Technology Diffusion

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Introduction

Why do we care about technology diffusion?

It is at least part of the answer to the question:

What are the sources of TFP growth?

The answer is important for understanding growth in developed countries, as well as cross-country income differentials, and growth in developing countries.

Today I will focus on **diffusion** of **producer** technologies.

Diffusion is critical for these innovations to have an impact.

I will focus on diffusion of **technologies**, as opposed to **ideas.**

Technologies are perhaps easier to measure and to match to observables.

Introduction

I will ignore

—R&D and other mechanisms for the invention of new technologies and products;

—adoption of consumer goods, which is explained by a different set of factors: tastes and the distribution of income;

—evidence on cross-country diffusion, which (at present) consists of information only about date of first adoption;

—adoption of High Yielding Varieties of corn, rice, and so on in India, sub-Saharan Africa and elsewhere, which also involves a different set of factors: information lags, credit constraints, risk.

The discussion will be selective, and I will omit a literature review.

Outline for the rest of the lecture

1. Look at the evidence on diffusion of particular technologies across producers in the U.S.: hybrid corn, a set of 12 industrial technologies, and tractors.

   The question here is how fast the new technology spreads:

   what factors explain differences in adoption speed.

3. Look at some cross-country evidence on productivity in agriculture.
4. Sketch a simple model of technology adoption based on Jovanovic and MacDonald (1994) that can be adapted to look at all of these examples.
5. Questions for further research.

1. Diffusion in U.S. industries: hybrid corn

Griliches's (1957) study of hybrid corn adoption is a classic.

Diffusion rates varied by geographic region, either states or smaller regions within states see Figure 1), and his goal is to explain the differences in the speed of adoption.

Adoption within each area is well approximated by a logistic curve.

Each logistic (for share of total corn **acreage**) is parameterized by:

—date of entry E_j (10% penetration)

—slope of the logistic curve b_j

—the "ceiling" K_j, the long run rate of penetration.

Griliches runs 3 sets of regressions, with the 3 parameters as dependent variables, to explain the cross-regional variation.

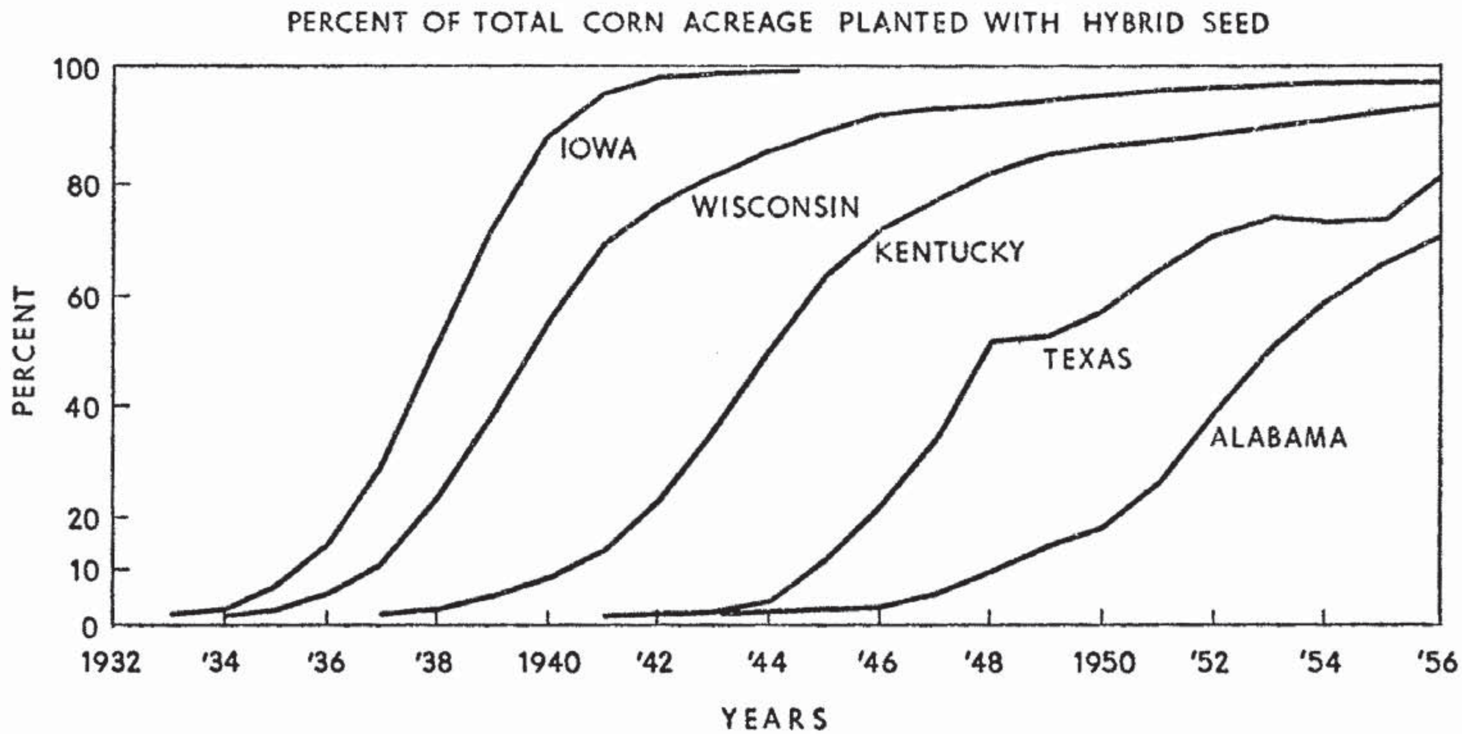


FIGURE 1.—Percentage of Total Corn Acreage Planted with Hybrid Seed. Source: U.S.D.A., *Agricultural Statistics*, various years.

1. Diffusion in U.S. industries: hybrid corn

The entry date is determined by suppliers: the USDA, which had an important role in developing the hybrids, and the seed suppliers.

Entry was earliest in the "Corn Belt" states and diffused outward.

Entry is well described by market density X_1, which affects marketing costs, and the earliest date of entry in a contiguous market, X_2. Access to a marketable hybrid for a nearly area lowers R&D costs.

For 222 reporting districts, the results are

$$\ln E_j = c_0 - \underset{(2.5)}{17.8} X_{1j} + \underset{(0.07)}{1.02} X_{2j}, \qquad R^2 = 0.982.$$

1. Diffusion in U.S. industries: hybrid corn

The rate of adoption (slope) is well explained by Average corn acreage per reporting farm X_3 and the superiority of hybrids.

Two measures of superiority work well: increase in yield per acre X_4 (from survey data) and pre-hybrid yield X_5 (the hybrids increased yields by about 20%).

Both linear and log forms fit well. For 132 crop reporting districts,

$$\ln b_j = c_0 + \underset{(0.04)}{0.440} \ln X_{3j} + \underset{(0.09)}{0.70} \ln X_{4j}, \qquad R^2 = 0.61,$$

$$\ln b_j = c_0 + \underset{(0.03)}{0.440} \ln X_{3j} + \underset{(0.05)}{0.57} \ln X_{5j}, \qquad R^2 = 0.69.$$

The long-run rate of penetration K_j is well explained by the same factors, with $R^2 = 0.71$ at the state level ($N = 31$).

