Frictionless Technology Diffusion: The Case of Tractors

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Many new technologies display long adoption lags, and this is often interpeted as evidence of frictions inconsistent with the standard neoclassical model. We study the diffusion of the tractor in American agriculture between 1910 and 1960 — a well known case of slow diffusion — and show that the speed of adoption was consistent with the predictions of a simple neoclassical growth model. The reason for the slow rate of diffusion was that tractor quality kept improving over this period and, more importantly, that only when wages increased did it become relatively unprofitable to operate the alternative, labor-intensive, horse technology.

Understanding the determinants of the rate at which new technologies are created and adopted is a critical element in the analysis of growth. Even though modeling equilibrium technology creation can be somewhat challenging for standard economic theory, understanding technology adoption should not be. Specifically, once the technology is available, *the adoption decision is equivalent to picking a point on the appropriate isoquant*. Dynamic considerations make this calculation more complicated, but they still leave it in the realm of the neoclassical model. A simple minded application of the theory of the firm suggests that profitable innovations should be adopted instantaneously, or with some delay depending on various forms of cost of adjustment.

The evidence on the adoption of new technologies seems to contradict this prediction. Jovanovic and Lach (1997) report that, for a group of 21 innovations, it takes 15 years for its diffusion to go from 10 percent to 90 percent, the 10-90 lag. They also cite the results of a study by Grübler (1991) covering 265 innovations who finds that, for most diffusion processes, the 10-90 lag is between 15 and 30 years.[1]

In response to this apparent failure of the simple neoclassical model, a large number of papers have introduced 'frictions' to account for the 'slow' adoption rate. These frictions include, among others, learning-by-doing (e.g. Jovanovic and Lach (1989), Jovanovic

[1]There are studies of specific technologies that also support the idea of long lags. Greenwood (1997) reports that the 10-90 lag is 54 years for steam locomotives and 25 years for diesels, Rose and Joskow's (1990) evidence suggest a 10-90 lag of over 25 years for coal-fired steam-electric high preasure (2400 psi) generating units, while Oster's (1982) data show that the 10-90 lag exceeds 20 years for basic oxygen furnaces in steel production. However, not all studies find long lags; using Griliches (1957) estimates, the 10-90 lag ranges from 4 to 12 years for hybrid corn.

and Nyarko (1996), Felli and Ortalo-Magné (1997), Greenwood and Yorukoglu (1997), and Atkeson and Kehoe (2007)), vintage human capital (e.g. Chari and Hopenhayn (1994) and Greenwood and Yorukoglu (1997)), informational barriers and spillovers across firms (e.g. Jovanovic and Macdonald (1994)), resistance on the part of sectoral interests (e.g. Parente and Prescott (1994)), coordination problems (e.g. Shleifer (1986)), search-type frictions (e.g. Manuelli (2002)) and indivisibilities (e.g. Greenwood, Seshadri and Yorukoglu (2004)).

In this paper we take a step back and revisit the implications of the neoclassical frictionless model for the equilibrium rate of diffusion of a new technology. Our model has two features that influence the rate at which a new technology is adopted: changes in the price of inputs *other* than the new technology and changes in the *quality* of the technology.[2] The application that we consider throughout is another famous case of 'slow' adoption, the farm tractor in American agriculture. The tractor was a very important innovation that dramatically changed the way farming was carried out and had a very large impact on farm productivity, making this a study worthwhile in its own right. In addition, there is a large literature on the diffusion of the tractor technology and the common finding in this literature is that diffusion was too slow.[3]

We assume a standard neoclassical technology that displays constant returns to scale in all factors. In order to eliminate frictions associated with indivisible inputs, we study the case in which there are perfect rental markets for all inputs.[4] The representative farm operator maximizes profits choosing the mix of inputs. Given our market structure, this is a static problem. We take prices and the quality of all inputs as exogenous and we let the model determine the price of one input, land, so as to guarantee that demand equals the available stock.

We use a mixture of calibration and estimation to pin down the relevant parameters. We then use the model, driven by the observed changes in prices, wages and real interest rates to predict the number the tractors and employment for the entire 1910-1960 period. The model is very successful in explaining the diffusion of the tractor —including the S-shape diffusion curve— and does reasonably well in tracing the demise of the horse. Even though it was not designed for this purpose, it does a very good job in capturing the change in employment over the same time period. In addition, the implications for land prices are in line with the available evidence. We conclude that there is no tension between the predictions of a frictionless neoclassical model and the rate at which tractors diffused in U.S. agriculture.

More generally, our findings show that stable S-shape diffusion curves need not be structural objects. Their shape need not reflect the "frictions" that we described above,

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[2]Given our focus, we ignore frictions that can explain the change in prices and the (maybe slow) improvement in the technology. We do this because our objective is to understand the role played by frictions on the adoption decision, given prices and available technology.

[3]Sally Clarke (1991) estimates a threshold model of adoption (assuming indivisibilities) for the corn belt and finds that in 1929 "for every farmer who owned a tractor there was another one that should have invested in the machine but did not do so." Warren C. Whatley (1985) finds support for the view that the organizational structure of the tenant plantation discouraged adoption of tractors. See also Byron Lew (2000) and Alan L. Olmstead and Paul W. Rhode (2001)

[4]This, effectively, eliminates the indivisibility at the individual level. Given the scale of the industry that we study, indivisibilities at the aggregate level are not relevant.

and may simply be the outcome of standard profit maximization when the model is correctly specified. In particular, we find that incorporating changes in the quality of a technology over time and in the costs of operating alternative (often less productive) technologies can account for the pattern of diffusion.

The paper is organized as follows. In section 2 we present a brief historical account of the diffusion of the tractor and of the price and quality variables that are the driving forces in our model. Section 3 describes the model, and Section 4 discusses the determination of the relevant parameters. Sections 5 and 6 present our results, and section 7 offers some concluding comments.

I. Some Historical Observations

This section presents some evidence on the use of tractors and horses by U.S. farmers, and on the behavior of wages and employment in the U.S. agricultural sector.

Diffusion of the Tractor. The diffusion of the tractor was not unlike most other technologies, it had a characteristic S-shape. Figure 1 plots the number of tractors on American farms. Diffusion was slow initially. The pace of adoption speeds up after 1940.
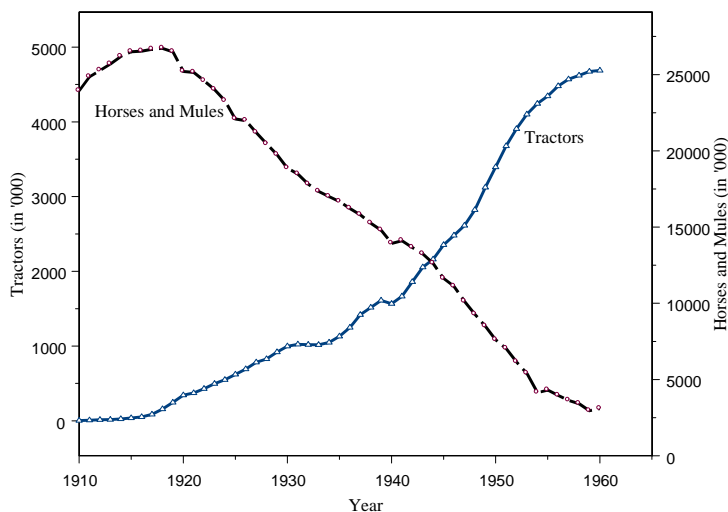

FIGURE 1. HORSES, MULES AND TRACTORS IN FARMS, 1910-1960

As the tractor made its way into the farms, the stock of horses began to decline. In 1920, there were more than 26 million horses and mules on farms. Thereafter, this stock began to decline and by 1960, there were just about 3 million. While the tractor was

primarily responsible for this decline, it should be kept in mind that the automobile was also instrumental in the elimination of the horse technology. As in the case of other technologies, investment in horses —the 'dominated' technology— was positive, even as the stock declined.

