

Waterpower Potentials (per m^2)

Raw Variation

Baseline Controls

Baseline controls

- Total stream flow, Ruggedness
- Dummy for navigable river, Distance to navigable river, 1850 market access
- Coal

Revisiting Fact 5a: (Potential) Waterpower Leads to (Actual) Waterpower

	All Mills (1)	Only Lumber Mills (2)	Only Flour Mills (3)
Panel A. Number of Waterpowered Mills			
Lower Waterpower	-1.055	-1.246	-0.783
	(0.130)	(0.173)	(0.109)
Panel B. Revenue of Waterpowered Mills			
Lower Waterpower	-1.127	-0.974	-1.178
	(0.249)	(0.215)	(0.302)
# County-Industries	1,199	612	587

Revisiting Fact 5a: (Potential) Waterpower Leads to (Actual) Steampower

	All Mills (1)	Only Lumber Mills (2)	Only Flour Mills (3)
Panel C. Steam Share of Mills			
Lower Waterpower	0.089	0.107	0.060
	(0.015)	(0.019)	(0.016)
Panel D. Steam Share of Revenue			
Lower Waterpower	0.123	0.160	0.060
	(0.022)	(0.031)	(0.021)
# County-Industries	1,199	612	587

In GE: (Potential) Waterpower Leads to Economic Activity

	All Mills (1)	Only Lumber Mills (2)	Only Flour Mills (3)
Panel E. Total Number of Mills			
Lower Waterpower	-0.956	-1.100	-0.738
	(0.119)	(0.156)	(0.105)
Panel F. Total Revenue of Mills			
Lower Waterpower	-0.876	-0.704	-0.973
	(0.215)	(0.173)	(0.291)
# County-Industries	1,199	612	587

Lower Waterpower → Earlier Steam Adoption and Economic Growth

	Steam Share of Mills (1)	Total Mills (2)	Total Mill Revenue (3)
Growth in Lower Waterpower Counties:			
From 1850 to 1860	0.067	0.220	0.183
	(0.016)	(0.062)	(0.081)
# County-Industries	1,084	1,199	1,199
From 1860 to 1870	0.034	0.113	0.203
	(0.013)	(0.052)	(0.097)
# County-Industries	1,061	1,199	1,199
From 1870 to 1880	-0.009	0.092	0.140
	(0.013)	(0.036)	(0.087)
# County-Industries	1,138	1,199	1,199

▸ Per Capita ▸ Robustness

Earlier Steam Adoption... especially of entrants

	Entrants (1)	Water Incumbents (2)	Difference (1) − (2) (3)
Adoption in Lower Waterpower Counties:			
In 1860	0.169	0.034	0.135
	(0.024)	(0.021)	(0.023)
# County-Industries	1,076	607	
In 1870	0.188	0.049	0.139
	(0.022)	(0.018)	(0.025)
# County-Industries	1,151	560	
In 1880	0.172	0.051	0.121
	(0.022)	(0.024)	(0.025)
# County-Industries	1,169	685	

Faster Growth... especially of entrants

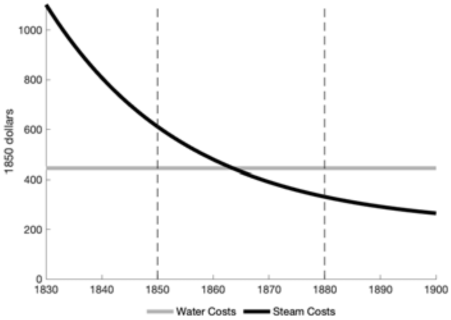
	Entry Rate (1)	Survival Rate (2)	Difference (1) − (2) (3)
Elasticity with Respect to Lower Waterpower:			
In 1860	0.323	-0.230	0.554
	(0.074)	(0.065)	(0.089)
# County-Industries	1,199	1,199	
In 1870	0.168	-0.266	0.434
	(0.058)	(0.057)	(0.072)
# County-Industries	1,199	1,199	
In 1880	0.158	-0.158	0.316
	(0.045)	(0.040)	(0.061)
# County-Industries	1,199	1,199	

Brief Digression: Agglomeration

Table: Waterpower and Non-Mills

	Total Non-Mill Establishments (1)	Steam User Share of Non-Mill Establishments (2)	Steam Makers, Relative to All Establishments (3)
Differences in Lower Waterpower Counties:			
In 1850	-0.546	0.016	0.410
	(0.229)	(0.005)	(0.162)
# Counties	690	674	690
In 1860	-0.428	0.023	0.326
	(0.328)	(0.008)	(0.211)
# Counties	690	661	690
In 1870	-0.525	0.035	0.501
	(0.234)	(0.010)	(0.242)
# Counties	690	678	690

Model & History: Purchase Price of Power



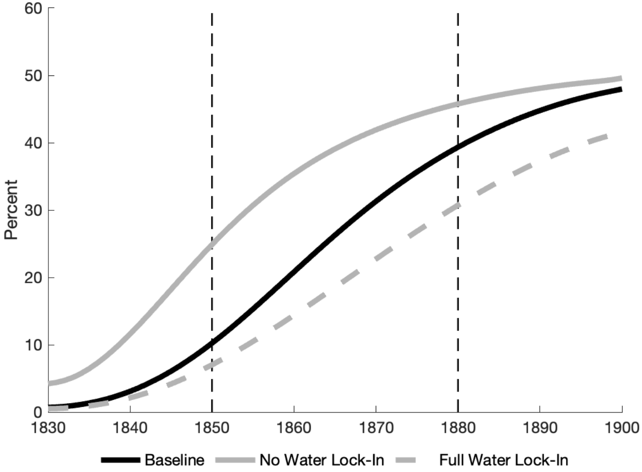
Historical evidence:

- Steam Engine costs $2500 in 1840 (Armistead et al. 1841)
- Purchase Price of Steam and Water similar in 1880 (Swain 1888)
- Operating costs of steam 2x water (Swain 1888)