1. Diffusion in U.S. industries: 12 industrial innovations

Mansfield (1964) looks at 12 major innovations in 4 industries:

bituminous coal, iron and steel, brewing, and railroads.

All of the innovations except one involved investment in heavy equipment that reduced cost.

Figure 1 shows plots of the percentage of **firms** that had adopted.

All of the plots start a 0% and end at 100% (unless truncated when the data ended in 1958).

Mansfield runs only one set of regressions, for the slope.

FIGURE 1.—Growth in the Percentage of Major Firms that Introduced Twelve Innovations, Bituminous Coal, Iron and Steel, Brewing, and Railroad Industries, 1890–1958.

a. By-product coke oven (CO), diesel locomotive (DL), tin container (TC), and shuttle car (SC).

b. Car retarder (CR), trackless mobile loader (ML), continuous mining machine (CM), and pallet-loading machine (PL).

c. Continuous wide-strip mill (SM), centralized traffic control (CTC), continuous annealing (CA), and highspeed bottle filler (BF).

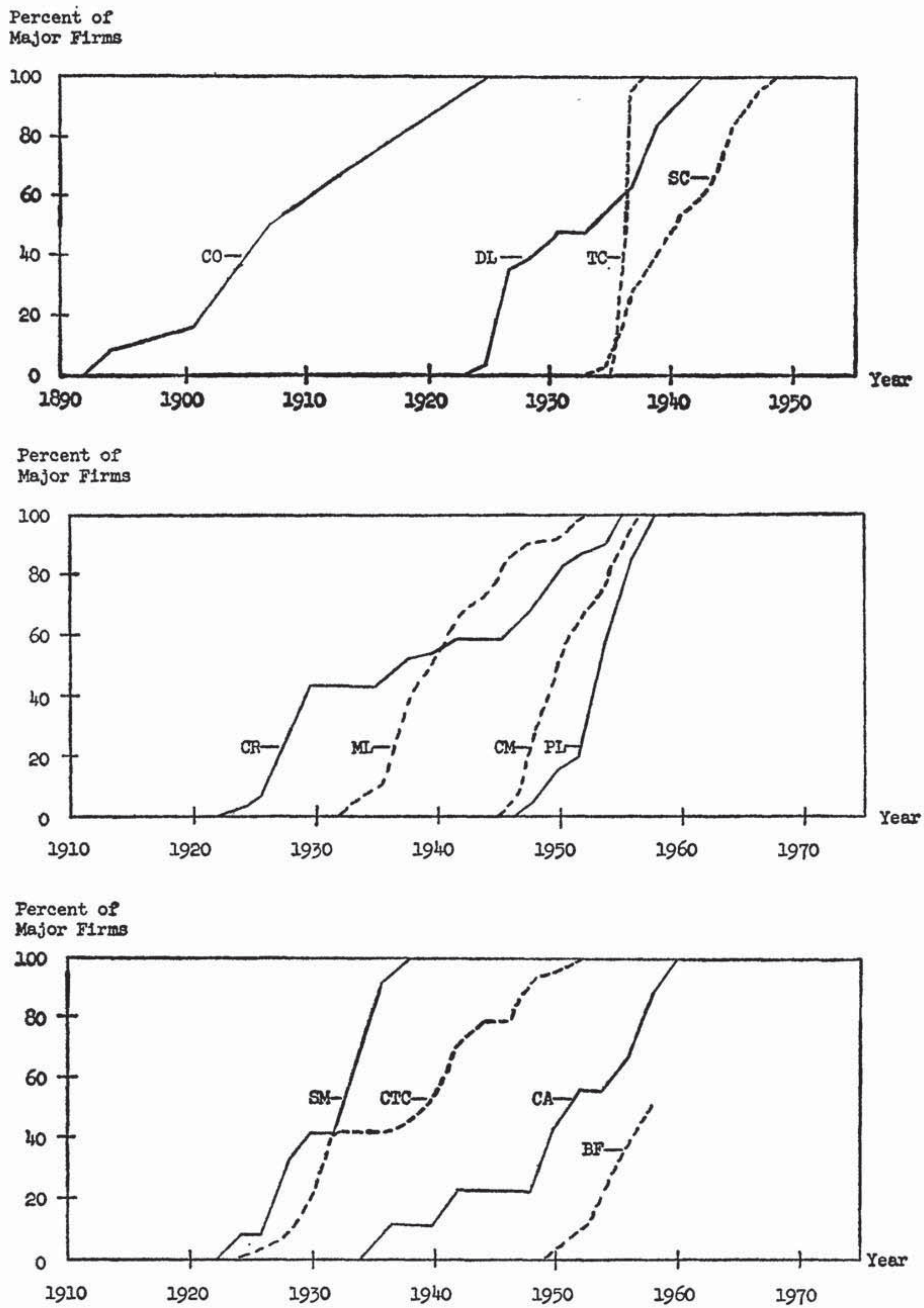


FIGURE 1.—Growth in the Percentage of Major Firms that Introduced Twelve Innovations, Bituminous Coal, Iron and Steel, Brewing, and Railroad Industries, 1890–1958.

1. Diffusion in U.S. industries: 12 industrial innovations

Diffusion rates vary a lot across innovations, from 0.9 years

to 15 years, with an average of 7.8, for 50% penetration.

Also uses regressions to study the slopes of the logistic curves.

As independent variables:

profitability (a measure similar to the internal rate of return),

cost of adoption (ratio of average initial investment to average

assets in the industry).

The coefficients are highly significant, and the fit is excellent,

$$\hat{b}_{ij} = \left\{ \begin{array}{c} -0.29 \\ -0.57 \\ -0.52 \\ -0.59 \end{array} \right\} + \begin{array}{cc} 0.530\pi_{ij} & -\ 0.27 S_{ij}, \\ (0.015) & (0.014) \end{array} \qquad r = 0.997.$$

Figure 2 plots the actual versus predicted b_{ij}'s.

