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**AN UNSUNG HERO:
THE FARM TRACTOR'S CONTRIBUTION
TO TWENTIETH-CENTURY UNITED STATES
ECONOMIC GROWTH**

DISSERTATION

**Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University**

By

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ABSTRACT

In his successful attack on the 'axiom of indispensability', Robert Fogel demonstrated that the railroads made only a modest contribution to the growth of nineteenth-century income in the United States. In his conclusions, he offered an opinion that growth resulted from countless small innovations and that no single new technology was important enough to study in isolation. My dissertation challenges Fogel's conclusion by presenting evidence of a 20th-century 'hero' – the farm tractor. By tripling labor productivity and replacing more than 24MM work animals, the tractor dramatically reduced total factor inputs to agriculture, freeing up resources for use in the rapidly-growing manufacturing sector. Through the use of a counterfactual analysis, I find the direct social savings to be in excess of 8% of 1954 GNP, more than double Fogel's highest estimate for railroads in 1890. When indirect benefits are added, such as the use of tractors to apply yield-increasing agricultural chemicals, its contribution to the growth of the economy in this century is quite significant.

Even with the large social benefits of mechanization, the new technology was adopted rather slowly. Over the years, social scientists have attributed this delayed response to ignorance, irrationality, and most recently, to several types of market failure. Threshold models have been used extensively in the literature to illustrate the technology choices

faced by the farmer. My work challenges the market failure hypotheses. Using a comprehensive production and quality database, I develop a hedonic index of tractor prices, which shows that quality-adjusted prices fell continuously from 1918 until about 1940, then stabilized at half of their initial level as the technology matured. Given this dynamic element, properly constructed threshold models show the pace and pattern of diffusion to be a rational market response to changing relative prices. As quality and features improved, and as cumulative production experience allowed manufacturers to reduce production costs, the tractor became a better replacement for animal power on all types and sizes of farms. The social benefits from this unsung hero then spread across the country, lowering food prices and freeing up labor for manufacturing and services.

DEDICATION

This work is dedicated to Maria: my wife, the love of my life, and my best friend.

Without her constant support and untiring efforts, I would never have had

the opportunity to pursue my dream and complete this research effort.

Throughout our time together, we have tried to model mutual support

and collegueship. I only hope that in the near future, I can pay back

her investment in me by helping her to achieve an equally valuable goal.

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I must also thank Howard Marvel, Ben Baack, and James Peck for their critical evaluation and re-direction of early drafts of the several papers which comprise this thesis. Additional helpful comments were received from Sally Clarke, Craig Heinicke, Matthew Martin, Peter Mayer, Joel Mokyr, and Peter Howitt, as well as participants in seminars at The Ohio State University, Northwestern University, and the Ohio Association of Economists and Political Scientists.

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INTRODUCTION

The United States has experienced tremendous improvements in its standard of living over the past hundred years, as have most nations in the developed world. We now accept as necessities many things that our grandparents would have considered to be luxuries; we also enjoy countless goods, devices, and services completely unknown a century ago. Far fewer workers are required to produce the necessities of life that we now consume, and therefore an increasing number of us have time to devote to leisure activities, such as entertainment and recreation.

Improvements in agricultural technology have played a large part in helping to generate this improved standard of living. Our agricultural production function has seen three major modifications over the last 150 years, each of which has dramatically increased crop output per unit of input: the mechanization of the harvest via the reaper and steam thresher; replacement of horses and mules with tractors as a source of farm power; and the scientific revolution, which has brought genetic crop selection and chemical fertilizers, herbicides, and pesticides. In this dissertation, I explore the second of these three transformations, and measure the economic benefits brought by the introduction of the farm tractor.

As Joel Mokyr pointed out many years ago in *The Lever of Riches*, there are at least four different types of growth that contribute to increasing the standard of living in an economy.¹ The first of these, which Mokyr terms 'Solovian', involves growth through capital accumulation, which is in turn fueled by redirecting some of current output away from consumption. This trade-off produces the economist's familiar 'no free lunch'.

The other three sources of growth involve some type of free lunch, driven by non-convexities that allow better economic outcomes than can be achieved with the optimal consumption and investment choices available in a fixed-technology, closed economy Solovian context. Mokyr describes commercial expansion growth through international trade and specialization as 'Smithian' growth. Scale economies, arising from fixed costs and indivisibilities, can produce a third type of growth, one that the 20th century command economies relied on, perhaps too much.

Finally, increases in the stock of human knowledge, which include both technological change and institutional improvements, can drive a fourth type of growth, which can be called 'Schumpeterian'. It is this type of growth that is engaging the energies of so much of the economics profession today. Mokyr claimed that prior to about 200 years ago, population growth increased at about the same rate as technological change, and so humankind remained close to subsistence level. The sustained increases in the standard of living encountered since then are driven in large part by increases in the rate and magnitude of this 'freest of all free lunches'.

¹ The following paragraphs rely on Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*, (New York: Oxford University Press, 1990), pp.4-6.

I believe that economists still have far too little understanding of the nature, causes, and consequences of this most important source of welfare improvement. The extensive literature in economics devoted to growth through technological change can be divided into two intellectual threads. The first discusses and models economies that exhibit the first three of Mokyr's types of growth, often with stunning mathematical complexity. Extremely sophisticated techniques are used to explain optimal growth paths, rates of capital accumulation, and trade patterns, even in the presence of limited scale economies or spillovers.²

Within the last 10-15 years, several prominent macroeconomists have begun to incorporate true technological change into macro models; the rationale is captured well by Paul Romer's 1990 note "Are Nonconvexities Important for Understanding Growth?" (Romer's answer is a resounding yes).³ The current state-of-the-art is found in the important work of Aghion and Howitt, who explicitly attempt to model Schumpeterian 'creative destruction' in their models.⁴

In order to allow these models to close, however, all of these economists must place restrictions on the nature of technological change and non-convexities considered. Indeed, if new technologies continually emerge and evolve such that factor inputs for a given output decrease irregularly over time, it becomes impossible to prove the existence

² Perhaps the best examples are in the work of Grossman & Helpman and Aghion & Howitt, although the literature is rapidly expanding. See Gene M. Grossman and Elhanan Helpman, *Innovation and Growth in the Global Economy* (Cambridge, Massachusetts: MIT Press, 1991); and Philippe Aghion and Peter Howitt, "A Model of Growth through Creative Destruction," *Econometrica* 60 (March, 1992), pp. 323-51.

³ Paul M. Romer, "Are Nonconvexities Important for Understanding Growth?," *American Economic Review* 80 (May, 1990), pp. 97-103.

⁴ Philippe Aghion and Peter Howitt, *Endogenous Growth Theory* (Cambridge, Massachusetts: MIT Press, 1998).

of a general equilibrium.⁵ The welfare properties and agent behaviors that emerge from such a dynamic situation cannot be successfully integrated into any microeconomic or macroeconomic models that require a stable equilibrium.

The second intellectual thread on growth and technological change, evidenced by the writing of Nathan Rosenberg and Joel Mokyr, does an excellent job of describing this dynamic instability over the course of recent economic history.⁶ They discuss not only key technological changes that produced surges of growth, but also the impacts on the welfare of the affected populations. However, their work does not contain formal equilibrium models to describe this process, most likely because of the inappropriateness of the underlying assumptions. Douglass North, in discussing the use of neoclassical synthesis in understanding of the development of institutions, made the following observation:

"From the viewpoint of the economic historian, this neoclassical formulation appears to beg all of the interesting questions."⁷

In fact, reference to the physical world should cause us to question our basic assumptions about equilibria. The world is just not a general equilibrium type of place! Biological populations continually increase and decline as their numbers interact with their environment. Chemical reactions most often are irreversible; those that tend to form an

⁵ Existence theorems in general equilibrium were developed in a context of a pure exchange economy, and have been extended to include production only if firms' technologies exhibit constant or decreasing returns to scale. If technologies exhibit globally increasing returns to scale, there is no equilibrium. Likewise, the production technology is static in these proofs of existence of equilibria.

⁶ Relevant works of these two authors include: Nathan Rosenberg, *Technology and American Economic Growth* (New York: Harper & Row, 1972); Rosenberg, *Inside the Black Box: Technology and Economics* (Cambridge: Cambridge University Press, 1982); Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*, (New York: Oxford University Press, 1990); and Mokyr, *Twenty-Five Centuries of Technological Change: An Historical Survey*, (Chur, Switzerland: Harwood Academic Publishers, 1990).

⁷ Douglass C North, *Structure and Change in Economic History*, (New York: Norton, 1981), p. 5.

equilibrium are easily driven to completion by addition or removal of one or more components. Even the sun which provides all of our energy is involved in a disequilibrium process - general equilibrium will only occur when the nuclear fires burn out and our world becomes cold and lifeless.

It is thus my contention that an empirical study of growth need not start from a general equilibrium framework. There have been many important partial-equilibrium analyses of the growth impacts of specific new technologies, including Robert Fogel's celebrated work on railroads and Zvi Griliches analysis of hybrid corn.⁸ Each of these seminal works has produced a number of derivative papers, which are considered in more detail in subsequent chapters. This thesis is an attempt, admittedly a modest one, to apply some structure and measurement tools to determine the welfare benefits of one of the most significant changes in the technology and the production function of our nation's agriculture: the replacement of draft animals with gasoline-powered tractors.

Economic and agricultural historians have debated the nature of this production-function change for a number of years, as well as the similar 19th century mechanization via the reaper and steam thresher. In developing his threshold model approach, Paul David argued that these changes can be thought of as affecting relative prices within an existing equilibrium. Zvi Griliches, Theodore Schultz and others believed that the new technologies brought about a disequilibrium, which might last for a number of years. In developing my approach, I am implicitly adopting the disequilibrium point of view as

⁸ Among the many publications which contain summaries of this work are: Robert W. Fogel, *Railroads and American Economic Growth: Essays in Econometric History* (Baltimore: The Johns Hopkins Press, 1964); and Zvi Griliches, "Research Costs and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy* 66 (October, 1958), pp. 419-31.

regarding the economy as a whole. In doing so, I am not claiming failures in product or factor markets, merely that the slowly diffusing technological change made achievement of general equilibrium impossible.

My thesis demonstrates that the farm tractor should be considered one of the most important technological advances of the 20th century. Its universal adoption, in raising the productive efficiency of inputs to agriculture, re-shaped the labor force, the face of rural America, and the structure of the American economy. The welfare benefits from the tractor have been quite significant. By freeing up one-quarter of the total labor force, and by eliminating the need to raise and maintain 25MM work animals, it has produced a social savings equivalent to almost 10% of GNP.

This benefit did not occur quickly, however. From the initial commercial debut of a gasoline-powered unit in 1902, adoption of the tractor proceeded slowly and irregularly until 1960, at which point it had replaced nearly all of animal-powered traction. Scholars over the years have attempted to understand this slow diffusion, trying to reconcile the actual data with economic principles. Many of these researchers have concluded that the adoption pattern has been too slow, indicating market failure or irrational behavior.

In a second major thrust of this work, I present and utilize a new data source to show that much of this analysis has been misplaced. The problem is in the time series of prices inherent in the calculations of farmers' optimal choice of technology. Using production, price, and technical data from a number of sources, I show that the quality-adjusted price of tractors fell by 50% during the period 1920 to 1940, during which time the nominal

price was largely unchanged. In the following period, nominal prices increased in line with the general rate of inflation, while real, quality-adjusted prices remained flat.

By using a more accurate series of prices, much of the 'slow diffusion' mystery disappears. Tractors were slow to diffuse initially because they were limited in capability and their cost/performance ratio was little better than competing technology. Sustained product and cost improvement, along with a number of significant technical breakthroughs, made the tractor an increasingly better replacement for animal powered-agriculture. Within the diverse group of farmer customers, a greater proportion of them moved across the threshold for which replacement became optimal. By the late 1940s, nearly every viable farm would conclude that a tractor was the best option.

I believe that the slow and unsteady rate of technological replacement seen with tractors is indicative of technological change in general, a third major theme of my dissertation. A series of product and process innovations, minor inventions, and cost reductions changed the tractor over time from a technology that was only superior for a small fraction of a heterogeneous group of farmers to one that completely replaced the horse and mule. Contrary to most if not all current macroeconomic growth models, the new technology was not 'born whole' at an instant in time, but evolved over a period of almost 60 years.

To make matters worse, the tractor-producing firms proved unable to accurately predict the future state of their production functions, and thus could not internalize scale economies or learning curve effects and operate at Minimum Efficient Scale (MES). I

present qualitative evidence that this, too is often the case in new technology areas; the over-expansion / shake-out phenomena depends on this type of knowledge failure.

The dissertation closes with a challenge to theorists of all stripes to work seriously to incorporate technological change, and the non-convexities and disequilibria that it generates, into the theoretical structure of the discipline. I am hopeful that others in the future will find better ways to utilize the mathematical tools currently in favor to improve the elegance and persuasiveness of this type of argument.

The structure of the dissertation is as follows. In Chapter 1, I lay out the major themes and provide background to the tractor study. Chapter 2 contains the bulk of the technical and historical information on the tractor and related 20th century mechanical innovations. The welfare benefits accruing to the country from adoption of the tractor are described and measured through means of a counterfactual analysis in Chapter 3. The second major theme of the dissertation, the tremendous change in quality-adjusted price in the years after introduction is introduced through the construction of a hedonic price index in Chapter 4. In Chapter 5, I use the price-index data to re-evaluate threshold models which have been widely used to try to understand the 'slow diffusion' puzzle. The implications of the technological development of the tractor for the study of innovation in general are qualitatively considered in Chapter 6, which also contains a discussion of extensions and future application of this research agenda.

CHAPTER 1

BACKGROUND

The twentieth century has seen tremendous technological change in the United States, as in most developed countries. For few people has it been as impactful as for those involved in agriculture, as farm operators, workers, or as members of farm families. The development and widespread adoption of the tractor precipitated a dramatic shift in resources out of agriculture, which continued with the development of agricultural chemicals, commercial fertilizers, hybrid seeds, and corporate farming. The agricultural way of life that existed at the turn of the twentieth century has been radically altered by the changes of the past 90 years.

The technological advances of the nineteenth century, most notably the steel plow, reaper, and steam thresher, had produced significant improvements in crop yields, productivity, and output, without fundamentally changing the farm way of life. Between 1850 and 1910, agriculture in the United States grew with the frontier: the land area in farms tripled; the number of farms more than quadrupled; and the average farm size declined somewhat, from 200 to 140 acres. This last, somewhat surprising statistic, resulted from the breakup of the large plantations in the South following the Civil War, and from a steady reduction in the size of bonanza farms in the West. Farm size increased

by about 10% over the period in the North Central regions, and average area under cultivation increased as well.⁹ Figure 1 shows this slow upward trend, using the various measures of crop acreage reported by the Census Bureau over the past 120 years.

During this period, farm population increased steadily to 32 million people, with about 13.6 million of these working in agriculture.¹⁰ The acreage and productivity increases allowed these farms to feed a rapidly-growing urban population, including large numbers of immigrants, while agricultural population declined as a percentage of the total, from 44% in 1880 to about 35% in 1910.

Beginning in 1910, the mechanization of the farm caused these long term trends in agriculture to reverse. The number of farms had fallen in half by 1964, farm population was one-third of its peak by 1969, and the average size of a U.S. farm had increased to 400 acres by that same date. The total farm land area in the United States continued to increase until 1940, and has remained constant since then, at about 1 billion acres.¹¹ Reference to Figure 1 shows that farm sizes, as measured by total crop acreage, began to accelerate rapidly after 1955.

Increases in labor productivity, mainly from mechanization, and improved crop yields, from hybrids and fertilizers, have allowed this shrinking farm sector to supply a continually growing population, as well as significant export markets. In 1910, for instance, one U.S. farmer supplied 8 people with food; by 1950, that same farmer was

⁹ Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970. Volume I.* Series K17-81.

¹⁰ *Historical Statistics.* Series D76 and K1.

¹¹ *Historical Statistics.* Series K17-81.

Figure 1. Average Crop Acreage per Farm

Source: Bureau of the Census, 1992 Census of Agriculture, 1954 Census of Agriculture

feeding 22 people.¹² These productivity improvements have continued up to the present day: a recent estimate is that one farmer was feeding 90 people by the late 1980s.¹³

The views of social scientists regarding this process have been decidedly mixed. Many economists of the period saw the significant increases in labor productivity from mechanization as a clear benefit to the economy, as fewer resources were needed to produce ever larger quantities of food stuffs. Prominent observers, including W. W. Rostow, saw this transformation as a necessary component of growth, as resources were shifted out of 'backward' agriculture into 'modern' industry. Most agricultural economists, influenced perhaps by their agricultural engineering colleagues' favorable view of the technologies of farm mechanization, adopted a similarly positivist bent.

Those in governmental organizations such as the U.S.D.A. and the Labor Department have been far less sanguine about the impact of farm power on the economy. The rapid increases in labor productivity prompted dislocation and migration of millions of farm people: from the countryside into the cities and from the South to the North. Expanding supply has led, despite massive government intervention since the 1930s, to steadily falling farm prices and incomes for most of this century. More recently, rural sociologists and historians have blamed mechanization for the destruction of rural towns, institutions, and the agrarian way of life.

It is my contention that the gloom of the past 20-30 years surrounding mechanization has hidden the tremendous contribution of the tractor to the growth of the United States.

¹² Fred R. Jones, *Farm Gas Engines and Tractors* (New York: McGraw-Hill, 1966), Table 1-1, p.3.

¹³ David B. Danbom, *Born in the Country: A History of Rural America* (Baltimore: The Johns Hopkins University Press, 1995), p. 234.

The rather straightforward substitution of tractors for horses as motive power for a wide variety of farm tasks led directly to the freeing up of a significant fraction of the total workforce – in 1910, 30% of the total labor force worked on farms; by 1955, less than 10% did. In addition, a large amount of acreage devoted to feed grains for draft animals was also made available for other crops and livestock: the 24MM horses and mules that provided power in 1910 dwindled to 4.3MM by 1955, and is below 3MM today.

From the standpoint of the overall U.S. economy and the consuming public, then, the benefits have been substantial. The efficiency of tractors in performing farm tasks has dramatically reduced the inputs required to produce the food we eat. The long secular decline in relative food prices has allowed increased consumption of other goods, even among the poorest in our society. Labor released from agriculture has long since been absorbed into manufacturing and services, fueling growth in these areas. Agricultural surpluses, stimulated by mechanization and yield improvements from the green revolution in farming, have helped feed people throughout the world.

CHAPTER 2

HISTORY AND TECHNOLOGY OF THE TRACTOR

A first step in this analysis is to establish the context for the development of the tractor. Farmers in 1900, whether engaged in growing wheat, corn, or cotton, raising livestock, producing dairy products, or combining a variety of these or other products, had only two sources of power aside from their own strength: steam engines and draft animals. Steam boilers provided motive power for threshing small grains, and a very small number of farmers were using recently-developed steam traction engines for plowing and other arduous tasks. Draft animals provided most of the power on all types of farms, however. As of 1904, there were more than 19MM horses and mules on American farms, about three or four animals for the average farm.¹⁴ By 1910, this number had risen to 24MM.¹⁵ In addition to supplying motive power, the horses were also relied upon for transportation, of both goods and people.

Horses and mules pulled an impressive variety of farm implements at the turn of the century, including plows, disks, harrows, planters, cultivators, mowers, and reapers.

¹⁴ R. B. Gray, *The Agricultural Tractor: 1855 - 1950* (St. Joseph, Michigan: American Society of Agricultural Engineers, 1954) Part II, p. 1.

¹⁵ *Historical Statistics*, Series K570, 572.

These implements were supplied by a large number of firms, but the largest were John Deere, International Harvester, Case, and Massey-Harris, all of whom would become important in the tractor business. Several important farm tasks were typically done by hand at this time, including picking of corn and cotton. The greatest amount of power was needed for plowing, often forcing farmers to keep one or two extra horses above the number needed for the remainder of the year. As an example, power requirements during plowing were estimated at 60% of the annual total needs for growing wheat at that time.¹⁶

A new source of power, then, would be valuable to the farmer if it could replace the horse-power requirements of plowing, as long as the cost was less than that of maintaining one to two extra horses. It would even more be valuable if it could economically replace all of the functions currently performed by draft animals, and further if it could facilitate automation of the cotton and corn picking operations. This was the market opportunity that developers of the tractor hoped to exploit.

The return of the constraint to plowing was an interesting result of nineteenth century technological improvements in small grain farming. In the early 1800s, the settlement of the Ohio valley and the prairies was limited by the rate at which land could be cleared and plowed. With hired labor expensive or non-existent, the amount of land a farm family could cultivate was severely limited, and farm sizes were small. Development of the steel plow and moldboard in the 1830s permitted farmers to plow larger acreage, and the constraint to farm size moved to the harvesting operation. The mechanical reaper, which diffused widely in the 1850s, sped up the harvesting process significantly; with reapers and

¹⁶ Robert C. Williams, *Fordson, Farmall, and Poppin' Johnny* (Urbana, Illinois: University of Illinois Press, 1987) p. 10.

the widespread adoption of contract steam threshing beginning in the 1870s, the technological constraint returned to plowing. With the size of the harvest determined by the amount of land that could be plowed after the fields dried out and before the planting window closed, the tractor would also prove valuable if it could speed up the rate of plowing.

The unmet needs of the farmer, as outlined above, provided a strong motivation for development of a powered vehicle for farm work.¹⁷ As early as the 1870s, engineers succeeded in producing steam traction engines, referred to today as steam tractors. These monsters, weighing in excess of 30,000 pounds (excluding water), could move under their own power, and had impressive horse-power capacity. Unfortunately, their huge size, mechanical complexity, and constant danger of explosion made these traction engines unusable for most farms in North America. In all but the driest soils, steam traction engines would become mired in the mud and refuse to move.

