Are Ideas Getting Harder to Find?

Bloom, Jones, Van Reenen, and Webb

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Overview

- New stylized fact:

  Exponential growth is getting harder to achieve.

Economic growth	=	Research productivity	$\times$	Number of researchers
e.g. 2% or 5%		$\downarrow$ (falling)		$\uparrow$ (rising)

- Aggregate evidence: well-known (Jones 1995)
- This paper: micro evidence
  - Moore's law, Agricultural productivity, Medical innovations
  - Firm-level data from Compustat

Exponential growth results from the rising research effort that offsets declining research productivity.

Conceptual Framework

Basic Framework

- Key equation in many growth models:

$$\frac{\dot{A}_t}{A_t} = \alpha\, S_t$$

where $\dot{A}_t/A_t$ = TFP growth
and S_t = the number of researchers

- Define ideas to be proportional improvements in productivity.
  - Since we don't observe ideas directly $\Rightarrow$ just a normalization
  - Quality ladder models assume this

- Productivity in the Idea Production Function:

$$\text{Research Productivity} := \frac{\dot{A}_t/A_t}{S_t} = \frac{\text{\# of new ideas}}{\text{\# of researchers}}$$

Null hypothesis: Research productivity $= \alpha \Rightarrow$ constant!

- Standard endogenous growth $\iff$ constant research productivity
  - Permanent research subsidy $\Rightarrow$ permanent $\uparrow$ growth
- Motivations for the paper
  - Inherently interesting: Is exponential growth getting harder to achieve?
  - Can a constant number of researchers generate constant exponential growth?
  - Informative about the growth models we write down

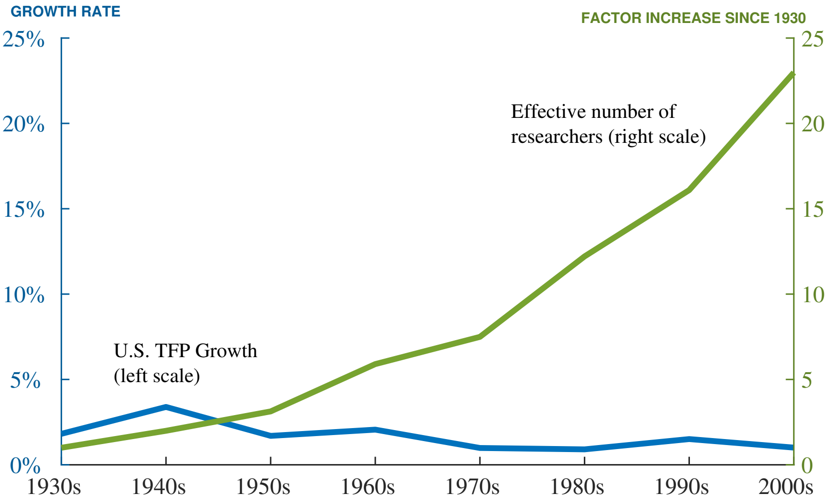
Aggregate Evidence

- What if research productivity declines sharply *within* every product line, but growth proceeds by developing new products?
  - Steam, electricity, internal combustion, semiconductors, gene editing, etc.
  - Maybe research productivity is constant via the discovery of new products?

- But the extreme of this $\Rightarrow$ Romer (1990)!

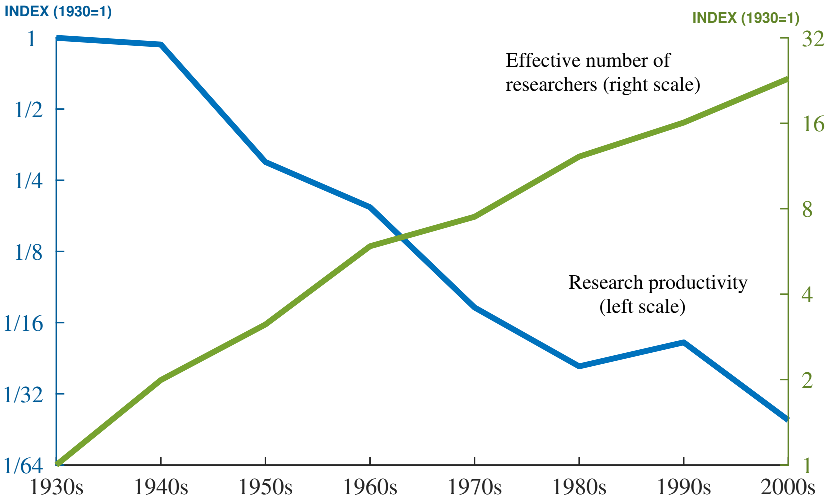
- Standard problem:
  - Growth is steady or declining (here BLS TFP growth)
  - Aggregate R&D rises sharply (here NIPA IPP deflated by the nominal wage for 4+ years of college/postgrad education)

Aggregate Evidence



Aggregate Research Productivity

Research effort: 23x (+4.3% per year)
Research productivity: 41x (-5.1% per year)



The Importance of Micro Data

- In response to the "scale effects" critique:
  - Howitt (1999), Peretto (1998), Young (1998) and others
  - Composition bias: perhaps research productivity *within* every quality ladder is constant, e.g. if number of products N_t grows at the right rate:

$$\frac{\dot{A}_{it}}{A_{it}} = \alpha S_{it} \qquad (*)$$

$\Rightarrow S_{it} = \frac{S_t}{N_t}$ invariant to scale, but responds to subsidies

  - Aggregate evidence would then be misleading
  - Permanent subsidies would still have growth effects.

- Key to addressing this concern:

Study (*) directly $\Rightarrow$ research productivity within a variety!

Extensions to the basic framework

The "Lab Equipment" Approach

- Setup

Goods production	$Y_t = K_t^{\theta}(A_t L)^{1-\theta}$
Resource constraint	$Y_t = C_t + I_t + R_t$
Idea production	$\dot{A}_t = \alpha R_t$

- Solution, with $s_t := R_t / Y_t$

$$Y_t = \left(\frac{K_t}{Y_t}\right)^{\frac{\theta}{1-\theta}} A_t L$$

$$\dot{A}_t = \alpha R_t = \alpha s_t Y_t = \alpha s_t \left(\frac{K_t}{Y_t}\right)^{\frac{\theta}{1-\theta}} A_t L.$$

- Therefore:

$$\frac{\dot{A}_t}{A_t} = \underbrace{\alpha \left(\frac{K_t}{Y_t}\right)^{\frac{\theta}{1-\theta}}}_{\text{research productivity}} \times \underbrace{s_t L}_{\text{"researchers"}}$$

What if the R&D input is expenditures instead of people?