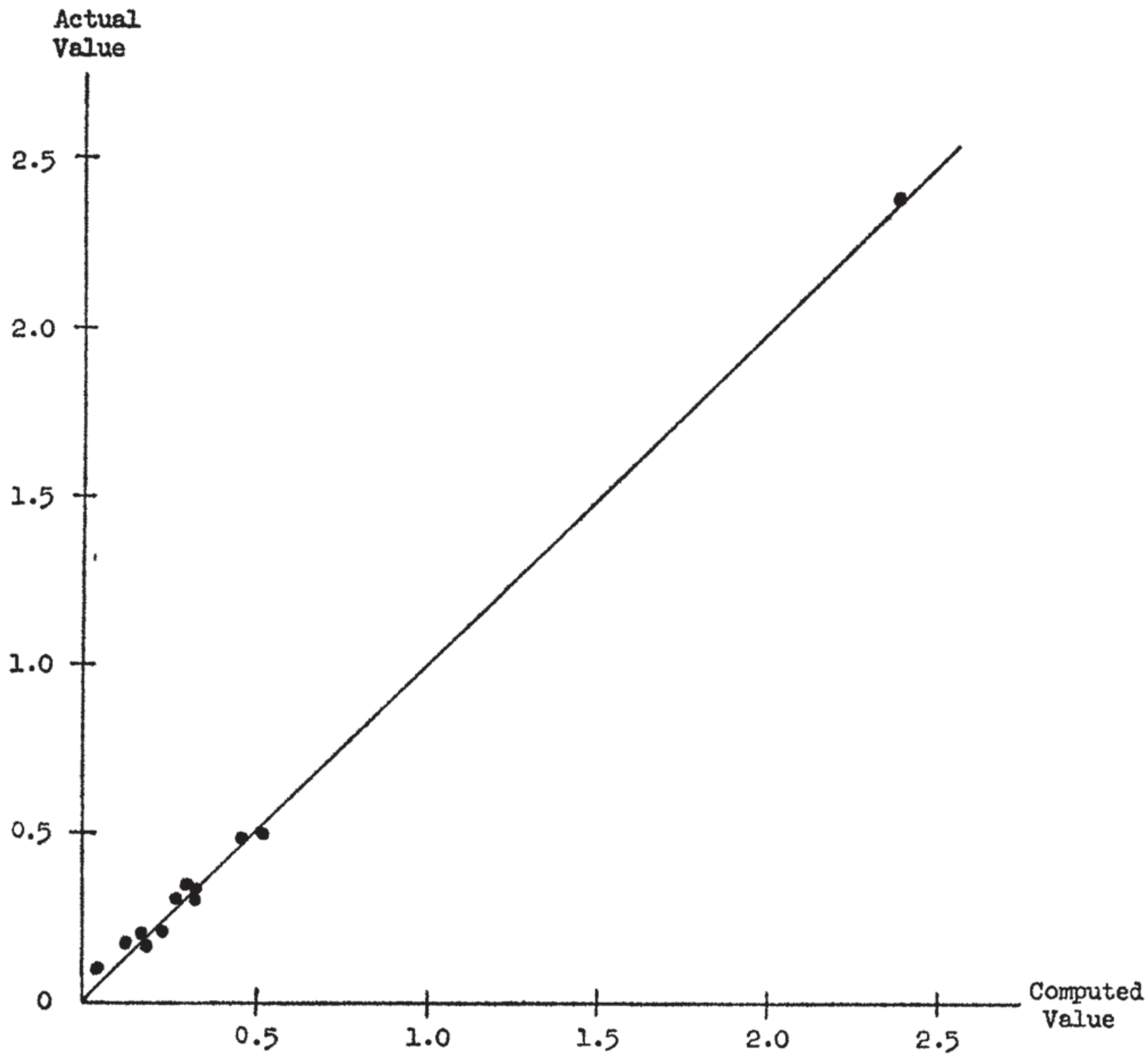
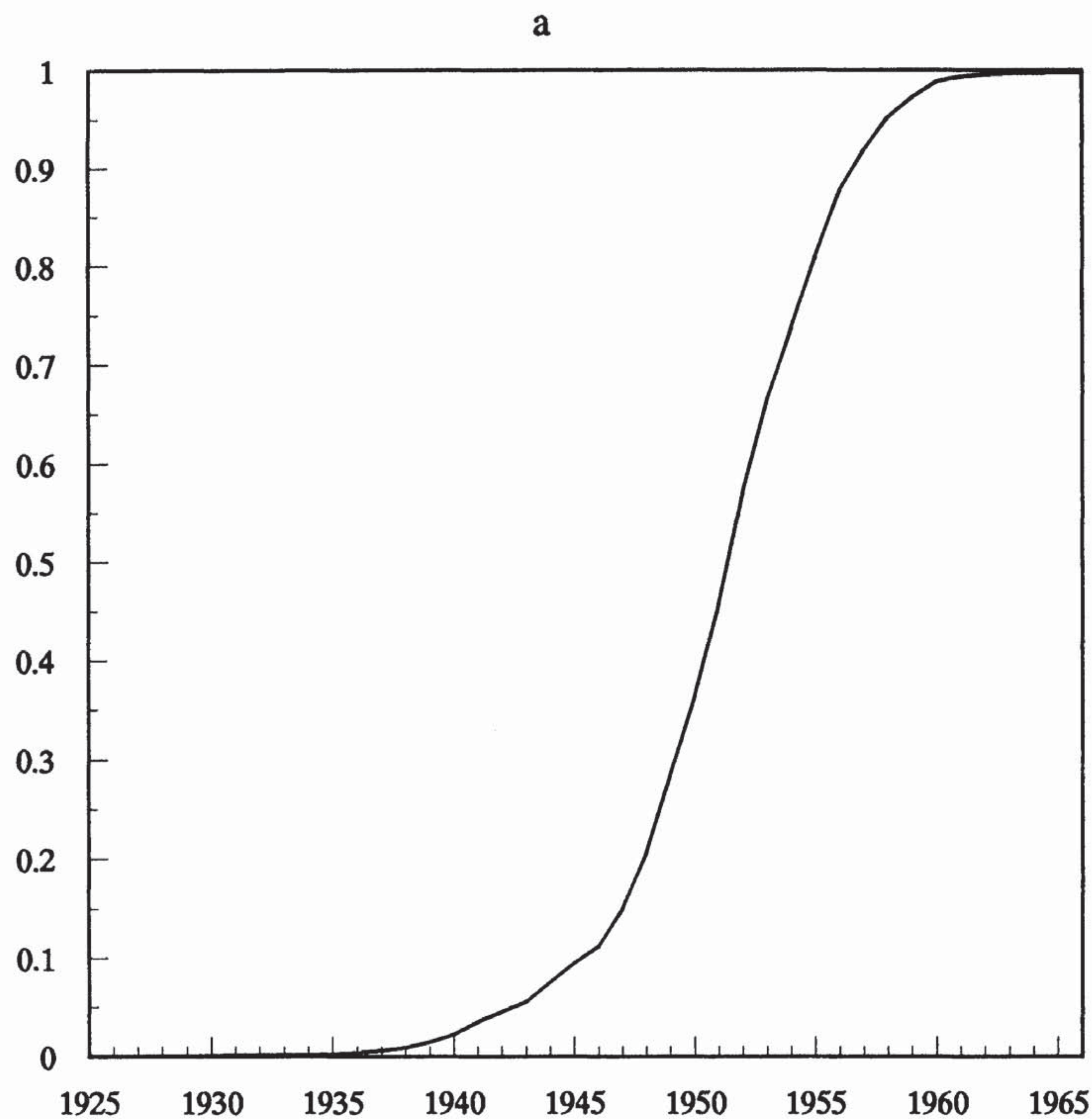


FIGURE 2.—Plot of Actual $\hat{\phi}_{ij}$ Against That Computed from Equation (14), Twelve Innovations.

1. Diffusion in U.S. industries: locomotives

Jovanovic and MacDonald (1994) show the diffusion of diesel locomotives (share of total locomotives).


a
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1925
1930
1935
1940
1945
1950
1955
1960
1965

1. Diffusion in U.S. industries: tractors

Manuelli and Seshadri (2014) look at the adoption of tractors.

Adoption was slow, and it was long a puzzle why it was so slow.

The authors show that adoption is well explained by cost and profitability.

Quality kept improving so (quality-adjusted) price kept falling.

- But the sharp decline came early, and did not induce widespread adoption.

Wages were about constant until 1930, and then fell slightly.

- They rose sharply during the 1940's, making (labor-saving) tractors more profitable.