Despite these handicaps, the use of steam tractors increased slowly in the United States throughout the last two decades of the 19th century. Reynold Wik, in a definitive work on these monsters, traced the development of the 'steam-engine boom.'¹⁸ Annual production of less than 2000 units per year in the 1890s had increased to around 4000 in the ten years after 1900. Nonetheless, the rate of growth of steam horsepower was far

¹⁷ The descriptions in this section rely heavily on Gray, *The Agricultural Tractor*; Williams, *Fordson, Farmall, and Poppin' Johnny*; and Robert K. Mills, ed. *Implement & Tractor* (Overland Park, Kansas: Intertec Publishing, 1986).

¹⁸ Reynold M. Wik, *Steam Power on the American Farm*, (Philadelphia: University of Pennsylvania Press, 1953).

smaller than the growth in animal horsepower.¹⁹ Adoption of steam power was clearly not a candidate to replace the horse.

With the commercialization of the internal combustion engine, a more practical alternative emerged. Farmers bought large numbers of stationary gasoline engines in the first decade of the 20th century, and quickly became familiar with their operation. A wide variety of household chores was simplified by the use of stationary engines, including pumping water, washing clothes, and churning butter. Companies began developing gasoline-powered traction engines during the same period; the first commercial machines were sold in 1902, and quickly became known as 'tractors'.

The first tractors shared similar traits to the steam traction engines. Weighing between 20,000 and 30,000 pounds, with huge steel wheels or tracks, these models were large and expensive. Fairly quickly, the large manufacturers, including Hart-Parr, International Harvester, Case, and Rumely had reduced the size and cost. By the time Ford introduced its Fordson model, the first successful small tractor, average weights were down to 2000-6000 pounds, and prices were under \$1000. These tractors proved to be excellent at plowing, and were quite capable of driving mowers and reapers. The large steel wheels, low clearance, and substantial weight made them unsuitable for cultivating growing crops like corn and cotton, however.

The corporate history of tractors, although largely beyond the scope of this dissertation, is interesting partly due to the role played by Henry Ford.²⁰ Although an

¹⁹ From 1880 to 1910, steam-engines increased from 2MM to 3.5MM HP; horses and mules jumped from 13MM to 23MM HP. Wik's data was originally published in U.S. Department of Agriculture *Miscellaneous Bulletin 157*, (Washington: U.S. Government Printing Office, April 1933).

²⁰ See Williams, *Fordson, Farmall, and Poppin' Johnny*; Cyrus McCormick, *The Century of the Reaper*

outsider in the tractor business, with no background in agricultural implements and no established dealer network, Ford nonetheless played a key role in the technological and commercial development of tractor technology. He introduced a small, inexpensive model which he called the Fordson during the first World War. This model sold well for several years, aided considerably by a war-caused shortage of horses.

After a post-war crash in farm prices drastically reduced sales in 1920-21, Ford initiated a price war in 1922 by cutting the price of its Fordson from \$625 to \$395. Alone of the large competitors, International Harvester matched Ford's price, and sales boomed throughout the rest of the 1920s. Ford's production of tractors were always a sidelight to his main business of manufacturing automobiles, however, and when the Fordson production lines were needed for the critical Model-A launch in 1928, Ford decided to leave the tractor business.²¹

The competition with Ford drove International Harvester to make significant improvements in their tractors. The first innovation to appear was the power take-off, offered after 1922. This device, a metal shaft turned by the rotation of the tractor motor, allowed implements to be driven directly by the tractor engine, as opposed to obtaining power from a wheel rolling along the ground. The power take-off quickly became a

(Boston: Houghton Mifflin, 1931); and Paul C. Johnson, *Farm Power in the Making of America* (Des Moines: Wallace-Homestead, 1978).

²¹ Many agricultural historian have claimed that Ford was driven from the business by losses incurred in his price-cutting, and by his lack of a dealer network. This is difficult to support in light of the fact that the Fordson still dominated tractor sales in 1927, with a market share of 55%. According to Nevins and Hill, when the Model-A was introduced, production was at capacity for a number of years - there were waiting lists for buyers until 1933 (Allan Nevins and Frank Ernest Hill, *Ford: Expansion and Challenge: 1915 - 1933*, New York: Charles Scribner's Sons, 1957, pp. 367-9).

standard feature on all tractors, and implement makers began the process of re-designing their equipment to take advantage of this innovation.

An even more important improvement by IH was their introduction of a general purpose tractor, the Farmall, in 1925. This model, with high ground clearance, small front wheels, and minimal weight, was designed for cultivating, as well as for plowing and cutting. It was tested in Texas in 1923, and was released for broad scale distribution in 1925. Competitors, such as Deere, Massey-Harris, and Case rushed to develop a general purpose tractor (a 'GP') of their own, and by the mid-1930s, GPs had replaced the standard Fordson-type tractor. In addition, these same firms began the process of modifying their implements for these tractors, and the wholesale replacement of the horse began in earnest.

Three other improvements were critical in completing the technology base for the tractor. Deere released a power lift for its models beginning in 1927. This device allowed the implement to be raised before every turn by pulling a lever. Prior to this, the farmer had to lift the implement by hand at each turn, which was a time-consuming and enervating task. As with the power takeoff, the power lift was rapidly adopted by other tractor makers. Rubber tires first became available for tractors in 1932, and by 1938 had largely replaced steel wheels. The zero-pressure tires not only did less damage to fields, but allowed a higher forward speed, due to reduced friction. Finally, the development of diesel engines in the mid-1930s gave farmers access to a lower-cost fuel for their machines. Many tractors from that time forward had a small gasoline tank for cold starts, and a large diesel tank for the majority of the operation.

International Harvester pioneered a 'one plow' tractor at about this time, and began selling it in 1934. This tractor was smaller and less expensive than the original Farmall, but had the same general purpose capabilities. Its introduction offered operators on small farms the chance to replace their one horse or mule with a tractor, and was responsible for the beginnings of the tractor's diffusion in the South. These small tractors often featured adjustable front wheels and high ground clearance, which made them considerably more flexible than the larger models. Within a few more years, manufacturers were offering their larger models in 'high-clearance' versions as well.

A final innovation was responsible for bringing Ford back into the tractor business in 1937. In that year, the firm agreed to enter into a joint venture with Irish inventor Harry Ferguson.²² Ferguson had worked for almost 20 years to perfect a 'three-point hitch', a device which produced superior plowing by continuously leveling the implement as it traveled over uneven terrain. The Ford-Ferguson tractors quickly amassed a significant market share (14% by 1940), and the hitch design was rapidly imitated.

By about 1938, the technology of tractor development had achieved what is known as a 'dominant design'. The Farmall-type general purpose tractors, both large and small, would change little over the next 30 years. Beginning in the mid-1930s, and despite the ongoing depression in the United States, tractor sales increased rapidly. Figure 2 shows the number of tractors on farms from 1910 through 1960. By the latter date, the process of diffusion was essentially complete. With the exception of the deep South, the increase in percent of farms with tractors from year to year had stopped.

²² This section relies on the definitive biography of Ferguson: Colin Fraser, *Tractor Pioneer: The Life of Harry Ferguson*, (Athens, Ohio: Ohio University Press, 1973).

Figure 2. Replacement of Horses by Tractors on U.S. Farms -
1910 to 1960

Source: Historical Statistics of the United States, Series K184, K570, K572.

The general-purpose tractor proved to be an excellent replacement for the horse in plowing, soil preparation, planting, and cultivating tasks for a wide variety of field crops. In addition, the tractor was fully capable of providing power for mowing hay and for harvesting of wheat and other small grains. In the latter application, it facilitated the practice known as 'combining', the simultaneous reaping and threshing of wheat. Horse-drawn combines had been available since the 1880s, and had found limited acceptance on the larger farms of the arid West. However, a large team of horses was required to drag the heavy, complex machine through the fields. The tractors of the 1930s and 1940s had no trouble pulling a re-designed combine, and they began a process of rapid adoption in the Midwest. Eventually, a self-propelled combine was produced, with the tractor engine and cab subsumed into the combine apparatus.

The general purpose tractor was not capable of bringing mechanization to the corn and cotton harvest until separate, but related innovations produced a corn picker in the 1920s and a mechanical cotton picker after the second World War. Prior to the development and adoption of the corn picker, corn was often cut with a binder, followed by manual shelling. One of the more important uses of stationary gas engines early in the 20th century was for the shelling of corn. The picker combined the operations of cutting and shelling, and also distributed the stalks back onto the field, eliminating an additional step.

Mechanical cotton pickers fundamentally altered not only the harvesting of cotton, but the very nature of cotton growing in the United States. This development has been well researched by economists and sociologists, so I will not spend a great deal of effort in this area. However, a brief summary seems appropriate. The mechanical picker, even after

extensive development, produced higher crop losses than hand picking in the hot, humid areas where most cotton was grown, Mississippi, Alabama, and east Texas. In the dry areas of west Texas, however, the picker was very efficient, both in terms of labor effort and crop yields. The mechanical cotton picker thus precipitated a relocation of cotton production westward, resulting in large scale migration out of the deep South in the years after World War II.

As with the combine, self-propelled corn and cotton pickers were soon developed, combining the power train and cab of the tractor within the implement's apparatus. For this reason, pickers and combines are often considered as separate machines, and their development and diffusion are not included in discussions of the impact of the tractor. It should be pointed out, however, that none of these devices could have been powered efficiently by horses or steam; the gasoline-powered tractor was necessary for their development. As such, I will include combines and mechanical pickers in assessing the impact of the tractor on inputs to agriculture.

The recent history of tractor development is less dramatic than the first 50 years. The peak year of tractor production was 1951, during which 564M units were made. From that time, the approaching saturation of the market produced a steady fall in production and sales. As one might expect, manufacturers responded by developing ever-larger tractors to supply farms which were growing in size. Interestingly enough, this pursuit of size left the small end of the market open to foreign competition, and (similar to the case of the automobile industry) imports grew to dominate the small-tractor market. Creature comforts have been improved markedly since the 1950s as well. Enclosed cabs soon had

heating and air conditioning, and are now likely to be supplied with a television and stereo-CD. As a result, modern tractors are quite comfortable in comparison with the machines of 40 years ago, let alone versus the monsters of the early tractor era.

CHAPTER 3

THE TRACTOR AS AN ENGINE FOR GROWTH

In his celebrated work on United States railroads, Robert Fogel used the emerging techniques of the New Economic History to attack a popular belief among historians that railroads were indispensable to the growth of the United States.²³ His counterfactual analysis of commodity transportation yielded a social savings estimate which suggested that railroads made only a modest contribution to national income in the year 1890. Fogel used his results to support Simon Kuznets' assertion that no single innovation was important enough to be worthy of study in isolation. Technological progress, although a key factor in promoting economic growth, was, in his view, made up of a large number of individual improvements, none large enough by itself to be significant.

Professor Fogel successfully defended his data and analysis against a number of critics many years ago, and his critique of the 'hero theory' has likewise been largely accepted. In my view, this emphasis seriously undervalues the contribution of the inventors, entrepreneurs, and firms that were and are the drivers of much technological change. A large literature has emerged over the past 20 years attempting to relate research &

²³ Fogel, Robert W., *Railroads and American Economic Growth: Essays in Econometric History*, (Baltimore: The Johns Hopkins Press, 1964).

development to growth, almost exclusively by econometrically relating R&D spending with total factor productivity increases. This work consistently shows strong correlation between the two factors, but convincing evidence demonstrating causation is lacking.

There have been relatively few attempts to quantify the direct economic impacts of new technology, however. Zvi Griliches early work on hybrid corn and Schmitz and Seckler's research on the mechanical tomato harvester are two of these related to agriculture.²⁴ Spurred on by the early work of Fogel and Albert Fishlow, scholars have investigated the impact of railroads on growth in a number of different countries, often finding direct social saving well far greater than that measured by Fogel.²⁵ Especially notable are the work of John Coatsworth and William Summerhill, who quantified social benefits in excess of 10% for Mexico and Brazil, respectively.²⁶

Although improvements in transportation, industrialization in general, R&D spending, and investments in education and other human capital are widely recognized as supporting economic growth, agriculture has been considered a laggard or hindrance. Upon finding that agricultural productivity measured in value terms was lower than that of manufacturing, and had increased at a slower rate over the past half-century, Denison and other pioneers of growth accounting, proposed that rapid transfer of resources out of

²⁴ Zvi Griliches, "Research Costs and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy* 66 (October, 1958), pp. 419-31; Andrew Schmitz and David Seckler, "Mechanized Agriculture and Social Welfare: The Case of the Tomato Harvester". *American Journal of Agricultural Economics* 52:4, (November, 1970), pp. 569-77.

²⁵ Fishlow's research, which was contemporaneous with Fogel's, also considered the railroad's impact on the U.S. economy. See Albert Fishlow, *American Railroads and the Transformation of the Ante-bellum Economy*, (Cambridge: Harvard University Press, 1965).

²⁶ John H. Coatsworth, *Growth Against Development: The Economic Impact of Railroads in Porfirian Mexico* (DeKalb, Illinois: Northern Illinois University Press, 1981) and William R. Summerhill, *Railroads and the Brazilian Economy Before 1914*, (Ph.D. Dissertation, Stanford University, 1995).

agriculture was a necessary condition for countries to grow.²⁷ An entire generation of development economists encouraged third-world countries to abandon agriculture and focus their energies on manufacturing or other inherently 'high-growth' activities.

This advice was based on two apparent misconceptions about the United States' agricultural history. Firstly, although productivity in farming was growing relatively slowly in the units measured, dollars of output per dollars of input, advances in physical terms (bushels per labor hour, for instance) were quite rapid. Due to quite low income and price demand elasticities, large increases in physical output had the primary effect of driving down output prices; thus, success in increasing productivity had the paradoxical effects of reducing agriculture's share in national output and total factor income, and produced total factor productivity numbers that appeared unimpressive.

Secondly, the period during which the growth accountants were gathering their data was one of massive adjustment of resources out of agriculture. The mechanization described in this paper forced the movement of more than eight million workers from farms to other employment, creating a large and long-lasting disequilibrium. In finding that wages in agriculture were well below that in other sectors, even after controlling for education and other differences, Theodore Schultz (among others) concluded that the labor market had failed to adjust optimally; growth in the United States could have been speeded up by accelerating the move out of agriculture.²⁸ It is important to understand the true implications of this finding. Labor and other resources devoted to agriculture

²⁷ Edward F. Denison, *Accounting for United States Economic Growth 1929 – 1969*, (Washington D.C.: The Brookings Institution, 1974).

²⁸ Theodore W. Schultz, *Economic Growth and Agriculture* (New York: McGraw-Hill, 1968), pp. 225-30.

were not inherently less productive; they had become so due to massive technological change and a failure to adjust quickly enough.

Agriculture in 1910²⁹

The decade between 1910 and 1920 marked the peak of animal-powered farming in the United States. With the frontier closed and population expanding through rapid immigration both before and after the first World War, food production needs forced farmers to employ more than 21MM horses and 5MM mules for farm power needs. Of the total land area in the continental United States in 1910, farmland comprised almost half, representing 879MM acres. Slightly more than a third of this, or 310MM acres, were used for growing crops, the remainder being woodland, pasture, structures, and unimproved areas. Agricultural output was sufficient to provide an exportable surplus of cotton, tobacco, grains, and animal products totaling \$900M, slightly exceeding farm product imports.³⁰

A summary of the most important crops is shown here as Table 1.³¹ Corn was the most important crop, both in terms of acreage planted and value. Then, as today, about four-fifths of the corn raised was fed to animals, including draft animals such as horses and mules, as well as hogs, cattle, chickens, and other food animals. Hay, likewise was fed to both types of animals, but not of course to people. Oats, the fifth most valuable crop, was

²⁹ Except as noted, all of the numerical data in this subsection comes from the 1910 Census (Bureau of the Census, *Thirteenth Census of the United States, 1910: Agriculture*, Washington: U. S. Government Printing Office, 1911).

³⁰ *Exports of Farm and Forest Products, 1909-1911, by Countries to Which Consigned*. U. S. Department of Agriculture Bureau of Statistics - Bulletin 96 (Washington: Government Printing Office, 1912).

³¹ This data, taken from the 1910 Census, represents crops grown in the 1909 farm season.

also fed mostly to animals, and made up a significant proportion of horse and mule feed. Wheat was grown almost exclusively for human consumption, and made up the third largest crop by acreage. Cotton, although not grown as widely as wheat or oats, was a more valuable crop, and a major source of export revenue: more than 70% of the 10.6MM bales grown in 1909 were exported.

Table 1. 1909 U. S. Agricultural Output - Major Crops

Acreage, production, and value data in Millions.

Crop	Acreage	Production	Value	Yield per acre
Corn, all purposes	98.4	2,552 (bu.)	\$1,444	25.9 (bu.)
Hay and Forage	72.3	97.5 (ton)	\$824	1.35 (ton)
Cotton	32.0	10.6 (bale)	\$703	0.33 (bale)
Wheat	44.3	683 (bu.)	\$658	15.4 (bu.)
Oats	35.2	1,007 (bu.)	\$415	28.6 (bu.)
Potatoes	4.3	448 (bu.)	\$202	104 (bu.)
Tobacco	1.3	1,056 (lbs)	\$104	815 (lbs)
Barley	7.7	173 (bu.)	\$92	22.5 (bu.)
Total field crops	310.4	n. m.	\$4,852	n. m.

Source: Bureau of the Census, *Thirteenth Census of the United States: Agriculture* (Washington: U. S. Department of Commerce, 1911), pp. 581-694.

Nearly all of these crops were grown, cultivated, and harvested using animal power or manual labor. Although steam-powered traction engines had been in use for plowing since the 1870s and gasoline tractors had been commercially available for a few years, neither had made a major impact on farming. Their massive size and weight made them usable

only for threshing grain and plowing, and even then only in areas with hard, dry ground. Before 1910, only about 58,000 steam traction engines and 2,500 gas tractors had ever been produced, and U. S. Department of Agriculture (USDA) estimates showed only about 1000 gasoline machines in use in 1910.³² As such, I am considering 1910 to be essentially pre-tractor, and am using its input-output structure as the basis for the counterfactual 1954 economy considered later.

The 1910 census places the value of horses and mules on farms at \$2,609MM, or about six percent of all farm property. With implements and machinery valued at \$1,265MM, U. S. farms had almost \$3.9B in 'crop-growing' capital. Capital intensity could thus be calculated at \$12.52 per acre, a number which remained almost constant in real terms through the first half of the century. This rather surprising finding will be considered in the counterfactual analysis later in the paper.

In 1910, more than 32MM people lived on the nation's farms, comprising 35% of the total population. Of these, the census records 12.1MM as farm workers, or about one-third of the total work force of 38MM. Some pertinent statistics on agricultural employment are shown here as Table 2.

It should be noted that these figures are significantly lower than the 13.6MM published by the USDA for the same period. This discrepancy stems from differences in method which persist today - the Census Bureau enumeration asks for each individual's primary occupation during the year, while the Agriculture Department asks farmers how many

³² Steam traction engine data is from Reynold Wik, *Steam Power on the American Farm*, (Philadelphia: University of Pennsylvania Press, 1953), p. 100-1. Gas tractor data is from *Changes in Farm Production and Efficiency*, Statistical Bulletin No. 233 (Washington: U. S. Department of Agriculture, rev. 1961), p. 31 and from the author's dissertation research.

people were at work on their farms during various weeks of the year. For this reason, the USDA captures many part-time laborers who may only work a few hours per week or a few weeks per year, while the Census data does a better job of identifying those who are dependent on farming for their livelihood. In a separate estimate, the UDSA calculated that a total of 22.55B hours of labor were expended in farming in 1910³³; this ties in reasonably well with the census work force number, indicating an average of about 1860 hours per worker per year.

Table 2. The Farm Work Force in 1910.³⁴

All figures in Thousands.

	Farmers	Family laborers	Hired laborers	Total
U. S. Total	5,995	3,311	2,820	12,126
Northeast	541	119	353	1,012
North Central	2,136	634	797	3,566
South Atlantic	1,040	927	597	2,563
South Central	1,937	1,569	792	4,299
West	342	62	282	685

Agriculture in 1954³⁵

By the mid-1950s, then, U.S. agriculture had changed dramatically from half a century earlier, and was approaching full mechanization.³⁶ Recent developments in genetic

³³ *Changes in Farm Production and Efficiency*. p. 20.

³⁴ *Thirteenth Census of the United States, 1910: Occupation Statistics*, pp. 91, 96-139.

³⁵ Except as noted, all of the numerical data in this subsection comes from: Bureau of the Census, *United States Census of Agriculture, 1954* (Washington: U. S. Department of Commerce, 1955).

selection of seed characteristics, and increased use of chemical fertilizers had launched the second major productivity revolution of the 20th century, that of dramatic yield improvement. Several important new crops had emerged and were being cultivated widely, most notably soybeans and sorghum. Two wars, the great depression, and several sharp agricultural slumps had alternately boosted and ravaged farm income. The population of the United States had increased by 80% to 165MM, while farms had lost more than 40% of their people.

Despite these changes, the amount of land used to grow field crops was little altered. The total reported for the census year of 1954 was 329MM acres, a six percent increase from 1909, and only 30MM less than the all-time high reached in 1929. Large decreases in corn and cotton acreage were balanced by the 18MM acres of soybeans and 16MM acres of grain sorghum added to the nation's output mix. Exports of farm products totaled \$3.1B, again dominated by cotton, wheat, and tobacco. Imports were even greater, however, and an overall agricultural products deficit of \$650MM was recorded.³⁷ Data for the most important crops is listed below as Table 3.

Although total cropland did not change drastically from 1909 to 1954, there were a number of notable regional and sectoral shifts. The West North Central states added 19MM and the Mountain states almost 14MM acres, as the last frontiers were filled in, aided considerably by improved irrigation techniques. These states added small grains, such as wheat and barley, as they were abandoned by farms in the east. Corn's net

³⁶ The only significant exception was in cotton-growing in the deep South, where the mechanical picker had not fully replaced hand methods for harvesting, and in cultivation and harvesting of tobacco, which was still done by hand years later.