Real Prices for Tractors and Horses. Figure 2 plots the real price of a mid-size tractor and a pair of draft horses between 1910 and 1960.[5] Between 1910 and 1920, there is a sharp decline in the price of tractors which is partially reversed in the 1930s. In the 1940s and 1950s prices are lower and comparable to those prevailing in 1920s. One simple conclusion from this evidence is that farmers should have adopted tractors in the 1920s at the same rate they did in the 1940s and 1950s. They did not. This observation lies behind the idea that adoption was slow. White (2000) collected data on some tractor characteristics and estimated a quality adjusted price for a tractor. The resulting series —labeled Tractor-quality adjusted in Figure 2— shows a steep decline until the mid-1920s, but very small changes after this. Thus, changes in the price of the technology —in the absence of frictions— appear to be insufficient to explain the pattern of adoption documented in Figure 1.

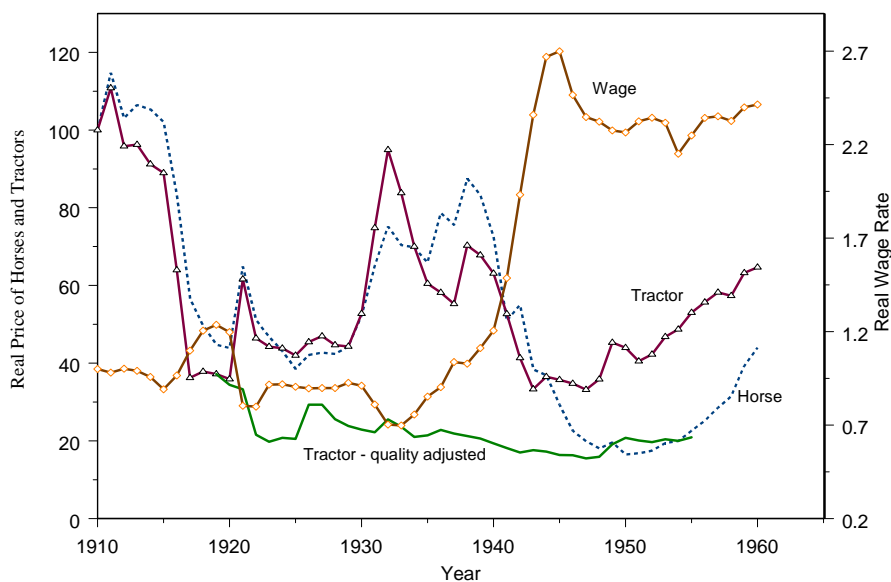FIGURE 2. REAL PRICES FOR TRACTORS, HORSES AND LABOR: 1910-1960

Farm Real Wage Rates and Employment. Real wages in the agricultural sector remained stagnant from 1910 till about 1930, fell by half between 1930 and 1934, and then doubled between 1940 and 1950. If the tractor was labor-saving, rising wages after

[5]The data are from Olmstead and Rhode (2001). We thank Paul Rhode for providing the data.

1940 would likely speed up adoption since holding on to the more labor intensive horse technology will be unprofitable. The falling wages in the early thirties might also go towards explaining the reluctance of farmers to switch to tractors during the same time period. Man-hours on farms remained fairly constant between 1910 and 1930, and then fell by 76 percent between 1930 and 1970. Farm population decreased dramatically too. In 1910, there were 11.67 million farm workers (full-time equivalents). By 1960, this number had fallen to 5.97 million.

In what follows we develop a simple neoclassical growth model of agricultural production and investment and show that the previous evidence is consistent with optimal frictionless adoption of tractors once the change in the effective price of operating the tractor technology —which depends on changes in quality and price of tractors as well as wage rates— relative to the cost of operating the more labor intensive horse technology are explicitly taken into account. In our setting, "slow" adoption is neither evidence of deviations from perfect markets, indivisibilities, or other "frictions."

Alternative Explanations. The standard approach to studying the diffusion of the tractor is based on the 'threshold' model. In its simplest form, the model takes as given the size of the farm (in acres) and considers the costs of different combinations of horse-drawn and tractor-drawn technologies required to produce a given amount of services. By choosing the cost minimizing technology, the model selects the type (size) of farm that should adopt a tractor. The predictions of the model — given the size distribution of farms — are then compared with the data. These calculations find that in the 1920's and early 1930's, U.S. farmers were too slow to adopt the relatively new tractor technology. Allowing for imperfect capital markets (Clarke (1991)) or introducing uncertainty about the value of output (Lew (2001)) help improve the fit of the model, but not to the point where it is consistent with the evidence. More recently Olmstead and Rhode (2001) estimate that changes in the price of horses and in the size distribution delayed, to some extent, the adoption of tractors. In their model the size distribution is exogenous. White (2000) emphasizes the role of prices and quality of tractors. Using a hedonic regression, he computes a quality-adjusted price series for tractors. White conjectures that the increase in tractor quality should be taken into account to understand adoption decisions.

II.   A Simple Model of Farming

Our approach is to model technology adoption using a standard profit maximization argument. Since we assume complete rental markets, the maximization problem is static.[6]

The one period profit of a farmer is given by,

$$\pi_t(\mathbf{q}_t, \mathbf{c}_t, w_t) \equiv \max_{k_t, h_t, \mathbf{n}_t, a_t} p_{ct} F(k_t, h_t, \mathbf{n}_t, a_t) -$$

$$\sum_{\tau=-\infty}^{t} [q_{kt}(\tau) + c_{kt}(\tau)] m_{kt}(\tau) - [q_{ht} + c_{ht}]h_t - w_t \bar{n}_t - [q_{at} + c_{at}]a_t,$$

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[6]Olmstead and Rhode (2001) provide evidence of the prevalence of contract work, i.e. of instances in which a farmer provides 'tractor services' to other farms.

where $F(k_t, h_t, \mathbf{n}_t, a_t)$ is a standard production function which we assume to be homogeneous of degree one in all inputs, and k_t is the demand for *tractor services*, h_t is the demand for *horse services* (which we assume proportional to the stock of horses), $\mathbf{n}_t = (n_{ht}, n_{kt}, n_{yt})$ is a vector of labor services corresponding to three potential uses: operating horses, n_{ht}, operating tractors, n_{kt}, or other farm tasks, n_{yt}, and a_t is the demand for land services (which we assume proportional to acreage), and $\bar{n}_t = n_{ht} + n_{kt} + n_{yt}$ is the total demand for labor.

On the cost side, $q_{ht} + c_{ht}$ is the full cost of operating a draft of horses. The term q_{ht} is the rental price of a horse, and c_{ht} includes operating costs (e.g. feed and veterinary services). The term $q_{at} + c_{at}$ is the full cost of using one acre of land, and w_t is the cost of one unit of (farm) labor. Effective one period rental prices for horses and land (two durable goods) are given by

$$q_{jt} \equiv p_{jt} - \frac{(1 - \delta_{jt}) p_{jt+1}}{1 + r_{t+1}}, \qquad j = h, a,$$

where δ_{jt} are the relevant depreciation factors, and r_t is the interest rate.