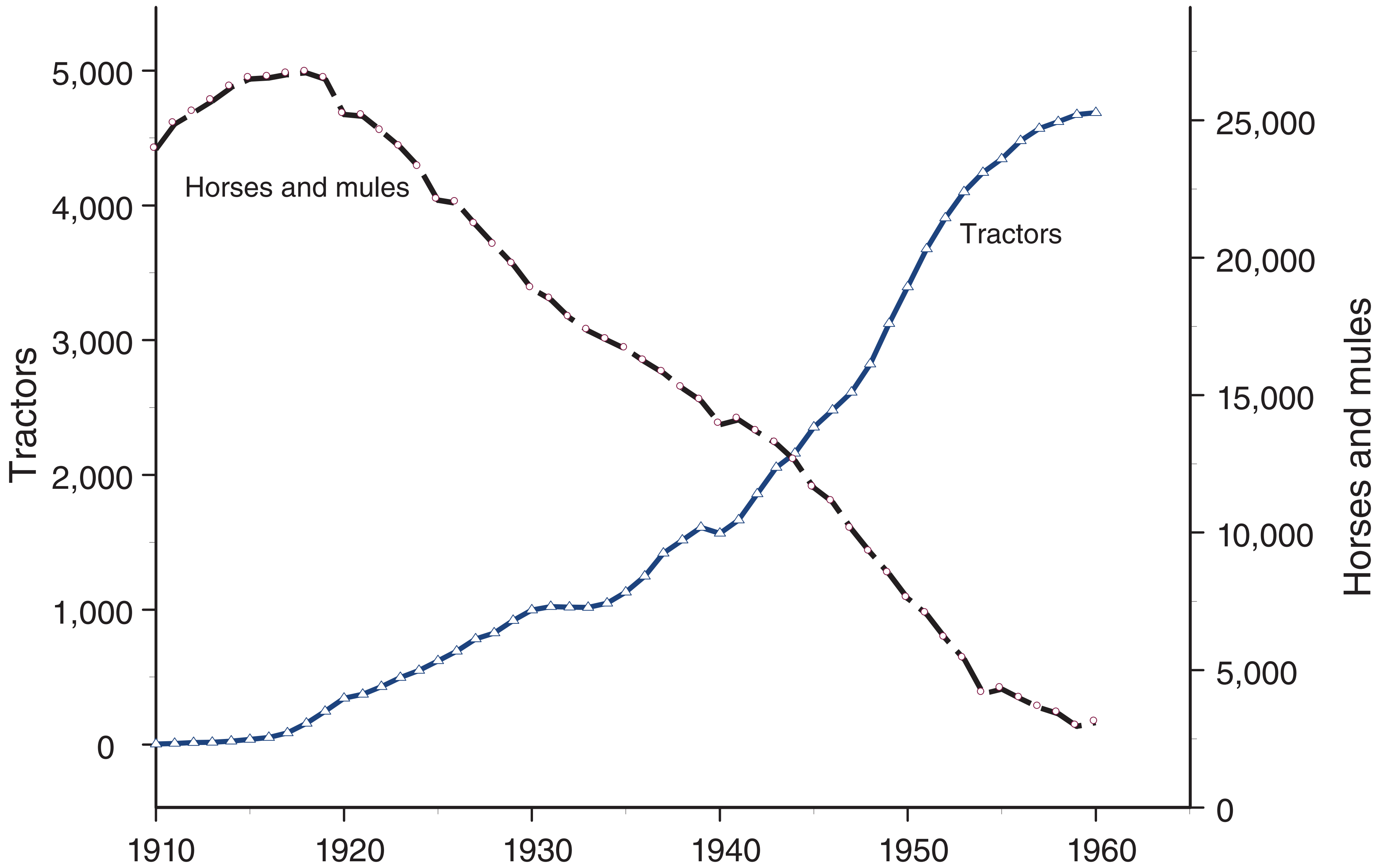


FIGURE 1. HORSES, MULES, AND TRACTORS IN FARMS: 1910–1960

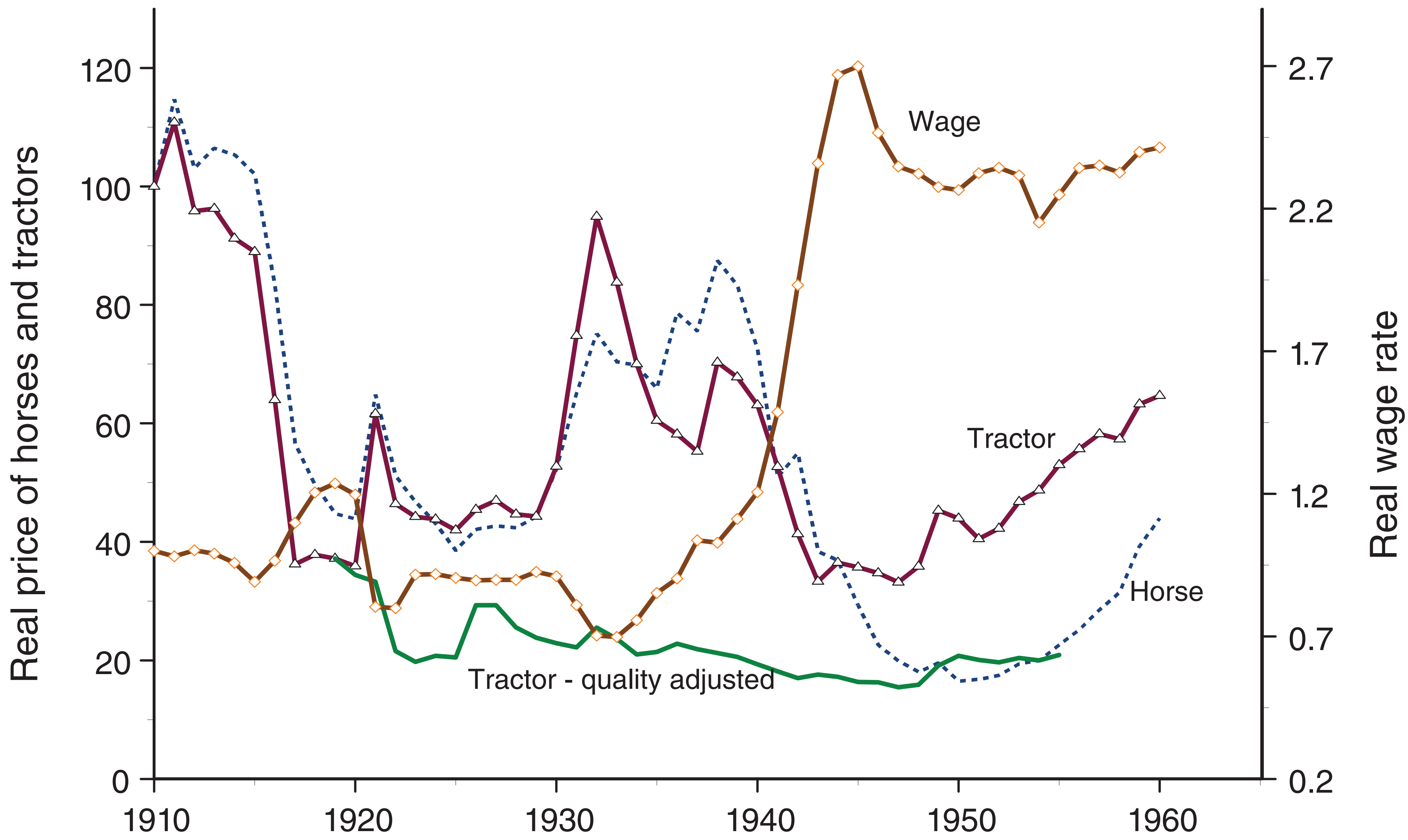


FIGURE 2. REAL PRICES FOR TRACTORS, HORSES, AND LABOR: 1910–1960

2. Cross-country diffusion: agriculture

Two facts about agriculture:

1. Inputs and outputs are (relatively) well measured in agr.
2. The equipment and intermediate inputs used in agriculture are

    largely distinct from those used in other sectors:

        seeds, fertilizer, tractors, combines, balers, etc.