³⁷ *Agricultural Statistics, 1956* (Washington: USDA, 1957), pp. 574-6

decrease of 20MM acres was almost entirely accounted for by four states: Missouri, Kansas, Oklahoma, and Texas, the last three of which increased their land in wheat by 9.5MM and sorghum by 13MM acres. Cotton acreage declined in every state in the South, as increasing yields collided with a declining export market. Finally, 15MM acres were taken out of production in the East and Southeast, as urbanization and lower output prices changed these farmers' ability to remain competitive in their markets.

Table 3. 1954 United States Agricultural Output - Major Crops.
Acreage, production, and value in Millions.

Crop	Acreage	Production	Value	Yield per acre
Corn for grain	66.8	2,613 (bu.)	\$3,758	39.1 (bu.)
Corn for silage, grazing	11.3	81.0 (ton)	\$529	7.15 (ton)
Hay and Forage	69.9	103.6 (ton)	\$2,302	1.48 (ton)
Cotton	18.9	12.9 (bale)	\$2,515	0.69 (bale)
Wheat	51.4	909 (bu.)	\$1,940	17.7 (bu.)
Oats	37.9	1,314 (bu.)	\$928	34.7 (bu.)
Potatoes	1.5	368 (bu.)	\$509	250 (bu.)
Tobacco	1.6	1,922 (lbs)	\$974	1,234 (lbs)
Soybeans for grain	16.4	1,386 (bu.)	\$816	19.7 (bu.)
Total field crops	329.2	n. m.	\$16,805	n. m.

Source: Bureau of the Census, *United States Census of Agriculture 1954* (Washington: U. S. Department of Commerce, 1955). pp. 610-847.

By 1954, tractors were used to plow and prepare nearly all of this land, seed, cultivate, and fertilize the crops, and harvest all of them except for cotton and tobacco. According to the census of that year, 2.7MM farms reported a total of 4.3MM tractors. There were,

in addition, 980M combines and 688M corn pickers.³⁸ Only about 500M farms had two or more work animals and no tractor, 80% of those in the South. The value of implements and machinery on U.S. farms in 1954 has been estimated at \$16.3B, including about \$4.3B of automobiles and trucks, or about 13% of the value of total farm property.³⁹ With slightly more than \$230MM in horses and mules added in, the value of 'crop-growing' capital was \$12.2B, or about \$36.70 per acre harvested. When deflated to 1910 dollars, the real capital intensity is \$12.77 excluding automobiles and trucks, little changed from the \$12.52 calculated for the earlier period.

The farm labor force of 1954 was significantly smaller than that of 1910. Not only had the numbers of farm proprietors, unpaid family workers, and hired workers all declined significantly, but a large proportion of the proprietors also farmed only part-time. Aided by productivity increases from mechanization and the growth of rural manufacturing, almost half of the nation's farm operators held paying jobs away from the farm. In addition, hired workers worked far fewer days per year, mostly during harvest time, as tractors had replaced the demand for more steady labor.⁴⁰

The labor force calculation for 1954 was pieced together from published data and a few assumptions. Full-time equivalent (FTE) workers were estimated for each of the three classes of farm workers: proprietors, unpaid family members, and hired labor. The

³⁸ *Changes in Farm Production and Efficiency*, p. 31.

³⁹ Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970*, (Washington: U. S. Department of Commerce, 1975), Series K12.

⁴⁰ The 1.9MM hired workers that worked 25 or more days in 1954 averaged only 142 days of work. An additional 1.1MM people worked 1-25 days during the year. Source: *The Hired Farm Working Force of 1954* (Washington: U. S. Department of Agriculture, Agricultural Marketing Service, 1956).

details of that effort are sketched here, with Table 4 providing a summary of the resulting worker and hours totals.⁴¹

Off-farm work by proprietors was reported in the 1954 Census of Agriculture. Of the 4.78MM operators, 570M worked 1-49 days in non-farming pursuits, 249M worked 50-99 days, 306M worked 100-199 days, and 1,027M worked more than 200 days per year off the farm!⁴² The remaining 2.6MM proprietors failed to report or reported no off-farm work. By assuming that the members of these classes worked 25, 75, 150, and 250 days outside of farming, respectively, I determined that a total of 1,343M equivalent people should be subtracted from the total number reported in the census, leaving 3,440M FTE operators.

Operators were reported by the Census Bureau and the USDA as family farm workers if they devoted at least one hour to farming or managing the farm business during each week data was collected. Other family members were included in this category if they spent 15 hours or more in unpaid labor during the survey week. The Agricultural Marketing Service of the USDA published this data by state on a monthly basis throughout the 1940s and 1950s. During 1954, an average of 6,579M family workers were reported; if the proprietors are subtracted out, a total of 1,796M unpaid family workers remain.⁴³ By assuming these individuals averaged 30 hours of work per week

⁴¹ The resulting number of agricultural workers of 5.98MM is very close to the 6.2MM from the Bureau of Labor Statistics Employment and Earnings reports. Source: *Historical Statistics of the United States*, Series K-16.

⁴² *United States Census of Agriculture, 1954*, p. 81, 105.

⁴³ *Farm Employment: Monthly by States 1950-57, United States by Years 1910-57, by Months 1940-5*, Statistical Bulletin No. 236 (Washington: U. S. Department of Agriculture, 1958), p. 18.

(0.75 FTE per person), I calculated that 1,347M full-time equivalent unpaid family members were providing labor to farming in 1954.

Of the roughly 3MM hired farm workers employed in 1954, the USDA counted 1,908M that worked 25 days or more, with an average of 142 days employed during the year.⁴⁴ The remaining 1,101M worked less than 25 days, with no average reported. To obtain a conservative estimate, I calculated full-time equivalents and hours under the conservative assumption that this latter group all worked the maximum 25 days per year. If 250 days per year is considered full-time, the labor input actually contributed by hired workers was 1,194M FTE people, about one-third of the total.⁴⁵

Table 4. Estimate of the 1954 Agricultural Work Force.

All figures in thousands

	Total People	FTE Workers	Hours / Year
Farm Operators	4,783	3,440	6,880M
Family Workers	1,796	1,347	2,694M
Hired Workers	3,009	1,194	2,388M
Total	9,588	5,981	11,962M

Source: See text.

⁴⁴ *The Hired Farm Working Force of 1954*, Agricultural Marketing Service #103 (Washington: U. S. Department of Agriculture, 1956), pp. 1,4.

⁴⁵ There is qualitative evidence presented in *The Hired Farm Working Force* that a majority of these part-time workers had outside sources of income during the substantial parts of the year in which they did no farm work. Such a situation is important for the social savings calculation, which assumes that they would be full-time farm workers in the counterfactual cases, with their marginal product in outside employment lost.

The Counterfactual Proposition

Following the example set by Fogel and repeated in more recent work, I attempt to assess the importance of the tractor by asking the following question: How much poorer would the United States have been in 1954 had the tractor not been invented? The loss in income calculated from this, admittedly, wholly artificial experiment will be construed as the social savings from farm mechanization. Specifically, I explore a hypothetical economy forced to grow crops with horse and mule power, as was the case in the actual 1910 economy described above.

Social savings analyses have most often used partial equilibrium models to compare prices of the relevant products or services in the actual and counterfactual economies. Initial assumptions that income effects are negligible and consumption price inelastic lead to a estimate which overstates the actual savings. Fogel, who was interested in showing how small the effects of railroads had been in the U.S. case, made adjustments directly from this high-side figure. Authors seeking an unbiased estimate, including Coatsworth and Summerhill, have employed a variety of reasonable price elasticity figures to reduce the preliminary social savings to a more 'realistic' value.

Jeffrey Williamson used a computable general-equilibrium framework in a counterfactual analysis of the impact of improved 19th century agricultural technology on U.S. output, productivity, and income. Such a treatment has the potential benefit of capturing both income and substitution effects directly, as long as reasonable parameters are supplied for a number of factors. Although this would seem to be an appealing way to analyze the advent of the tractor, Williamson's study uses two critical assumptions that are

problematic in the 20th century case. First, the U.S. is treated as a 'small country', whose production has no effect on the world grain prices. In this way, price is eliminated as an endogenous variable. Secondly, he assumed price and income elasticities for purchases of food of 0.8, much higher than mid-20th century estimates of 0.20-0.25.⁴⁶

A more serious concern for the present work is that both of the above approaches require an equilibrium in the relevant product or service markets as a starting point of the analysis. Observed prices are then construed as market clearing values for supply and demand, and factors are assumed to earn their marginal product. The distortion in agricultural markets from 1933 onward caused by government farm programs mean that assumptions of equilibrium are ill-founded. The loan provisions of the Commodities Credit Corporation (CCC) set a price floor for each product covered, with the government committed to purchase unlimited amounts of crops at that support level. The farm recession of 1953-54 resulted in large purchases of unsold foodstuffs for several years. By mid-1955, the CCC owned \$4.6 billion in unsold crops, and had spent over \$2.1 billion over the previous year storing, handling, and disposing of surpluses.⁴⁷

The extent of the distortion of prices can be judged by reference to the 'parity ratio', defined as the ratio of farm output to input prices. It was a clear objective of the government to adjust price supports and other farm policies so that this ratio would remain at 100% of its 1910-14 base value. In fact, the government was successful in this

⁴⁶ The combination of these two assumptions produces the interesting result that eliminating late 19th century U.S. farm improvements (primarily in harvesting technology) would have drastically reduced both food consumption and exports. Although I have not seen details of the simulations, it appears that the Williamson counterfactual turns the U.S. into an importer of grains. The source is Jeffrey G. Williamson, *Late Nineteenth-Century American Development*, (Cambridge: Cambridge University Press, 1974).

⁴⁷ *Historical Statistics of the United States*, Series K-339, K-343.

effort from 1942 through 1952, aided to a great extent by price controls during the Second World War and the Korean conflict.⁴⁸ From 1953 onward, however, the size of the surplus food mountain and continued decrease in farm prices forced the government to allow the parity ratio to fall slowly from year to year. For this reason, and those discussed in the introduction, attempting to recover free-market equilibrium prices for 1954 for use in the counterfactual is well beyond the scope of this dissertation.

Model of the Physical Inputs to Farming

With a social savings calculation based on changes in output prices beyond reach, I have chosen to develop a model based on physical inputs to farm production. Mechanization saved labor directly, both by reducing the number of people involved in farm tasks and by speeding up the performance of each task. By eliminating animal draft power, it also indirectly saved the land and labor which would have been required to raise animal feed. Power farming replaced horse and mule capital with that of tractors, combines, and pickers. Finally, there were minor impacts on other inputs: fuel and lubricants were an added cost, while horseshoes and veterinary care declined; seed, irrigation, and fertilizer inputs, so important for increasing yields, are not considered within this counterfactual analysis.

⁴⁸ Falling farm output prices were largely the result of rapid decreases in producer cost driven by mechanization and yield improvements. With properly calculated input prices, parity could have been maintained without large surpluses. Unfortunately, the input price series often did not account properly for new goods or quality improvement; the resulting, overstated input number led to an erroneously low parity ratio figure; attempts to raise this ratio by increasing price floors led to large surpluses. A good discussion of the problems with input measurement can be found in Zvi Griliches, "Measuring Inputs in Agriculture: A Critical Survey," *Journal of Farm Economics* 42:2 (May 1960), pp. 1411-33. For tractor quality measurement, see William J. White, "Adjusting for Quality in Historical Time Series," an unpublished working paper which is available upon request.

It may be helpful to describe the conceptual experiment in more detail. Imagine a hypothetical external agent buying up all of the internal combustion and diesel powered farm equipment in 1954, paying current asset values for these items. These machines are then destroyed, along with the knowledge and technology of their creation and use. The farmers are then free to use the proceeds to purchase the inputs necessary to produce farm products with the next best available technology, which in this case is the horse and mule-powered agriculture of the turn of the century. The ability to produce new crops and to use chemical and biological knowledge to increase yields is retained by all agents in the system. I make several assumptions relative to this conceptual process.

1. Farmers need large numbers of work animals to meet their power needs. Based on the calculations of the previous sections which showed that real capital intensity did not change appreciably with the switch to tractors, I assume that all of the proceeds from the hypothetical tractor purchase would be required to purchase work stock.⁴⁹
2. Tractors are dis-invented simultaneously around the world. Although the United States was a leader in mechanization, by the 1950s most of the developed world had introduced tractors. Assuming other countries had this technology while the U.S. didn't would create a fundamentally different, and quite strange counterfactual analysis, with trade flows dominating. In this effort, changes in the trade balance will only be considered to the extent that land required for animal feed displaces that used for exports.

⁴⁹ In 1910, the value of work stock and farm machinery was \$12.55 per acre. In 1954, the value of all farm machinery (less automobiles and trucks) plus remaining work stock was \$36.70, or \$12.77 in 1910 dollars.

3. Farmers are initially constrained to produce the same amount of crops in the counterfactual 1954 as in the historical year, except that surpluses need not be generated. The switch to horses and mules requires a significant increase in acreage for animal feed. The farm sector's task was to minimize total acreage (and therefore, costs) subject to this output constraint. Two output mix options are evaluated. In the first case, production of major crops is identical to 1954 output, including items such as sorghum and soybeans, which were not produced in large amounts early in the century. Secondly, the output mix from 1910 is reproduced, having been scaled up to account for population increase.⁵⁰
4. Additional labor required for farm operations is pulled from the manufacturing and service sectors. It is assumed that labor demand in these sectors is perfectly elastic, so that their wages represent their marginal product, and their loss does not affect the productivity of remaining workers. Under these conditions, the welfare loss from relocating them into agriculture is exactly their wage.
5. The welfare losses from this experiment reduces income enough to impact consumption. However, preferences among all goods are not homothetic; food demand is highly income inelastic. In keeping with a number of estimates made this century by the USDA, I set this elasticity at 0.2.⁵¹ Output requirements for the counterfactual are reduced proportionately as income falls.

⁵⁰ It is not clear a priori which would be less costly in the counterfactual 1954 - a revealed preference argument can tell us that the new crops were preferred to those which declined in production (such as peanuts, potatoes, rye, buckwheat), but not whether the substitution was due to mechanization or perhaps to yield increases in the new varieties.

⁵¹ A recent study which quotes earlier work is: Jitendar S. Mann and George E. St. George, *Estimates of Elasticities for Food Demand in the United States* (Technical Bulletin 1580, Washington: United States Department of Agriculture, 1978). The same 0.2 estimate is found in Earl O. Heady, "Extent and Conditions of Agricultural Mechanization in the United States," in J. L. Meij, ed. *Mechanization in Agriculture* (Chicago: Quadrangle Books, 1960), p. 68.

6. The 1910 production technology is assumed to use inputs in fixed proportion. The farmer's decision was essentially to choose an area of land to cultivate. Given that choice, a certain number of operations had to be performed, each requiring a specific amount of labor and capital, in the form of equipment and work stock. Feed for the work animals required an additional amount of land to be cultivated, using inputs in the same proportion. The output yield, which was largely out of the control of the farmer, simultaneously determined the absolute return to the three factors.⁵²

More formally, total crop production in the United States can be written as:

$$Y = \sum_{i=1}^I \sum_{j=1}^J \psi_{ij} \min \{ R_{ij} ; L_{ij} / \alpha_i ; H_{ij} / \beta \} \quad (1)$$

where: ψ_{ij} is the 1954 yield, in bushels per acre, of crop i in state j ;

R_{ij} is acreage, L_{ij} is labor, and H_{ij} the horses used for crop i in state j

α_i is the labor requirement per acre in state j , assumed the same for all crops⁵³

β is the work stock requirement per acre, for all crops and states.

Production is utilized for consumption, animal feed, exports, and surplus:

$$Y = C + Y^H + X + S \quad \text{for each crop } i; \quad (2)$$

Animal feed requirements can be expressed as:

$$Y^H = (\gamma_{\text{corn}} + \gamma_{\text{oats}} + \gamma_{\text{hay}}) \sum_{i=1}^I \sum_{j=1}^J H_{ij} \quad (3)$$

⁵² Although this fixed proportions assumption is made to facilitate the empirical analysis, it is not likely to lead to a significant over-estimate of social savings. To do so, the hypothetical 1954 farm sector would have to exhibit a lower labor intensity than what was found in the actual 1910. It is difficult to envision the form that such an increased bias might take; generations of labor scarcity had produced a technology about as capital intensive as could be achieved.

⁵³ Because most farm workers worked on several crops, separability of labor inputs has always been problematic. The labor input data collected for this paper are specific to each state, but pooled across crops.

with γ_f the quantity of crop f needed to feed one work animal for a year.

Because optimization of a fixed proportion technology requires that the three arguments in the braces of equation (1) be equalized, we can re-write (3) as:

$$Y^H = (\gamma_{\text{corn}} + \gamma_{\text{oats}} + \gamma_{\text{hay}}) \beta \sum_{i=1}^I \sum_{j=1}^J R_{ij} \quad (4)$$

Treating land as the limiting factor, equations (1) and (4) can be combined and rearranged to give the following:

$$C = \sum_{i=1}^I \sum_{j=1}^J (\psi_{ij} R_{ij}) - (\gamma_{\text{corn}} + \gamma_{\text{oats}} + \gamma_{\text{hay}}) \beta \sum_{i=1}^I \sum_{j=1}^J R_{ij} - X - S \quad (5)$$

Equation (5) represents the consumption constraint in the farm sector's acreage minimization problem. The objective function is simply to minimize the total acreage cultivated, and thus the total cost incurred. Additional constraints include binding upper limits on acreage of each crop in each state, determined from the maximum number of acres raised during the period 1900 to 1954, and a limit to the state's total crop acreage, also determined from 20th century census data.

The formal statement of the farm sector's minimization problem is:

$$\begin{aligned} & \text{Minimize } R^T = \sum_{i=1}^I \sum_{j=1}^J R_{ij} \\ \text{s.t. } & \sum_i \sum_j (\psi_{ij} R_{ij}) - (\gamma_{\text{corn}} + \gamma_{\text{oats}} + \gamma_{\text{hay}}) \beta \sum_i \sum_j R_{ij} - X - S \geq C \\ & R_{ij} \leq \bar{R}_{ij} \quad \forall i, j \\ & \sum_i R_{ij} \leq \bar{R}_j \quad \forall j \end{aligned}$$

Requirements for labor and horse capital for each crop and state are determined by:

$$L_{ij} = \alpha_i R_{ij} \quad (6) \quad \text{and} \quad H_{ij} = \beta R_{ij} \quad (7)$$

All of the data necessary to solve this constrained optimization are available, including the technical parameters α_i , β , γ_f , ψ_{ij} , and the constraints, C , R_{ij} , and R_j . The next section provides details of the data and the acreage-minimizing solutions for both the 1910 and 1954 output crop mixes. An additional iteration is made on the latter option with consumption reduced due to the income effect.

The Counterfactual Data

With this framework in place, the experiment is straightforward. The first step is to determine the effect of horses on the net output of a given acreage. A number of studies by the USDA and other government agencies early in this century provided information on optimal feeding of horses and other work animals. One USDA study widely cited in the diffusion literature reported that work horses were fed, on average, 49 bushels of oats, 31 bushels of shelled corn, and 4980 lbs of hay annually, in addition to six months of feeding in the pasture.⁵⁴ Depending on availability of feed, the proportion of corn and oats could be varied, with a bushel of corn replacing about 1.8 bushels of oats. At yields prevailing in 1954, then, maintaining a horse for a year would require 1.3 acres of oats, 0.75 acres of corn, and 1.7 acres of hay. If insufficient land existed to grow the required amounts of

⁵⁴ L. A. Reynoldson, W. R. Humphries, S. R. Speelman, E. W. McComas, and W. H. Youngman, *Utilization and Cost of Power on Corn Belt Farms* (Technical Bulletin No. 384, Washington: U. S. Department of Agriculture, 1933), p.33.

oats (as is the case here), then an alternative scenario would use 0.3 acres of oats, 1.25 acres of corn, and 1.7 acres of hay.⁵⁵

The 310MM acres of cropland harvested in 1910 used the services of 17.4MM horses and 3.8MM mules, or 0.0682 work animals per acre. This factor intensity would suggest a farm with 44 crop acres would use three work animals, and one growing 60 crop acres would have four horses or mules. These numbers seem quite reasonable in reviewing the literature of the period and the more recent tractor diffusion studies.

With this information, the net effect of work stock on land requirements can be calculated. Cultivation of 100 acres of crops would require 6.82 animals, which, in turn, would eat the product of 2.05 acres of oats, 8.5 acres of corn, and 11.6 acres of hay. Crop failure would be expected to claim another 4 acres of the total planted, based on 1954 census data. In total, about 26 of the 100 acres would be lost or consumed as an intermediate input, leaving the yield from 74 acres for consumption. As labor would have to be supplied to farm all 100 of the acres, the consumption of part of the output by the power source has the effect of reducing the productivity of labor.

The next step is to apply feed requirements to the 1954 production data, which is reproduced here as the first column in Table 5. Raising crops on the 329MM acres shown would require an additional 9.2MM acres of oats, 38.3MM acres of corn, and 52.1MM acres of hay, based on the low-oats feeding regime discussed above.⁵⁶ The resulting total

⁵⁵ National averages are used for yields of feed materials, as many farmers purchased animal feeds, rather than growing them locally. Detailed calculations and additional sources are available from the author upon request

⁵⁶ An initial allocation, based on the feed quantities seen in Reynoldson, et. al. would have required a total of 80MM acres of oats to be grown in the U.S., almost double the maximum acreage ever raised. Oats require a cool, moist climate in which to grow with reasonable yields, and little of that type of land was available in 1954; farmers would have certainly substituted away from oats to corn, and perhaps barley.

acreage appears as in the second column of the table. Unfortunately, this amount of cropland is well above the maximum levels utilized in the historical experience of the United States. It is possible that this acreage could not even be farmed, or would have resulted in substantially higher inputs or lower yields than for land areas actually cultivated.