- Key: Deflate R&D spending by the nominal wage to get the "effective" number of researchers.
  - Gives the "researchers" term in lab equipment model
  - Additonally allows heterogeneous researchers — weights by their wage $\Rightarrow$ efficiency units
- The maintains the appropriate null hypothesis:
  - Constant "effective" research generates constant exponential growth $\Rightarrow$ fully endogenous growth
  - In contrast: Naively dividing $\frac{\dot{A}_t}{A_t}$ by R will incorrectly show a decline in "research productivity" even w/ endog. growth
- Empirically: the nominal wage = mean personal income from CPS for males with 4 or more years of college/post education

Stepping on Toes?

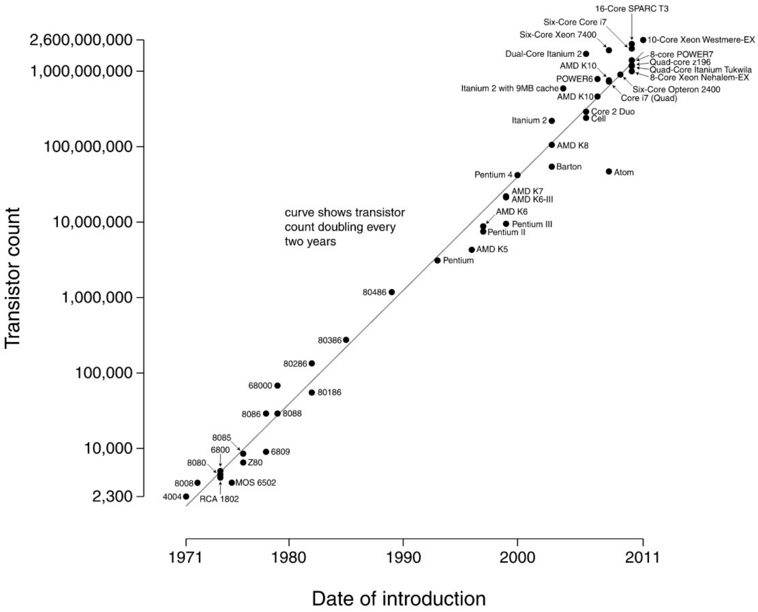
- Perhaps the idea production function depends on S_t^λ rather than on S_t?
- We focus on $\lambda = 1$ for three reasons:
  - Only affects the magnitude of whatever trend we find — easy to multiply by your preferred value (appendix table $\lambda = 3/4$)
  - R&D spending already controls for heterogeneity in talent
  - No consensus on the right value of λ
- Statements like "we have to double research every T years to maintain constant growth" are invariant to λ

Selection of Our Cases and Measures

- How did we pick the cases to study and report?
  - Require good measures of idea output and research input
  - Also considered
    - internal cumbustion engine, airplane travel speed
    - Nordhaus (1997) price of light
    - solar panel efficiency
    - price of human genome sequencing
  - Problem: Could not measure research input...
- How do we choose our idea output measure?
  - Need to match up well with research input.
  - Highly robust — results driven by “no trend” versus “trend”

Moore's Law

The Steady Exponential Growth of Moore's Law



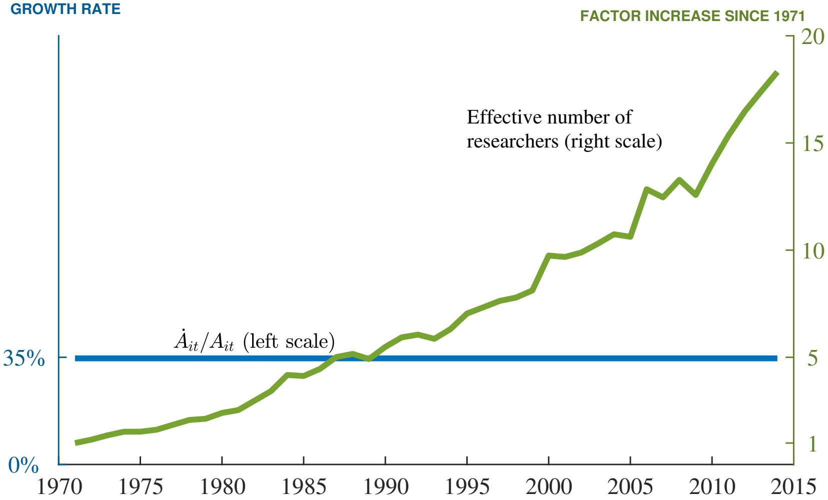
Moore's Law and Measurement

- Idea output: Constant exponential growth at 35% per year

$$\frac{\dot{A}_{it}}{A_{it}} = 35\%$$

- Idea input: R&D spending by Intel, Fairchild, National Semiconductor, TI, Motorola (and 25+ others) from Compustat
  - Pay close attention to measurement in the 1970s, where omissions would be a problem...
  - Use fraction of patents in IPC group H01L ("semiconductors") to allocate to Moore's Law

Evidence on Moore's Law



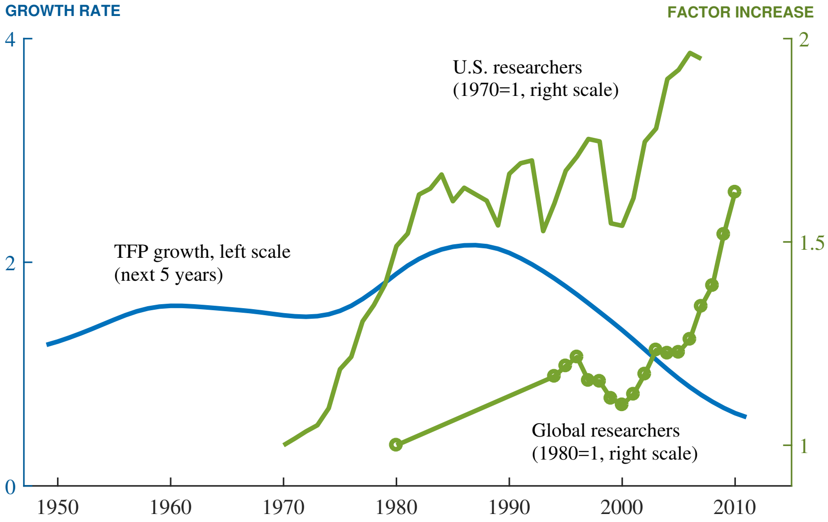
Research Productivity for Moore's Law – Robustness

Version	Factor decrease	Average growth	Half-life (years)
Baseline	18	-6.8%	10.3
(a) Narrow R&D	8	-4.8%	14.5
(b) Narrow (adj. congl.)	11	-5.6%	12.3
(c) Broad (adj congl.)	26	-7.6%	9.1
(d) Intel only (narrow)	347	-13.6%	5.1
(f) TFP growth (narrow)	5	-3.2%	21.4
(h) TFP growth (broad)	11	-5.6%	12.3

We have to double our research effort every decade just to keep up with declining research productivity!