Together, these two facts make a 2-sector model with agr. and nonagr.

    a good "laboratory" for studying diffusion of a **set** of technologies.

Much technical change in agr. is "embodied" in new equipment:

    tractors, trucks, combines, balers, etc.

2. Cross-country diffusion: agriculture

Cross-country patterns in agriculture:

1. Cross-country differences in labor productivity are larger in agriculture than in nonagriculture. [Caselli 2005; Restuccia, Yang & Zhu 2008.]

Per capita GDP of the richest 5% is **34** times that of the poorest 5%.

Labor productivity in agriculture is **78** times that of the poorest. (RYZ)

2. The same is true of capital intensity by sector. [Chen (2017)]
3. In poorer countries a larger share of employment is in agriculture.
4. For the U.S. the same development pattern is seen in time series:

—labor productivity growth was faster in agr,

—capital deepening was faster in agr,

—share of employment in agr. fell.

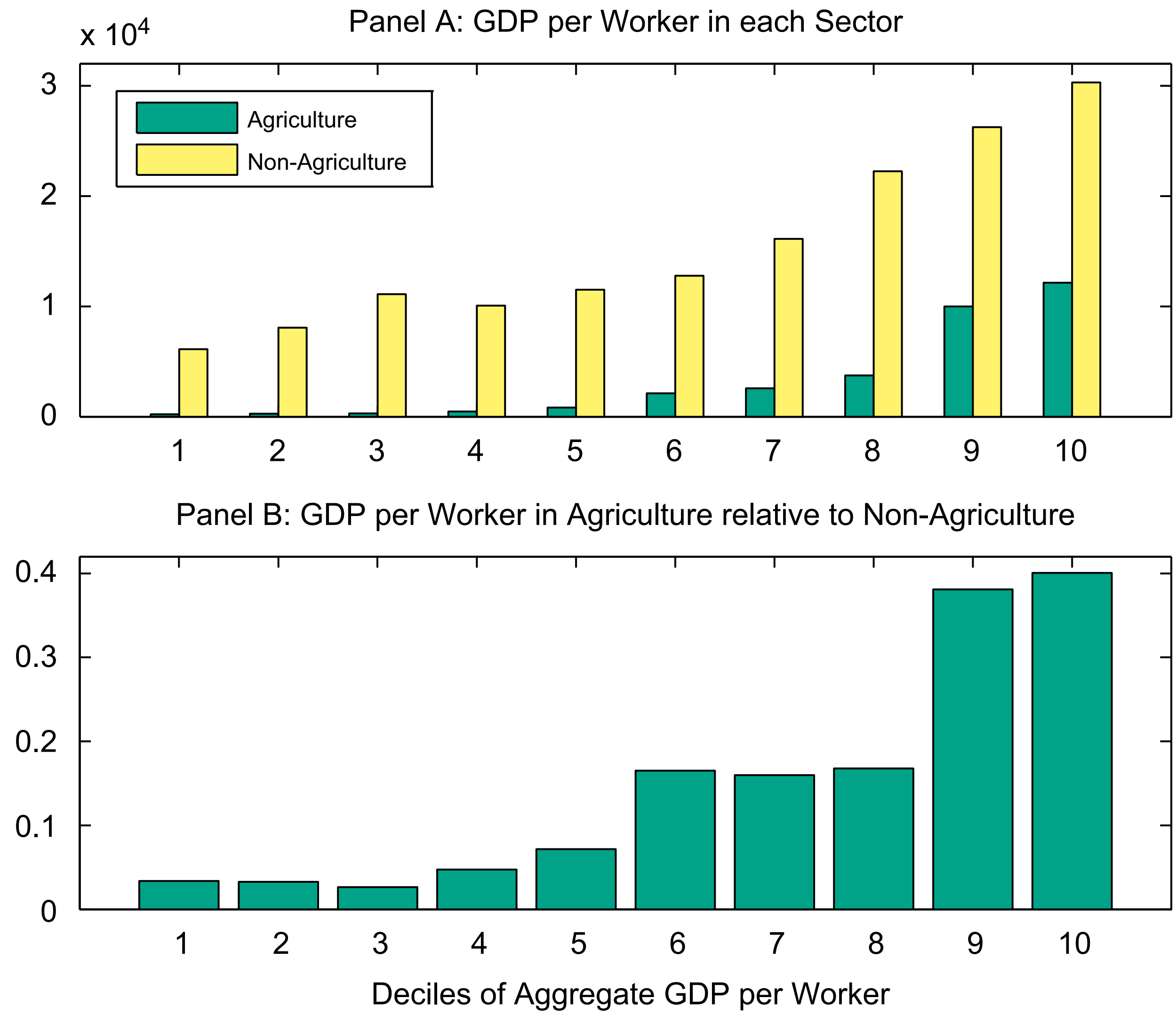
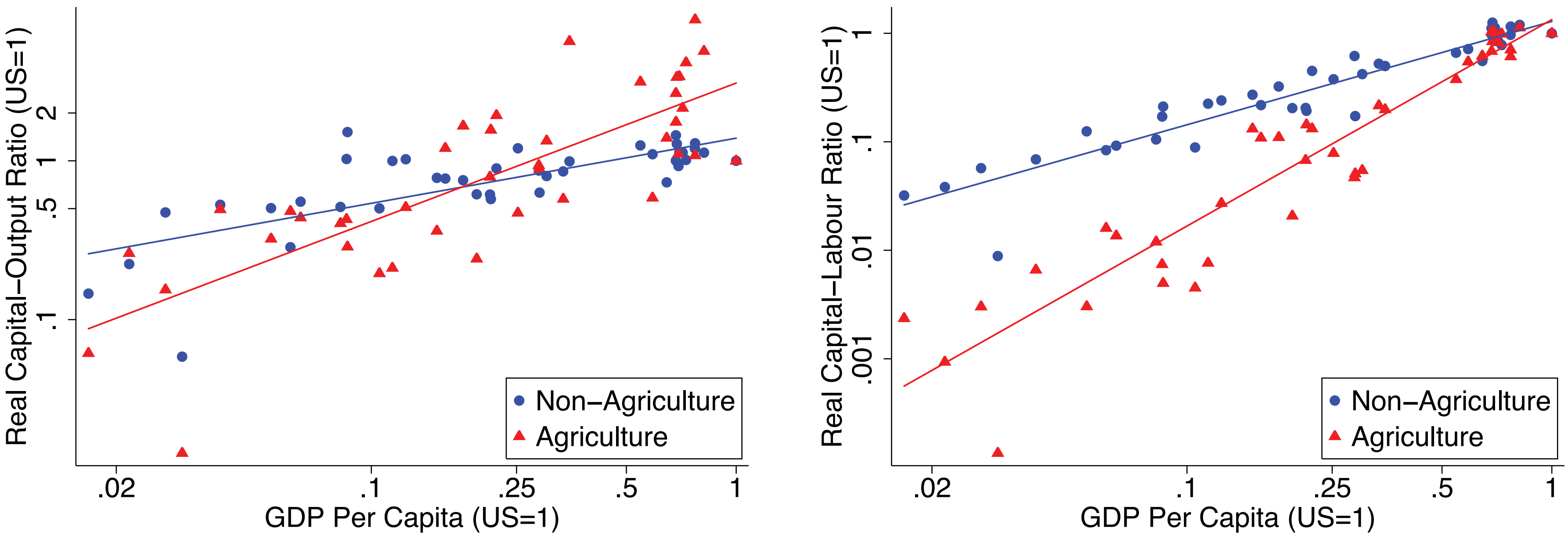


Fig. 2. Sectoral labor productivity across countries—1985. Countries are ranked according to aggregate GDP per worker from PWT5.6 where decile 10 groups the richest countries. Each decile contains eight countries (10% of countries in our sample) except decile 5, which contains 13 countries.