Table 5. Actual and Counterfactual Acreage Requirements, Using 1954 Crop Mix

All numbers in thousands of acres

Crop	Actual 1954 Production	Add in Feed Acreage	Cut out Stock Build, Exports	Adjust for Income Effect	'Feasible' Allocation
Corn	78,522	116,827	105,320	103,301	101,928
Sorghum	17,278	17,278	14,866	14,555	14,678
Oats	37,921	47,114	44,399	43,610	41,613
Wheat	51,362	51,362	35,959	35,034	37,719
Other Grains	19,672	19,672	18,074	17,675	19,894
Soybeans	17,812	17,812	17,812	17,491	17,562
Hay	69,940	122,035	116,349	114,273	117,671
Cotton	18,858	18,858	17,107	16,767	16,858
Minor Crops	17,830	17,830	14,091	13,770	13,963
Total	329,195	432,453	383,977	376,478	381,886

Source: See text.

To answer this concern, I have constructed a detailed breakdown of cropland use by state and by crop, using the historical levels from 1909 to 1954 as denoting a feasible region. Land denoted by the 1954 census as 'cropland harvested' or 'cropland used only for pasture' was deemed to be usable for the hypothetical, whereas crop failure and

summer fallow areas were not considered potentially available.⁵⁷ Permanent pasture and woodland areas were also not included in the calculation, mostly due to the impossibility of determining their suitability for crop agriculture. The details of this effort are not included here, but my results suggest that just less than 400MM acres could be utilized for crops, although the yields on the additional land would be slightly lower than the national averages for the major crops considered. The 432MM shown as the total for the counterfactual could not be supported within the existing farmland use patterns.

Fortunately, this counterfactual exercise need not stray into the wilder fringes of speculation, as there were two sources of 'excess' production in 1954 for which the value is known, and which can be eliminated in calculating social savings. The early 1950s were times of surpluses, as the combination of farm programs, yield improvements, and an export slump following the Korean War created an imbalance of supply over demand. Large stocks of unsold farm products accumulated in storage, and the level of stocks of several important crops was still increasing in 1954. Clearly, stock accumulation can be eliminated from the counterfactual without any difficulty. Despite the slump, U.S. exports were still a significant user of cropland, especially for wheat and cotton.

By eliminating the build-up of stocks and releasing the land devoted to exports of corn, wheat, and other small grains, a significant decrease in required acreage is achieved. Not surprisingly, the cotton areas which could be freed up are not nearly as useful. The small grains do not grow well in the warm climates where cotton is grown, and corn yields in

⁵⁷ This data can be found in *United States Census of Agriculture, 1954*, pp. 8-9, 32-37. 'Cropland used only for pasture' included rotational pasture as well as idle cropland; the name indicates that this land had been used for crops at some time in the past.

Texas and the deep South were among the lowest in the country. As a result, it is unlikely that even extreme land pressures as envisioned by this counterfactual would cause abandonment of cotton acreage. The third column of figures in Table 5 shows the net requirements after elimination of surpluses.

Finally, the impact of the movement of labor out of manufacturing needs to be considered. A rough calculation of the social savings with this level of agricultural activity suggests that hypothetical income in 1954 would have been slightly more than 9% lower than it actually was.⁵⁸ With an income elasticity of food consumption of 0.2, food purchases by consumers could be expected to drop by 1.8%. This, in turn, would reduce the land requirements by the same amount. The fourth column of Table 5 shows the results of this adjustment.

To this point, all of the calculations regarding land use for each crop in the counterfactual have been at the national level. In an attempt to simulate the local optimization which would have occurred and in hopes of avoiding gross distortions which could be caused by this high-level analysis, I have constructed a 'feasible allocation' using state-level data from the census.⁵⁹ In essence, the heuristic I used adds additional production to each state's output level based on the average yield of the land already in use for that crop. Constraints are included to prevent individual crop acreage from rising above levels supported by historical experience or statewide totals from exceeding the sum

⁵⁸ The calculations are an exact parallel to the ones which will be seen later in this section, so they are not shown at this point.

⁵⁹ This same exercise could be conducted with county-level data for an even greater level of confidence, at the cost of a considerable increase in data gathering effort and computational complexity.

of available cropland harvested and cropland pastured. The results of this feasible allocation are included as the last column in Table 5.

A breakdown by region should provide some additional insights into the adjustments created by the counterfactual analysis. In Table 6, I have included data on actual cropland harvested, the feasible allocation discussed above, and the total cropland available for the year 1954, divided by census region. The allocation exceeds total cropland in both Northeast regions, but falls below the acreage actually farmed in 1909. In my hypothetical economy, therefore, about 2MM acres of Eastern farmland abandoned through the course of this century would have remained in production instead. The other significant change is in the South Central states, where about 22MM acres listed in the census as cropland used only for pasture would need to be shifted into growing crops.

A second scheme for calculating the counterfactual acreage requirements uses the 1909 output crop mix rather than actual 1954 production. In this thought experiment, the economy is, in effect, frozen in time, growing those crops which were available in the earlier period in the same proportions, but with output volumes determined by 1954 yields and population. As the 1909 economy was essentially pre-tractor, no separate determination is needed to establish animal feed acreage; it is already included in the amounts farmed. In addition, there is no negative income effect on consumption to be considered. As average incomes were rising rapidly through the first half of the century, per capita food consumption should increase, in the counterfactual as well as the real world. Since this undertaking is primarily a check on the validity of the first method, however, I will not attempt to increase food requirements in line with income.

Table 6. Actual and Counterfactual Acreage Requirements by Region

All numbers in thousands of acres

Regions	1909 Cropland Harvested	1954 Cropland Harvested	Feasible Allocation	1954 Total Cropland
New England	4,640	2,397	4,486	3,304
Mid Atlantic	17,241	11,464	15,228	14,307
E N Central	59,662	59,191	67,534	70,067
W N Central	114,527	133,514	140,077	146,653
S Atlantic	30,210	23,019	26,349	28,897
E S Central	25,735	19,613	30,600	30,886
W S Central	39,010	43,510	54,492	57,782
Mountain	8,839	22,479	24,797	26,664
Pacific	10,571	14,114	18,324	20,380
U S Total	310,435	329,301	381,886	398,940

Source: Bureau of the Census, *United States Census of Agriculture 1954* (Washington: U. S. Department of Commerce, 1955). pp. 36, 46-56.

Table 7 summarizes the data and results from this second counterfactual. Actual 1909 production of the major crops is shown in the first data column. As stated in section II of this paper, exports were significant for many crops, especially cotton and wheat. It is necessary to subtract out these exports prior to adjusting for population and yield increases, the results of which appear in the second column. The next two columns record the effect of these population and yield adjustments. The last column is the results of a state-level allocation of land identical in technique to that performed for the first counterfactual. This analysis concludes that 397MM acres would have been needed to

produce the 1909 crop mix with horse and mule-powered cultivation, an amount of land which was actually available in 1954.

Table 7. Actual and Counterfactual Acreage Requirements, Using 1909 Crop Mix

All numbers in millions of acres

Crop	Actual 1909 Production	1909 for Dom. cons.	Adjust to 1954 Pop	Adjust to 1954 Yields	Feasible Allocation
Corn	98,383	96,982	174,278	115,569	114,229
Oats	35,159	35,104	63,082	52,141	48,892
Wheat	44,263	37,460	67,316	58,729	60,976
Other Grains	13,591	13,282	23,866	19,274	21,085
Hay	72,281	72,236	129,809	118,157	121,372
Cotton	32,044	9,011	16,192	7,854	12,215
Minor Crops	14,714	14,247	23,400	18,857	18,672
Total	310,435	278,322	497,944	390,581	397,441

Source: See text.

Several interesting observations arise from this second thought experiment. Most obviously, it suggests that it might have been impossible to feed the 1954 population of the country without the two agricultural productivity shocks, mechanization and yield improvement. The total acreage shown in the third column of Table 7 is far in excess of that which has ever been cultivated in the United States; even if crops could be grown on the wide expanse of pasture land in the West, yields would likely have been low and extensive irrigation required. The rising food prices of the last decade of the 19th century

and first decade of this century would have continued unabated, and it is very likely that immigration would have slowed considerably.

Secondly, yield improvements in cultivation of corn were far more important than that for any other crop in freeing up acreage during this period. This resulted not only from the use of hybrid seed and better understanding of plant biochemistry, but also from a sectoral shift out of the poor yielding South and Southeast, and into the better soils of the upper Mid-west, a shift which would have been partially reversed under the counterfactual. In contrast, the more than doubling of cotton yields would have had a relatively minor effect in aggregate. Although exports were removed before adjusting for population and yield changes, and would certainly have re-emerged in the counterfactual economy, overseas markets were too competitive to absorb more U. S. cotton. Physical exports of cotton actually fell from 1909 to 1954, from 7.7MM to 3.6MM bales.

Finally, a comparison of Tables 5 and 7 shows very similar results, which boosts confidence in the variety of assumptions made in the counterfactuals. Total crop area requirements differ by 15MM acres, or less than 4%. The requirements for the three animal feed stocks, hay, corn, and oats, are quite close together. The greatest differences appear with the two new crops, soybeans and sorghum, which were both grown in very small quantities in 1909, and wheat, which takes up 23MM less acres in the 1954-crop mix based hypothetical economy. These last results stem from the second specification's freezing in time of the output proportions from the earlier period. The substitution of soybeans and soybeans for wheat in the two counterfactuals is a direct reflection of the substitution that actually occurred in U.S. agriculture.

Social Savings Calculations

Having assembled reasonable crop land numbers for a hypothetical 1954 horse-powered agriculture sector, labor savings estimates are the next step. I have assumed labor is used in fixed proportion to land input, with the factor set equal to its value in the base year of 1909. Reference to Table 2 shows that 12.1MM workers were required to farm the 310.4MM acres harvested in 1909. This produces a figure of 0.039 workers per acre, or about two full-time workers for an average-sized farm with 50 crop acres. However, labor intensity in 1909 varied considerably from state to state. Our counterfactual economy, by changing the relative amounts of the various crops grown, would also impact labor utilization. To improve the precision of this allocation, I calculated hypothetical labor requirements on a state-by-state basis, for both of the counterfactuals detailed above. Producing the 1954 crop mix with the 1909 technology would be expected to employ 14.4MM workers, and the alternate 1909-crop mix economy would use 15.0MM laborers.⁶⁰

Table 4 captured the effort hours and number of full-time equivalent workers for the actual, tractor-using farm sector of 1954. A total of 11,962MM hours were expended in agricultural labor, representing 5.98MM full-time equivalent workers. In addition to forcing the farm operators with substantial off-farm employment and part-time wage workers to return to essentially full-time work, several million additional workers would have had to be retained in agriculture, preventing them from moving into the rapidly

⁶⁰ The calculated values using the nationwide average is about 500M higher in both cases, i.e., 14.9MM and 15.5MM workers, respectively.

expanding manufacturing sector of the 1940s and 1950s. Using the average weekly wage in manufacturing of \$70.49 in 1954, the direct labor savings are estimated at \$29.6B using the 1954 crop mix scenario, and \$31.9B with the 1909 crop mix.⁶¹

Although labor makes up the bulk of the social savings, contributions from exports and stock building, the use of grazing land, and a deduction for fuels used by tractors also need to be included. In order to make the acreage allocations feasible, all exports except cotton and increases in inventories of harvested crops were eliminated. In effect, these products were 'eaten up' by the hypothetical horses. The inventory increases foregone, if valued at the current price of crops sold, were worth \$575MM in 1954. The lost exports for that year had a value of \$1039MM.

Likewise, about 53MM acres of pasture land is converted to growing animal feed under the first counterfactual. Had it not been needed for crops, it would likely have been used for feeding cattle, as was the bulk of the nation's pasture land in the real 1954. Using the 1954 census data on cattle production and value, I estimate the contribution of this land to grazing to be \$3.16 per acre, or about 12.5% of the total value of the cattle sustained on it. The resulting social savings of \$167MM is another part of the total contribution of the tractor.⁶²

Finally, tractor operating costs should be deducted from the social savings previously calculated, to the extent that they exceed out-of-pocket expenses for maintaining work stock. I have stated previously that the capital cost per acre, when adjusted for changes in

⁶¹ Average weekly wage data is from *Historical Statistics*, Series D-804.

⁶² This calculation is somewhat speculative, but its contribution to the social savings is quite small. It indicates that the marginal value of grazing land was low in the surplus days of the 1950s, as it is today.

the price level, was approximately the same for tractors as for horses. Tractors, in addition, required fuel and lubricants to operate, and on occasion repair parts or shop maintenance were needed. In the case of horses, shoes, harnesses, and veterinary care were the major expense items incurred, in addition to feed, which has been extensively covered above. Of all of these factors, the only one of significant magnitude is fuel purchase. Based on a USDA estimate of consumption of various fuels by tractors in 1953 and 1955, I estimate total fuel expense for 1954 at \$416MM.⁶³

I have summarized the social savings calculations here as Table 8. Total savings for the year 1954 are \$30.9B under the most reasonable and thoroughly-developed scenario. With total output in that year measured at about \$365B, the tractor and its related machines are shown to have contributed savings worth 8.4% of total U.S. GNP.

Table 8. Social Savings from the Farm Tractor in 1954.
All values in millions of dollars

Source	1954 Crop Mix	1909 Crop Mix
Wage labor freed up	29,554	31,938
Land reallocated	167	228
Exports maintained	1,039	1,039
Crop inventory increased	575	575
Less: Fuels used	(416)	(416)
Total savings	30,918	33,364
1954 U. S. GNP	364,800	364,800
Savings as % of GNP	8.48 %	9.15 %

⁶³ Julius J. Csorba, *Farm Tractors: Trends in Type, Size, Age, and Use*, Agricultural Information Bulletin No. 231 (Washington: United States Department of Agriculture, 1960), p. 4. Prices of the various fuels are from *Platt's oil price handbook and Oilmanac*, 63rd edition. (New York: McGraw-Hill, 1986). Detailed calculations are available upon request from the author.

Discussion

The preceding analysis quantified the contribution that agricultural mechanization made to the growth of output and welfare in the United States, under a set of reasonable, but somewhat restrictive assumptions. In this section, I discuss implications of changes in some of those assumptions and introduce some issues that did not easily fit into the quantitative analysis. As I went to great lengths to be conservative in formulating the counterfactual, most of these issues would raise the social benefits above the level calculated in section III.

In determining the amount of land required to raise the hypothetical quantities of crops required, I assume that 1954 levels of yields per acre would be achieved in the absence of mechanization. This assumption is to a great extent, warranted by the significant increases in scientific knowledge that was obtained in universities, at agricultural experiment stations, and in field trials during the first half of this century. Although advances in corn hybridization have been widely celebrated, careful scientific study improved growth potential, drought and pest resistance, and nutrient uptake for all of the major crops grown in the United States. In response to the creation and wide dissemination of this knowledge, farmers increased their use of hybrid seed, chemical fertilizers, and irrigation, and higher yields resulted.

Not all of the yield increases were due to scientific knowledge alone, however. The higher speeds in plowing and harvesting facilitated by tractors eliminated time constraints in both spring and fall of the year. Faster planting meant that the farmer could wait to sow

until the risk of a late frost was minimized. Quicker harvests allowed the operators to wait until the crop had reached peak of ripeness, then rapidly bring in the entire crop. A horse-drawn combine or binder, for instance, operated at less than half of the speed of the tractor-drawn or self-propelled models. A horse-powered farmer on a large plot who began harvesting when the crop was not quite ripe might not finish before the last of the crop dried out and became difficult to cut and thresh. As a result, mechanization contributed to yield improvement by cutting losses due to weather-related causes and by increasing the quality of the crop harvested.

Although I did not attempt to separate out the impacts of science versus technology on yield improvements for all crops, an example with corn should suffice as an illustration. Johnson and Gustafson estimated in an important 1960 book that mechanization was responsible for one-third of the increase in corn yields this century.⁶⁴ With this as a basis, I re-calculated the entire counterfactual, using the same process as described in the previous section. With lower corn yields, an additional 11.5MM acres would have to be cultivated to produce the output required by the population and by work animals. This, in turn, would require an increase of 500,000 in the farm labor force, bringing the total to 14.9MM full-time workers. The resulting social savings calculation raises the benefit to 9.0% of 1954 GNP, versus the 8.48% determined above. Clearly, the contribution of tractors to yield improvements of other crops would raise the social savings even further.

A second factor related to yields is more difficult to quantify. The use of chemical fertilizers, herbicides, and pesticides had already become widespread in the years after the

⁶⁴ D. Gale Johnson and Robert L. Gustafson, *Grain Yields and the American Food Supply*, (Chicago: University of Chicago Press, 1962), p. 53.

second World War. In most parts of the country, these chemicals were applied by tractor. In addition, the fast speed and low out-pocket cost of tractor operation meant that farmers conditioned their soil more than with horse teams. An extra disking or pass with a harrow just prior to planting made the soil more resilient and encouraged the growth process. While soil conditioning and chemical application could have been done by horse or mule teams, the added labor expense and time requirements meant that they did much less. These considerations also indicate that the true social savings from mechanization are higher than what I have presented.

Another unmeasured benefit from the tractor is the improvement of the quality of work life for agricultural workers. Farming at the turn of the century was back-breaking work, for the farmer who drove a team of horses, for the laborer who picked cotton, raked hay and gathered forage, and for family workers that fed and cared for the horses. The physical stress in plowing seems incredible for those of us comfortably ensconced in the late 20th century: at the end of each row or if the plow became stuck, one or two workers had to lift the plow out of the soil, turn the team around, and replace the plow.

With the development of general purpose tractors, hydraulic implement lifts and weight levelers, and the power take-off, farmers entered the era of 'fingertip farming'. Although field operations were still time-consuming and could be monotonous, the tremendous physical strain had been eliminated. Related mechanical inventions such as the corn picker/sheller, the cotton picker, pickup hay baler, and field forage harvester, all dependent on the tractor engine for their power, eliminated the more physically demanding

of the laborer's tasks.⁶⁵ I have not attempted to measure these benefits in a way that would allow them to be added to social savings, but the benefits to the farmers and farm workers seem clear.

Conclusions

This counterfactual analysis has shown that agricultural mechanization as embodied in the tractor and related equipment has made a significant contribution to the growth of U.S. output. The social savings is calculated at \$31B, or 8.4% of U.S. GNP in 1954, an amount twice as large relative to the size of the economy than Fogel's high-side estimates for railroads in 1890. Why should such an unheralded technology prove to be more important than the mighty railroads, that united the country and captured the bulk of the country's stock investment for half a century?

I believe the answer lies in two aspects of tractors that differ considerably from the railroad experience. In the first place, waterways and canals were a fairly good substitute for railroads in the transportation of commodities at the end of the last century. The geography of the United States is such that most of the population lived close to a navigable waterway; railroads were efficient enough to capture much of the shipment volume, but their costs were not radically lower than that of water transport.⁶⁶ In the case of tractors, however, horses were not a very good substitute. Once the dominant design emerged in the 1930s, tractors were able to deliver mobile power with a far lower cost in

⁶⁵ An exception to this general trend is in harvesting of tobacco and some fruits and vegetables, which still today involve a good deal of physical labor.

⁶⁶ The work of Summerhill and Coatsworth shows that railroads did generate large social savings in countries where water transport was not a good substitute.

terms of labor, at a comparable expenditure of capital, and without consuming a large portion of the output in the process. It is interesting to note that shipment of goods by water is still common today, whereas horses and mules have completely disappeared from commercial agriculture.

A second important aspect of the tractor is that it is used to produce food, consumption of which is vital to sustaining life. In any economy producing insufficient food, if imports cannot be increased, resources quickly flow back into agriculture. I have described this mechanism as inelastic demand leading to rising food prices, which induces higher factor returns in agriculture, leading to a flow of factors out of manufacturing or services and a consequent expansion of agricultural output.⁶⁷ The productivity improvements from mechanization and yield improvements lead to the opposite result. Food surpluses brought about by the productivity improvements, if exports cannot be increased, cause low returns in agriculture, leading to a flow of factors out into manufacturing and services, allowing agriculture to contract output to bring it back into balance with demand.

In most pre-industrial economies, the food supply imperative causes almost the entire economy to be devoted to agriculture. Any improvement to farm productivity will have a huge impact on the wealth of the population, as long as there is alternate employment for the resources released from agriculture. The United States, in its first century as a nation, although well on its way to industrialization, had a large proportion of its population engaged in agriculture. If data could be found to analyze the impact of the 19th century

⁶⁷ The historical record shows us that if these adjustments are delayed or prevented, starvation in cities, food riots, and social unrest are common outcomes.

inventions of the reaper and thresher, a proper social savings calculation should show significant social savings.⁶⁸ In the case of the tractor, its adoption allowed the U.S. to reduce farm employment from 33% of the work force in 1909 to 10% in 1954.

With this observation, I wish to return to one of the earlier themes of this paper. Economists studying the process of growth earlier in this century believed that releasing resources from agriculture was a significant source of wealth improvement; Rostow even identified it as one of his pre-conditions. Although they may have correctly described the impact of this process, I believe they failed to identify the true cause. It was the technology improvements in agriculture that created the opportunity for growth. The releasing of resources into other sectors was merely the invisible hand directing factors to their most profitable use. Attempting to pull labor out of an inefficient agriculture sector leads inevitably to high food prices and import dependency, as many Third-world countries have learned to their sorrow. Only if the manufacturing and service sectors are productive enough to pay the import bill, as in the case of several of the Southeast Asian countries, can the agricultural sector be abandoned.

To conclude, this chapter has shown that the farm tractor made a major contribution to the growth of the United States in the 20th century. It is clear that many fewer resources were required to produce the nation's agricultural output in 1954 than would have been needed using the best available alternate technology, which I have simulated using 1910 data. The pace and timing of this technological change are the topics of the next two chapters.

⁶⁸ Indeed, I plan to estimate the social savings from reaper and thresher in future work, using analysis similar to that in this paper.