Agricultural Innovation

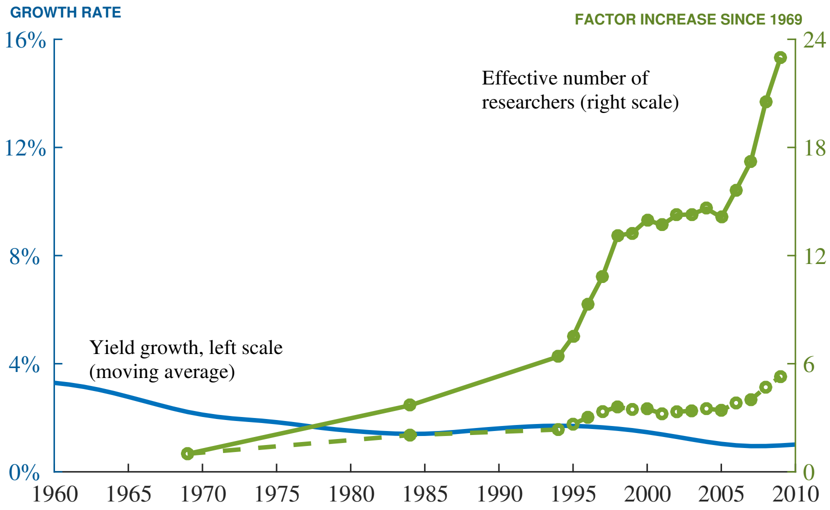
TFP Growth and Research Effort in Agriculture



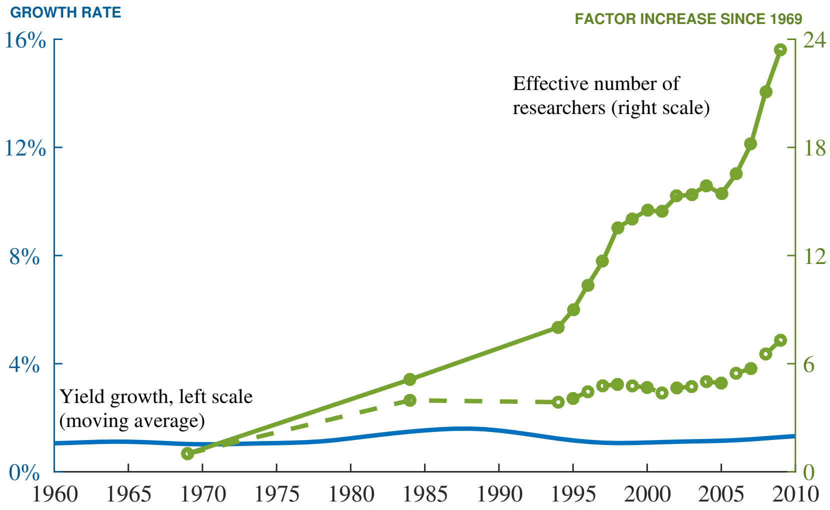
Seed Yields for Corn, Soybeans, Cotton, Wheat

- Idea output:
  - Realized yields per acre on U.S. farms (no TFP data)
  - Approximately doubles since 1960
    $\Rightarrow \frac{\dot{A}_{it}}{A_{it}} \approx$ 2% (stable, or even declining slightly)
- Idea input: two measures, both show large increases
  - Narrow: public and private R&D to increase biological efficiency (cross-breeding, genetic modification, insect/herbicide resistance, nutrient uptake)
  - Broader: Also add in crop protection and maintenance R&D (developing better herbicides and pesticides).

Yield Growth and Research: Corn



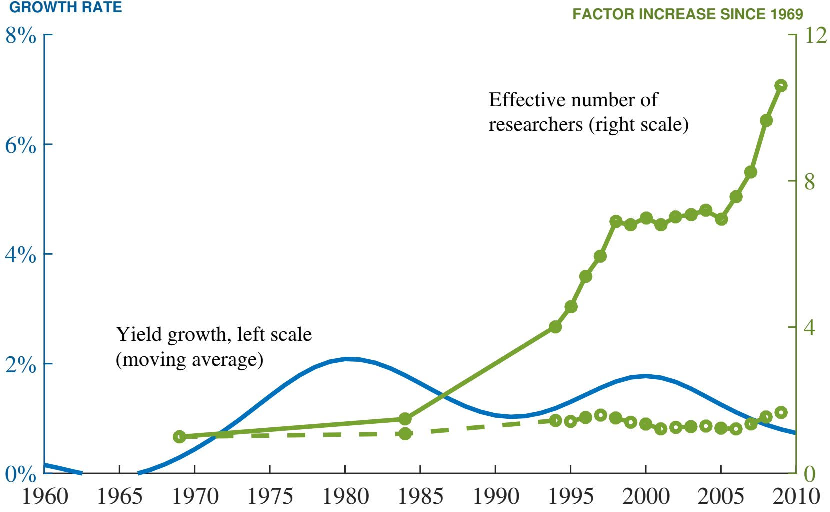
Yield Growth and Research: Soybeans



Research Productivity for Agriculture: 1969–2010

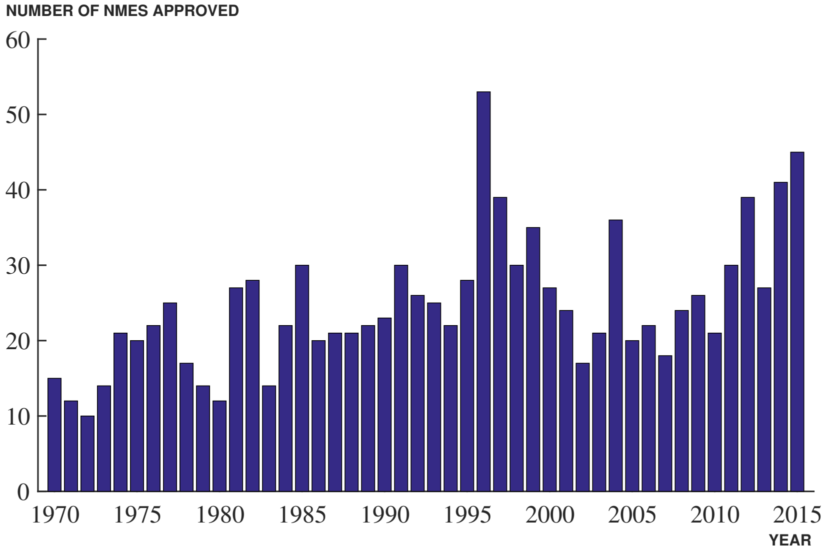
	Effective research		Research productivity	
Crop	Factor increase	Average growth	Factor decrease	Average growth
Seed efficiency only				
Corn	23.0	7.8%	52.2	-9.9%
Soybeans	23.4	7.9%	18.7	-7.3%
Cotton	10.6	5.9%	3.8	-3.4%
Wheat	6.1	4.5%	11.7	-6.1%
+ crop protection				
Corn	5.3	4.2%	12.0	-6.2%
Soybeans	7.3	5.0%	5.8	-4.4%
Cotton	1.7	1.3%	0.6	+1.3%
Wheat	2.0	1.7%	3.8	-3.3%