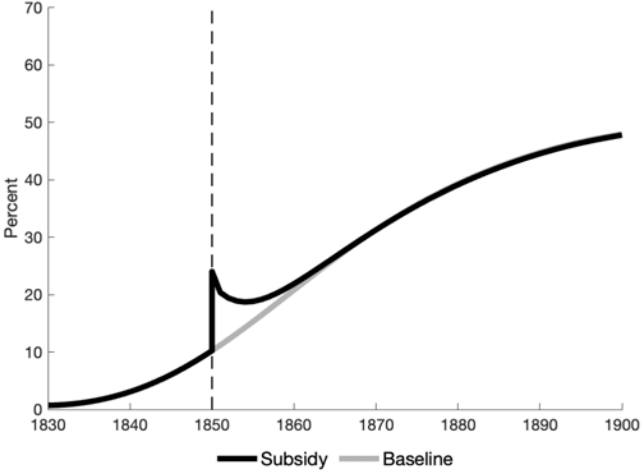
Other Model Estimates

- With complete irreversability - sunk costs are 95% of barriers
- Agglomeration benefits aren't huge - 2.5% increase in productivity with 100% steam use - but generate large increases in aggregate output

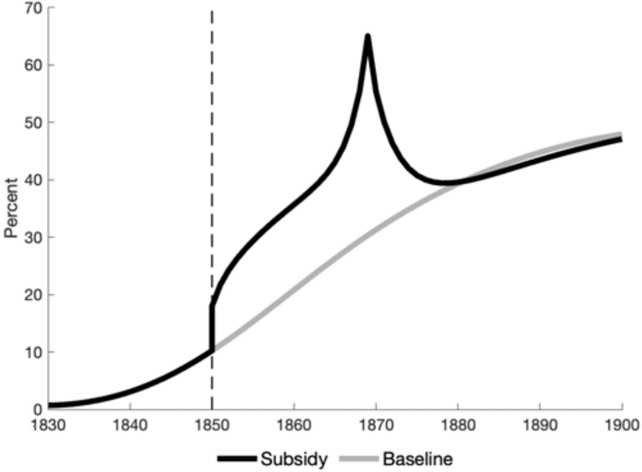
Counterfactuals: Effects of Switching Barriers



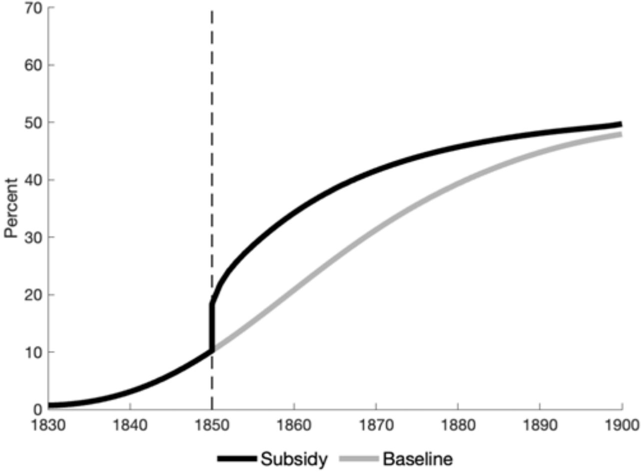
Counterfactuals: Diffusion of Steam Power with a 1 year subsidy



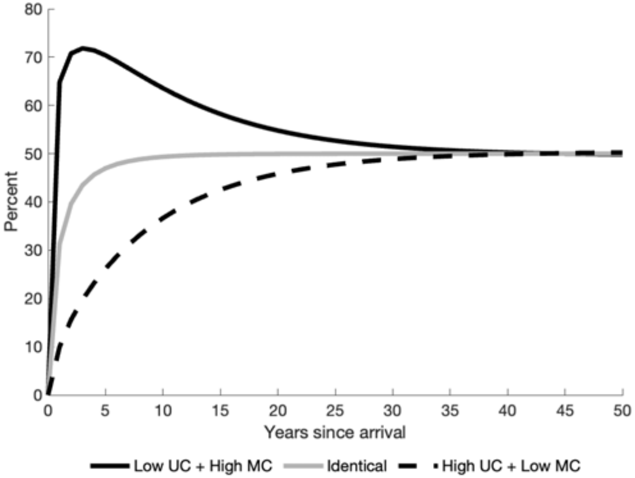
Counterfactuals: Diffusion of Steam Power with a 20 year subsidy



Counterfactuals: Diffusion of Steam Power with a permanent subsidy



Switching Costs AND Fixed Costs Matter



Conclusion

Previous investments in waterpower

- Slowed the adoption of steam
- Barred incumbents from benefits of steam

Switching costs are quantitatively important

- Steam would have diffused faster without water lock-in
- Entry/exit does not neutralize switching costs
- Spillovers small enough that temporary policies would have temporary effects

Thank You!

Model Ingredients

1. Manufacturers: select locations, choose power sources, sell output locally
   - → Forward-looking decision: future adoption costs, future demand, etc.
2. Steam power is easier to scale, but incumbents face switching costs
   - → Option value of steam power vs. market stealing by steam entrants
3. Locations differ by water adoption costs
4. Steam adoption costs fall everywhere

Production & Demand

Productivity determined by a baseline productivity φ, an additional productivity from its power source γ_R, and an agglomeration force $\alpha_{R_{jlt}}$ in local steam-use s_{lt}

$$y_{jlt} = \exp(\varphi_{jlt} + \gamma_{R_{jlt}} + \alpha_{R_{jlt}} s_{lt}) x_{jlt}$$

Consumers have nested CES demand, with elasticity ϵ within sector and η across

So, a firm's sales and profits are

$$y_{jlt} = p_{jlt}^{-\epsilon} P_{lt}^{\epsilon-\eta}$$

$$\pi_{jlt}(R) = \frac{1}{\epsilon} {P_{lt}}^{\epsilon-\eta} \left(\frac{\epsilon}{\epsilon - 1} \frac{w}{\exp(\varphi_{jlt} + \gamma_{R_{jlt}} + \alpha_{R_{jlt}} s_{lt})} \right)^{1-\epsilon}$$