CHAPTER 4

THE DURATION AND TIMING OF TECHNOLOGICAL CHANGE - QUALITY ADJUSTED TRACTOR PRICES, 1918 - 1955

The previous chapter has shown that replacement of horses and mules with gasoline powered tractors brought significant benefits to the 20th century United States economy. This clear-cut conclusion brings some important questions to light. If this technological change was so beneficial to the economy, why did it not proceed more quickly? If the substitution of machine power for animal power was labor and land saving and capital neutral, why did it take more than half a century to replace the horse?

In looking at similar transformations, many researchers have offered the opinion that we must be looking at a factor substitution, with changing factor prices over time driving the observed diffusion pattern. Others have implicitly claimed that the extended overlap was due to vintage capital and quasi-rents that operators of the old technology enjoyed. Both of these approaches, as well as a majority of the previously-mentioned macro growth models, take the position that the new technology arrives fully formed and capable at a point in time.

Although there is some merit in these approaches, the assumption of an instantaneous technology shock is not consistent with empirical data. The discussion in Chapter 2 shows

that the developmental period of the tractor was extensive, perhaps on the order of 40–50 years. This chapter explores that insight rigorously through the construction of a hedonic price index for tractors over the period 1918 to 1955, the period during which the new technology diffused. Armed with this data, Chapter 5 investigates the diffusion issue in depth, and explains why previous research efforts have failed to adequately describe the tractor diffusion process.

Background

Historians often have occasion to use time series of goods and factor prices in their research and writing. The use of such data over an extended period of years involves a double set of stability assumptions: that the good or factor in question remains unchanged in quality and that the general price level likewise is constant. If rapid inflation or deflation makes the latter assumption untenable, the researcher often will choose to adjust for price level changes through the use of a deflator or by comparing changes to a reference series, such as wages or food prices. When the quality of the good is changing over time, however, adjustments are rarely ever made, leading to bias in reporting results.

The nature of the good itself is critical in evaluating the degree of risk. Assuming that a bushel of wheat was the same in 1950 as in 1980 is not likely to cause concern. Treating a day of unskilled labor as unchanged over the same 30-year period would likely raise a few eyebrows, but would still be seen as reasonable by many researchers. Compiling a series of computer costs over the same period, without adjusting for the huge speed, performance, and capability improvements which have occurred, would be unsupportable.

Fortunately, techniques such as hedonic price indices have been developed to account for improvements in quality over time, and thus to reveal underlying changes in data series.

The word 'hedonic', as used in economics, refers to the underlying enjoyment or utility received by the consumer of a good, rather than to consumption of the good itself. A product that meets several needs, or has a variety of features, thus generates a number of hedonic services. Each one of these services can be thought of as generating its own demand, along with a resulting hedonic price. Although each separate component is not observable, the aggregation of all the components results in the observed product demand and equilibrium price.

As the qualities inherent in a product change over time, due to technological advances, addition of new features, and improved service life or reliability, the underlying hedonic demands should change also. The quality improvements will appear to an observer as an outward shift of the product demand curve, as consumers are willing to purchase more at the prevailing price. If the change in the service value of the product over time is not recognized, then any analysis of the demand shift will be faulty – it may be erroneously attributed to an increase in population or wealth, changes in taste, or elimination of a market imperfection.

The importance of adjusting for quality changes in creating price indices has long been recognized. The first such use of a hedonic price index was in a paper on automobiles by Andrew Court, which appeared in a book edited by General Motors.¹ Zvi Griliches produced several important works on hedonic regression in a series of early 1960s papers

¹ Andrew Court. "Hedonic Price Indexes with Automotive Examples," in *The Dynamics of Automobile Demand*, General Motors Corporation, ed. (New York: General Motors Corporation, 1939), pp. 99-117.

also concerned with automobile prices.² Sherwin Rosen developed the theoretical basis which underlies hedonic models in a widely cited paper.³ Since that time, an extensive literature has developed on hedonic indices and quality adjustments, primarily focused on durable goods. This approach has gained wide enough acceptance that it is used by U.S. government agencies in adjusting the computer and automobile components of the Consumer Price Index.

In the past few years, the debate over the accuracy of the CPI in measuring the true rate of inflation has served to create increased interest in the measurement of the effect of quality improvements on demand. Given that few adjustments are made for quality improvements, the measured level of general price increases likely overstates the rate of inflation. A portion of the measured price increases represents improvements in the value of the service flows generated by the products. A panel of prominent economists recently worked to address this and other problems with the CPI; their recommendations, although not fully accepted by the government, may generate a great deal of empirical work to assess quality change in the large number of products which make up the CPI.⁴

In a new book, Bresnahan and Gordon have brought together a number of recent papers on this subject. One of these, by Raff and Trajtenberg, uses the hedonic approach to construct quality-adjusted prices for the early years of automobile production, 1906 to

² The first of these was: Zvi Griliches, "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Zvi Griliches, ed. (Cambridge, Massachusetts: Harvard University Press, 1961).

³ Sherwin Rosen, "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition," *Journal of Political Economy* 82 (January, 1974), pp. 34-55.

⁴ Michael J. Boskin, E. Dulberger, R. Gordon, Z. Griliches and D. Jorgenson, *Toward a More Accurate Measure of the Cost of Living: The Final Report of the Advisory Committee to Study the Consumer Price Index*, (Washington: Government Printing Office, 1996).

1940.⁵ As the authors point out, most previous hedonic studies on automobiles dealt with the later years in this century, when the car was a relatively mature technology. As their interest was primarily in the automobile's contribution to growth, they were interested in the early years after introduction, when performance and quality were improving rapidly. In the case of tractors, as well as with automobiles then, the early years of this century should be a fruitful area for investigation.

Raff and Trajtenberg collected an exhaustive database on car models, using annual trade show publications as the source for technical specifications and prices. They defend the use of an advertised price, rather than records of actual transactions (which are unavailable), by making the reasonable claim that manufacturers typically set prices once per year, a process which is still observable today. The authors were not able to find production or sales quantities to match against the model specifications, and so their hedonic regressions are unweighted, a possible source of bias that they discuss in the paper.

The social science literature yields a few previous attempts to analyze quality-adjusted prices of tractors. Lyle Fetting, a student of Griliches at Chicago, constructed a quality-adjusted price index in his 1963 dissertation.⁶ Focusing on the period 1950 to 1962, Fetting showed that the tractor component of the Wholesale Price Index was biased upward, due to the lack of suitable adjustment for increasing quality. More recently, Peter

⁵ Daniel M. G. Raff and Manuel Trajtenberg, "Quality-Adjusted Prices for the American Automobile Industry: 1906 – 1940," in Timothy F. Bresnahan and Robert J. Gordon, eds., *The Economics of New Goods* (Chicago: The University of Chicago Press, 1997), pp. 71-101.

⁶ Lyle P. Fetting, *Price Indexes for New Farm Tractors in the Postwar Period*, (PhD Dissertation, University of Chicago Department of Economics, 1963).

Berck authored a note which used a hedonic regression to look at real cost changes for tractors in the period 1923 to 1934.⁷ Although his purpose and approach were similar to my current effort, he presented data for only three years: 1923, 1930, and 1933. His limited results suggested that real prices had fallen for large tractors, but not small ones over the period examined, and that the change in real price was important in shifting farmers from horses to tractors.

Robert Gordon included a hedonic series for tractors in his seminal work on durable goods prices. His study, which covered the years 1947 to 1983, drew its data from a series of Blue Book Guides, and included only tractors from the leading manufacturer, International Harvester.⁸ Gordon was primarily concerned with extending and improving on Fetting's series as a part of his challenge to the government's producer price indices. The present paper's index can be merged with Gordon's data for the post-1955 period to yield a complete series on hedonic prices from 1918 to 1983.

Quality Attributes and Technological Development of Tractors

In order to determine quality-adjusted prices, it is necessary to determine which features of the product create benefits for the purchasers, and how those features have evolved over time. A tractor is, at the most basic level, a source of power for a variety of

⁷ Peter Berck, "A Note on the Real Cost of Tractors in the 1920s and 1930s," *Agricultural History* 59:1 (January, 1985), pp. 66-71. The regression equation used by Berck is discussed later in this chapter.

⁸ Robert J. Gordon, *The Measurement of Durable Goods Prices*, (Chicago: University of Chicago Press, 1990), pp. 383-95. The tractor guides were produced under a number of different titles from 1919 to the present, and contain data on prices for new and used farm equipment. As they were primarily used by dealers to evaluate trade-ins and were issued several times per year, they contain much useful data. Unfortunately, issues produced prior to the late 1940s are almost impossible to locate.

farm tasks. As such, it serves as a durable input to a farmer's production process, and is imperfectly substitutable with other mobile power sources, including draft animals (horses, mules, and oxen), steam traction engines, and human exertion. An internal combustion engine burning gasoline, kerosene, or a similar fuel has provided power since the earliest successful models were produced in 1892.⁹

The power produced by the engine and subsequently converted into productive work is a key quality attribute. All tractors have a drawbar as a part of the frame, which allows it to pull a wide variety of implements. The amount of power delivered to the drawbar directly affects the size and weight of implements which can be pulled. Early machines featured a belt pulley driven directly by the engine, providing power for stationary tasks, such as threshing grain, shelling corn, or sawing wood. Starting in 1922, International Harvester replaced the belt pulley with a rotating shaft, called a power take-off (PTO), allowing the efficient use of complex attachments, including mowers and combines. The other major manufacturers soon followed suit, and the PTO became a standard feature of all but the smallest tractors.

The first tractors produced were large and heavy, and used up much of their power merely to pull their own weight around. As producers became more skilled in tractor production, they were able to reduce the size and weight, and thus the cost of providing a given level of pulling power at the drawbar and belt/PTO. Henry Ford entered the tractor industry in 1917 with a small, cheap, mass-produced tractor called the Fordson, producing

⁹ Some of this historical and descriptive material is similar to the more extended discussion in Chapter 2. It is restated here to highlight its impact on quality and performance of the tractors over time.

the first great boom in tractor sales.¹⁰ In a competitive response, International Harvester developed and introduced the Farmall, the first row-cropping tractor, in 1924. By the early 1930s, large tractors had disappeared, and all of the leading producers were making both standard and row-crop models.

The speed at which a tractor can accomplish farm tasks is a second critical quality attribute. Clearly, an increase in power allows implements to be pulled faster; alternately, a larger implement can be substituted, one that covers more ground per pass.¹¹ The introduction of rubber tires in 1930 by Allis-Chalmers as a replacement for steel wheels made additional increases in speed possible. The use of rubber reduced the rolling friction of the tractor and also helped prevent bogging down in wet soil. As rubber tires also made travel over paved roads possible, tractors were increasingly used to haul materials and even crops over considerable distances. Manufacturers also increased the number of speeds provided on their machines, to support hauling and fast field operations.

Fuel efficiency is a third important quality feature. Purchase of fuel was one of the larger cash costs for a mechanized farmer in the time period under consideration, and tractors varied widely in their fuel consumption. Most early models were designed to operate on kerosene, and were not very efficient. Introduction of high-compression gasoline engines reduced fuel consumption, at a price per gallon comparable to gasoline.

¹⁰ From a total estimated U.S. production of around 30,000 units in 1916, Ford alone sold an average of 75,000 per year from 1918 to 1927. This data is from Allan Nevins and Frank Ernest Hill, *Ford: Expansion and Challenge: 1915 – 1933*, (New York: Charles Scribner's Sons, 1957), p. 685; and Bureau of the Census, *Census of Manufactures, 1923*, (Washington: U.S. Government Printing Office, 1923), p. 935.

¹¹ Pull speed is related to power through the following calculation: $hp = \text{speed} * \text{weight} / 375.1$, where speed is measured in mph and weight pulled in pounds.

John Deere introduced tractors which could burn low-grade distillate fuel as early as 1930; the lower price was partly offset by a reduction in performance, but distillate remained popular through the end of World War II. Diesel engines were increasingly adopted after the war, the combination of excellent efficiency and a low fuel price convincing farmers to pay the significantly higher price for a diesel tractor.

Several other technical features, although important for raising performance, came rather late in the evolution of the tractor. Ferguson's three-point hitch, which used hydraulic leveling to provide more even plowing and cultivation, was introduced in the U.S. by Ford in 1939, but was not widely adopted by other manufacturers until the early 1950s. Electric starters became popular options in the mid-1930s, but were not universal until many years later. Power steering was introduced to tractors in the early 1950s, as tractor size began growing rapidly.

Data Sources and Collection

The data for this project was amassed from a variety of sources, and although some was quite easy to obtain, achieving the level of completeness required for the hedonic regressions proved quite challenging. United States government publications, mostly from the Agriculture and Commerce departments, proved to be an excellent source of aggregate production and sales figures. Books produced by and for tractor enthusiasts contributed a great deal of information on technical specifications, annual production volumes, and prices. A few business histories provided additional information on specific models, and corporate archives yielded much data not available elsewhere.

USDA and Commerce Department figures provide a reasonable basis for the total number of farm tractors produced in the U.S. from 1916 to 1955, with the exception of the years 1932-34, during which data was not collected from manufacturers.¹² The aggregate production time series appears here as Figure 3, with my estimates for 1932-34 appearing as a dashed line. Inspection of the graph reveals many of the key events in the tractor's history. Fairly steady growth in production volumes from 1916 to 1946 is punctuated by three sharp declines, representing the agricultural depressions of 1921 and 1931-34 and wartime limitations in 1942-43. Significant increases just prior to the two world wars can also be seen, likely the result of sustained increases in crop prices. Output peaked at 564M tractors in 1951, a figure which has never been equaled.

Although the government data is very useful in establishing the total size of the market in each year, it does not provide a good starting point for the hedonic index, as neither individual models nor manufacturers are listed. In fact, in cases where the data subdivisions would have revealed information specific to a single producer, that data was omitted from the publication.¹³ The model-by-model production information, then, had to

¹² The USDA began collecting tractor production data from manufacturers in 1916. The first five years' information was published in 1920 as USDA Circular No. 212. The Commerce Department took over the task in 1921, and has published the information as "Manufacture and Sale of Farm Equipment" from 1921 to 1940, and "Facts for Industry" from 1941 through the late 1950s.

¹³ This long-standing Commerce Department practice is necessary to insure that accurate data is provided. It is quite likely that had this privacy protection not been afforded to manufacturers, they would have had a strong incentive to withhold or distort the data they submitted.

**Figure 3. Tractors Produced in the U.S.
1916 - 1955**

Source : U. S. Department of Agriculture (1942, 1947, 1957)

be built up from other sources, with the aggregate government data serving as a valuable check.

I was fortunate to be able to obtain most of the annual model production of individual manufacturers from a number of books produced by tractor enthusiasts throughout the country.¹⁴ Almost all of these books contain a serial number cross-reference, as an aid in preservation and restoration. Every U.S. tractor that I am familiar with has a serial number stamped on the frame, and the make-model-serial number combination is unique to that unit. This information can be linked back to the year of manufacture and thence to the particular features and components that would have been provided when the unit was made.

Most manufacturers, including the three largest producers (International Harvester, Ford, and John Deere) maintained a separate series for each model, continuing in order from year to year as long as the model was produced. If the first and last serial number

¹⁴ These include David Erb and Eldon Brumbaugh, *Full Steam Ahead: J. I. Case Tractors & Equipment 1842 – 1955*, (St. Joseph, Michigan: American Society of Agricultural Engineers, 1993); Lee Klancher, *Farmall Tractors*, (Osceola, Wisconsin: Motorbooks International, 1995); Klancher, *International Harvester Photographic History*, (Osceola: Motorbooks International, 1996); Randy Leffingwell, *John Deere Farm Tractors*, (Osceola: Motorbooks International, 1993); Leffingwell, *Classic John Deere Tractors*, (Osceola: Motorbooks International, 1994); Leffingwell, *Farm Tractors, A Living History*, (Osceola: Motorbooks International, 1995); Peter Letourneau, *John Deere General Purpose Tractors, 1928-1953*, (Osceola: Motorbooks International, 1993); Robert N. Pripps, *Farmall Tractors*, (Osceola: Motorbooks International, 1993); Pripps, *Illustrated Ford and Fordson Tractor Buyer's Guide*, (Osceola: Motorbooks International, 1995); Pripps, *Illustrated International Harvester Tractor Buyer's Guide*, (Osceola: Motorbooks International, 1995); Pripps, *Vintage Ford Tractors*, (Stillwater, Minnesota: Voyageur Press, 1996); Pripps and Andrew Morland, *Oliver Tractors*, (Osceola: Motorbooks International, 1994); Ralph W. Sanders, *Vintage Farm Tractors*, (Stillwater: Voyageur Press, 1996); Norm Swinford, *Allis-Chalmers Farm Equipment, 1914 – 1985*, (St. Joseph: American Society of Agricultural Engineers, 1994); Bill Vossler, *Orphan Tractors*, (Osceola: Motorbooks International, 1996); Charles H. Wendel, *150 Years of International Harvester*, (Sarasota, Florida: Crestline Publishing, 1981); Wendel, *The Allis-Chalmers Story*, (Sarasota: Crestline Publishing, 1988); Wendel, *Minneapolis-Moline Tractors, 1870-1969*, (Osceola: Motorbooks International, 1990); Wendel, *150 Years of J. I. Case*, (Sarasota: Crestline Publishing, 1991); and Michael Williams, *Massey-Ferguson Tractors*, (London: Blandford Press, 1987).

made each year is known, an annual production volume can be obtained for that model. This would be a completely accurate representation of production if all serial numbers were used and if no tractor was scrapped after a number was issued.

Even though these conditions were not met exactly for all models, the correspondence between serial numbers and production is extremely close for those that can be checked. For one manufacturer, International Harvester, I was able to compile two distinct production series, one based on serial numbers, the other based on production records. With over 2.8MM units produced over the 46 year period, the two series agree to within 0.6%¹⁵ From this and similar comparisons of two smaller data sets, I concluded that the use of serial numbers is a good representation of production.¹⁶

Table 9 provides a brief summary of the production data, summarized by manufacturer. Out of a total of 8.7MM wheel tractors the government data show were produced between 1910 and 1945, I have manufacturer, model, and year information on 8.4MM, or better than 96%. Almost half of the missing data is from the years prior to 1920, for which records are unavailable, while much of the remainder involves the production of the three firms which merged to form Minneapolis-Moline in 1929.¹⁷

The technical specification information was easier to obtain than the model-by-model production data. The key source of data in this regard is the Nebraska Tractor tests, which have included almost every tractor manufactured in the United States since their

¹⁵ The serial number lists were obtained from Wendel, *150 Years of International Harvester*, while production record data was found in Klancher, *Farmall Tractors*.

¹⁶ Gaps appear in several of the series, but are almost always noted by the source.

¹⁷ One of the three, the Minneapolis Steel & Machinery company, made the popular Twin City line of tractors from 1913 to 1929. Unfortunately, production records could not be located in the M-M corporate archives in Minneapolis.

inception in 1920.¹⁸ Any company wishing to sell a tractor model in Nebraska and intending to make performance claims, such as horsepower rating, plowing capacity, or fuel efficiency, had to submit a machine to the University of Nebraska for a standardized battery of tests. These test data, which were published by contemporary trade magazines as well as by the University of Nebraska, are still available today, and provide a tremendous source of performance data. Of the 283 models summarized in Table 9, all but 33 were tested at Nebraska.¹⁹

Specifications recorded for each tractor include engine dimensions, rotational speed, cylinder configuration, and type of fuel used, number of gears, type of tires, and weight. Drawbar performance tests yielded pull speed, calculated horsepower, and fuel efficiency at both a rated weight pull and at maximum pull. Similar tests on the belt pulley and/or power takeoff produced comparable information to that of the drawbar test. Once rubber tires were introduced as an option, manufacturers often requested that their machines be tested with both types of wheels; rubber tired tractors typically exhibited similar power to steel wheels, but were capable of much faster plowing due to reduced friction.

¹⁸ In addition to those sources noted above, useful technical data was found in Wayne G. Broehl, *John Deere's Company*, (New York: Doubleday, 1984); Deere & Company, *John Deere Tractors: 1918-1994*, (St. Joseph, Michigan: American Society of Agricultural Engineers, 1994); R. B. Gray, *The Agricultural Tractor: 1855 - 1950*, (St. Joseph: American Society of Agricultural Engineers, 1954); Robert K. Mills ed., *Implement & Tractor*, (Overland Park, Kansas: Intertec Publishing, 1986); E. P. Neufeld, *A Global Corporation: A History of the International Development of Massey-Ferguson, Limited*, (Toronto: University of Toronto Press, 1969); Walter F. Peterson, *An Industrial Heritage: Allis-Chalmers Corporation*, (Milwaukee: Milwaukee County Historical Society, 1976); Norman F. Thomas, *Minneapolis-Moline: a History of its Formation and Operations*, (New York: Arno Press, 1976); and Robert C. Williams, *Fordson, Farmall, and Poppin' Johnny*, (Urbana, Illinois: University of Illinois Press, 1987).

¹⁹ In several cases, only one version of a specific model was tested at Nebraska. For instance, John Deere's model GP was tested twice during its seven-year production span from 1928 to 1935, but the GP-Wide Tread and GP-Orchard were not tested. In such cases, I used the contemporaneous test data from the 'parent' model for the offshoots. I do not believe any serious errors will result from this operation.