Yield Growth and Research: Cotton



Medical Innovation

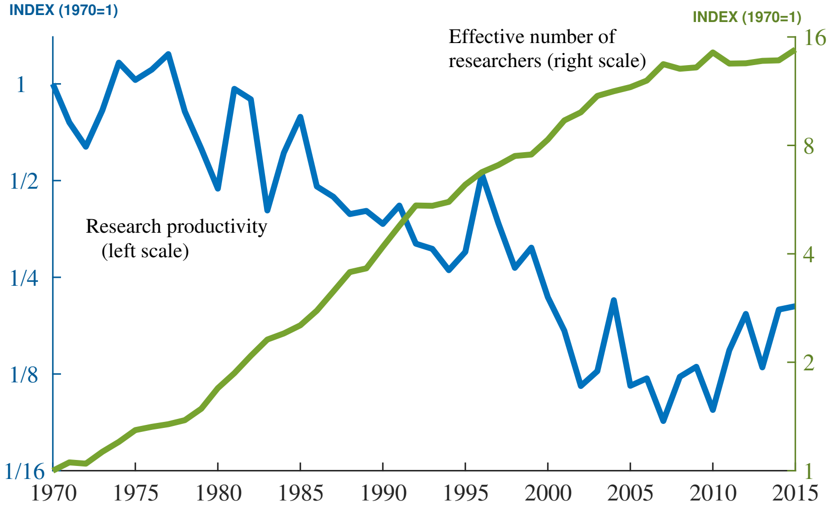
New Molecular Entities Approved by the FDA



New Molecular Entities

- Idea output: FDA approvals of new molecular entities. Usually 2 or 3 of these become blockbuster drugs
  - Limitation: Simple counts do not adjust for quality
- Idea input: R&D spending measured by the Pharmaceutical Researchers and Manufacturers of America survey.
  - Includes research performed abroad by U.S. companies and research performed in the U.S. by foreign companies.
  - But not research performed abroad by foreign companies.

Research Productivity for New Molecular Entities



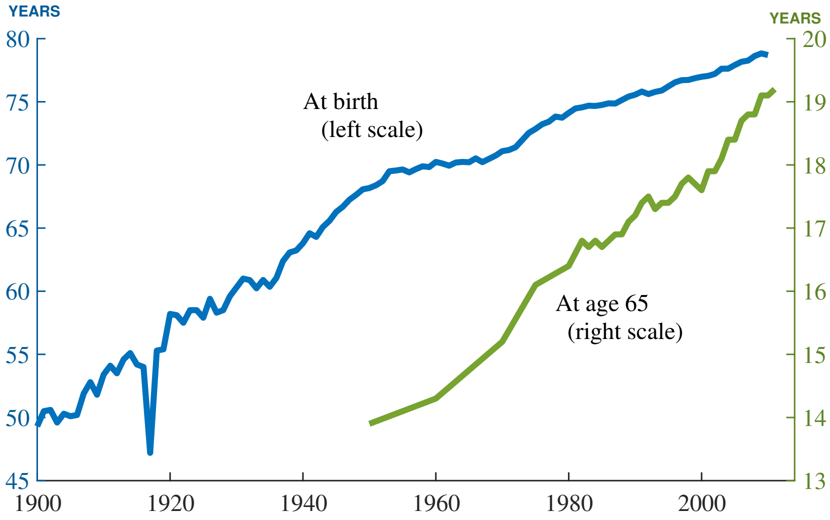
Better Micro Data? Disease Mortality

- Idea output: Years of life saved per 1000 people
  - Based on declines in mortality (Vaupel and Canudas 2003)

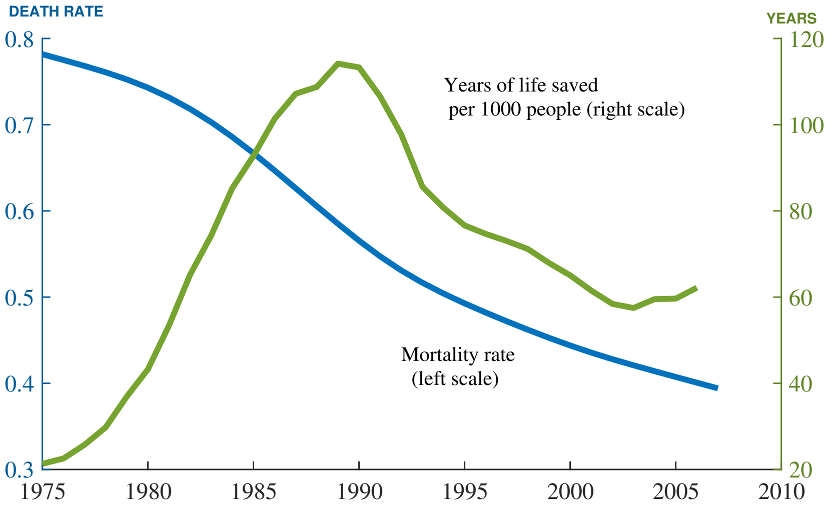
$$d\,LE(a) = \frac{\delta_i}{\delta_1 + \delta_2} \cdot LE(a) \cdot \left(-\frac{d\delta_i}{\delta_i} \right).$$

  - Three diseases: all cancers, breast cancer, heart disease
- Idea input: Scientific publications with the relevant Medical Subject Heading (e.g. "Neoplasms")
  - Two approaches: all publications versus those documenting clinical trials