Since we view changes in the quality of tractors as a major factor influencing the decision to adopt the technology, we specified the model so that it could capture such variations. Specifically, we assume that tractor services can be provided by tractors of different vintages, τ, according to

$$k_t = \sum_{\tau=-\infty}^{t} m_{kt}(\tau) \tilde{k}_t(\tau),$$

where $\tilde{k}_t(\tau)$ is the quantity of tractor services provided by a tractor of vintage τ (i.e. built in period τ) at time t, and $m_{kt}(\tau)$ is the number of tractors of vintage τ operated at time t. We assume that the amount of tractor services provided at time t by a tractor of vintage τ is given by,

$$\tilde{k}_t(\tau) \equiv \upsilon(\mathbf{x}_\tau)(1 - \delta_{k\tau})^{t-\tau},$$

where $\delta_{k\tau}$ is the depreciation rate of a vintage τ tractor, and $\upsilon(\mathbf{x}_\tau)$ maps model-specific characteristics, the vector $\mathbf{x}_\tau$, into an overall index of tractor 'services' or 'quality.' Thus, our model assumes that the characteristics of a tractor are fixed over its lifetime (i.e. no upgrades), and that tractors depreciate at a rate that is (possibly) vintage specific. The rental price of a tractor is given by

$$q_{kt}(\tau) = p_{kt}(\tau) - \frac{p_{kt+1}(\tau)}{1 + r_{t+1}},$$

where $p_{kt}(\tau)$ is the price at time t of a $t - \tau$ year old tractor, while the term $c_{kt}(\tau)$ captures the variable cost (fuel, repairs) associated with operating one tractor of vintage τ at time t.

The resulting demand function for input is denoted by

$$m_t = m(\mathbf{q}_t, \mathbf{c}_t, w_t),$$

where $m \in \{k, h, a, \bar{n}\}$ indicates the input type, $\mathbf{q}_t$ is a vector of rental prices, $\mathbf{c}_t$ is a vector of operating costs, and w_t denotes real wages in the farm sector. Given that agricultural prices are largely set in world markets, and that domestic and total demand do not coincide, we impose as an equilibrium condition that the demand for land equal the available supply. Thus, land prices are endogenously determined.

A. Aggregate Implications

Aggregation in this model is standard. However, it is useful to make explicit the connection between the demand for tractor services and the demand for tractors.

The aggregate demand for tractor *services* at time t, K_t is given by

$$(1) \qquad\qquad K_t = k(\mathbf{q}_t, \mathbf{c}_t, w_t),$$

while the *number of tractors* purchased at t, m_{kt} is

$$(2) \qquad\qquad m_{kt} = \frac{K_t - (1 - \delta_{kt-1})K_{t-1}}{v(\mathbf{x}_t)}.$$

The law of motion for the stock of tractors (in units), K_t^s, is[7]

$$(3) \qquad\qquad K_t^s = (1 - \delta_{kt-1})K_t^s + m_{kt}.$$

It follows that to compute the implications of the model for the stock of tractors, which is the variable that we observe, it is necessary to determine the depreciation factors and the quality of tractors of each vintage.

We assume that horse services are proportional to the stock of horses and, by choice of a constant, we set the proportionality ratio to one. Thus, the aggregate demand for horses is

$$(4) \qquad\qquad H_t = h(\mathbf{q}_t, \mathbf{c}_t, w_t).$$

We let the price of land adjust so that the demand for land predicted by the model equals the total supply of agricultural land denoted by A_t. Thus, given wages, agricultural prices and horse and tractor prices, the price of land, p_{at}, adjusts so that

$$(5) \qquad\qquad A_t = a(\mathbf{q}_t, \mathbf{c}_t, w_t).$$

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[7]An alternative measure of the stock of tractors is given by $K_{t+1} = K_t + m_{kt+1} - m_{kt-T}$ were T is the lifetime of a tractor of vintage $t - T$. This alternative formulation assumes that tractors are of the one-hose shay variety and that after T periods they are scrapped.

B.   Modeling Tractor Prices

From the point of view of an individual farmer the relevant price of tractor is $q_{kt}(\tau)$, the price of tractor services corresponding to a $t - \tau$ year old tractor in period t. Unfortunately, data on these prices are not available. However, given a model of tractor price formation, it is possible to determine rental prices for all vintages using standard, no-arbitrage, arguments.

As indicated above, we assume that a *new tractor* at time t offers tractor services given by $\tilde{k}_t(t) = \upsilon(\mathbf{x}_t)$, where $\upsilon(\mathbf{x}_t)$ is a function that maps the characteristics of a tractor into tractor services. We assume that, at time t, the price of a new tractor is given by

$$p_{kt} = \frac{\upsilon(\mathbf{x}_t)}{\gamma_{ct}}.$$

In this setting γ_{ct}^{-1} is a measure of markup over the level of quality. If the industry is competitive, it is interpreted as the amount of aggregate consumption required to produce one unit of tractor services using the best available technology $\mathbf{x}_t$.[8]   However, if there is imperfect competition, it is a mixture of the cost per unit of quality and a standard markup. For the purposes of understanding tractor adoption we need not distinguish between these two interpretations: any factor —technological change or variation in markups— that affects the cost of tractors will have an impact on the demand for them. In what follows we ignore this distinction, and we label γ_{ct} as productivity in the tractor industry.

No arbitrage arguments imply that

(6) $q_{kt}(t) = p_{kt} \left[1 - R_t(1)(1 - \delta_{kt}) \frac{\gamma_{ct}}{\gamma_{ct+1}} \right] + (1 - \Delta_t) C(t + 1, T - 1),$

where

$$\Delta_t = \frac{\upsilon(\mathbf{x}_t)(1 - \delta_{kt})}{\upsilon(\mathbf{x}_{t+1})},$$

$$C(t + 1, T - 1) \equiv \sum_{j=0}^{T-1} R_{t+1}(j) c_{kt+1+j},$$

$$R_t(j) \equiv \prod_{k=1}^{j} (1 + r_{t+k})^{-1}$$

given that T is the lifetime of a tractor, and c_{kt} is the cost of operating a tractor in period t.

This expression has a simple interpretation. The first term, $1 - R_t(1)(1 - \delta_{kt}) \frac{\gamma_{ct}}{\gamma_{ct+1}}$, translates the price of a tractor into its flow equivalent. If there were no changes in the

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[8]We assume that the cost of producing 'older' vectors x_t is such that all firms choose to produce using the newest new technology.

unit cost of tractor quality, i.e. $\gamma_{ct} = \gamma_{ct+1}$, this term is just that standard capital cost, $(r_{t+1} + \delta_{kt})/(1 + r_{t+1})$. The second term is the flow equivalent of the present discounted value of the costs of operating a tractor from t to $t + T - 1$, $C(t + 1, T - 1)$. In this case, the adjustment factor, $1 - \Delta_t$, includes more than just depreciation, total costs have to be corrected by the change in the 'quality' of tractors, which is captured by the ratio $\frac{v(\mathbf{x}_t)}{v(\mathbf{x}_{t+1})}$.

Equation 6 illustrates the forces at work in determining the rental price of a tractor,

- Increases in the price of a new tractor, $p_{kt}(t)$, increase the cost of operating it. This is the (standard) price effect.

- Periods of anticipated productivity increases —low values of $\frac{\gamma_{ct}}{\gamma_{ct+1}}$— result in increases in the rental price of tractors. This effect is the complete markets analog of the option value of waiting, buyers of a tractor at t know that, due to decreases in the price of new tractors in the future, the value of their used unit will be lower. In order to get compensated for this, they require a higher rental price.