Power

Technology states

$$R \in \{\text{Entrant}, \text{Water}, \text{Steam}\}$$

Costs of switching reflect buying prices, resale values, and other frictions

$$c_{lt}(R, R') = \begin{cases} 0 & \text{if } R = R' \\ c_{lt}(R') & \text{if } R = E \\ c_{lt}(R') - \omega^R c_{lt}(R) + c(R, R') & \text{otherwise} \end{cases}$$

Power

Technology states

$$R \in \{\text{Entrant}, \text{Water}, \text{Steam}\}$$

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Price of water $c_l(W)$ varies over space but not time
Price of steam $c_t(S)$ varies over time but not space

Dynamic Choices

1. Prospective entrants decide to enter
2. Entrants draw & incumbents update productivity
3. Firms choose if they want to produce
4. Surviving firms decide if they want to change power source

▸ Solution algorithm

Dynamic Choices

1. Prospective entrants decide to enter:

$$\mathbb{E}_{\varphi}\left[V_{It}(E,\varphi)\right] - f^{e} \geq 0$$

▸ Solution algorithm

Dynamic Choices

2. Entrants draw & incumbents update productivity:

Productivity of incumbents follow an AR(1) process

$$\varphi_{jt} = \pi\varphi_{jt-1} + \sigma\xi_{jt}$$

Entrants draw productivities from the resulting stationary distribution

▸ Solution algorithm

Dynamic Choices

3. Firms choose if they want to produce:

Compare the expected value from paying the operating cost to the value of exit

$$V_{lt}(R,\varphi) = \max\{\mathbb{E}_{\varepsilon}\left[V^{o}_{lt}(R,\varphi)\right] - f^{R} - \nu^{R}_{jlt}(0), \Omega^{R}_{lt} - \nu^{R}_{jlt}(1)\}$$

▸ Solution algorithm

Dynamic Choices

4. Surviving firms decide if they want to change power source:

$$V^{o}_{lt}(R,\varphi) = \max_{R' \in \{W,S\}} \{\pi_{lt}(R',\varphi) - c_{lt}(R,R') - \varepsilon_{jlt}(R') + \delta \mathbb{E}_{\varphi'}\left[V_{lt+1}(R',\varphi')\right]\}$$

▸ Solution algorithm

Equilibrium

1. Firms enter, exit, and adopt power to maximize expected discounted profits
2. Firms compete in local product markets
3. Transition path along $c_t^S \rightarrow \underline{c}^S$

Distributional Assumptions

Operation/exit cost shocks

$$\varepsilon_{jt}^{k} \overset{\text{iid}}{\sim} \text{GEV}(\rho_1^k), \quad \forall (k, j, t)$$

Adoption cost shocks

$$\varepsilon_{jt}^{R} \overset{\text{iid}}{\sim} \text{GEV}(\rho_2), \quad \forall (R, j, t)$$

Baseline productivities

$$\phi_{jt} \sim \begin{cases} \mathcal{N}(\kappa + \pi\phi_{jt-1}, \sigma^2) & \text{if } j \text{ is incumbent} \\ \mathcal{N}\left(\dfrac{\kappa}{1-\pi}, \dfrac{\sigma^2}{1-\pi^2}\right) & \text{if } j \text{ is entrant} \end{cases}$$

▸ Owner characteristics

Parameters and Moments (Method of Simulated Moments)

Within-Region Moments (*Stylized Facts*)

Between-Region Moments (*Effects of Lower Waterpower*)

Model Validation

Parameters and Moments (Method of Simulated Moments)

Within-Region Moments (*Stylized Facts*)

1. Fixed costs of entry/operation $\leftarrow$ Entry/exit rates
2. Steam adoption costs $\leftarrow$ Steam adoption rates over time
3. Switching costs $\leftarrow$ Adoption rates of incumbents vs. entrants
4. Steam productivity $\leftarrow$ Relative size of steam plants

Between-Region Moments (*Effects of Lower Waterpower*)

Model Validation

Parameters and Moments (Method of Simulated Moments)

Within-Region Moments (*Stylized Facts*)

1. Fixed costs of entry/operation ← Entry/exit rates
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Between-Region Moments (*Effects of Lower Waterpower*)

1. Water costs by region ← Initial water adoption by LW
2. Elasticity of demand across sectors ← Initial economic activity by LW
3. Steam agglomeration ← Additional economic growth by LW

Model Validation

Parameters and Moments (Method of Simulated Moments)

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Between-Region Moments (*Effects of Lower Waterpower*)

1. Water costs by region $\leftarrow$ Initial water adoption by LW
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3. Steam agglomeration $\leftarrow$ Additional economic growth by LW

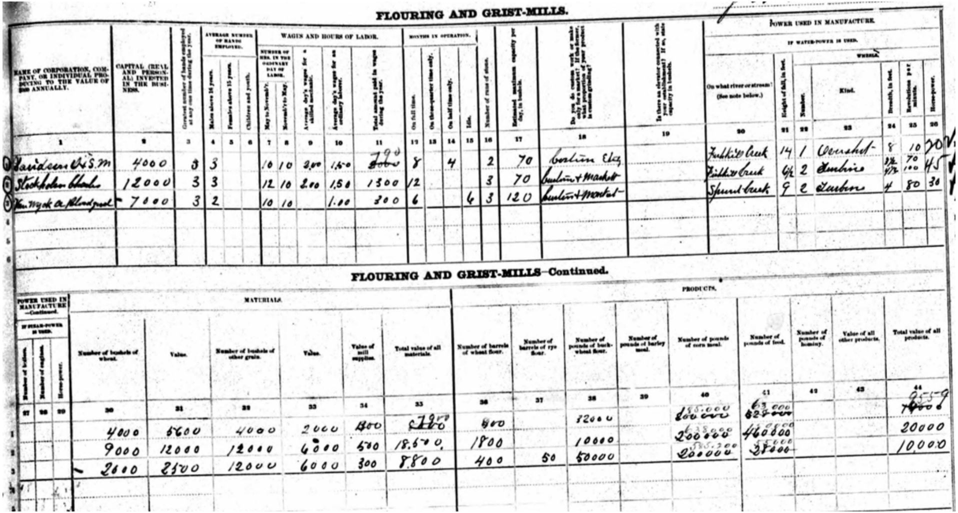
Model Validation

- Rationalize diffusion curves across regions?