Figure 1: The Capital Intensity across Countries



(a) Real Capital-Output Ratio

(b) Capital-Labor Ratio

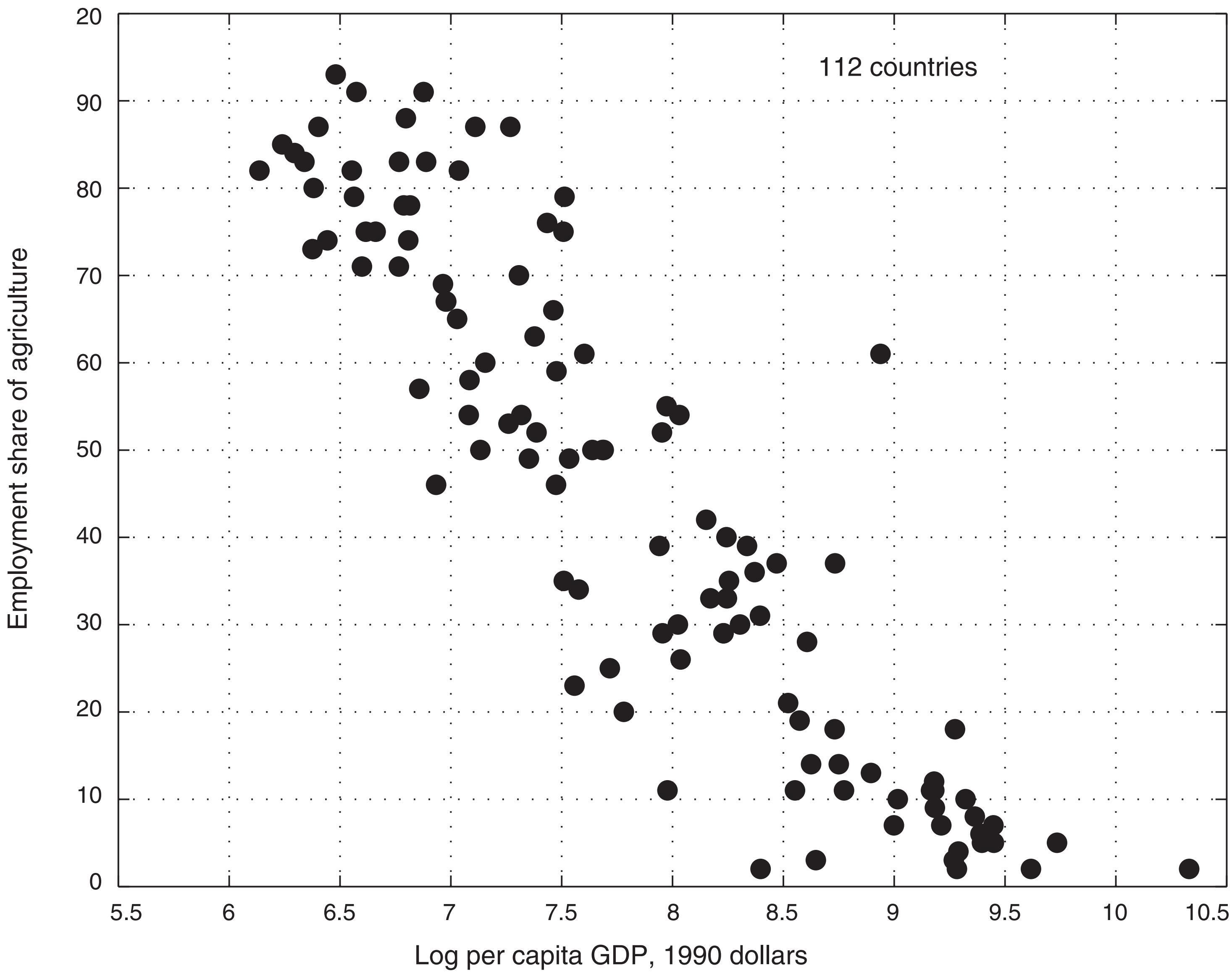


Figure 11. Agricultural Employment Shares, 1980

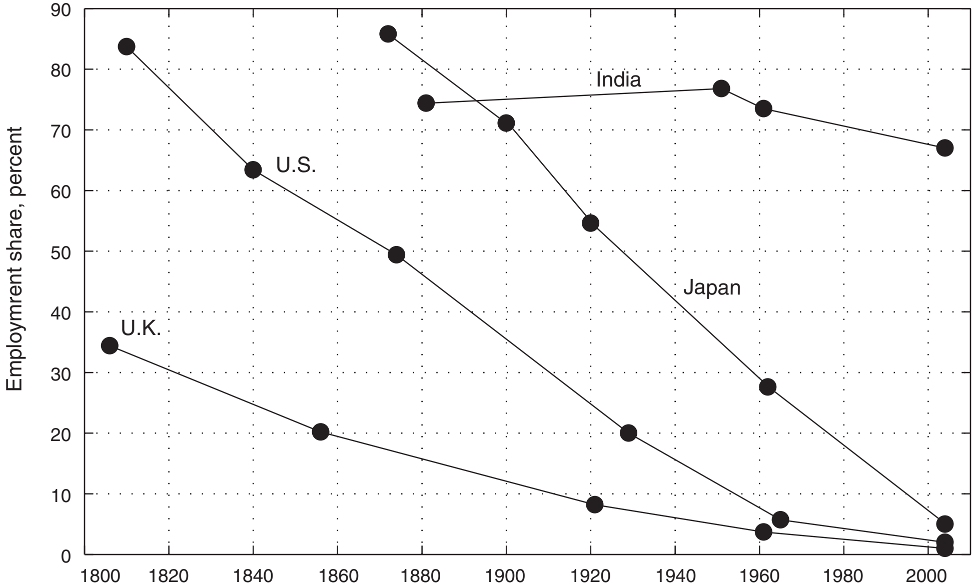


FIGURE 12. EMPLOYMENT SHARES IN AGRICULTURE

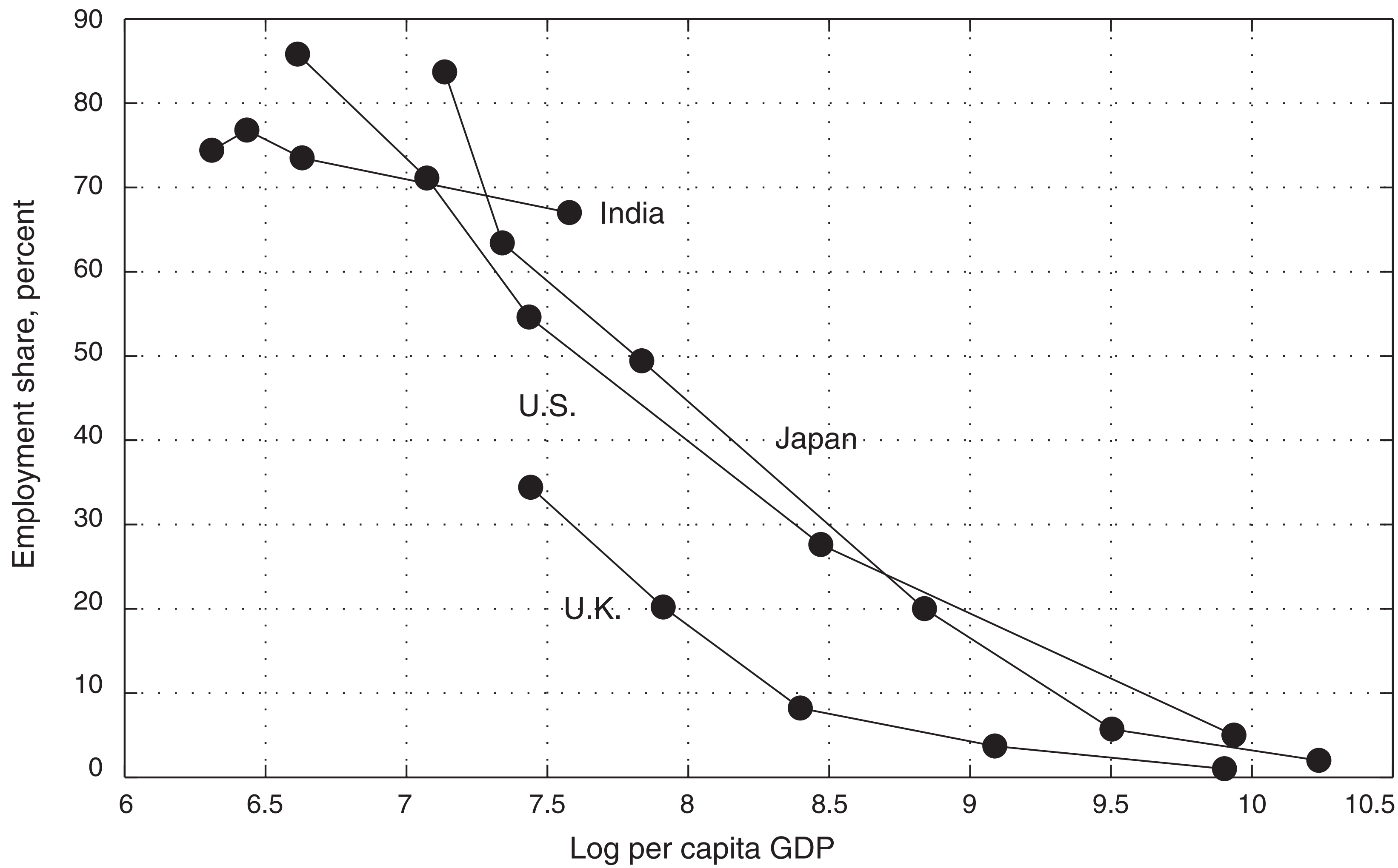


Figure 13. Employment Shares in Agriculture

3. A model of technology diffusion

A simple theoretical framework, based on Jovanovic & MacDonald (1994), can be used to explain the different types of evidence above: hybrid corn, Mansfield's 12 examples (fixed investment, endogenous price), tracctors (wage rate), cross-country adoption, (wage rate).

3. A model of technology diffusion: hybrid corn

Suppose there are two technology levels, indexed by $i = 0, 1$, where

$i = 0$ ($i = 1$) denotes the old (new) technology.

Assume the interest rate $r > 0$ is constant over time.

Assume demand is infinitely elastic, so the output price p is also fixed.

Let $\nu \in [0, 1]$ denote the fraction of firms that have already adopted

the new technology. It is the state variable.

3. A model of technology diffusion: hybrid corn

For hybrid corn, the goal is to explain differences across regions.

Adoption of hybrid corn requires no capital investment.

The seeds—and perhaps other inputs—may be more expensive, and the hybrid offers a higher yield per acre.

But yields, and hence profits, may vary across geographic regions j.

Let $\pi_{1j} > \pi_{0j} > 0$ denote profits **per acre** in region j with and without the hybrid.

Farms vary in size (acreage) within each region, and the size distribution varies across regions.

Let $F(z; j)$ denote the CDF for size in region j.

If there were no other costs, all farms in j would adopt immediately if $\pi_{1j} > \pi_{j0}$, and none would ever adopt otherwise

3. A model of technology diffusion: hybrid corn

To explain gradual diffusion, suppose there is one-time fixed (sunk) cost of adopting hybrids.