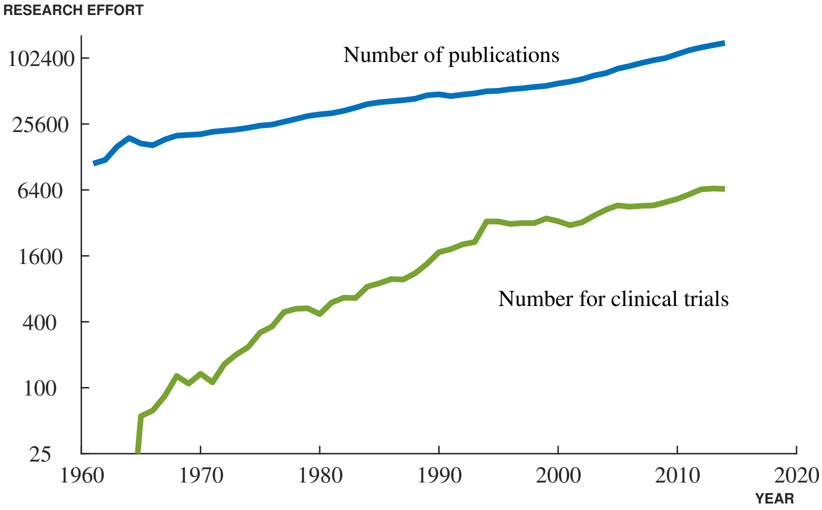
U.S. Life Expectancy Rises Linearly



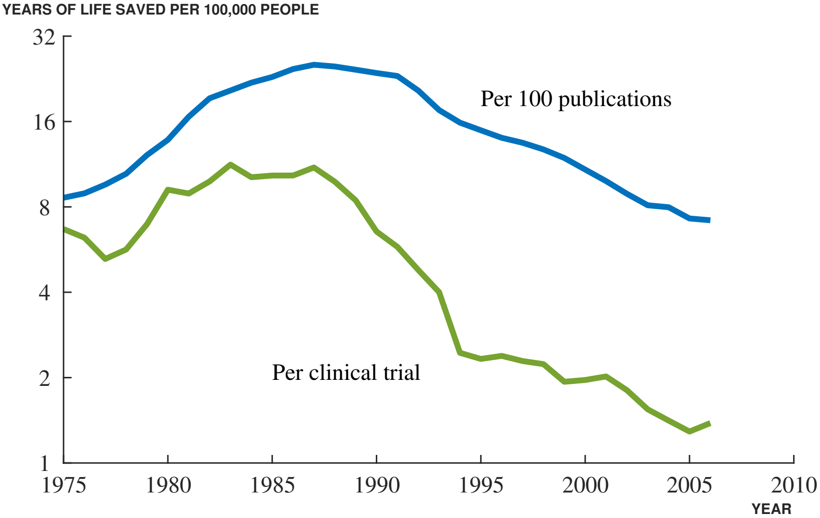
Mortality and Years of Life Saved: All Cancers



Medical Research Effort: All Cancers



Research Productivity for Medical Research: All Cancers



Research Productivity for Medical Research

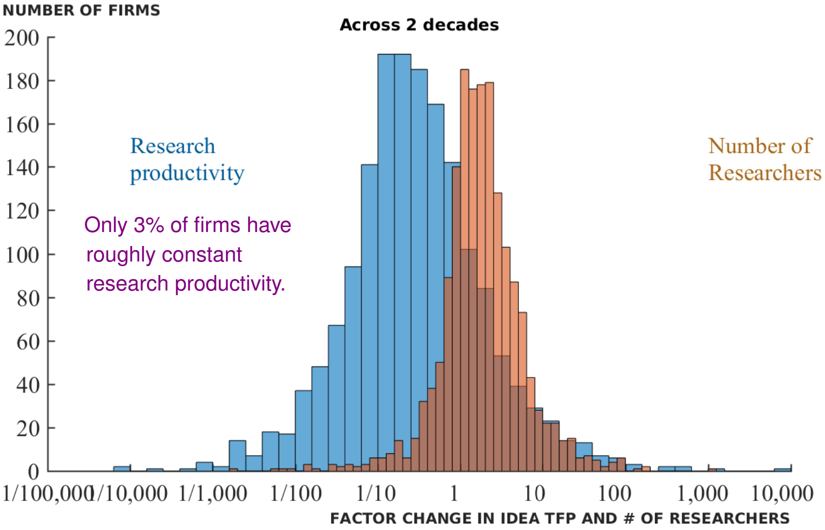
Category	Effective research		Research productivity	
	Factor increase	Average growth	Factor decrease	Average growth
New molecular entities	14.8	6.0%	4.9	-3.5%
All publications				
Cancer, all types	3.5	4.0%	1.2	-0.6%
Breast cancer	5.9	5.7%	8.2	-6.8%
Heart disease	5.1	3.6%	5.3	-3.7%
Clinical trials				
Cancer, all types	14.1	8.5%	4.8	-5.1%
Breast cancer	16.3	9.0%	22.6	-10.1%
Heart disease	24.2	7.1%	25.3	-7.2%

Firm-Level Data from Compustat

Firm-Level Data from Compustat

- Compute research productivity for each firm in Compustat since 1980
- Idea output:
  - Decadal growth rates of sales revenue, market capitalization, or employment
- Idea input: R&D expenditures
- Various robustness checks for sample selection (below)

Histogram of Research Productivity and Effort across Firms



Research Productivity using Compustat Data (weighted averages)

Sample	Effective research: Factor increase	Effective research: Average growth	Research productivity: Factor decrease	Research productivity: Average growth
Sales Revenue				
2 dec. (1712 firms)	2.0	6.8%	3.9	-13.6%
3 dec. (469 firms)	3.8	6.7%	9.2	-11.1%
4 dec. (149 firms)	13.7	8.7%	40.3	-12.3%
Market Cap				
2 dec. (1124 firms)	2.2	8.0%	3.4	-12.2%
3 dec. (335 firms)	3.1	5.6%	6.3	- 9.2%
4 dec. (125 firms)	7.9	6.9%	14.0	-8.8%
Employment				
2 dec. (1395 firms)	2.2	8.0%	2.8	-10.3%
3 dec. (319 firms)	4.0	6.9%	18.2	-14.5%
4 dec. (101 firms)	13.9	8.8%	31.5	-11.5%

Compustat Sales Data across 3 Decades: Robustness

Case	Research productivity Factor decrease	Research productivity Average growth
Benchmark (469 firms)	9.2	-11.1%
Winsorize $g < .01$ (986 firms)	7.9	-10.3%
Winsorize top/bottom (986 firms)	6.0	- 8.9%
Research must increase (356 firms)	11.6	-12.3%
Drop if *any* negative growth (367 firms)	17.9	-14.4%
Median sales growth (586 firms)	6.3	-9.2%
Unweighted averages (469 firms)	9.2	-11.1%
Revenue labor productivity (337 firms)	2.5	-4.5%

Discussion

Summary: Evidence on Research Productivity

Scope	Average annual growth rate	Half-life (years)	Extent of Diminishing Returns, β
Aggregate economy	-5.3%	13	3.4
Moore's law	-6.8%	10	0.2
Agriculture (seeds)	-5.5%	13	4.8
New molecular entities	-3.5%	20	...
Disease mortality	-5.6%	12	...
Compustat firms	-11.1%	6	1.1

Implications for Economic Growth

- Ideas are getting harder to find!
    - Exponential growth is getting harder to achieve
    - We have to double research effort every 13 years to maintain constant growth.
- "Red Queen" result
    - We have to "run" faster and faster to stay in the same place (i.e. to maintain a constant growth rate)
    - If the growth rate of research effort slows, economic growth may slow

Caveats: How could this interpretation be wrong?

- Composition bias: increase in R&D occurs within varieties, but R&D toward inventing *new* varieties is constant and faces constant research productivity?
  - The one place where research productivity is constant is the one place where R&D is not growing??? In equilibrium?
- Composition bias II: Even more varieties (e.g. within firms, within corn, within computer chips) so that true research per variety is actually constant?
- Mismeasured growth? Are growth rates actually increasing? Would have to be substantial...
- Other factors? Rising regulation? Defensive R&D? Changing emphasis away from chip speed or yield per acre or years of life?

Why does research productivity fall so quickly for semiconductors?