Table 9. Tractor Production by Manufacturer
Thousands of Units Produced by Sub-period, 1910 - 1955.²⁰

Manufacturer	# of Models	Total Production	1910-1925	1926-1935	1936-1945	1946-1955
Int'l Harvester	41	2,835	219	542	794	1,280
Ford	5	1,460	550	190	0	720
John Deere	25	1,265	35	152	461	618
Massey-Harris	55	798	16	38	264	524
Allis-Chalmers	33	791	50	58	262	422
Case	31	540	56	66	167	252
Oliver	45	386	20	42	98	226
Minn.-Moline	48	271	44	12	64	151
Others	n. a.	341	229	59	14	39
Total	283	8,729	1,218	1,156	2,124	4,231

Source: Author's database discussed in text

Of all the information needed for this project, prices were the most challenging to obtain. References to prices in tractor books were much less complete and accurate than the technical details, with introductory prices most commonly quoted. I did find useful information in the John Deere, Minneapolis-Moline and International Harvester archives, and in the latter came across price lists, blank invoices, and a few actual sales records. Farm and trade magazines were a useful auxiliary source of information, through new product announcements, advertisements, and the occasional feature article.²¹ A Federal

²⁰ Note: The following predecessor or successor companies are included in the totals listed: Ford includes Ford-Ferguson; Deere includes Waterloo Boy; Massey-Harris includes Case Plow, Ferguson, and Massey-Ferguson; Allis-Chalmers includes Advance-Rumely; Oliver includes Hart-Parr and Cockshutt; Minneapolis-Moline includes M. S. M., Minneapolis Threshing Machine, and Moline Plow.

²¹ One useful source of price data was the *Hot Line Farm Equipment Guide – Quick Reference Guide*, 14th Edition. (Fort Dodge, Iowa: Heartland Ag-Business Group, 1995). Although containing primarily information on used equipment, this guide includes a suggested retail price and last year of production for each model listed.

Trade Commission study from 1938 contained a information on prices of a few of the major firms from 1929 to 1937.²²

With a fair amount of effort, I was able to assemble a reasonably complete set of list prices for each model. If I lacked a price for a certain year, I assumed that it had remained unchanged from the previous year. From the few models for which I had annual data, this assumption appears to be acceptable. The year-to-year changes in list prices were quite small compared to model-to-model differences, even in periods during which the overall price level was changing rapidly. Two exceptions to this general pattern include a general slashing of prices precipitated by Henry Ford during the depression of 1921-22, and a steady inflation of prices following the elimination of controls on raw materials, wages, and production volumes after World War II.

The price data assembled is presented here as Figure 4. The progression of prices is shown as volume-weighted averages, in both real and nominal terms. There are two striking aspects of the current dollar series: almost complete flatness from 1921 to 1942, and the steep increase after 1946. Deflating the prices to constant 1918 dollars reveals a real price increase of 25% through the 1920s, with a similar decrease during the 1930s, leaving the 1942 real price almost identical to that of 20 years earlier. Without adjusting for quality, it would appear that little of significance was occurring in tractor prices during these two decades, an assumption that many observers have made. The hedonic regressions in the next section will help show the erroneous nature of this assumption.

²² Federal Trade Commission (1938), *Report on the Agricultural Implement and Machinery Industry*, (Washington: U. S. Government Printing Office, 1938).

Figure 4. Weighted Average Tractor Prices:
Nominal and 1918 Dollars.

Source: author's database described in text

Hedonic Regressions and Price Indices

One of the difficulties with hedonic regression is that it is not based on any underlying theoretical model. As a result, the specification of regressors and their relationship to price is somewhat arbitrary. If the services generated by the product include emotional and psychic benefits, or others difficult to quantify, the task is made especially difficult. Raff and Trajtenberg refer to these issues in identifying a set of attributes for their automobile study.²³ As others have done, they restrict their focus to engineering and performance data which can be quantified, leaving aside aspects such as ride, comfort, and safety, which might be more likely to appear in a consumer's subjective utility function.²⁴

Fortunately, my task was more straightforward. It seems quite defensible to consider a tractor as a durable input to a farmer's production function, without considering creature comforts or psychic benefits. The performance attributes detailed in the last section, drawbar and belt horsepower, plowing speed, and fuel efficiency should all be expected to directly affect the tractors value. The presence or absence of a PTO, type of tires, and style (standard or row-crop) may also be significant. Dummy variables for manufacturer would serve to isolate any perceived firm-specific effects, such as reputation for quality, technical service, or strength of dealer network. Finally, dummy variables for the year capture the quality-adjusted price changes.

The functional form of the regression equation is also open to variation. The hedonic literature includes double-log, semi-log, and linear forms. Fetting tested all three forms in

²³ Raff and Trajtenberg, "Quality-Adjusted Prices."

²⁴ Raff and Trajtenberg, "Quality-Adjusted Prices," p. 79.

his dissertation, choosing the one which fit his data best for extended analysis. In his note, Berck fitted his tractor data to the following non-linear regression equation:

$$(1) \quad \ln(\text{price} / \text{WPI}) = c + a * \text{year} + (b + d * \text{year}) * \ln(\text{hp}),$$

where hp refers to drawbar horsepower.²⁵ In a preliminary regression analysis, Berck had found fuel efficiency to be an insignificant factor, so he eliminated it from his model. His interaction between the year and horsepower helped him highlight the extent to which different size tractors had dropped in price.

For the present study, I performed a number of preliminary regressions to test all three simple forms, excluding any interaction terms. I estimated both unweighted and volume-weighted regressions, with the nominal price as well as one converted to real values using the GDP deflator. In each case, the best fits and the most consistent sets of coefficients were obtained with the log-log form. Additional valuable information emerged from these trials. Use of both drawbar and belt horsepower in the same regression produced a negative coefficient on the drawbar variable in several cases. Simple diagnostics showed that this situation resulted from a high correlation (0.94) between the two horsepower measures. I thus chose to eliminate the belt horsepower measure from succeeding tests.²⁶ Finally, the number of cylinders and engine rpm were not significant in the regressions, so they were eliminated from further consideration.²⁷

²⁵ Berck, "A Note", p. 68.

²⁶ I ran a pair of regressions each containing one of the horsepower measures. The one with drawbar horsepower had a lower mean square error and higher adjusted correlation coefficient.

²⁷ I was unable to include a dummy variable for PTOs in the trials due to a lack of precise source data. Several different types of power take-offs were provided through the years, with differing rotational speeds and capabilities. The early 'non-live' PTOs only worked while the tractor was in gear; the 'live' PTOs which appeared late in the period could operate regardless of the position of the clutch.

The fuel efficiency variable required some additional data conversion. The raw efficiency measure reported by the Nebraska tests was in horsepower-hours per gallon of fuel. I used several published price series, including BLS Wholesale Price Index for 1920 to 1950, to convert each model's performance into horsepower-hours per dollar of fuel.²⁸ The resulting data should accurately measure the which varied from year to year with changing wholesale prices.

With the simplifications just discussed, the resulting model was as follows:

$$(2) \quad \ln(\text{price}) = \delta_0 + \delta_1 \ln(\text{drawhp}) + \delta_2 \ln(\text{spds}) + \delta_3 \ln(\text{pspd}) + \delta_4 \ln(\text{feff}) \\ + \delta_s \text{ Style} + \delta_t \text{ Tires} + \delta_m \text{ Mfg} + \delta_y \text{ Yr}$$

where drawhp is drawbar horsepower, spds is the number of forward speeds, pspd is plowing speed, feff is fuel efficiency, and the remainder are vectors of dummy variables: Style - standard, row-crop, and high-clear; Tires - steel and rubber; Mfg - Deere, IH, Ford, Allis-Chalmers, Massey-Harris, Oliver, Case, and Minneapolis-Moline; and Yr - the years 1920 to 1955.²⁹

Hedonic price coefficients can be generated using two different techniques within this general framework. In the pooled regression method, all of the year dummies are included in a single model, and their coefficients form the price index directly. Coefficients on the other explanatory variables represent an average effect over the entire time period. In the adjacent-year method, each pair of years is considered in a separate regression, with the

²⁸ Platt's Oilmanac provided the yearly data for the 1951 to 1955 period. The WPI numbers are complicated by the major revision in format and data sources which occurred in 1951. All but one of the series I used for 1920 to 1950 had been discontinued by 1952.

²⁹ The lack of complete data prior to 1920 led to widely divergent and mostly insignificant coefficients on the dummy variables for the earliest years. As a result, I eliminated all of the data from the years 1910 to 1919.

hedonic price change established through the use of a dummy variable for the second year. Each quality or performance variable thus has a different coefficient for each year.³⁰ In periods during which a particular quality parameter is undergoing rapid improvement, the effect can be seen quite clearly, while during stable periods, the coefficients may not be significant. To highlight these different effects, I chose to use both methods for my analysis.

The pooled regression results are summarized for the unweighted sample in Table 10 and for production-weighted data in Table 11. Note that the log-log specification allows all the variables except the year dummies to be unaffected by the real vs nominal price. The explanatory power of the models is fairly high, with r^2 values ranging from .785 to .914, those based on real prices considerably better than the nominal fits, and the weighted samples outperforming the unweighted ones.

The coefficient for drawbar horsepower is large and significant for weighted and unweighted models. Fuel efficiency has the expected positive effect on price. Plow speed is significant and carries the correct sign in the weighted regression, while the number of speeds enters positively in the absence of production weights.³¹ Although most of the

³⁰ Discrete variables must be omitted from an adjacent regression if there is no variation during the two years considered. For instance, since there were no rubber-tired tractors prior to 1930, the tires dummies can not appear in any of the 1920s regressions.

³¹ The number of speeds is fairly highly correlated with plowing speed, as might be expected ($r^2 = .68$). Using both in any regression led to inconsistent results.

Table 10. Pooled Hedonic Price Regressions for Tractors - Unweighted Results.

	Nominal Price	Real Price		Nominal Price	Real Price
Constant	4.592 (43)	4.592 (43)	<u>Yr Dummies</u>		
<u>Variables</u>			1919	0.080 (1.14)	-0.052 (-0.74)
Draw hp	0.791 (54)	0.791 (54)	1920	0.070 (0.97)	-0.193 (-2.69)
Speeds	0.106 (4.0)	0.106 (4.0)	1921	0.022 (0.32)	-0.058 (-0.86)
Fuel Efficiency	0.154 (6.7)	0.154 (6.7)	1922	-0.234 (-3.4)	-0.230 (-3.3)
<u>Tech Dummies</u>			1923	-0.302 (-4.3)	-0.322 (-4.6)
Hi-Clear	0.029 (1.27)	0.029 (1.27)	1924	-0.349 (-4.9)	-0.367 (-5.2)
Standard	0.039 (3.3)	0.039 (3.3)	1925	-0.375 (-5.1)	-0.406 (-5.6)
Steel	-0.079 (-2.60)	-0.079 (-2.60)	1926	-0.357 (-5.0)	-0.373 (-5.2)
<u>Mfg Dummies</u>			1927	-0.420 (-5.8)	-0.415 (-5.7)
Deere	0.051 (2.70)	0.051 (2.70)	1928	-0.478 (-6.5)	-0.488 (-6.7)
Ford	-0.150 (-4.0)	-0.150 (-4.0)	1929	-0.575 (-8.3)	-0.581 (-8.4)
Allis-Chalmers	-0.005 (-0.26)	-0.005 (-0.26)	1930	-0.781 (-11)	-0.761 (-11)
Massey-Harris	0.084 (4.4)	0.084 (4.4)	1931	-0.933 (-12)	-0.817 (-11)
Oliver	0.064 (3.3)	0.064 (3.3)	1932	-0.914 (-12)	-0.690 (-9.3)
Case	0.019 (1.02)	0.019 (1.02)	1933	-0.947 (-12)	-0.700 (-9.2)
Minn-Moline	0.076 (3.9)	0.076 (3.9)	1934	-0.934 (-13)	-0.759 (-10)
			1935	-0.927 (-13)	-0.761 (-10)
			1936	-0.891 (-12)	-0.727 (-10)
			1937	-0.882 (-12)	-0.760 (-11)
			1938	-0.885 (-12)	-0.749 (-10)
			1939	-0.917 (-12)	-0.765 (-10)
			1940	-0.980 (-13)	-0.844 (-11)
			1941	-0.996 (-13)	-0.932 (-12)
			1942	-0.976 (-13)	-1.028 (-14)
			1943	-0.922 (-12)	-1.043 (-14)
			1944	-0.931 (-12)	-1.077 (-14)
			1945	-0.927 (-12)	-1.099 (-15)
			1946	-0.817 (-11)	-1.099 (-15)
			1947	-0.749 (-10)	-1.143 (-16)
			1948	-0.641 (-9.3)	-1.100 (-16)
			1949	-0.535 (-7.7)	-0.988 (-14)
			1950	-0.478 (-6.9)	-0.944 (-14)
			1951	-0.452 (-6.5)	-0.983 (-14)
			1952	-0.432 (-6.2)	-0.986 (-14)
			1953	-0.418 (-5.9)	-0.980 (-14)
			1954	-0.412 (-5.8)	-0.990 (-14)
			1955	-0.382 (-5.3)	-0.974 (-13)
			r ²	.845	.790
			N	1496	1496

Note: Log of price was regressed against logs of explanatory variables. Numbers in parentheses are t-statistics. Omitted variables are row-crop, rubber tires, International Harvester, and 1918.

Table 11. Pooled Hedonic Price Regressions - Production Weighted Results.

	Nominal Price		Real Price			Nominal Price		Real Price	
Constant	4.701	(45)	4.701	(45)	<u>Yr Dummies</u>				
<u>Variables</u>					1919	0.039	(0.75)	-0.093	(-1.81)
Draw hp	0.644	(45)	0.644	(45)	1920	0.091	(1.76)	-0.171	(-3.3)
Plow speed	0.169	(5.2)	0.169	(5.2)	1921	-0.125	(-2.12)	-0.205	(-3.5)
Fuel Efficiency	0.165	(6.8)	0.165	(6.8)	1922	-0.641	(-12)	-0.638	(-12)
<u>Tech Dummies</u>					1923	-0.705	(-14)	-0.725	(-14)
Hi-Clear	-0.151	(-9.9)	-0.151	(-9.9)	1924	-0.656	(-12)	-0.674	(-12)
Standard	0.047	(4.2)	0.047	(4.2)	1925	-0.657	(-12)	-0.689	(-13)
Steel	-0.021	(-0.72)	-0.021	(-0.72)	1926	-0.316	(-5.9)	-0.332	(-6.3)
<u>Mfg Dummies</u>					1927	-0.387	(-6.9)	-0.381	(-6.8)
Deere	0.049	(4.1)	0.049	(4.1)	1928	-0.458	(-7.9)	-0.468	(-8.1)
Ford	-0.097	(-6.4)	-0.097	(-6.4)	1929	-0.532	(-9.3)	-0.538	(-9.4)
Allis-Chalmers	0.054	(3.5)	0.054	(3.5)	1930	-0.597	(-9.8)	-0.577	(-9.5)
Massey-Harris	0.037	(1.98)	0.037	(1.98)	1931	-0.725	(-9.7)	-0.609	(-8.2)
Oliver	0.018	(0.88)	0.018	(0.88)	1932	-0.694	(-6.9)	-0.470	(-4.6)
Case	-0.016	(-0.95)	-0.016	(-0.95)	1933	-0.793	(-7.4)	-0.546	(-5.1)
Minn-Moline	0.177	(7.4)	0.177	(7.4)	1934	-0.839	(-11)	-0.663	(-8.6)
					1935	-0.812	(-13)	-0.645	(-10)
					1936	-0.745	(-12)	-0.581	(-9.4)
					1937	-0.746	(-12)	-0.624	(-10)
					1938	-0.788	(-12)	-0.652	(-9.8)
					1939	-0.835	(-12)	-0.683	(-9.9)
					1940	-0.883	(-13)	-0.747	(-11)
					1941	-0.875	(-13)	-0.811	(-12)
					1942	-0.822	(-12)	-0.875	(-13)
					1943	-0.720	(-10)	-0.842	(-12)
					1944	-0.717	(-11)	-0.863	(-13)
					1945	-0.713	(-11)	-0.914	(-14)
					1946	-0.636	(-9.6)	-0.918	(-14)
					1947	-0.575	(-9.2)	-0.969	(-15)
					1948	-0.485	(-8.0)	-0.944	(-16)
					1949	-0.306	(-5.0)	-0.758	(-12)
					1950	-0.207	(-3.4)	-0.674	(-11)
					1951	-0.176	(-2.92)	-0.708	(-12)
					1952	-0.176	(-2.88)	-0.730	(-12)
					1953	-0.132	(-2.12)	-0.694	(-11)
					1954	-0.136	(-2.12)	-0.713	(-11)
					1955	-0.077	(-1.21)	-0.669	(-10)
					r^2	.913		.855	
					N	1490		1490	

Note: Log of price was regressed against logs of explanatory variables. Numbers in parentheses are t-statistics. Omitted variables are row-crop, rubber tires, International Harvester, and 1918.

technical dummies are insignificant in the pooled regressions, standard tractors were slightly more expensive than row-crop models. The hypothetical average tractor in the regression database pulled a rated 21hp, plowed at 3.8mph, and achieved fuel efficiency of 160 hp-hr/\$. Compared to this average tractor, an extra 5hp would add 15% to the price, an extra 1mph 3.9%, and 40 more hp-hr/\$ an extra 3.8%.

The manufacturer variables provide quite interesting information. Compared to market leader International Harvester, which is the omitted class in all of these regressions, Ford models were more than 10% cheaper, and Deere tractors about 5% more expensive. The models of all the other manufacturers were within a few percent of IH's in the pooled regression, with the exception of Minneapolis-Moline, which charged a quality-adjusted 15% premium.

The series of hedonic price coefficients were all highly significant, except for the first few years. Figure 5 shows the progression over time, for weighted and unweighted regressions. Comparison to the raw price data of Figure 4 shows that the 20+ years of price stability is no longer seen. The quality adjusted price for the average tractor fell in half from 1920 to 1947, from around \$1900 to \$900 in real terms.³² Volume weighting changes the results meaningfully for only a few years, from 1922 to 1926. This was the period when Ford slashed prices for his market-dominant Fordson tractors to well below

³² The representative tractor is a row-crop machine with the attributes listed in the text above. Because the model chosen is double-log, the dollar difference would vary for a larger or smaller tractor, but the percentage changes would be the same.

**Figure 5. Quality Adjusted Real Price of Tractors
Using Pooled Regression Method**

Quality-adjusted price for 21hp tractor plowing at 3.8mph and achieving 160hp-hours/\$ of fuel.
Source: regression results summarized in Tables 10 and 11.

cost, in an attempt to build sales following the deep farm depression of 1921. As his competitors did not follow the deep price cuts with most of their models, the unweighted regression does not show the extent of below-cost selling.

In the years after 1940, and especially after the end of the Second World War, hedonic prices increased rapidly in nominal dollars, but remained almost flat in real terms. The post-war wage and price inflation caused by the release of pent-up demand is responsible for the rise in current dollars. During this period, the size and horsepower capability of tractors was also on the rise; real prices appear to have risen in step with this performance and quality improvement.

The adjacent-year regressions, performed only with real prices in the double-log model, yielded similar information to the pooled trials. Table 12 shows the results for the 35 separate analyses performed on the production-weighted data.³³ An identical number of regressions were completed for the unweighted samples, but they are not included here to avoid data overload.

The coefficients on the drawbar horsepower variable are large and positive, with a high degree of significance throughout the entire period. Plow speeds are significant in the early years of the database and then again after 1937, when widespread availability of rubber tires made faster plowing possible. Fuel efficiency has a modest positive effect through most of the first 20 years, as the more efficient high-compression gasoline engines sold at a premium compared to kerosene

³³ The manufacturer dummy variables were eliminated from these regressions to preserve degrees of freedom, and in light of the rather modest manufacturer effect noted in the pooled trials.

Table 12. Adjacent-Year Hedonic Price Regressions for Tractors - Production Weighted Results.

	1918 - 1919	1919 - 1920	1920 - 1921	1921 - 1922	1922 - 1923	1923 - 1924
Constant	2.668 (3.2)	2.835 (4.0)	2.800 (3.8)	-1.051 (-0.91)	2.352 (2.08)	1.225 (1.06)
Draw hp	0.979 (11)	0.950 (10)	0.886 (8.8)	1.257 (8.1)	1.763 (10)	1.712 (14)
Plow speed	0.834 (7.1)	0.669 (6.3)	0.721 (7.8)	1.121 (11)	0.820 (5.3)	0.137 (1.04)
Fuel Eff'cy	0.385 (1.55)	0.364 (1.58)	0.475 (1.85)	1.177 (2.81)	-0.178 (-0.46)	0.315 (1.11)
Standard			-0.233 (-2.37)	0.036 (0.37)		-0.349 (-0.66)
Second Year	-0.081 (-1.40)	-0.011 (-0.16)	-0.102 (-2.50)	-0.504 (-6.4)	0.051 (0.25)	-0.054 (-0.34)
r^2	.925	.933	.925	.956	.912	.944
N	28	30	35	38	35	39

	1924 - 1925	1925 - 1926	1926 - 1927	1927 - 1928	1928 - 1929	1929 - 1930
Constant	1.645 (1.87)	1.204 (1.66)	2.111 (3.2)	2.739 (5.1)	3.391 (5.8)	3.972 (9.0)
Draw hp	1.413 (15)	1.309 (14)	1.167 (16)	0.994 (15)	0.663 (12)	0.514 (14)
Plow speed	0.036 (0.37)	0.066 (0.76)	-0.040 (-0.70)	-0.090 (-1.34)		
Speeds		0.410 (2.70)	0.481 (4.6)	0.350 (3.7)	0.027 (0.33)	-0.090 (-1.33)
Fuel Eff'cy	0.400 (2.00)	0.414 (2.17)	0.345 (2.38)	0.313 (2.85)	0.380 (3.2)	0.348 (3.9)
Hi-Clear				0.313 (0.81)	0.271 (1.48)	0.248 (2.24)
Standard	-0.466 (-2.29)	-0.336 (-3.4)	-0.251 (-4.8)	-0.196 (-5.0)	-0.113 (-2.75)	-0.070 (-2.33)
Second Year	-0.029 (-1.12)	0.284 (5.2)	-0.105 (-1.95)	-0.026 (-1.14)	-0.053 (-1.99)	-0.101 (-3.1)
r^2	.954	.970	.911	.906	.839	.846
N	40	37	39	41	47	56

	1930 - 1931	1931 - 1932	1932 - 1933	1933 - 1934	1934 - 1935	1935 - 1936
Constant	5.566 (12)	7.785 (18)	4.043 (4.3)	3.092 (3.0)	3.718 (8.2)	3.749 (12)
Draw hp	0.415 (11)	0.407 (15)	0.452 (8.6)	0.703 (12)	0.630 (13)	0.585 (14)
Plow speed						-0.118 (-0.90)
Speeds	0.042 (0.58)	-0.053 (-0.88)	0.155 (1.48)	0.102 (1.08)	0.023 (0.22)	
Fuel Eff'cy	0.040 (0.47)	-0.348 (-4.8)	0.315 (2.22)	0.372 (1.86)	0.287 (2.75)	0.334 (5.3)
Hi-Clear	0.218 (1.91)	0.238 (2.96)	0.459 (4.4)	0.517 (3.9)	0.491 (2.99)	0.479 (2.59)
Standard	-0.010 (-0.36)	0.015 (0.71)	0.091 (2.37)	0.141 (3.5)	0.075 (2.06)	0.044 (1.69)
Steel			-0.108 (-0.20)	-0.184 (-2.85)	-0.154 (-3.4)	-0.100 (-3.1)
Second Year	0.025 (0.58)	-0.018 (-0.58)	-0.113 (-3.13)	-0.107 (-2.98)	0.031 (1.13)	0.084 (4.2)
r^2	.783	.873	.786	.860	.881	.897
N	57	53	51	58	68	70

Note: t-statistics are in parenthesis. Blank cells indicate variable was not included in regression.