- The term $(1 - \Delta_{t+1})C(t + 1, T - 1)$ captures the increase in cost *per unit of tractor services* associated with operating a one year old tractor, relative to a new tractor.

III. Model Specification, Calibration and Estimation

We begin by describing how we estimate the rental price of tractor services. To compute $q_{kt}(t)$ we need to separately identify $v(\mathbf{x}_t)$ and γ_{ct}.[9] To this end we specified that the price of a tractor of model m, produced by manufacturer k at time t, p_{mkt}, is given by

$$p_{mkt} = e^{-d_t} \Pi_{j=1}^N (x_{jt}^m)^{\lambda_j} e^{\epsilon_{mt}},$$

where $\mathbf{x}_t^m = (x_{1t}^m, x_{2t}^m, ...x_{Nt}^m)$ is a vector of characteristics of a particular model produced at time t, the d_t variables are time dummies, and ϵ_{mt} is a shock. This formulation is consistent with the findings of White (2000).[10] We used data on prices, tractor sales and a large number of characteristics for almost all models of tractors produced between 1919 and 1955 to estimate this equation. In the Appendix, we describe the data and the estimation procedure. Given our estimates of the time dummy, $\hat{d}_t$, and the price of each tractor, $\hat{p}_{mkt}$, we computed our estimate of average quality, $\bar{v}(\mathbf{x}_t)$ as

$$\bar{v}(\mathbf{x}_t) = \bar{p}_{kt}\hat{\gamma}_{ct},$$

where

$$\bar{p}_{kt} = \sum_m s_{mkt} \hat{p}_{mkt},$$

$$\hat{\gamma}_{ct} = e^{\hat{d}_t},$$

[9]It is clear that all that is needed is that we identify the changes in these quantities.

[10]Formally, we are assuming that the shadow price of the vector of characteristics x_t does not change over time. This is not essential, and the results reported by White (2000), Table 10, can be interpreted as allowing for time-varying shadow prices. Comparing the results in Tables 10 and 11 in White (2000) it does not appear that the extra flexibility is necessary.
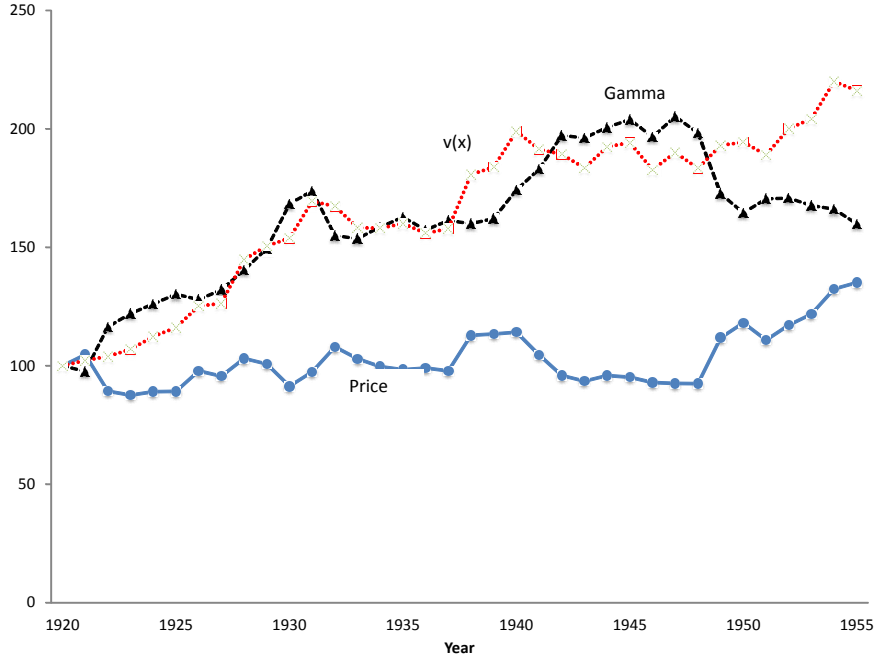
FIGURE 3. TRACTOR PRICES, QUALITY AND PRODUCTIVITY. 1920-1955. ESTIMATION

with s_{mkt} being the share of model m produced by manufacturer k in total sales at time t. The resulting time-series for $\bar{v}(\mathbf{x}_t)$, $\hat{\gamma}_{ct}$ and $\bar{p}_{kt}$ are shown in Figure 3.

Even though the real price of the average tractor does not show much of trend after 1920, its components do. Over the whole period our index of quality more than doubles, and our measure of productivity shows a substantial, but temporary, increase in the 1940s relative to trend, only to return to trend in the 1950s. In the 1920-1955 period γ_{ct} increases by about 50 percent. Thus, during this period there were substantial increases in quality and decreases in costs; however, these two factors compensated each other (except at the very end), so that the real price of a tractor shows a modest increase.

We assume that the interest rate is time varying and that $R = (1 + r)^{-1}$. We consider the following specification of the farm production technology

$$
\begin{aligned}
F^c(z, n_y, a) &= A_{ct} z^{\alpha_{zy}} n_y^{\alpha_{ny}} a^{1 - \alpha_{zy} - \alpha_{ny}}, \\
z &= F^z(z_k, z_h) = [\alpha_z (z_k)^{-\rho_1} + (1 - \alpha_z) z_h^{-\rho_1}]^{-1/\rho_1}, \\
z_k &= F^k(k, n_k) = [\alpha_k k^{-\rho_2} + (1 - \alpha_k) n_k^{-\rho_2}]^{-1/\rho_2}, \\
z_h &= A_h F^h(h, n_h) = [\alpha_h h^{-\rho_3} + (1 - \alpha_h) n_h^{-\rho_3}]^{-1/\rho_3}.
\end{aligned}
$$

This formulation captures the idea that farm output depends on services produced by tractors, z_k, services produced by horses, z_h, and labor, n_j, $j = y, h, k$. We take a

standard approach and use a nested CES formulation.[11] We assume that the elasticity of substitution between tractors and labor in the production of tractor services is $1/(1+\rho_2)$ while the elasticity of substitution between horses and labor in the production of horse services is $1/(1+\rho_3)$. Since we allow the elasticity of substitution between horses and labor to be different from that between tractors and labor, this formulation allows us to capture potential differential effects of a change in the wage rate upon the choice between tractor and horses. Second, we also assume that basic tractor services, z_k, and horse services, z_h, are combined with elasticity of substitution $1/(1+\rho_1)$ to produce power services, z.

The first order conditions for cost minimization imply that

$$
(7) \qquad \ln\left(\frac{k_t}{h_t}\right) \;=\; \frac{1}{1+\rho_1}\ln\left[A_h^\rho\frac{\alpha_z}{1-\alpha_z}\frac{\alpha_k^{\rho_1/\rho_2}}{\alpha_h^{\rho_1/\rho_3}}\right] + \frac{1}{1+\rho_1}\ln\left(\frac{q_{ht}+c_{ht}}{q_{kt}+c_{kt}}\right)
$$

$$
-\frac{\rho_1-\rho_3}{\rho_3(1+\rho_1)}\ln\{1+(\frac{1-\alpha_h}{\alpha_h})^{\frac{1}{1+\rho_3}}(\frac{q_{ht}+c_{ht}}{w_t})^{-\frac{\rho_3}{1+\rho_3}}\}
$$

$$
+\frac{\rho_1-\rho_2}{\rho_2(1+\rho_1)}\ln\{1+(\frac{1-\alpha_k}{\alpha_k})^{\frac{1}{1+\rho_2}}(\frac{q_{kt}+c_{kt}}{w_t})^{-\frac{\rho_2}{1+\rho_2}}\}.
$$

The above equation is an implication of profit maximization which can be estimated by nonlinear least squares given data on prices and quantities. Note, however, that not all parameters are identified. The procedure that we use to determine the parameters is as follows,

1) Given values of $(\alpha_{zy}, \alpha_{ny}, \alpha_z, \alpha_k, \alpha_h)$, we estimate equation (7). This allows us to recover value of the parameters that determine the elasticities of substitution (ρ_1, ρ_2, ρ_3) as well an estimate of A_h.