Model Fit

	Moment	Years	Model	Data
	Baseline Region			
$c(W,S)$	Water Choice Differential: Water Incumbents vs. Entrants	1850-1880	0.552	0.553 (0.062)
$c(S,W)$	Steam Choice Differential: Steam Incumbents vs. Entrants	1850-1880	0.977	0.977 (0.123)
$c_S^{(init)}$	Steam Adoption Rate	1850	0.102	0.103 (0.006)
$c_S^{(term)}$	Steam Adoption Rate	1880	0.393	0.393 (0.011)
f_o^E	Log Sales Differential: Incumbents vs. Entrants	1850-1880	0.132	0.131 (0.015)
f_o^W	Water Exit Rate	1850-1880	0.789	0.789 (0.003)
f_o^S	Steam Exit Rate	1850-1880	0.835	0.835 (0.006)
γ	Log Sales Differential: Steam vs. Water Users	1850-1880	0.855	0.855 (0.029)
	Differences Between Low Water and Baseline Region			
$c_L(W)$	Steam Adoption Rate	1850	0.089	0.089 (0.016)
η	Log Total Output	1850	-0.876	-0.876 (0.215)
κ	Change in Steam Adoption Rate	1850-1880	0.092	0.092 (0.019)
α	Growth of Output	1850-1880	0.525	0.525 (0.118)

Establishment-Level Census of Manufactures, 1880



FLOURING AND GRIST-MILLS.

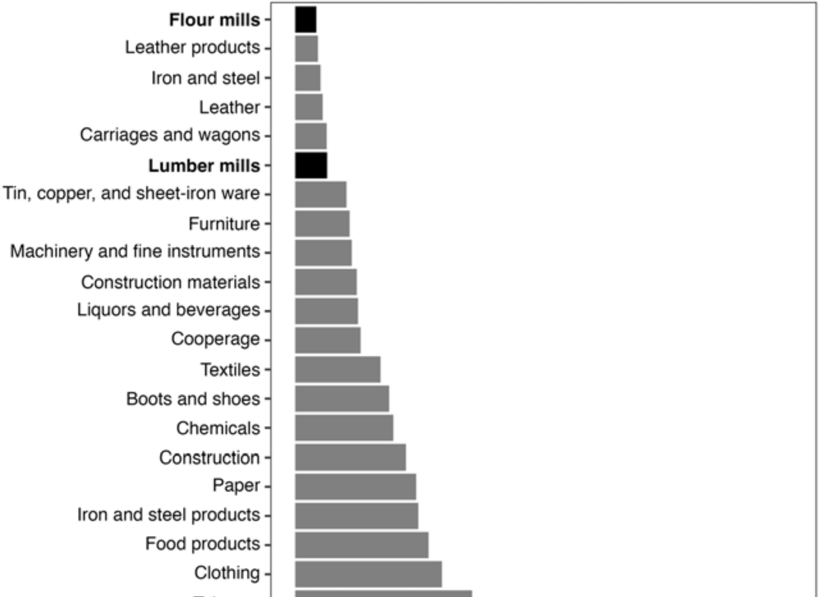
	Name of corporation, company, or individual producing to the value of $500 annually.	Capital (real and personal) invested in the business.	Greatest number of hands employed at any one time during the year.	Average number of hands employed: Males above 16 years.	Females above 15 years.	Children and youth.	Number of hours in the ordinary day of labor: May to Nov.	Nov. to May.	Average day's wages for a skilled mechanic.	Average day's wages for an ordinary laborer.	Total amount paid in wages during the year.	Months in operation: On full time.	On three-quarter time only.	On half time only.	Idle.	Number of runs of stone.	Estimated maximum capacity per day, in bushels.	Do you do custom work or make only for a market? If the former, what proportion of your product is custom grinding?	Is there an elevator connected with your establishment? If so, state capacity in bushels.	Power used in manufacture — If water-power is used: On what river or stream? (See note below.)	Height of fall, in feet.	Wheels: Number.	Kind.	Breadth, in feet.	Revolutions per minute.	Horse-power.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	Davidson O. & S. M.	4000	3	3			10	10	2.00	1.50	~~2000~~ 720	8		4		2	70	Custom Exc.		Fishkill Creek	14	1	Overshot	8	10	70
2	Stockholm [illegible]	12000	3	3			12	10	2.00	1.50	1300	12				3	70	Custom & Market		Fishkill Creek	6½	2	Turbine	3½ 4½	70 100	45
3	Van Wyck & Bloodgood	7000	3	2			10	10		1.00	300	6			6	3	120	Custom & Market		Sprout Creek	9	2	Turbine	4	80	30
4																										
5																										
6																										

FLOURING AND GRIST-MILLS—Continued.