Table 12, cont. Adjacent-Year Hedonic Price Regressions - Production Weighted Results.

	1936 - 1937	1937 - 1938	1938 - 1939	1939 - 1940	1940 - 1941	1941 - 1942
Constant	4.096 (14)	4.457 (12)	3.535 (6.1)	2.720 (3.8)	2.018 (2.26)	2.565 (2.5)
Draw hp	0.587 (15)	0.674 (15)	0.764 (18)	0.716 (17)	0.624 (12)	0.614 (12)
Plow speed	-0.011 (-0.10)	0.210 (1.94)	0.510 (5.4)	0.799 (8.2)	0.817 (7.2)	0.681 (5.8)
Speeds					0.215 (2.52)	0.301 (3.9)
Fuel Eff'cy	0.259 (4.3)	0.088 (1.10)	0.123 (1.17)	0.226 (1.68)	0.330 (1.97)	0.232 (1.16)
Hi-Clear	0.273 (1.05)	-0.249 (-3.6)	-0.165 (-3.9)	-0.258 (-7.0)	-0.264 (-6.6)	-0.204 (-4.7)
Standard	0.028 (1.11)	0.014 (0.49)	0.008 (0.27)	-0.014 (-0.39)	0.034 (0.73)	0.085 (1.77)
Steel	-0.100 (-3.7)	-0.056 (-2.20)	-0.021 (-0.79)	-0.066 (-1.48)	0.149 (0.89)	
Second Year	-0.044 (-2.41)	-0.022 (-0.80)	-0.027 (-1.11)	-0.054 (-2.10)	-0.029 (-0.70)	-0.069 (-2.22)
r^2	.882	.870	.893	.900	.882	.847
N	75	83	91	96	94	95

	1942 - 1943	1943 - 1944	1944 - 1945	1945 - 1946	1946 - 1947	1947 - 1948
Constant	4.251 (20)	4.930 (22)	4.969 (26)	4.961 (24)	4.424 (20)	3.765 (20)
Draw hp	0.541 (8.8)	0.457 (6.7)	0.483 (8.4)	0.469 (7.7)	0.543 (8.1)	0.640 (11)
Plow speed	0.487 (3.7)	0.336 (2.44)	0.302 (2.37)	0.335 (2.43)	0.554 (3.6)	0.761 (5.6)
Speeds	0.223 (2.62)	0.049 (0.50)				
Hi-Clear	-0.209 (-3.3)	-0.326 (-4.3)	-0.361 (-6.4)	-0.429 (-8.0)	-0.267 (-4.3)	0.033 (0.57)
Standard	0.211 (4.7)	0.197 (4.1)	0.155 (4.1)	0.136 (3.5)	0.126 (2.97)	0.032 (0.89)
Second Year	-0.000 (-0.02)	-0.013 (-0.35)	-0.022 (-0.68)	-0.039 (-1.14)	-0.101 (-2.66)	-0.038 (-1.15)
r^2	.740	.676	.745	.745	.686	.758
N	90	86	92	99	113	130

	1948 - 1949	1949 - 1950	1950 - 1951	1951 - 1952	1952 - 1953	1953 - 1954	1954 - 1955
Constant	3.274 (4.6)	3.078 (13)	3.310 (20)	3.496 (28)	3.496 (28)	3.572 (32)	3.516 (28)
Draw hp	0.694 (15)	0.748 (28)	0.755 (30)	0.775 (29)	0.775 (29)	0.769 (31)	0.707 (27)
Plow speed	0.514 (4.6)						
Speeds		0.121 (2.31)	0.097 (1.91)	0.040 (0.77)	0.012 (0.21)	0.074 (1.28)	0.159 (2.56)
Fuel Eff'cy	0.142 (0.89)	0.299 (5.7)	0.274 (7.5)	0.283 (8.9)	0.236 (9.1)	0.203 (9.4)	0.220 (8.7)
Hi-Clear	0.003 (0.07)	-0.048 (-1.84)	-0.064 (-2.79)	-0.075 (-3.1)	-0.063 (-2.55)	-0.011 (-0.48)	0.017 (0.62)
Standard	-0.042 (-1.38)	-0.034 (-1.81)	-0.063 (-3.9)	-0.074 (-4.5)	-0.040 (-2.28)	0.007 (0.41)	0.032 (1.88)
Second Yr.	0.183 (6.7)	0.088 (5.7)	-0.032 (-2.31)	-0.015 (-1.08)	0.018 (1.25)	-0.029 (-2.12)	0.045 (2.94)
r^2	.866	.936	.937	.936	.943	.959	.951
N	141	146	150	155	143	120	101

models. From 1949 onward, diesel tractors sold at a large upcharge compared to gasoline models; by the late 1950s, diesel would be universal.

The style and tires variables reveal information in the adjacent regressions that remained hidden in the pooled analysis. Once row-cropping tractors became available in 1925, standard tractors sold at a discount - the std coefficients are negative from 1924 to 1931. The conversion from steel wheels to rubber tires occurred in the latter half of the 1930s. The data show that steel wheels reduced prices from 1933 to 1940, after which they disappear from the database.

The results of the adjacent-year regressions are shown graphically in Figure 6. Using 1918 as a base (100), the real quality-adjusted cost fell to an index of 21 by 1948, rising only slightly to 26 by 1955. Once again, Ford's price cut in the early 1920s causes the production-weighted index to undercut the one based on models offered. A steep fall to 40 in 1922 is partly reversed by 1932 (up to 50), from which point the index falls steadily, leveling off at one-quarter of the 1918 value.

Concluding Remarks

In this chapter, I describe a hedonic regression technique for adjusting price time series for quality and performance improvement. The technique is used with a newly developed database on tractor prices over the period 1918 to 1955, which in turn was the result of substantial empirical research. I show that quality-adjusted prices fell to less than half of their 1918 level by the early 1940s, after which they remained level in real terms through the end of the period. These indices will be used in the next chapter to reconsider the

Figure 6. Real Quality-Adjusted Tractor Costs.
Calculated Using Adjacent Year Regressions

Source: Regression results summarized in Table 12.

puzzle regarding the slow pace of tractor adoption, and to suggest that recent interpretations would benefit from consideration of quality change.

In addition, I would suggest that hedonic regression techniques should be added to the toolkit of quantitative social scientists. The needed computing power and statistical software packages are readily available, the methodology is not overly difficult, and almost 40 years of literature attest to their usefulness. The heavy data requirements needed for robust results are increasingly available, especially as more historical work focuses on the data-rich 20th century.

Creativity in seeking data sources is a great asset in this respect. Gordon (1990) collected prices on hundreds of durable goods from annual Sears Catalogs, Margo and Villaflor (1987) uncovered antebellum U. S. Army quartermaster reports, Margo (1996) used newspaper advertisements, other housing price literature makes use of real estate listings and government surveys, and my own work capitalizes on several unusual data sources.³⁴ Only with this type of data and the proper use of hedonic techniques can product quality and performance improvement be properly captured, and thus the true progress of prices over time be measured.

³⁴ The references in the text are to: Gordon, *The Measurement of Durable Goods Prices*; Robert A. Margo and Georgia C. Villaflor, "The Growth of Wages in Antebellum America: New Evidence," *The Journal of Economic History* 47 (1987), pp. 873-95; and Margo, "The Rental Price of Housing in New York City, 1830-1860," *The Journal of Economic History* 56 (1996), pp. 605-25.

CHAPTER 5

THE QUALITY FACTOR - EXPLAINING THE 'SLOW DIFFUSION' OF THE TRACTOR

The farm tractor was a major productivity-improving technology for the agricultural sector and for the U.S. economy as a whole. It revolutionized the business of farming and helped shape employment, land-use practices, food prices, and the rural landscape that we know today. Its role in increasing labor productivity in agriculture has long been understood and appreciated; the finding that it significantly reduced total factor inputs to the production of food and other farm products is a finding of the present research effort.³⁵ The counterfactual analysis presented in Chapter 3 shows that adoption of the tractor generated social savings in excess of 8.5% of GNP, using the year 1954 as a base.

These tremendous social savings were not generated quickly, but over an extended period of time. Initial technical feasibility was demonstrated in 1892 and commercial units were sold as early as 1902, but the heavy, expensive monsters first produced were not the

³⁵ Researchers have typically described mechanization as simply substituting capital for labor, with only modest improvements in total factor productivity. I have shown that capital investment per acre did not increase significantly with the adoption of the tractor; decreases in labor inputs and intermediate output consumption by work stock produced unambiguous productivity improvements.

answer to most farmers' needs. Sustained technological development would produce small, light tractors by 1918, more versatile row-cropping models in the mid-to-late 1920s, and a number of minor innovations during the 1920s and 1930s. Even after emergence of a dominant design in the mid-1930s, however, it would take another 25 years for tractors to fully replace horse and mule-powered agriculture in the United States.

The previous chapter has shown one of the reasons for the gradual diffusion of the tractor, which is the substantial increase in quality and performance, almost from its inception. When combined with nearly constant average prices in the interwar period, the quality adjusted price dropped sharply over time, reaching its low point in 1942 in both nominal and real terms. In the post-war period, hedonic tractor prices followed the general price level upwards, maintaining approximately the same real price, as should be expected with a mature technology where existing units are available as potential substitutes for new models.

The so-called slow diffusion of the tractor has been a tremendous concern, both to contemporaries writing as early as 1918, and continuing throughout the period of its evolution up to the present day. Debates about the tractor have played a role in the development of our understanding of technological change in general. The tractor is not unlike many other new technologies, in which its diffusion can be well-described by an s-shaped logistic curve. To illustrate, I include Figure 7, showing a tractor diffusion curve for the U.S. as a whole, and Figure 8, with the data for a few representative states.

Figure 7. Diffusion of the Tractor in the U.S.

Source: U. S. Censuses of 1920, 1940. Agriculture censuses of 1925, 1945, 1959, 1964, 1974.

Figure 8. Diffusion of the Tractor - Selected States

Source: See Figure 7

Review of Diffusion Literature

In his celebrated study of hybrid corn, Zvi Griliches fitted his diffusion data analytically to a logistic distribution.³⁶ This distribution has three characteristic parameters, which Griliches attributed to the onset, maximum rate, and terminal extent of the diffusion. Regional or state-by-state differences in the values of these fitted parameters were attributed to the underlying profitability of farming in the area, as well as the availability and proximity of government funded genetic research.

Paul David and others correctly pointed out that this econometric exercise by Griliches was not consistent with an economy always in general equilibrium.³⁷ Between the time that the new technology was developed and the time its diffusion reached the maximum extent, a dis-equilibrium situation was implicitly assumed, with the driving force to restore equilibrium strongest where the profit motive was the highest. David was not willing to assume that the economy could remain out of equilibrium for such an extended period of time – several years in the case of hybrid corn and the adoption of the reaper.

David instead assumed that the new technology was not cost-effective for all its potential customers, at all relative factor prices. Only those buyers for whom the innovation was clearly superior would purchase the new product at a given date. A change in relative factor prices over time, or perhaps in the customers themselves, would lower the break-even point, thus accounting for the observed diffusion pattern. The markets involved would remain in equilibrium at each point in time; all of those for whom

³⁶ Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25:4 (October, 1957), pp. 501-22.

³⁷ Paul A. David, "The Mechanization of Reaping in the Antebellum Midwest," in Henry Rosovsky, ed. *Industrialization in Two Systems*. (New York: Wiley, 1966) pp. 3-39.

it was profitable to switch would do so, not merely those seeing the highest profits, as suggested by Griliches.

In the case of the reaper, David cited the presence of fixed costs, in the form of indivisible capital, as the factor which could change relative prices over time. In his analysis, the fixed cost of the reaper made it more profitable to use on a large farm than on a small one. For any combination of input prices, there was an acreage 'threshold', above which it was profitable to replace a team of horses with a reaper. As input prices, especially labor rates, changed over time, the level of this threshold continuously dropped, accounting for the characteristic s-shaped adoption curve. In addition, as the distribution of land changed, due to clearing of additional acreage or farm consolidation, the threshold dropped as well.

Paul David is not without his critics, however. The most notable of them is Alan Olmstead, who in a series of papers over more than 20 years, has repeatedly challenged both David's assumptions and his conclusions.³⁸ Several criticisms are noted here, as they are quite important in light of the present work. Firstly, farm size was not exogenous to the choice of technology. A decision to purchase a reaper might indicate that the new technology was cost-effective for the farmer's current acreage, or it could have led to a consequent expansion of land under cultivation.

Secondly, Olmstead questioned the assumption that the new equipment was an indivisible capital asset. In detailed historical research, Olmstead found evidence of

³⁸ Relevant papers include Alan L. Olmstead, "The Mechanization of Reaping and Mowing in American Agriculture, 1833-1870," *Journal of Economic History* 35 (June 1975), pp. 327-52; and Alan L. Olmstead and Paul W. Rhode, "Beyond the Threshold: An Analysis of the Characteristics and Behavior of Early Reaper Adopters," *Journal of Economic History* 55 (March 1995), pp. 27-57.

significant joint-purchase, asset sharing, and renting or leasing of neighboring land to take advantage of the labor-saving reaper technology. In the 1995 paper, Olmstead and Rhode analyzed census manuscript schedules and found that many of the reapers sold during the 1850s were to small landowners, those well below the threshold calculated by David.

Finally, Olmstead pointed out that the calculations used in threshold studies are quite sensitive to assumptions of key parameter values, and often even small changes in one or more variables can lead to large changes in the resulting threshold. In some cases, such an adjustment can drive the threshold below zero, indicating complete dominance by either the old or new technology, or to the point where the new technique appears to be fixed-cost saving and variable-cost using.³⁹ As will become apparent in the next section, the debate over tractor diffusion has suffered from both types of model instability.

Threshold Models and the Tractor

Despite these concerns, threshold models are still widely used today, and are understood to reveal important information about new technologies, especially where old vintages of capital are to be replaced by new capital with a significant indivisible fixed-cost component. A number of studies of the adoption of the gas tractor have been published over the past 30 years, most following David's methodology to a large extent. Their conclusions have generated additional controversy, involving possible externalities and market failures in agricultural institutions, as well as recalling concerns about the

³⁹ If the old technology is lower in both fixed and variable costs, the new technology is not viable and should not be observed; if the new technique is lower in both types of costs, the old technique should be immediately abandoned.

techniques used. My current work is intended to resolve or redirect much of the conflict brought about by this literature.

Some of the more important analytical work on tractor costs and adoption decisions predates David's reaper work, including the critical issue of whether tractors were fixed-cost using or fixed-cost saving. This issue arose in the 1930s, when a series of surveys analyzed by the U.S. Department of Agriculture measured the total costs of raising crops with horses and with several types of tractors. These surveys showed that total costs were similar for the (mostly large-scale) farmers who had purchased tractors, and suggested that their higher fixed costs were more than offset by lower operating expenses.⁴⁰ However, these studies treated the feed for draft animals as a variable cost of farming, ignoring the fact that horses and mules had to be fed whether they worked or not. Naum Jasny first pointed this out in a research paper published in 1938. When he recalculated the surveyed farmers' finances with feed considered as fixed, Jasny concluded that tractors actually saved fixed costs, while generating higher operating expenses.⁴¹

Acceptance of this conclusion would flip the entire tractor diffusion discussion on its head: the smallest farms should have purchased tractors and larger units retained their horses. Since the historical data show that larger farms purchased tractors in higher proportions, this would create a deeper mystery. It should be noted that the USDA

⁴⁰ Some of the more widely cited papers are: H. R. Tolley and L. A. Reynoldson, "The Cost and Utilization of Power on Farms where Tractors are Owned," USDA Bulletin No. 997 (Washington: USGPO, 1921); L. A. Reynoldson et. al., "Utilization and Cost of Power on Corn Belt Farms," USDA Technical Bulletin no. 384 (Washington: USGPO, 1933); W. M. Hurst and L. M. Church, "Power and Machinery in Agriculture," USDA Miscellaneous Publication No. 157 (Washington: USGPO, 1933); and L. A. Reynoldson, "Utilization and Cost of Power on Mississippi and Arkansas Delta Plantations," USDA Technical Bulletin No. 497 (Washington: USGPO, 1935).

⁴¹ Naum Jasny, *Research Methods on Farm Use of Tractors*, (New York: Columbia University Press, 1938).

studies that formed the data source for all of the later authors surveyed only fairly large farms. For instance, of the 736 farms in the corn-belt study, about one-fifth cultivated less than 100 acres, and only 28 had less than 60 crop acres. Conclusions about very small farms, based on this data, are somewhat speculative.⁴²

Researchers attempting to apply David's diffusion model to the case of the tractor were forced to struggle with this dilemma. Papers which considered feed to be entirely a fixed cost found tractors to be fixed-cost saving, those that treated feed as partly fixed achieved mixed results.⁴³ Robert Ankli, writing the third of his tractor diffusion papers on the corn belt experience, used some of Jasny's data to conclude that 70% of horse feed costs were borne regardless of work intensity.⁴⁴ This entirely reasonable assumption has become the basis for the most recent studies. Ankli's threshold results, however, were far less satisfying. He found that, given his data and assumptions, it was profitable for a corn farmer to switch from a small team of horses to a tractor at a fairly low 47.6 crop acres, but that large farms should have switched back to horses!

The predominant conclusion of the 1970s papers, including those by Ankli, was that adoption of the tractor proceeded much more slowly than one would expect, given relative prices and the size distribution of farms in the 1920s and 1930s. In this respect,

⁴² Reynoldson, et al, "Utilization and Cost of Power on Corn Belt Farms," pp. 2-6.

⁴³ Examples of the first include: Nicholas Peter Sargen, *"Tractorization" in the United States and its Relevance for the Developing Countries*, (New York: Garland Publishing, 1979); and Robert E. Ankli and Alan L. Olmstead, "The Adoption of the Gasoline Tractor in California," *Agricultural History* 55 (July 1981), pp. 213-30. The second include Ankli, "Horses vs. Tractors on the Corn Belt," *Agricultural History* 54 (Jan. 1980), pp. 134-148; and Warren Whately, "Institutional Change and Mechanization in the Cotton South: The Tractorization of Cotton Farming," Ph.D. Dissertation (Stanford University, 1983).

⁴⁴ Ankli, "Horses vs Tractors", p. 143.

they echoed David's earlier findings on the reaper. The most recent tractor papers have attempted to explain this puzzle of 'slow diffusion'.

In a 1983 dissertation on the use of the tractor in the cotton South, Warren Whately identified several important characteristics of that evolution.⁴⁵ Although tractors were available for plowing and cultivating cotton fields by the mid-1920s, the mechanical cotton picker was not perfected until after World War II. Reference to census data showed that the diffusion of the tractor in the South closely followed the invention and improvement of the cotton picker during the 1950s and 1960s, i.e., the ability to completely replace animal power and hand labor.

Nonetheless, the ability to mechanize partially, by using tractors for plowing and cultivation, should have generated savings for cotton farmers. According to the threshold model, the largest farms could have benefited from reduction in labor costs and elimination of animal husbandry. Whately's calculations, which are too complex to summarize here, indicated that the threshold acreage was far below that which the census data showed to maximize the likelihood of tractor ownership.⁴⁶ Whately deduced from this that an externality relating to tenancy and sharecropping must be involved. He concluded that because hand labor would still be needed for harvest time, a cotton grower that mechanized plowing and weeding, and thus displaced the tenants and croppers who worked the plantation, might have trouble hiring enough pickers to bring in the crop.

⁴⁵ Whately, "Institutional Change".

⁴⁶ To find the threshold, Whately regressed tractor ownership versus the number of large plantations, using a series of cutoff values for 'largeness'. The cutoff which generated the highest correlation was identified as the threshold.

More recently, Sally Clarke attacked the slow diffusion issue head-on in the case of Iowa and Illinois corn-belt farmers.⁴⁷ In her work, Clarke carefully built on the methodologies of both Ankli and Whately, returning to the original USDA and State agency studies for her source data. She created a 'model' corn-belt farm for her analysis, one which raised oats and hay for animal feed, in addition to corn and some soybeans as cash crops. Using Ankli's assumption that feed costs were 70% fixed, she calculated thresholds for the purchase of a general-purpose tractor in 1929, replacing two horses on the farm. This modeling decision, which closely matched the actual experience of the surveyed farmers, resulted in fairly 'normal' threshold calculations: in each case, tractors were found to be fixed cost using and variable-cost saving.⁴⁸

Despite the fact that Ankli and Clarke used the same sources, their different methodologies and a few errors caused them to reach different conclusions in their studies. Clarke noted one particularly important error in Ankli's corn-belt paper. By omitting one of the fixed cost components from his 'large-team horse farm' calculation, Ankli found a rather low 126.5 acres threshold for a conversion from a tractor to a large team; substituting the correct figure leads to an inversion threshold of 411 crop acres, larger than almost every farm in the corn belt.⁴⁹ Clarke's interpretation, based on somewhat

⁴⁷ Sally H. Clarke, "New Deal Regulation and the Revolution in American Farm Productivity: A Case Study of the Diffusion of the Tractor in the Corn Belt, 1920-1940," *The Journal of Economic History* 51 (Mar. 1991) pp. 101-123; Clarke, *Regulation and the Revolution in United States Farm Productivity*, (Cambridge: Cambridge University Press, 1994).