2) Given those estimates, and using the series for full prices of the two technologies —$(q_{kt}+c_{kt})$ and $(q_{ht}+c_{ht})$— we obtain the unit costs of z_k and z_h, the services of the two technologies.

3) With estimates of unit costs and given the level of gross farm output, F^c, we determine the quantity of each factor (k, h, n_y, n_k, n_h) used in the production of farm output from the profit maximization conditions. We adjust TFP so that the model's predictions for output match what is observed in the data each year.

4) Next, we compute the implications of the model for

   a) Land share in agriculture.

   b) The stock of horses relative to output in 1910 and 1960.

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[11] We set the efficiency level of tractor services, A_k, equal to one. This cannot be separately identified from aggregate productivity. Given our choice of normalization, the term A_h captures the relative productivity of horse vs. tractor services (i.e. A_h/A_k).

   c) The stock of tractors relative to output in 1910 and 1960.[12]

5) Finally, we iterate by choosing different values of $(\alpha_{zy}, \alpha_{ny}, \alpha_z, \alpha_k, \alpha_h)$, and reestimating the model in each round, until the predictions of the model match the data.

The results of the NLLS estimation of equation (7) with a Gaussian error term added to it are given in Table 1.[13] The dependent variable is $\ln\left(\frac{k_t}{h_t}\right)$, the ratio of tractor services to horse services which is a variable that we constructed according to the model described in the previous section.

TABLE 1—NLLS ESTIMATION

Parameter	Estimate	t-statistic
ρ_1	-0.8167	-8.26
ρ_2	-0.4068	-2.88
ρ_3	-0.100	-2.31
$R^2(adj)$	0.920	

We take the process $\{A_{ct}\}$ to correspond to total factor productivity. Even though there are estimates of the evolution of TFP for the agricultural sector, it is by no means obvious how to use them. The problem is that, conditional on the model, part of measured TFP changes is due to changes in the quality of tractors, $v(\mathbf{x}_t)$, as well as the rate of diffusion of tractors. Thus, in our model, conventionally measured TFP is endogenous. To compute (truly) exogenous TFP we used the following identification assumption, TFP is adjusted so that the model's prediction for the change in output between 1910 and 1960 match the data. This gives us an estimate of γ, the growth rate of TFP, which corresponds to an end-to-end change by a factor of 1.6. By way of comparison, the Historical Statistics reports that overall farm TFP grew by a factor of 2.3.

Table 2 presents the match between the model and U.S. data for our chosen specification - the five moments are used for calibration purposes. The match is good in terms of all of the aggregate moments.

The parameters that we use are in Table 3.[14]

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[12]The mapping between observed input ratios and shares and the corresponding objects in the model is given by:

$$(1 - \alpha_{zy} - \alpha_{ny}) = land\ share\ of\ output,$$
$$\frac{p_k k(\mathbf{q}, \mathbf{c}, w)}{y(\mathbf{q}, \mathbf{c}, w)} = tractors/output\ ratio,$$
$$\frac{wn(\mathbf{q}, \mathbf{c}, w)}{y(\mathbf{q}, \mathbf{c}, w)} = labor\ share\ of\ output,$$

[13]We experimented using urban wages as instruments for rural wages, and adjusted automobile prices as instruments for tractor prices and the results are very similar.

[14]Data for land's share of agricultural output come from Binswanger and Ruttan (1978), Table 7-1. Between 1912 and 1920, land's share is around 20%, falls subsequently to 17% in 1940 and then increases to 19% by 1968. In our analysis,

TABLE 2—MATCH BETWEEN MODEL AND DATA, 1910 & 1960

| Moment | 1910 | | 1960 | | Source |
	Model	Data	Model	Data	
Land - share of output	0.2	0.2			Binswanger and Ruttan (1978)
Horses/output ratio	0.25	0.25	0.009	0.01	Hist.Stat.of U.S.
Tractors/output ratio	0.0031	0.0031	0.135	0.135	Hist.Stat.of U.S.

TABLE 3—CALIBRATION

Parameter	A_h	α_{zy}	α_{ny}	α_z	α_k	α_h
Value	0.75	0.38	0.42	0.56	0.54	0.41

The estimated values for ρ_1, ρ_2 and ρ_3 deserve some discussion. The estimate of the degree of substitutability between the two services, ρ_1 is 5.46. This implies that tractor services and horse services are very good substitutes. Furthermore, the degree of substitutability between tractors and labor (1.7) is greater than the degree of substitutability between horses and labor (1.1). This differential substitution effect plays an important role when the wage rate changes.[15]

IV. Was Diffusion Too Slow?

The results for 1960 indicate that the model does a reasonable job of matching some of the key features of the data. However, they are silent about the model's ability to account for the *speed* at which the tractor was adopted.

Was diffusion too slow? To answer this question, the entire dynamic path from 1910 to 1960 needs to be computed. To do this, we took the observed path for prices (p_k, p_h, p_c, w, r), operating costs (c_k, c_h, c_a) and depreciation rates (δ_k, δ_h, δ_a), and use them as inputs to compute the predictions of the model for the 1910-1960 period.[16] At the same time, we adjusted the time path of TFP so that the model matches the data in terms of the time path of agricultural output, the analog of our steady state procedure. This helps to get the scale right along the entire transition. Thus, the model matches agricultural output by construction.

The predictions of the model and data for the number of tractors (in logs on the left

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land's share is constant at 20% owing to the Cobb-Douglas assumption. We performed a sensitivity analysis assuming that the coefficient on land in the production of output varied over time and this did not change our results appreciably. Incidentally, Binswanger and Ruttan (1978) also report a decline in the labor's share from 38% to 27% and our model comes close to matching this decline between 1910 and 1960.

[15]Our estimate of the elasticity of substittuion between horse and tractors services is quite a bit higher higher than the value of 1.7 estimated by Kislev and Petersen (1982). However, they completely ignored horses and their estimate is likely to be some weighted average of the two elasticites of substitution: labor and capital and labor and horses.