- Consider Jones / Kortum / Segerstrom framework:

$$\frac{\dot{A}_t}{A_t} = (\alpha A_t^{-\beta}) \cdot S_t$$

which implies

$$g_A = \frac{g_S}{\beta}$$

LR growth = the growth rate of researchers
deflated by the extent of diminishing returns, β

- Can measure $\beta \equiv$ extent of diminishing returns
- Semiconductors has the least diminishing returns!
  - It is just that we've expanded R&D so quickly...

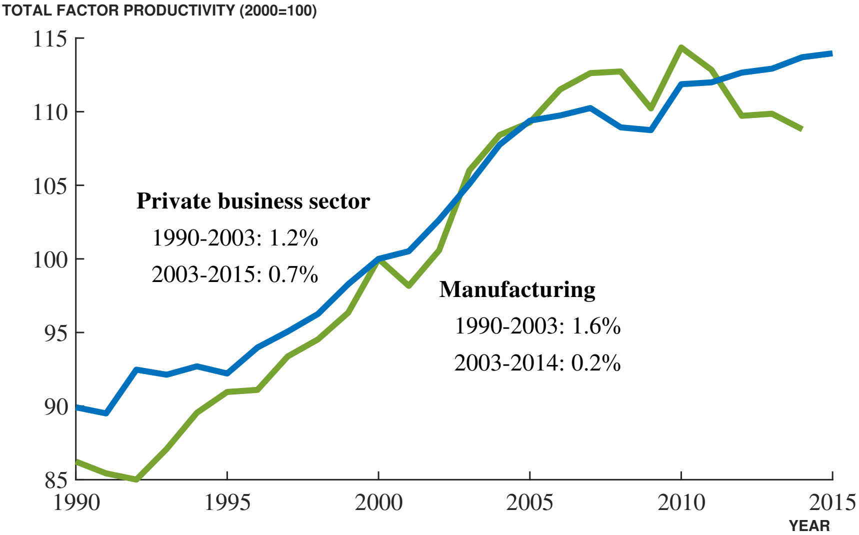
A clarification of endogenous growth theory, not a critique!

- Naive reading is that this is a criticism of endogenous growth
- Instead, I think it strongly supports the key insight: nonrivalry
  - If you are satisfied with constant research productivity, there is no need for nonrivalry!
  - Fully rivalrous ideas can lead to constant exponential growth with perfect competition (Akcigit, Celik, Greenwood 2016)
  - But with declining research productivity, the increasing returns implied by nonrivalry becomes essential

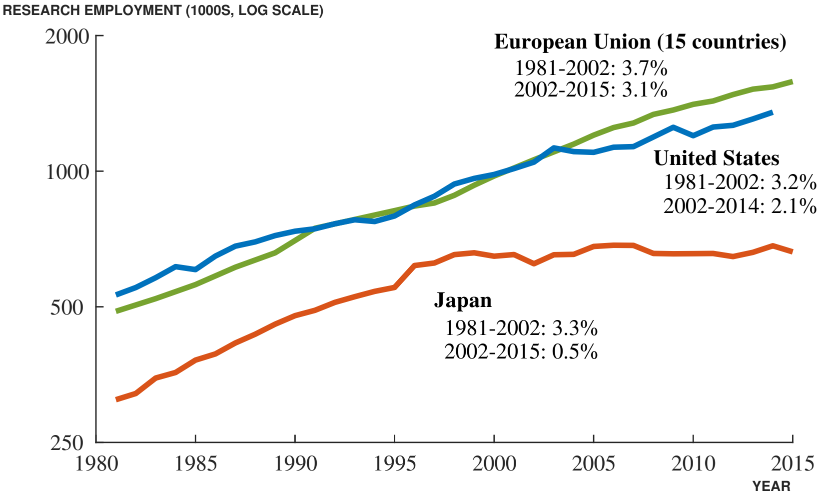
Exponential growth in research ⇒ exponential growth of ideas.
Increasing returns implied by nonrivalry ⇒
exponential growth in per capita income.