It can be interpreted as the cost of learning about the growing method.

The fixed cost $c_F(\nu)$ falls with the share of other farms (or acreage) in the region that have already adopted.

Assume c_F is the same across regions.

Adoption involves intertemporal tradeoffs, so to study equilibrium adoption pattern it is useful to introduce value functions.

3. A model of technology diffusion: hybrid corn

Let $V_i(z,\nu;j)$, $i=0,1$, denote the value of a farm of size z, in region j, when the state is ν.

A farm that has already adopted makes no more decisions, so clearly

$$V_1(z,\nu;j) = \frac{1+r}{r}\ \pi_{1j}\ z.$$

For a farm that has not yet adopted, the Bellman equation is

$$\begin{aligned} V_0(z,\nu;j) &= \max\{ \quad \text{adopt} \quad , \quad \text{wait}\} \\ &= \max\left\{ V_1(z,\nu;j) - c_F(\nu), \quad \pi_0 z + \frac{1}{1+r} V_0\left[z, \Phi(\nu;j); j\right] \right\}, \end{aligned}$$

where $\Phi(\nu;j) = \nu'$ is the share of farmers who will have adopted by next year.

$\Phi(\cdot;j)$ is an **equilibrium** object, determined by adoption decisions.

3. A model of technology diffusion: hybrid corn

Adopting immediately is the optimal choice if

$$\left(\pi_{j1} - \pi_{j0}\right) z + \frac{1}{1+r} \left\{ V_1(z; j) - V_0\left[z, \Phi(\nu; j)\right] \right\} > c_F(\nu).$$

Larger farms adopt earlier.

But farmers do not necessarily adopt on the first date when adopting this period dominates never adopting.

Later dates **reduce adoption costs**, but also **delay** the arrival of the gains.

The continuation value $V_0\left[z, \Phi(\nu; j)\right]$ includes an **option** of adopting later.

Since the fixed cost falls over time, this option is valuable.

3. A model of technology diffusion: hybrid corn

Alternatively, the net gain from adopting in period t can be written as

$$\text{Gain}(z, t; j) = \left(\frac{1}{1+r}\right)^t \left[\frac{1+r}{r}(\pi_1 - \pi_0) z - c_F(\nu_{jt})\right],$$

where $\nu_{j,t+1}$ is the share of adopters in region j in period t.