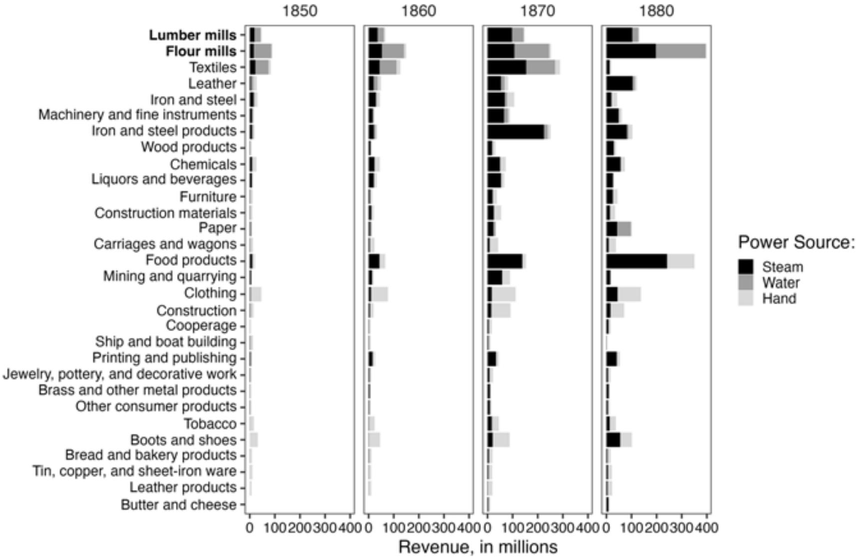
	Power used in manufacture—Continued. If steam-power is used: Number of boilers.	Number of engines.	Horse-power.	Materials: Number of bushels of wheat.	Value.	Number of bushels of other grain.	Value.	Value of mill supplies.	Total value of all materials.	Products: Number of barrels of wheat flour.	Number of barrels of rye flour.	Number of pounds of buckwheat flour.	Number of pounds of barley meal.	Number of pounds of corn meal.	Number of pounds of feed.	Number of pounds of hominy.	Value of all other products.	Total value of all products.
	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
1				4000	5600	4000	2000	1800	~~7200~~ 7900	800		32000		~~800000~~ 185,000	~~628000~~ 63,000			~~14000~~ 9559
2				9000	12000	12000	6000	500	18,500	1800		10000		~~200000~~ 638,000	~~460800~~ 450,000			20000
3				2600	2500	12000	6000	300	8,800	400	50	50000		~~200000~~ 585,200	~~28000~~ 55,000			10,000