Extra Slides

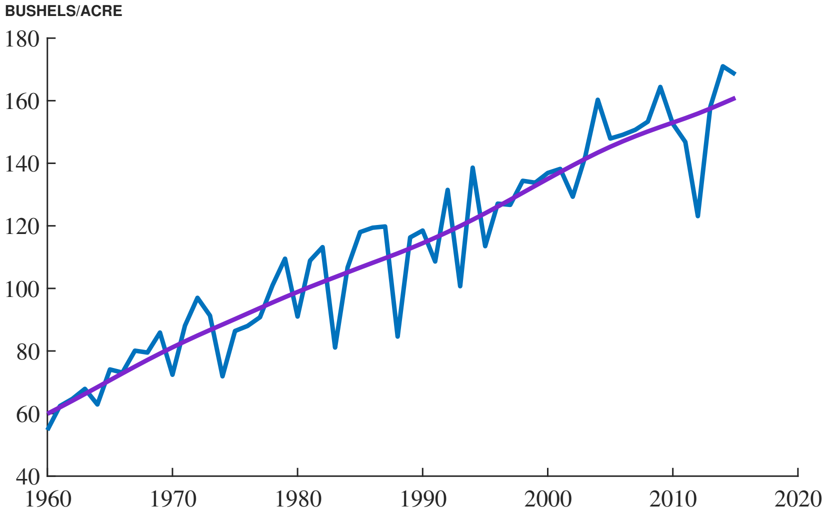
U.S. Total Factor Productivity



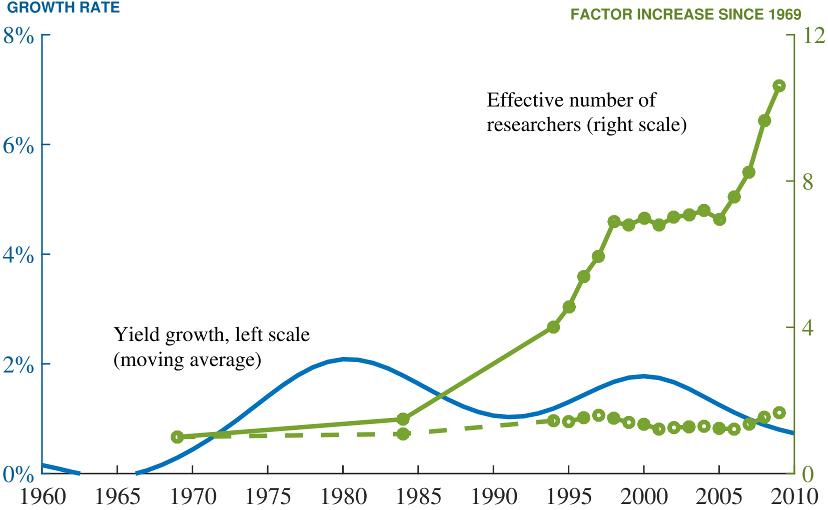
Research Employment in Select Economies



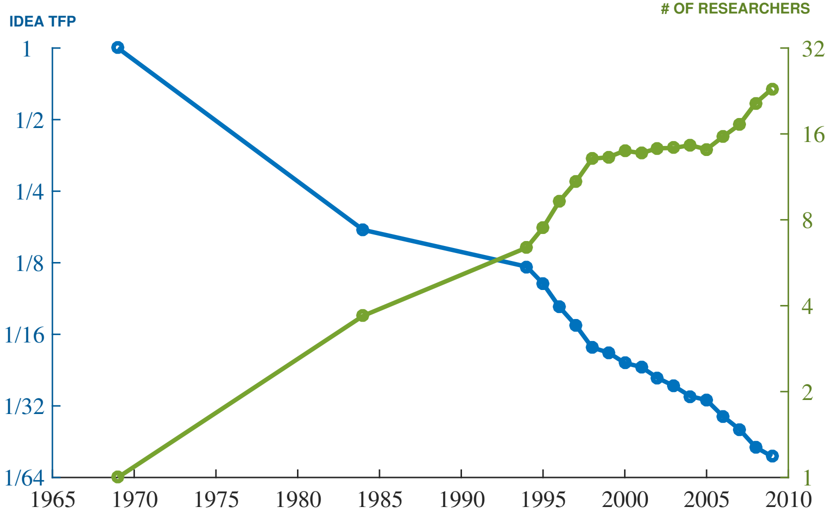
U.S. Crop Yields: Corn



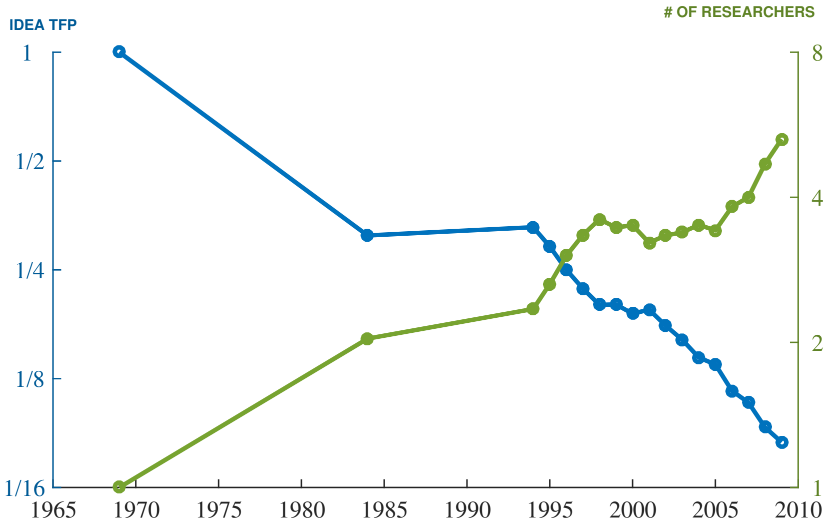
Yield Growth and Research: Cotton



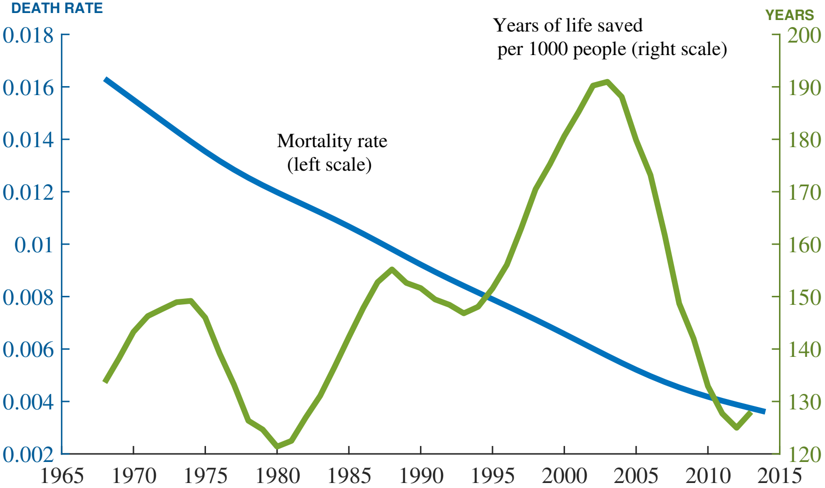
Research Productivity for Corn, Version 1 (biological efficiency only)



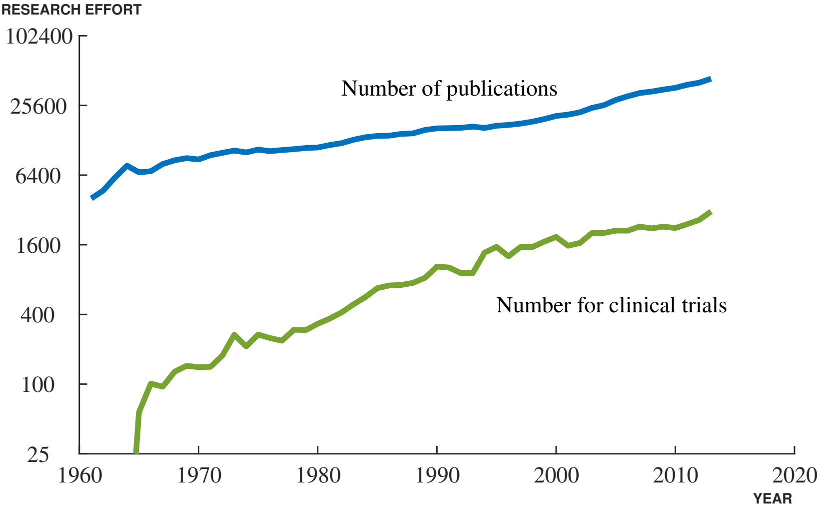
Research Productivity for Corn, Version 2 (w/ crop protection)



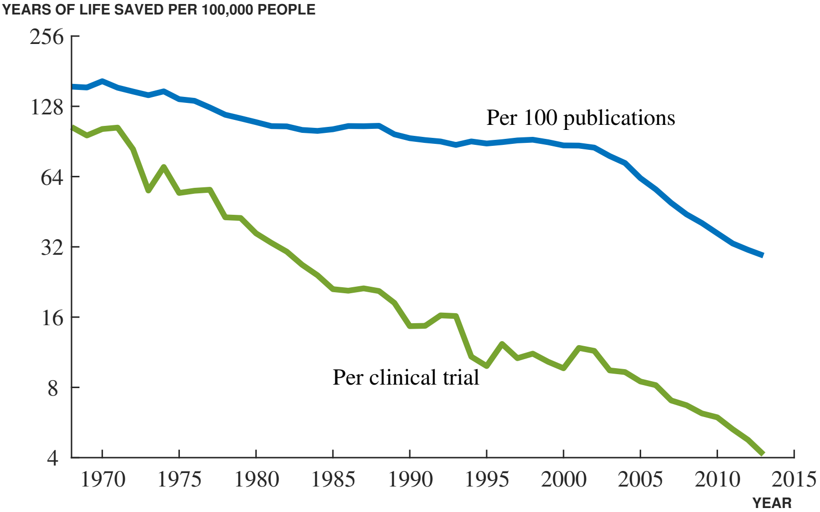
Mortality and Years of Life Saved: Heart Disease