[16]We use five-year moving averages for all these sequences. For the years 1910 and 1960, we use actual data (remember that these dates are viewed as steady-states). For all other years, the five year average was constructed as the average of the the year in question, the two years before and the two years. In a sense, using a five year average substitutes for the lack of adjustment costs in the model.
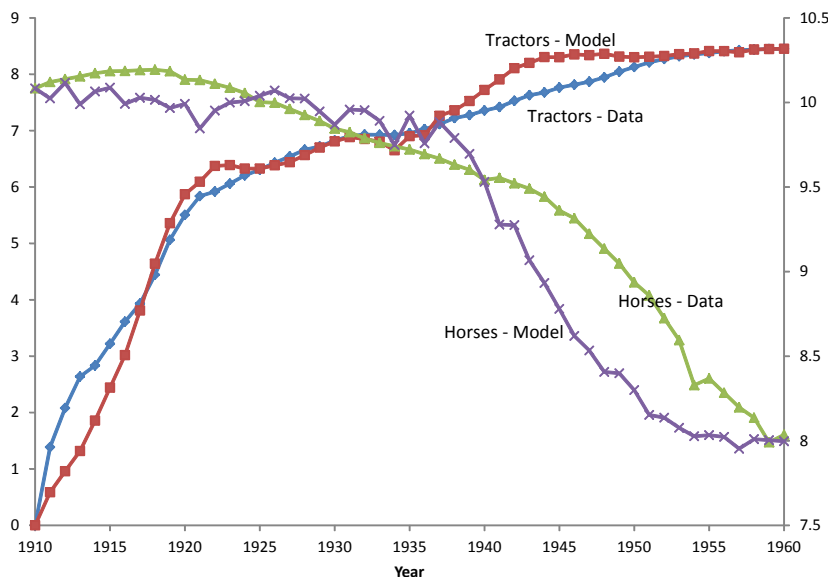
FIGURE 4. TRANSITIONAL DYNAMICS, 1910-1960 - TRACTORS AND HORSES

axis) and horses (in logs on the right axis) is depicted in Figure 4. The model does a remarkable job of tracking the actual diffusion of the tractor.[17] A large fraction of the variability around the sample mean for both tractors and horses is accounted for by the model. In addition, the correlation coefficients between the predictions of the model and the data are fairly high. The dramatic rise in wages also implies a rather steep fall in the stock of horses, accounting for the large discrepancy between model and data in the post 1940 time period.

How does the model perform along other dimensions? There are two dimensions along which we can compare model and data. First, we look at the model's predictions (and the U.S. values) for employment in the agricultural sector. The model's estimates track the data quite well and, in particular, they capture the sharp decreases in employment in agriculture in the 1940s and 1950s. The correlation between model and data for the stock of labor is 0.73. The fact that the model is able to capture most of the rural to urban migration over the period in question suggests that push factors (the replacement of muscle for machines) were very important in contributing to urbanization. This mechanism is quite different from, say, Lucas (2004) who relies on externalities to generate slow urbanization in accounting for urbanization. Second, we also look at the predictions of the model for the price of land which fell and then rose. The model is able to track this

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[17]The *stock of tractors*, given an estimate of the equilibrium level of *tractor services,* depends heavily on our model of productivity and quality adjustment. The steps udertaken to construct stocks from flows are described in section 3.

pattern and the correlation between model and data is 0.67. These two additional predictions lend further confidence to the mechanism generating the diffusion of tractors in American agriculture. In addition, we also experimented with a Lucas (1978) style span of control model. As is well known, that model aggregates. Its aggregate implications are exactly the same as the standard growth model. We find that such a framework with heterogeneity in farm managerial ability and changing wages in the urban sector relative to the rural sector (this represents the outside option for farming and leads to farmers with a comparative disadvantage to migrate) does a very good job of tracking the changes in farm size over the period under study.

V. The Role of Wages and Quality Changes

The previous section established that, relative to a standard equilibrium model, adoption of the tractor by U.S. farmers was not 'slow.' A key innovation of our setup is that we explicitly took into account the role of substitution along an isoquant (as captured by changes in the prices of inputs), as well as quality upgrades. In this section we explore the role that each of the factors we identified above played in determining the equilibrium speed of adoption. We do this by using the model to analyze a series of counterfactuals. In each case, TFP is adjusted so that the alternative specification perfectly matches agricultural output.

The Effect of Wages. We examine the predictions of the model under the assumption that wages are fixed at their 1910 level. In this case, the model predicts that adoption would have been even slower. This specification underpredicts tractor adoption by about 30 percent in the late 1950s.

The Effect of Quality Changes. Our model emphasizes that a 'tractor' in 1960 is not the same capital good as a 'tractor' in 1920. Not only there are significant differences in the quality of each tractor, but the cost of operating a tractor per unit of quality also varies significantly. To ascertain the quantitative importance of this dimension we conducted two counterfactual experiments that ignore quality changes. In one experiment, we assumed that there is no quality increase. That is, the level of quality is fixed at its 1910 level. In this case, the model severely underpredicts the stock of tractors. This is the case in all decades, but it is particularly severe in post 1940 period. At the other end, if one were to treat a 'tractor' in 1910 as equivalent to a 'tractor' in 1960, then the conclusion is that adoption was slow.

Discussion. The fact that these two factors play a major role in accounting for the diffusion of the tractor is comforting in that these forces should be generalizable. Gradual quality change is certainly an important factor in the diffusion of many innovations - early incarnations of the new technology are pretty crude and slowly evolve with time.[18] While quality change has been considered before, they have not been modeled in the gradual fashion in which we model it. The close tie between the estimation and our model simulation is a feature worth emphasizing. Furthermore, most other work (see,

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[18]Bils and Klenow (2001) estimate that quality has been increasing at about 1.5 percent per year for the past 20 years or so which is higher than the .5 percent annual rate of quality growth that the U.S. Bureau of Labor Statistics uses in adjusting its inflation figures.

for instance, Greenwood and Yorukoglu, 1997) model the evolution of quality as a one shot event, moving up to the frontier right away - even though they assume a gradual decline in the price of capital. Our results make it very clear that such a consideration would lead the researcher to conclude, rather incorrectly, that diffusion was slow!

One of the key mechanisms identified in the prevailing literature on technology diffusion is that if old capital and new capital are complementary inputs, the marginal product of investment depends not only on the vintage of technology but also on the amount of old capital available for that specific vintage. Even when new technologies are available, people invest in old technologies if there exist abundant old capital for these technologies. As a consequence, diffusion of new technologies is slow. This is the mechanism at work in both Chari and Hopenhayn (1991) and many subsequent papers. Indeed in Chari and Hopenhayn (1991) $\rho_1 = -1$; in this case, only one of the two technologies will be in use and the gradual diffusion will be inconsistent with the standard model. The mechanisms at work in our model generate a slower pattern of adoption if the services obtained from the two technologies are (imperfect) substitutes. Imperfect substitutability of the two technologies plays a crucial role in understanding the diffusion of the tractor.

VI.   The Role of Other Factors

We explored the sensitivity of the results to changes in a number of other factors. For brevity, we do not report the detailed results. Our analysis describes the effects of other 'counterfactuals' holding the path of TFP constant.

The Role of Horse Prices. Recent research on the topic of adoption of tractors has emphasized that adjustment of horse prices delayed the diffusion of tractors (see Olmstead and Rhode (2001)). In the context of this model, fixing horse prices at their 1910 levels has hardly any effect on adoption. The reason is simple, horse prices are a relatively unimportant component of the cost of operating the horse technology. Should we conclude that explicitly modeling the fact that farmers had a choice between an 'old' and a 'new' technology is an unnecessary feature of the model? No. The reason is simple, given that the horse technology is labor intensive, we would have missed a channel through which wage changes induce changes in the degree of mechanization.

Elasticity of Substitution. Our specification of the technology is such that, at our preferred parameterization, the elasticity of substitution between tractor and horse services is rather high. In order to quantitatively assess the importance of this specification, we studied a version of the model in which $\rho_1 = \rho_2 = \rho_3 = 0$. In this case, the model severely underpredicts the diffusion of the tractor. The reason for this result is simple, the Cobb-Douglas functional form implies constant input shares. In the absence of spectacular price decreases in the own price — and tractor prices showed a large, but not spectacular decrease over this period — the model predicts modest increases in the quantities demanded.