▸ back

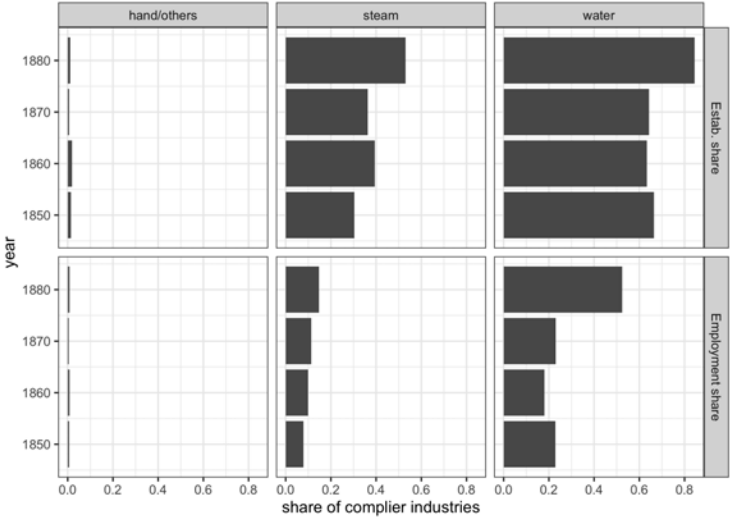
Geographic Spread of Production



Power Use By Sector, output-weighted

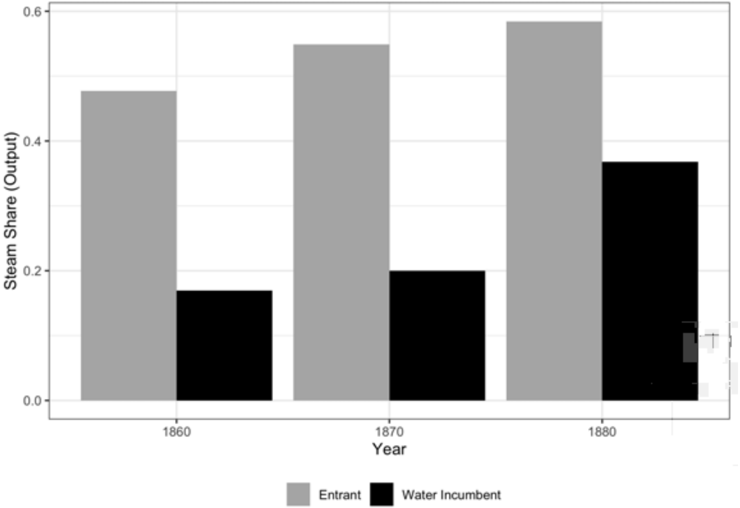


Share of Power in Grist + Lumber



Back

Fact 1: Entrants more likely to use steam



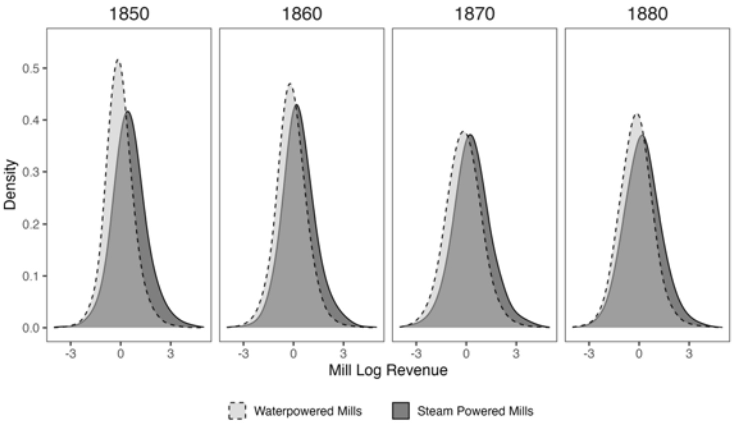
Back

Steam Users Are Younger, More Likely Immigrant, and Professional Millers

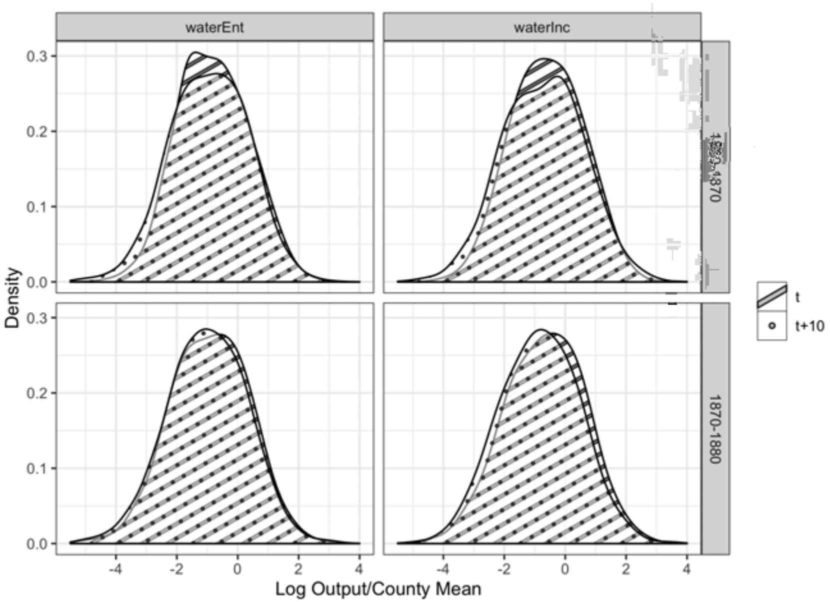
	Mean Value	Uses Steam			
	(1)	(2)	(3)	(4)	(5)
Immigrant	0.069	0.076			0.075
	[0.253]	(0.015)			(0.015)
Age, in years	44.7		-0.0018		-0.0016
	[13.3]		(0.0002)		(0.0002)
Professional Miller	0.395			0.041	0.035
	[0.489]			(0.006)	(0.006)
# Mills	30,777	30,777	30,777	30,777	30,777
Mean of Dependent Variable		0.203	0.203	0.203	0.203

Back: Facts Back: Model

Fact 4: Steam Diffuses to Smaller Mills over Time (Within-County

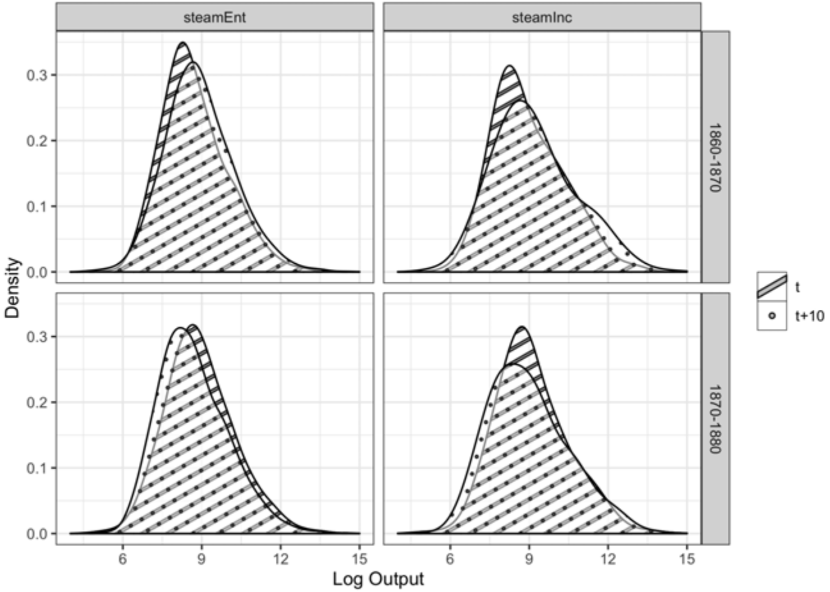


Back



waterEnt
waterInc
Density
Log Output/County Mean
1860-1870
1870-1880
t
t+10

Back



steamEnt
steamInc
1860-1870
1870-1880
Density
Log Output
0.0
0.1
0.2
0.3
6
9
12
15
t
t+10

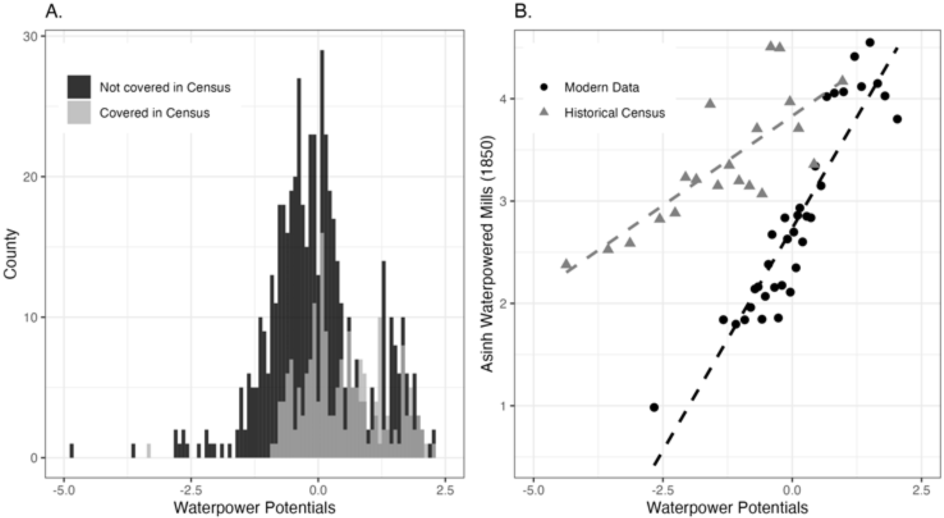
▸ Back

County-Level Activity

	Population (1)	Mills Per Capita (2)	Mill Revenue Per Capita (3)
Panel A. Differences in Lower Waterpower Counties:			
In 1850	-0.284	-0.672	-0.592
	(0.226)	(0.233)	(0.232)
Panel B. Growth in Lower Waterpower Counties:			
From 1850 to 1860	0.094	0.126	0.088
	(0.029)	(0.065)	(0.082)
From 1860 to 1870	0.067	0.046	0.136
	(0.040)	(0.060)	(0.066)
From 1870 to 1880	0.075	0.017	0.065
	(0.024)	(0.044)	(0.101)
# County-Industries		1,199	1,199