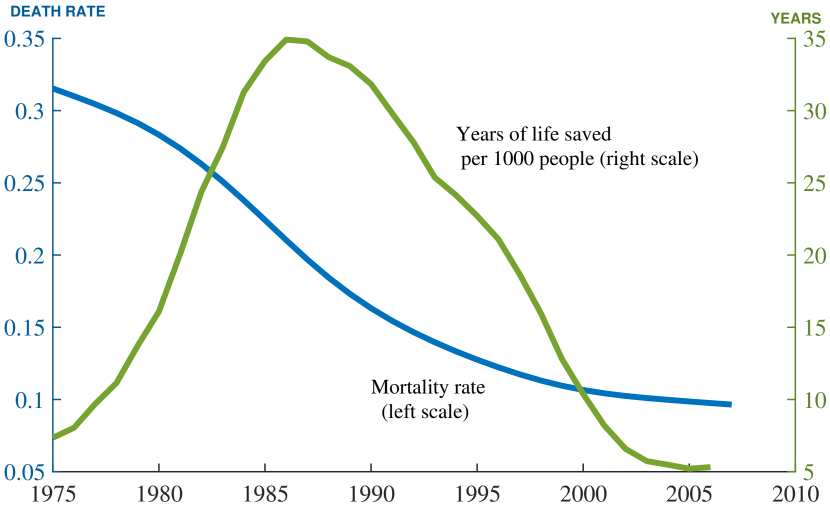
Medical Research Effort: Heart Disease



Research Productivity for Medical Research: Heart Disease



Mortality and Years of Life Saved: Breast Cancers



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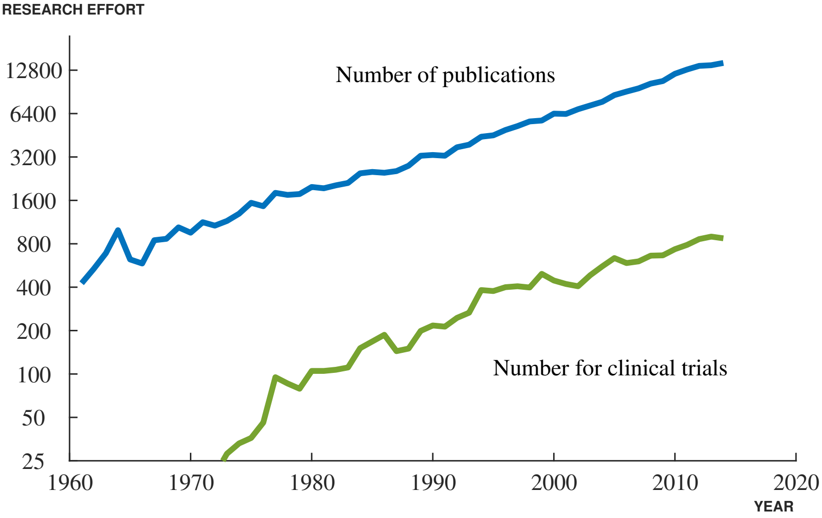
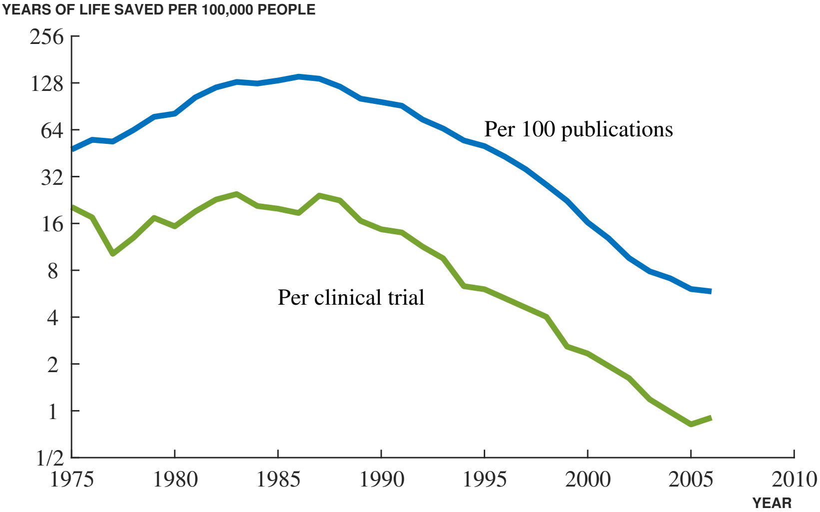
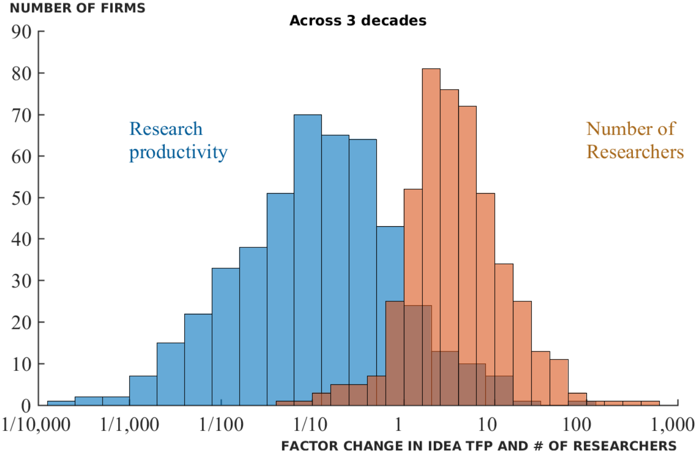


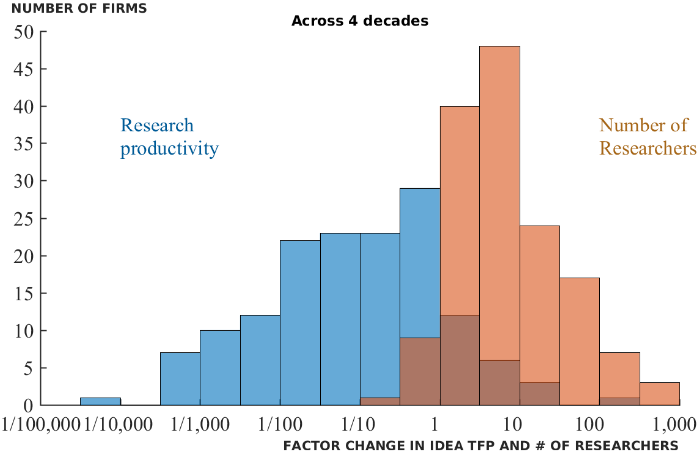
Research Productivity for Medical Research: Breast Cancers



Compustat Distributions, Sales Revenue (3 Decades)



Compustat Distributions, Sales Revenue (4 Decades)



Main Results from Compustat (Sales Revenue)