Finally, one can ask whether the level of generality in the nested CES added value. We conducted a series of experiments and our conclusion is that the degree of substitutability between tractor and horse services is the most important one. Indeed, if we set $\rho_1 = \rho_2$ and set $\rho_3 = 0$, the equation governing the k/h ratio becomes linear and the fit of the

equation is nearly as good as the NLLS presented above. This experiment suggests that the key to our results is allowing for the two types of services to be substitutable. Restricting the horse services technology to be Cobb-Douglas and assuming that the degree of substitutability between the two types of services to be the same as that between capital and labor in the production of tractor services does little violence to the predictions of the model.

VII. Conclusions

The frictionless neoclassical framework has been used to study a wide variety of phenomena including growth and development.[19] However, the perception that the observed rate at which many new technologies have been adopted is too slow to be consistent with the model has led to the development of alternative frameworks which include some 'frictions.' In this paper we argue that a careful modeling of the shocks faced by an industry suggests that the neoclassical model can be consistent with 'slow' adoption.[20] Since most models with 'frictions' are such that the equilibrium is not optimal, the choice between standard convex models and the various alternatives has important policy implications. It is clearly an open question how far our results can be generalized. By this, we mean the idea that to understand the speed at which a technology diffuses it is necessary to carefully model both the cost of operating alternative technologies and the evolution of quality. We point to some examples that suggest that the forces that we emphasize play a role more generally.

Consider first, the diffusion of nuclear power plants. While the technology to harness electricity from atoms was clearly available in the 1950s, diffusion of nuclear power plants was rather 'slow'. Rapid diffusion did not take place until 1971. In 1971, Nuclear's share of total electricity generation was less than 4 percent. This number shot up to 11 percent by 1980 and around 20 percent by 1990 and remained at that level. What was the impetus for such a change? The obvious factor was the oil shock of the 1970s which dramatically increased the real price of crude oil and induced a substitution away from the use of fossil fuels to uranium. Furthermore, when the price of oil came down, the United States stopped building nuclear reactors. The other factor that played an important role in putting a stop to the diffusion of nuclear power plants is the high operating cost associated with waste disposal. Nuclear power plants have generated 35000 tons of radioactive waste, most of which is stored at the plants in special pools or canisters. But the plants are running out of room and until a permanent storage facility is opened up, the diffusion of nuclear power plants will proceed slowly. All this suggests that changes in the price of substitutes (oil) and changes in operating costs can go a long way toward accounting for the diffusion of nuclear power plants.

A second example is the case of diesel-electric locomotives. The first diesel locomotive was built in the U.S. in 1924, but the technology did not diffuse until the 1940s and 1950s. It seems that the key factor in this case was a substantial improvement in quality,

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[19]It has even been used as a benchmark by Cole and Ohanian (2004) in the study of the great depression.

[20]More generally, our model suggests that to understand the adoption of a technology in a given sector it may be critical to model developments in another sector.

increased fuel efficiency relative to its steam counterpart and possibly more important, reduced labor requirements. Since, as we documented in the paper, wages rose substantially during World War II, quality improvements reduced the cost of operating the diesel technology relative to the steam technology.

Our theory is rather simple - perhaps the simplest possible theory wherein the evolution of relative prices can account for slow adoption. There is nothing inherent in the Neoclassical theory that suggests that adoption will be slow. However, not all historical episodes suggest slow adoption. One example is the rather rapid adoption of ATM machines replacing bank tellers in India. Our preliminary analysis of that case study indicates that changes in the prices of ATMs relative to wages can account for a very large fraction of diffusion.

Of course, a few examples, no matter how persuasive they appear, cannot 'prove' that factors that are usually ignored in the macro literature on adoption are important. However, at the very least, they cast a doubt on the necessity of 'frictions' in accounting for the rate of diffusion of new technologies.

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APPENDIX

A1. Data Sources

This section details the available data, the sources which they were obtained and what they were used for. The data were used to calibrate the model and to compare the model and the data.

Income and Output

Value of Gross Farm Output: HS Series Da1271 - used for computing factor shares and for calibration.

Land

Land in Farms: HS Series Da566 - used to compute the prices of land over time and to compare model and data.

Land Prices

Lindert, Peter H. (1998), "Long-run Trends in American Farmland Values," Working Paper, UC-Davis.

Labor

Farm Employment: HS Series Da612 - used to compute Labor's share of income and to compare model and data.

Wage Rates: Data from HS Series K177 - used to compute labor's share of farm income and as an exogenous driving process.

Capital - Tractors and Horses

Number of Tractors on farms: HS Series Da623 - used to compute tractor's share of farm income

Number of Horses and Mules on farms: HS Series Da991 and Da992 - used to compute horses's share of farm income

Depreciation Rates and Operating Costs for Tractors: For the period 1910-1940, we used data from United States Department of Agriculture (USDA), *Income Parity for Agriculture, Part II*. For the period 1941-1960, we used data from USDA, Agricultural Statistics - used as exogenous driving processes.

Horse Prices: Data provided by Paul Rhode - used to compute horses's share of farm income and as an exogenous driving process.

Tractor Prices: From 1920 to 1955, we used data from our hedonic estimations. These estimations were based upon data on tractor prices and characteristics kindly provided to us by William White and augmented to include additional characteristics from Dunning (2000). For the period 1910-1919, and 1956-1960, we extrapolated the data using our estimation and data on average price of tractor available from the USDA, Agricultural Statistics. The exact manner in which this was done is described in the Appendix. This series is used to compute tractor's share of farm income and as an exogenous driving process.

A2. *Derivation of the User Cost of a Tractor*

From

$$p_{kt}(t) = \frac{v(\mathbf{x}_t)}{\gamma_{ct}},$$

and given that a vintage-τ tractor at time t provides tractor services equal to $\tilde{k}_t(\tau) \equiv v(\mathbf{x}_\tau)(1 - \delta_{k\tau})^{t-\tau}$, the rental price of such a tractor at time t is

$$q_{kt}(\tau) = p_{kt}(\tau) - \frac{p_{kt+1}(\tau)}{1 + r_{t+1}}.$$

This simply says that a $t - \tau$ year old tractor at time t will be a $t - \tau + 1$ year old tractor at $t+1$. This formula has the drawback that it depends on the price of used tractors. Since there are no data available on used tractor prices we now proceed to derive an expression for $q_{kt}(\tau)$ using simple arbitrage arguments. One can show that the optimal choice of

$m_{kt}(\tau)$ requires that

$$p_{ct}F_k(t)\tilde{k}_t(\tau) = p_{kt}(\tau) - \frac{p_{kt+1}(\tau)}{1+r_{t+1}} + c_{kt}(\tau).$$

Iterating forward and denoting by $T(\tau, t)$ the number of periods of useful life that a $t - \tau$ old tractor has left, we get that

$$p_{kt}(\tau) = \sum_{j=0}^{T(\tau,t)} R_t(j)\{p_{ct+j}F_k(t+j)\tilde{k}_{t+j}(\tau) - c_{kt+j}(\tau)\},$$

where $R_t(j)$ is as defined in the text.