Back

Sample Selection in the Historical Water Census



▸ Return

County-Level Activity

	Estimated Impact of LowerWater on:					
	Establishment growth			Steam diffusion		
	50-60	50-70	50-80	50-60	50-70	50-80
	(1)	(2)	(3)	(4)	(5)	(6)
Baseline specification	0.299	0.447	0.593	0.090	0.091	0.065
	(0.069)	(0.069)	(0.079)	(0.019)	(0.019)	(0.025)
Restrict to counties with $\geq$ 3 mills in 1850	0.264	0.395	0.519	0.090	0.099	0.064
	(0.074)	(0.075)	(0.076)	(0.019)	(0.019)	(0.026)
Restrict to counties with $\geq$ 5 mills in 1850	0.224	0.365	0.479	0.088	0.100	0.063
	(0.071)	(0.066)	(0.069)	(0.018)	(0.019)	(0.028)
Restrict to counties with $\geq$ 1 mill 1850-1880	0.323	0.456	0.606	0.090	0.091	0.065
	(0.067)	(0.070)	(0.080)	(0.019)	(0.019)	(0.025)
Exclude largest 20 cities in 1850-1880	0.292	0.444	0.610	0.105	0.114	0.098
	(0.077)	(0.076)	(0.088)	(0.021)	(0.027)	(0.040)
Control for 1850 agri. employment share	0.266	0.396	0.537	0.082	0.079	0.049
	(0.069)	(0.069)	(0.071)	(0.015)	(0.016)	(0.020)
Control for precipitation and temperature	0.238	0.363	0.489	0.059	0.064	0.029
	(0.079)	(0.098)	(0.103)	(0.026)	(0.026)	(0.031)
Control for all resource regions	0.276	0.421	0.537	0.066	0.055	0.029
	(0.056)	(0.073)	(0.092)	(0.024)	(0.019)	(0.022)
Control for all resource subregions	0.246	0.371	0.502	0.054	0.046	0.027
	(0.073)	(0.098)	(0.118)	(0.027)	(0.029)	(0.039)
Control for longitude and Atlantic coastline	0.202	0.357	0.462	0.029	0.034	0.018
	(0.065)	(0.077)	(0.097)	(0.020)	(0.018)	(0.030)

Back

County-Level Activity

	Estimated Impact of LowerWater on:					
	Establishment growth			Steam diffusion		
	50-60	50-70	50-80	50-60	50-70	50-80
	(1)	(2)	(3)	(4)	(5)	(6)
Baseline specification	0.299	0.447	0.593	0.090	0.091	0.065
	(0.069)	(0.069)	(0.079)	(0.019)	(0.019)	(0.025)
Control for the 13 original colonies	0.227	0.368	0.498	0.059	0.044	0.028
	(0.071)	(0.076)	(0.097)	(0.018)	(0.018)	(0.022)
Control for State fixed effects	0.126	0.243	0.343	0.039	0.031	0.016
	(0.067)	(0.071)	(0.084)	(0.018)	(0.014)	(0.021)
Control for 1850 population	0.277	0.417	0.559	0.078	0.079	0.049
	(0.068)	(0.069)	(0.077)	(0.016)	(0.019)	(0.028)
Control for 1850 output	0.198	0.313	0.443	0.066	0.063	0.031
	(0.069)	(0.067)	(0.074)	(0.016)	(0.016)	(0.025)
Control for time-varing market access	0.272	0.431	0.564	0.078	0.082	0.051
	(0.071)	(0.073)	(0.083)	(0.018)	(0.017)	(0.024)
Control for 1870 acres of woodland	0.301	0.449	0.596	0.091	0.093	0.066
	(0.068)	(0.069)	(0.078)	(0.019)	(0.019)	(0.025)
Control for 1850 access to banks	0.274	0.436	0.587	0.086	0.093	0.071
	(0.073)	(0.075)	(0.087)	(0.019)	(0.018)	(0.030)
Control for 1850 machine producers/engineers	0.247	0.402	0.541	0.082	0.076	0.047
	(0.068)	(0.067)	(0.073)	(0.016)	(0.019)	(0.028)
Control for coal resources	0.281	0.423	0.560	0.076	0.074	0.047
	(0.067)	(0.075)	(0.086)	(0.020)	(0.018)	(0.020)

Back

Solving the Firm's Dynamic Program

Expected value of operation (given paths $\{c_t^S, P_{ct}, s_{ct}\}_t$)

$$\mathbb{E}_\varepsilon[V_{ct}^o(R,\varphi)] = \log\left[\sum_{R'} \exp\left(\frac{1}{\rho}(-c_{ct}^{RR'} + \pi_{ct}(R,\varphi') + \delta\mathbb{E}_{\varphi'} \max\{\mathbb{E}_\varepsilon[V_{ct+1}^o(\varphi', R')] - f^o, 0\})\right)\right]$$

1. At period T, solve stationary value function by iteration (contraction mapping)
2. From period T, solve value function by backward recursion in $T-1, T-2, \ldots, t_0$

Back: Dynamic Choices Back: Equilibrium

Dynamic Equilibrium

An equilibrium of county c is a time path for the mass of entrants M_{ct}, the mass of operating firms $F_{ct}(R, \varphi)$, and the policy functions for operation/exit $O_{ct}(R, \varphi)$ and power $R'_{ct}(R, \varphi)$, such that taking the time path of steam costs $c_{ct}(S)$ as given:

1. Firms enter, exit, and adopt power sources to maximize expected discounted profits.
2. Firms source inputs x to maximize flow profits period-by-period.
3. Output markets clear:

   $$P_{ct} Y_{ct} = w X_{ct} + \Pi_{ct},$$

   where $\Pi_{ct} = \int \pi_{ct}(R, \varphi) dF_{ct}(R, \varphi)$ are total local profits, and $X_{ct} = \int x_{ct}(R, \varphi) dF_{ct}(R, \varphi)$ is local demand for inputs. We assume inputs are elastically supplied at price w.
4. The free entry condition holds:

   $$\mathbb{E}_{\varphi} \left[V_{ct}(E, \varphi) \right] \leq f^e.$$

5. The evolution of firm masses $\{F_{ct}\}_t$ is consistent with the policy functions $\{O_{ct}, R'_{ct}\}_t$.

◂ Return ◂ Return: Counterfactuals

Modeling the Arrival of Steam

1. Prior to 1830, agents anticipate

$$\mathbb{E}_t[c^S_\tau] = \infty, \quad t < 1830, \forall \tau$$

2. At 1830, news of breakthrough inventions
3. From 1830, agents correctly foresee

$$\mathbb{E}_t[c^S_\tau] = c^S_\tau, \quad t \geq 1830, \forall \tau$$

with $dc^S_t / dt < 0$ and $c^S_t \to \underline{c}^S$ as $t \to 1900$

Solving and Simulating the Steam Arrival

1. Solve the initial steady state in $t = 1830$, in which agents expect that steam adoption cost will stay at $\bar{c}^S$ forever (shooting algorithm for the masses of operating firms and entrants)
2. Solve the terminal steady state at $t = 1900$, in which agents expect that steam adoption cost will stay at $\underline{c}^S$ forever
3. From $t > 1830$, feed in expectation of

$$\mathbb{E}_t[c^S_\tau] = c^S_\tau, \quad \tau \geq t$$

4. Solve the transition path from 1830 to 1900
5. Simulate the economy from 1830 to 1900, verifying convergence to the terminal steady state at 1900

Higher water costs cause faster steam adoption, especially among entrants

Proposition: Let $\mathbb{P}^E_{ct}(S)$ and $\mathbb{P}^I_{ct}(S)$ denote the shares of entrant and incumbent mills that use steam. Higher costs of water induce faster steam adoption, especially among entrants:

$$\frac{d}{dc^W_c}\mathbb{P}^E_{ct}(S) > \frac{d}{dc^W_c}\mathbb{P}^I_{ct}(S) > 0$$

Sketch of proof: Higher water costs affect steam adoption through

+ Technology costs
+ Productivity selection
+ Competition
+ Agglomeration

Incumbents differ from entrants due to switching costs, which make their steam adoption decisions less responsive to the cost of waterpower.

Return

Higher water costs cause faster growth, especially through entry

Proposition: Let N_{ct} denote the total number of mills and N_{ct}^E the number of entrants. Higher costs of water induce faster growth of mills, especially of entrant mills:

$$\frac{d}{dc_c^W}\Delta \log N_{ct}^E > \frac{d}{dc_c^W}\Delta \log N_{ct} > 0$$

Sketch of proof: Higher water costs affect operating values through

+ Technology costs (especially for entrants)
+ Agglomeration (especially for entrants)
– Competition (for all mills)

Return

Unclear if incumbents are crowded out in counties with higher water costs

Proposition: Let $\mathbb{S}_{ct}$ denote the survival rate of mills. It is unclear if higher costs of water hurt or help the survival of incumbent mills when steam arrives:

$$\frac{d}{dc_c^W}\mathbb{S}_{ct} \gtrless 0.$$

Incumbents are crowded out if switching costs are prohibitively high.

Sketch of proof: Higher water costs affect operating values of incumbents through

+ Option value of steam power (if switching costs are low)
– Competition from new entrants

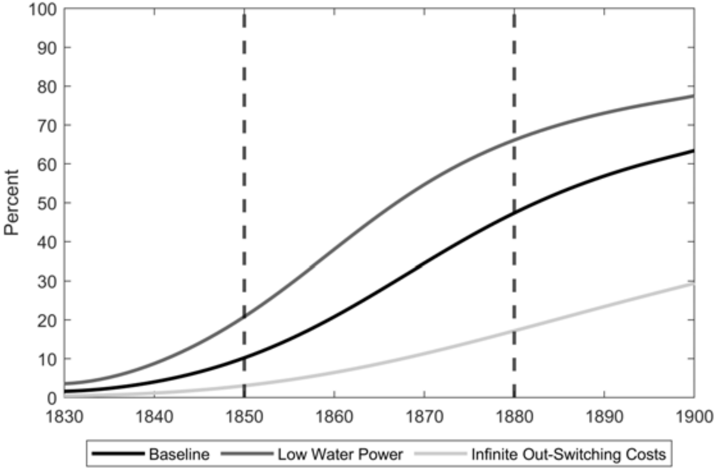
▸ Return

Parameters and Moments

1. Power switching costs $c_o^R \leftarrow$ Power adoption DiD
2. Power adoption costs $c_b^R \leftarrow$ Power diffusion rates
3. Power cost shocks $\rho_2 \leftarrow$ Overlap in adoption
4. Steam productivity $\gamma \leftarrow$ Size premium of steam users
5. Baseline productivity $(\pi, \sigma) \leftarrow$ Autocorrelation and dispersion of firm sales
6. Entry cost $f^e \leftarrow$ Entry rates
7. Operating cost $f^o \leftarrow$ Exit rates
8. Operating cost shocks $\rho_1 \leftarrow$ Overlap in exit

▸ Back

Model Counterfactuals: No Switching



Return