Each farmer chooses the date t of adoption to maximize gain.

$\text{Gain}(z, t; j)$ depends on t in two ways:

—later dates **reduce adoption costs**, but

—they also **delay** arrival of the gains, the discounting term.

One way to explain adoption patterns is to posit functional forms for $[c_F, G(z;j)]$ that, taken together, produce an adoption rule that delivers the desired pattern—logistic or something else.

Alternatively, assume the fixed cost has an idiosyncratic term, $\theta c_F(\nu)$, where θ varies across farms.

Posit a joint distribution for (z, θ) that delivers the desired pattern.

3. A model of technology diffusion: industrial technologies

Mansfield's technologies require substantial investments in new equipment, which can be included in $c_F(z, \nu)$.

Also price—and hence profits—may depend on ν as well as z.

Except for those two changes the model is similar.

In the industrial context the adoption cost c_F declines with ν if industry experience matters: later adopters can learn from others, perhaps by poaching their workers.

It might also include a declining price of equipment, because of learning-by-doing at the firm producing the new equipment or as part of the overall secular decline in the price of equipment relative to consumption goods.

3. A model of technology diffusion: cross-country model

For tractors, differences in **wage rates** are the key feature.

For the cross-country evidence, the same is true.,

Many new technologies are labor-saving and capital-using.

Remember where they are developed!

Suppose the cost of equipment is similar across countries, since they all buy from the same supplier(s).

Suppose interest and depreciation rates are also similar.

Then the user cost of capital is also similar.

But the gains from adoption will be smaller, and perhaps nonexistent, in countries with lower wages.

For a concrete example, consider a case where the old technology uses only labor, and the new one uses both labor and capital.

3. A model of technology diffusion: cross-country model

In particular, suppose

$$y_{0i} = A_i^{1-\beta} \ell_0^{\beta}, \qquad y_{1i} = (BA_i)^{1-\beta} \left(k_1^{\alpha} \ell_1^{1-\alpha}\right)^{\beta}.$$

The constant A_i varies across producers i, a Lucas span-of-control.

For simplicity, assume returns to scale β are the same across technologies, and the shifter $B > 1$ is the same across producers.

Let p be output price, and let (R, w_j) be factor returns in country j, where $R = (r + \delta)\, q$ is the implicit rental rate for the new equipment.

It is straightforward to show that profits for the two technologies are

$$\begin{aligned} \pi_{ij0} &= A_i d_0 p^{1/(1-\beta)} w_j^{-\beta/(1-\beta)}, \\ \pi_{ij1} &= BA_i d_0 p^{1/(1-\beta)} \left[\left(\frac{R}{\alpha}\right)^{\alpha} \left(\frac{w_j}{1-\alpha}\right)^{1-\alpha} \right]^{-\beta/(1-\beta)}, \end{aligned}$$

where $d_0 > 0$ involves β.

3. A model of technology diffusion: cross-country model

Hence the gain from adoption is

$$\Delta\pi_{ij} = A_i d_0 p \left(\frac{p}{w_j}\right)^{\beta/(1-\beta)} \left\{ B\left[\alpha^{\alpha}\left(1-\alpha\right)^{1-\alpha}\left(\frac{w_j}{R}\right)^{\alpha}\right]^{\beta/(1-\beta)} - 1 \right\}.$$

The term in braces is increasing in w_j, and can have either sign.

Adoption in j is worthwhile if and only if the wage w_j is sufficiently high.

If the wage w_j in country j grows over time, adoption may eventually become worthwhile, even if it is not profitable when the innovation is first introduced.

In other ways the cross-country model for industrial products is similar to the others.

The model suggests that important factors for explaining differences in the speed of diffusion are:

—the ratio of the rental rate to the wage rate, R/w_j,

—the relative profitability of the new technology, p/w_j,

—distribution of firm size

—the availability of skilled workers, if the new technology requires skill,

—the rate of decline in $c(\nu)$.

3. A model of technology diffusion: agriculture

A number of papers have used 2-sector models (ag., nonag.) to look at employment patterns, the productivity gap, relative wages, overall growth rates, and other issues.

The data on imports of equipment (and other inputs) provides a way to relate TFP growth in both sectors to measurable aspects of technology adoption.

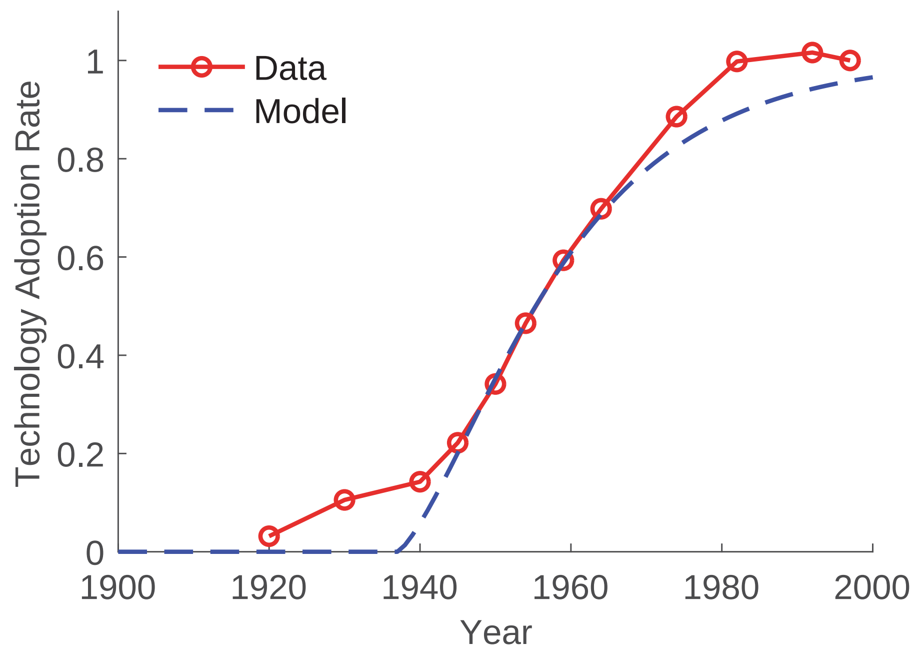
3. A model of technology diffusion: agriculture

Chen (2017) embeds a model of agr. production similar to the one above in a 2-sector setup to look at long run growth.

For agriculture, he assumes there is no market for wage labor, so the purchased inputs are capital and **land.**

He fits growth and convergence patterns pretty well.

Figure 5: Technology Adoption Curve



Note: The technology adoption rate of the model is the percentage of output produced using modern technology; the rate in the data is the average percentage of output produced by farms with modern machines. See the text for a detailed description.

But there are other possibilities as well.

Does better equipment substitute for land or labor?

Or is it a complement to land?

Does it increase the farmer's span of control?

Then tractors would increase farm size and free up labor.

Is there evidence about all this?

What happens when tractors, other equipment, and material inputs come in?

4. Conclusions

Research to date has identified some of the factors that explain/predict faster diffusion, but there are still many unanswered questions.

How well do factor price differentials explain slow adoption in developing countries?

How important are noneconomic 'barriers'?

Has adoption in nonagr. been faster because of factor price differentials or because FDI and other mechanisms for knowledge transfer, which help overcome the 'fixed cost', work better in the nonagr sector?

Thank you!