Using the special structure of $k_t(\tau)$ it follows that

$$
\begin{aligned}
p_{kt+1}(\tau) &= \gamma_{k\tau}\upsilon(\mathbf{x}_\tau)(1-\delta_{k\tau})^{t+1-\tau}\sum_{j=0}^{T(\tau,t+1)} R_{t+1}(j)p_{ct+1+j}F_k(t+1+j)(1-\delta_{k\tau})^j \\
&\quad - \sum_{j=0}^{T(\tau,t+1)} R_{t+1}(j)c_{kt+1+j}(\tau).
\end{aligned}
$$

Let the present discounted value of the cost of operating a tractor for $T - 1$ periods starting at $t + 1$ be given by

$$C(t+1, T-1) \equiv \sum_{j=0}^{T-1} R_{t+1}(j)c_{kt+1+j}.$$

Let $T(\tau, t)$ be the remaining lifetime at time t of a tractor of time τ vintage. Then, it follows that

$$
\begin{aligned}
p_{kt+1}(t) &= \frac{\upsilon(\mathbf{x}_t)(1-\delta_{kt})}{\upsilon(\mathbf{x}_{t+1})}p_{kt+1}(t+1) - \left[1 - \frac{\upsilon(\mathbf{x}_t)(1-\delta_{kt})}{\upsilon(\mathbf{x}_{t+1})}\right]\sum_{j=0}^{T(t,t+1)} R_{t+1}(j)c_{kt+1+j} \\
&\quad + \frac{\upsilon(\mathbf{x}_t)(1-\delta_{kt})}{\upsilon(\mathbf{x}_{t+1})}\{\sum_{j=0}^{T(t,t+1)} R_{t+1}(j)p_{ct+1+j}F_k(t+1+j)(1-\delta_{kt})^j(1-(1+\varphi)^j) \\
&\quad - \sum_{j=T(t,t+1)}^{T(t+1,t+1)} R_{t+1}(j)[p_{ct+1+j}F_k(t+1+j)(1-\delta_{kt+1})^j - c_{kt+1+j}]\},
\end{aligned}
$$

where

$$\delta_{kt+1} = \delta_{kt} - \varphi(1-\delta_{kt}).$$

To simplify the presentation we assume that two consecutive vintages of tractors have the same depreciation and economic lifetime ($\varphi = 0$ and $T(t+1, t+1) = T(t, t+1)+1$). Moreover, we assume that operating costs vary over time, but are not a function of the

vintage, i.e. $c_{kt+j}(\tau) = c_{kt+j}$, for all τ. In this case, using the previous formula for $\tau = t$ (one period old tractors) and $\tau = t + 1$ (new tractors) it follows that

$$
\begin{aligned}
p_{kt+1}(t) &= \frac{v(\mathbf{x}_t)(1 - \delta_{kt})}{v(\mathbf{x}_{t+1})} p_{kt+1}(t+1) - \left[1 - \frac{v(\mathbf{x}_t)(1 - \delta_{kt})}{v(\mathbf{x}_{t+1})}\right] \sum_{j=0}^{T-1} R_{t+1}(j) c_{kt+1+j}(t) \\
&\quad + \frac{v(\mathbf{x}_t)(1 - \delta_{kt})}{v(\mathbf{x}_{t+1})} R_{t+1}(T) \left[p_{ct+1+T} F_k(t+1+T) v(\mathbf{x}_{t+1})(1 - \delta_{kt})^T - c_{kt+1+T} \right].
\end{aligned}
$$

However, the last term in square brackets must be zero, since a tractor of vintage $t + 1$ is optimally scrapped when the marginal product of its remaining tractor services, $p_{ct+1+T} F_k(t+1+T) v(\mathbf{x}_{t+1})(1 - \delta_{kt})^T$, equals the marginal cost of operating it, c_{kt+1+T}.

Let the 'effective' depreciation of a vintage t tractor between t and $t + 1$ be $\Delta_{t+1} \equiv \frac{v(\mathbf{x}_t)(1-\delta_{kt})}{v(\mathbf{x}_{t+1})}$. It follows that,

$$
q_{kt}(t) = p_{kt}(t) \left[1 - R_t(1)(1 - \delta_{kt}) \frac{\gamma_{ct}}{\gamma_{ct+1}} \right] + (1 - \Delta_{t+1}) C(t+1, T-1)
$$

which is the expression (6) in the text.

A3. Estimation of Tractor Prices

In order to compute the user cost of tractor services, we need to estimate the effect that different factors have upon tractor prices. Our basic specification is

$$
\ln p_{mkt} = -d_t + \sum_{j=0}^{N} \lambda_j \ln x_{jt}^m + \epsilon_{mt},
$$

where p_{mkt} is the price of a model m tractor produced by manufacturer k at time t, the vector $\mathbf{x}_t^m = (x_{1t}^m, x_{2t}^m, \ldots x_{Nt}^m)$ is a vector of characteristics of a particular model produced at time t, the d_t variables are time dummies, and ϵ_{mt} is a shock that we take to be independent of the x_{jt}^m variables and independent across models and years. We estimated the previous equation by OLS using a sample of 1345 tractor-year pairs covering the period 1920-1955. The basic data comes from two sources. William White very generously shared with us the data he collected which includes prices, sales volume and several technical variables. A description of the sample can be found in his dissertation, White (2000). We complemented White's sample with additional technical information obtained from the Nebraska Tractor Tests covering the 1920-1960 period, as reported by Dunning (1999). The variables in the **x** vector included technical specifications as well as manufacturer dummies. In the following table we present the point estimates of the technical variables.[21]

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[21] To avoid confusion, we rename Speed variable in White's data set to Gears. Speed variable in White's data set actually denotes the number of total gears.

TABLE A1—REGRESSION RESULTS

Continuous variables	Estimate	t	Dummy variables	Estimate	t
Fuel Cost	0.129	5.19	Row Crop	-0.031	-2.56
Cylinders	0.047	0.93	High Clear	-0.026	-0.98
Gears	0.103	3.58	Rubber Tires	0.162	5.17
RPM	-0.170	-3.26	Tractor Fuel	-0.164	-2.82
HP	0.627	21.89	Kerosene-Gasoline	0.028	1.27
Plow Speed	0.067	1.33	Distillate-Gasoline	-0.029	-1.74
Slippage	-0.030	-2.38	All Fuel	-0.041	-1.70
Length	-0.127	-2.36	Diesel-Gasoline	-0.042	-1.65
Weight	0.163	5.24	Diesel	0.006	0.09
Speed	-0.081	-2.38	LPG	-0.207	-1.95

In addition, we included 15 manufacturer dummies and 35 time dummies. We selected the variables we used from a larger set, from which we eliminated one of a pair whenever the simple correlation coefficient between two variables exceeded 0.80. We experimented using a smaller set of variables as in White (2000), but our estimates of the time dummies were practically identical.[22]

Our data covers the period 1920-1955. However, the period we are interested in studying is 1910-1960. Thus, we need to extend the average price and the time dummies to cover the missing years. The price data for 1910-1919 comes from Olmstead and Rhode (2001), and it corresponds to the price of a 'medium tractor'. For the period 1956-1960 we used the price of an average tractor as published by the USDA. Inspection of the pattern of the time dummies —the line labeled Gamma in Figure 3— suggests a fairly non-linear trend. If we exclude the war-time years, it seems as if productivity was relatively constant since the mid 1930s. Thus, for the 1956-1960 period we assume that there was no change in γ_{ct}. The situation is quite different from 1910 to 1920, as this is a period of rapidly falling prices. We estimated the time dummies for the period 1910-1919 from a regression of the time dummies over the 1920-1935 period (before they 'stabilize') on time and time square. Our estimated values imply that most of the drop in tractor prices in this period is due to increases in productivity (more than 80 percent). This is consistent with the accounts that important changes in the tractor technology did not occur until the 1920s.

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[22]When all the variables are included, the predictions of the model for the estimated values of $v(x)$ and γ_{ct} are virtually identical. We decided to use this non-standard criteria to eliminate variables, in order to report significant coefficients. In the case in which all the variables are included, serious collinearity problems result in (individual) coefficients that are very imprecisely estimated.