⁴⁸ Clarke relied on Reynoldson et al, "Utilization and Cost of Power on Corn Belt Farms" for the bulk of her micro data. In this study, the purchasers of General Purpose tractors had 2-3 less horses for equivalent crop acres than the owners of ordinary horse farms. All of these 'GP' farms had more than 100 crop acres, as did most of the horse and standard tractor farms. Without exception, the GP farms still had horses, and most of these used animal power for planting, wagon hauling, and some cultivating.

⁴⁹ Clarke, *Regulation and the Revolution*, p. 286; Ankli, "Horses vs Tractors", pp. 143-4.

better quality data and a more thorough investigation, was that a farmer with six horses should replace two of them with a tractor if more than 67.5 acres of crops were raised; there was no upper threshold above which it paid to move back to horses.

More important for Clarke's major thesis was her finding that the percentage of corn belt farms reporting ownership of a tractor in the agricultural census was significantly lower than the number of farms with crop acreage above her calculated threshold. She repeated the calculations for 1939, adjusting for changes in several of the cost components, although using the same 1929 survey for her productivity data.⁵⁰ Her findings that the gap between actual and predicted adoption levels had narrowed considerably during the 1930s led her to conclude that farmers were closer to making optimal decisions at the end of the period, and therefore that it was likely that some externality or market failure had prevented such optimality in 1929. Table 13 presents the relevant data from Clarke's study.

Table 13. Tractor Threshold Data from Clarke

State	% of farms above threshold - 1929	% of farms with tractor - 1929	% of farms above threshold - 1939	% of farms with tractor - 1939
Ohio	40.8	23.1	38.2	35.6
Indiana	45.0	22.3	43.3	37.1
Illinois	62.6	30.9	61.1	51.8
Iowa	72.1	29.4	71.5	55.3
Missouri	52.3	9.3	51.5	16.4

Source: Clarke, *Regulation and the Revolution*, pp. 93, 176.

⁵⁰ This reliance on old productivity data is questionable due to the rapidly changing tractor technology of the time. In 1929, general purpose tractors had just recently been introduced. As the information in Chapter 2 indicates, only two manufacturers had introduced GP units, and farmers were still learning how to use them optimally. By 1939, on the other hand, power take-offs, hydraulic lifts, rubber tires, and adjustable front ends had become standard; Ferguson's three-point hitch had been introduced, and farmers had more than 10 years experience with row-cropping tractors.

Faced with a number of potential explanations, including the frequent allegations that farmers were overly conservative or irrational, or that they systematically mis-calculated the true costs of non-purchased inputs like feed and animal power, Clarke opted to examine the more likely possibility that farmers faced incomplete or imperfect credit markets. According to this hypothesis, many farmers were unable to obtain loans to purchase tractors in the 1920s due to high levels of mortgages and limited cash flow. Following 1933, the New Deal programs, such as the crop loan provisions of the CCC and subsidized loans from the FCA, relieved this constraint and allowed farms to purchase the socially-desirable tractors and increase their productivity. My work in the earlier portions of this dissertation certainly support the contention that mechanization brought significant social gains, and that earlier adoption would have been a substantial benefit to the U.S. economy.

Reevaluating Threshold Models - The Quality Factor

Unfortunately, none of the authors who have used threshold models to study tractor diffusion have properly considered changes over time in the quality-adjusted price of the machines themselves. This omission has hindered the authors' analysis, and in many cases, has affected their conclusions. As the previous chapter has shown, there were tremendous increases in power and other performance characteristics of tractors during the 1920s and 1930s. In fact, the quality-adjusted price of a tractor fell by more than half in nominal terms between 1918 and 1942. Authors that have used USDA or BLS tractor price series

have usually not been aware that these indices handle quality change very poorly. With the extreme sensitivity of threshold models to even small changes in fixed and variable cost loadings, serious distortions can result. Figure 9 shows a comparison of the BLS series to the hedonic index I developed in Chapter 5.

I will illustrate this issue with reference to Sally Clarke's corn belt diffusion studies, which are, without a doubt, the most well developed and convincing of the recent body of work. She is the only author to make explicit adjustments for technological change or quality improvement during the time period under consideration. In her comparison of 1929 and 1939 thresholds, she observed that the introduction of rubber tires made it possible to cut the time required for most farm tasks by about one-fourth; as a result, she reduced 1939 variable costs accordingly. In addition, she noted that greater reliability had increased the expected life of a new unit from about eight years to thirteen. This adjustment reduced the annual fixed cost by a substantial amount.⁵¹

However, even these changes are insufficient to capture the full quality impact of the directed development and substantial innovation that occurred during the 1930s. As my hedonic index data in Figure 9 shows, a tractor selling for \$900 in 1929 would have cost about \$600 ten years later. For instance, this \$600 would have purchased a 1939 Farmall Model A, which developed 40% more horsepower than the comparable model from ten years earlier. In contrast, Clarke actually adjusted tractor selling prices upward for 1939, citing Iowa and U.S. government data which averaged out to a 7.4% increase.

⁵¹ Clarke, *Regulation and the Revolution*, p. 287.

Figure 9. Comparison of Tractor Price Series
Hedonic Index vs BLS Values

Hedonic index is for 10hp 4-speed tractor w/ 4mph plow speed, 140 hp-hrs per dollar of fuel; BLS data is from series for 10-20 tractors

To make matters worse, there is a problem with the 1929 tractor price as well. Clarke actually made a significant error in this first threshold calculation by assigning a cost of \$1000 to a general purpose tractor in that year.⁵² The USDA survey which was the source of her productivity data actually reported an average purchase price of \$890 by the farmers in the sample.⁵³ In support of this figure, the extensive production and price data I collected reveal only two general purpose models for sale in 1929: the Farmall T was priced at \$875 and the John Deere GP retailed for \$800. Merely changing the purchase price from \$1000 to \$890 reduces the 1929 threshold from 67.5 to 37.7 acres, and dramatically expands the gaps shown in Table 13.

Returning to the 1939 calculations, Clarke's inadequate price and quality adjustment led her to report a threshold of 61 acres, little changed from the figure of ten years earlier. Using the more accurate \$600 figure for tractor purchase price, even without the efficiency improvement Clarke estimated from the use of rubber tires, eliminates the threshold entirely. According to this new analysis, tractors were both fixed and variable cost saving by 1939. Instead of a shrinking gap between predicted and actual adoption rates during the 1930s, we now find an expanding gap in four out of the five states.⁵⁴ Such behavior would support the prevailing view, prior to Clarke's work, that the Depression of the 1930s actually hindered small farmers' attempts to mechanize, and that the New Deal programs were not effective in reversing this, except perhaps in Iowa.

⁵² Clarke, *Regulation and the Revolution*, p. 272.

⁵³ Reynoldson, et. al., "Utilization and Cost of Power on Corn Belt Farms", p. 28.

⁵⁴ In Iowa, with 55% of farms owning tractors in 1939, the 'gap' narrowed from 57% to 45% between the two census years. The gap increased in Illinois by 3%, in Indiana by 29%, in Missouri by 42%, and in Ohio by a whopping 51%!

A Re-interpretation of Tractor Diffusion History

Looking back at the technological development of the tractor, it should not be a surprise that we find this observation regarding the 1930s, as a dominant design was just emerging. Still, we do see substantial increases in diffusion throughout many sectors of the country, excepting 1932-34, the worst years of the Depression. In this sense it is unfortunate that the 1935 Agricultural Census failed to ask questions about ownership or use of tractors on farms, and that the USDA opted not to collect production and sales information for the three poor years. From 1934 onward, the production data shows a rapid rate of increase all the way up to the war years, during which production was curtailed by war planning restrictions.

As with many manufactured goods, it was the Second World War that provided the final spur to full diffusion into every part of the country except the South. In a very real sense, eight million people left the farm between 1939 and 1945, either to fight in the war or to replace those who were fighting in industry; none of these people came back to the farm when the war was over. If financial market imperfections had been restricting mechanization during the 1920s and 1930s as Clarke suggested, the sustained rise in crop prices and input costs removed these barriers and allowed adoption of the new technology. Of the 8 million tractors manufactured between 1918 and 1955, fully half were produced and sold after the war's end.⁵⁵

⁵⁵ See the production data in chapter 2 for details.

Confirmation of this dramatic and almost complete conversion (admittedly of a somewhat unpleasant nature) can be found in the evidence of horse slaughtering during this period. With tractors replacing horses on farms, and the automobile and truck having already done so in the transportation sector, farmers had little incentive to maintain these expensive, obsolete inputs. Figure 10 shows the annual slaughter numbers from 1926 through 1954; Figure 11 shows the annual figures as a percent of the total number of horses on farms in the United States.⁵⁶

It is quite likely that the 100M horses slaughtered per year from 1928 to 1932 were the unlucky fifth and sixth horses identified by Clarke and others in their studies. During the next 10 years, reductions in breeding and mortality appeared to be sufficient to keep overall numbers in check, an observation which is supported by rising horse prices through the period. As late as 1940, about 80% of farms with tractors also owned horses, a number which fell to 72% by 1945. It may have been the case that they still needed horses for some tasks, or that the horses were being kept on the farm for precautionary or sentimental reasons. With the ending of the war, it is evident that the situation had changed. From 1946 to 1954, an average of 170M horses per year would be killed, taking away a cumulative 40% of the stock at the end of the war. By 1954, only 35% of farms with tractors still had horses, and most of those only one or two.

⁵⁶ Data on slaughtering and horses on farms are from *Agricultural Statistics, 1936* (Washington: USGPO, 1937), p. 249-50; *Agricultural Statistics, 1945* (Washington: USGPO, 1946), p. 335-8; and ; *Agricultural Statistics, 1955* (Washington: USGPO, 1956), p. 357-9.

Figure 10. Horses Slaughtered Annually
in the United States: 1926 - 1954

Figure 11. Horses Slaughtered Annually as a Percentage of Those on Farms
in the United States: 1926 - 1954

Buying a tractor and getting rid of horses was to a large extent, an irreversible decision, a one-way bet on the future. Those who invested in the new technology would have to modify or abandon the physical facilities devoted to taking care of horses, a crop mix geared to provide the hay, oats, and corn the animals consumed, an entire line of horse-drawn implements, and a system of husbandry that often involved all the members of the family. Many of the capital items had little or no value on the secondary market, especially in an area where many farmers were converting their operations simultaneously. These unrecoverable abandonment and setup costs drove a wedge between the two technologies that make the simple decision-making process envisioned by the threshold model much less relevant.⁵⁷

Whereas this may point out a possible explanation for the slow diffusion of the tractor, it was certainly as important to farmers as potential cash constraints. A phenomenon much remarked about at the time, although perhaps less recognized today, is that the same farmers that Clarke concluded might not have been able to obtain a loan for a tractor were cheerfully buying automobiles for cash. In fact, the 1930 census reported that over 58% of all farms owned cars, versus 13.5% with tractors; a similar fraction had trucks.⁵⁸ Table 14 presents some selected statistics on ownership of automobiles, trucks, and tractors.

⁵⁷ This vintage capital viewpoint on diffusion was expressed by Salter in a book published the same year as David's initial work (W. E. G. Salter, *Productivity and Technical Change*, Cambridge: Cambridge University Press, 1966). According to Salter, owners of long-lived capital have a sunk cost investment, which cannot be recovered through disposal in an efficient resale market. These owners earn quasi-rents from the use of this capital, rents which decrease over time along with depreciation of the asset. When a new innovation renders their capital economically obsolete, they still have an incentive to retain the existing asset as long as the quasi-rents exceed any variable-cost disadvantages. The new technology is adopted only after its full cost falls below the variable cost of the obsolete method, or when the old capital fails.

⁵⁸ Bureau of the Census, *Fifteenth Census of the United States, 1930, Agriculture*, Volume II, Part 1 (Washington: Department of Commerce, 1932), p. 54-5.

Table 14. Motor Vehicles on Farms, 1930

Region	Number of farms (1000s)	% of farms with automobiles	% of farms with tractors	% of farms with motor trucks
U. S.	6,289	58.0	13.5	13.4
E N Central	967	79.7	24.7	19.6
W N Central	1,113	82.8	26.5	15.7
E S Central	1,062	30.2	2.1	4.1
S Atlantic	1,058	42.1	4.2	8.3
Iowa	215	90.2	29.4	14.8
Illinois	214	79.5	30.8	18.1

Source: Bureau of the Census, *Fifteenth Census of the United States 1930, Agriculture*, pp. 54-5.

This data on vehicle ownership is striking. In the major grain and corn growing regions of the country, more than 80% of the farms owned cars; in Iowa, the figure is over 90%! The ratio of cars to tractors was 4.3 nationwide, slightly lower in the North Central regions, and much higher in the South, where tractors were not as capable. In the East South Central, the ratio was 14:1, and in the South Atlantic, 10:1. Mississippi had a ratio of 17 cars for every tractor, and 3 trucks per tractor. In the South as a whole, there were about two trucks for each tractor.

I believe this indicates that farmers, in general, were not liquidity constrained. They bought millions of cars, which were mostly for consumption and personal welfare improvement, yet bought tractors in much lower numbers, due to their lack of clear superiority to horses. They were also slow to purchase trucks, which replaced horsepower in delivering goods. In the poorest regions of the South, where tractors were virtually useless in 1930, tractors were not purchased - yet cars and trucks were. Farmers

in the North Central (Corn Belt) states owned cars at the highest rate of any region in the country; it is difficult to escape the conclusion that they were affluent enough to afford them and isolated enough to need them. The historical evidence that they bought fewer numbers of tractors is strong evidence that they were not cost efficient for many of the Corn Belt farmers in 1929!

Rehabilitating the Tractor Threshold Model

Where does this leave the threshold models in the study of technological diffusion, then? I have shown that the model produced by Clarke and corrected in this paper predicts much higher rates of adoption than have been seen in the historical record. If we accept the conclusion that the 1929 threshold for purchasing a general purpose tractor was 37.7 crop acres, then the facts that the average Iowa and Illinois farms contained 158 and 143 acres, respectively, suggests that many more than 50% of the farms should have owned tractors.⁵⁹ The actual percentage, from Table 14, was about 30% in both states.

Of course, the threshold works well on a qualitative basis: the corn belt state with the smallest farms, Missouri, had the lowest rate of tractorization, which the two states mentioned above had the highest rates. Reference back to Figure 8 shows that North Dakota, a representative wheat-growing state, led the diffusion process and had the nation's largest non-ranch farms. Mississippi, heavily dependent on cotton, showed a very

⁵⁹ Clarke's assumption that the typical corn-belt farm harvested two-thirds of its total acreage is well supported by census records for the North Central states. A 'threshold' farm in 1929 would have contained about 56 acres.

low rate of diffusion, as well as the smallest average farm size. Ohio, with intermediate-sized mixed farms, also adopted tractors at a middling pace.⁶⁰

Although these results are qualitatively reasonable, there is still a quantitative problem if these threshold models are to be used for prediction rather than description. Alan Olmstead might suggest that the problems are so daunting that threshold models should be abandoned and research energies placed elsewhere. I believe, to the contrary, that threshold models, if properly constructed and interpreted, can be useful in attempting to understand diffusion of the tractor. To illustrate this, I used the hedonic price index data developed in the last chapter to construct thresholds on a year-by-year basis.

As Griliches suggested with his study of hybrid corn and a contemporaneous paper on tractor investment, optimal replacement theory predicts that firms will not always switch technologies when the total cost of the new technique falls below that of the existing one.⁶¹ If the old capital will become obsolete after conversion and therefore has a low or zero resale value, then the new technology will not be adopted until the total cost of the new technique falls below the variable cost of the incumbent. The sunk cost of the old capital has, thus, been lost. This is clearly the case in the replacement of horse-power in farming, in which horse-drawn implements and even the horses themselves had next to no value once complete conversion was effected. In such a regime, it might not be at all

⁶⁰ Average farm sizes for 1930 are from Bureau of the Census, *United States Census of Agriculture 1935* (Washington: USGPO, 1936), p. 22.

⁶¹ The tractor work is Zvi Griliches, "The Demand for a Durable Input: Farm Tractors in the United States, 1921-57," in Arnold C. Harberger, ed., *The Demand for Durable Goods* (Chicago: The University of Chicago Press, 1960). See also note 23 for a reference on vintage capital.

surprising to find that the actual rate of diffusion might fall behind the predicted level by a few years.

In putting together a threshold model for each year, I continued to use, to the greatest extent possible, Clarke's rationale, method of analysis, and much of the data she assembled from the original sources. Values for years both prior to and following 1929 were adjusted for changes in line with published indices of costs and prices. Table 15 shows the critical input parameters which were changed over time.

Table 15. Input Values to Yearly Threshold Calculations: 1923 - 1940

Year	Tractor Price	Tractor Life	Horse Price	Feed Cost Index	Wage Cost Index	Wholesale Fuel Price
1921	\$1,539	8	\$65.74	55	18	\$.243
1922	\$1,230	8	\$69.32	58	18	\$.208
1923	\$1,150	8	\$70.49	63	20	\$.125
1924	\$1,097	8	\$65.39	63	21	\$.072
1925	\$1,069	8	\$64.28	69	21	\$.072
1926	\$1,088	8	\$65.31	64	22	\$.071
1927	\$1,021	8	\$63.73	62	22	\$.070
1928	\$965	8	\$66.71	65	22	\$.068
1929	\$875	8	\$69.68	65	22	\$.069
1930	\$712	9	\$69.98	55	21	\$.052
1931	\$612	9	\$60.64	38	16	\$.038
1932	\$624	10	\$53.48	29	12	\$.050
1933	\$603	10	\$54.12	31	10	\$.044
1934	\$611	11	\$66.88	40	12	\$.046
1935	\$616	11	\$77.05	48	13	\$.049
1936	\$638	12	\$96.73	50	13	\$.053
1937	\$644	12	\$99.14	54	15	\$.053
1938	\$642	12	\$90.89	43	15	\$.052
1939	\$621	12	\$84.32	42	15	\$.051
1940	\$584	12	\$77.30	44	15	\$.050

- Notes: 1. Tractor prices are from hedonic index, with 1929 price equal to Farmall T.
2. Horse prices taken from average farm values, as reported in annual Agricultural Statistics.
3. Wage index and feed cost index taken from annual USDA parity data.
4. Fuel costs from BLS wholesale price series for kerosene.

Relative tractor prices were derived from the hedonic index generated in the previous chapter, with the 1929 value normalized to the \$875 purchase price of a Farmall 'T', the first and still dominant general purpose tractor at the time. Horse prices were taken from the average farm values reported in the annual issues of *Agricultural Statistics*. Fuel costs were adjusted using the BLS wholesale price series for kerosene, which dates back to 1913; recognizing that the retail prices farmers paid were approximately double the wholesale price, I used the USDA Corn-Belt study's figure of 13.9 cents per gallon for 1929, and estimated the other years' farm prices with the same markup as in that year. For farm labor and horse care, I used the farm wage component of the Index of Prices Paid and Received, an annual publication of the USDA; to adjust feed prices, I used the crop price component of the same annual publication.

With these annual series, extended from 1920 to 1945, I calculated appropriate thresholds for each year, comparing a large farm with six horses to the same farm using a tractor and four horses. The following equations summarize the calculations involved:

1. Fixed Cost (T) = Annual tractor cost + tractor repairs + implement premium +
4 * [annual horse cost + horse care + 70% of annual feed cost]
2. Fixed Cost (H) = 6 * [annual horse cost + horse care + 70% of annual feed cost]
3. Variable Cost (T) = feed cost per acre (T) + labor cost per acre (T) + fuel cost per acre
4. Variable cost (H) = feed cost per acre (H) + labor cost per acre (H)
5. Threshold acreage = [FC(T) - FC(H)] / [VC(H) - VC(T)]

The annual tractor cost can be determined from multiplying the purchase price by a rental rate, which in turn is found by $RR = r / (1 - e^{-rd})$, where r is the interest rate and d the service life.⁶²

The same type of calculation is used to find the annual horse cost. Tractor repairs were estimated at 2% of the purchase price, and a constant premium of \$10 per year was used to capture the somewhat higher costs of tractor implements versus their horse-drawn equivalents. Horse care, estimated at \$10.35 per year by Clarke, was adjusted up or down based on changes in the parity wage index. Feed, fuel, and labor costs were adjusted from the previous study based on movements in the corresponding price index. The fixed and variable costs calculated for the two schemes, along with the resulting thresholds, are shown here as Table 16.

For 1921 and 1922, there is no threshold calculation, primarily because the high price of fuel meant that tractors were actually higher in both fixed and variable cost for these years. This finding fits in well with the historical experience: during the agricultural depression of 1920-21, few tractors were sold, despite massive production by Ford. As a result, Ford dropped its price in 1921 quite dramatically, an event described in chapter 2 of this work. Within two years, the backlog was sold (perhaps to small farmers for whom the new lower price caused tractors to be temporarily fixed-cost saving?). The new data here suggests that lower gasoline and kerosene prices might have had as much to do with Ford's sales recovery as the price reduction.

⁶² This usage follows Whately, "Institutional Change", p. 206, and Clarke, *Regulation and the Revolution*, p. 271.

Table 16. Annual Threshold Calculations: 1923 - 1940

	Total FC w/ Tractor	Total FC w/ Horses	Feed Cost per Acre - H	Feed Cost per Acre - T	Labor Cost per Acre - H	Labor Cost per Acre - T	Fuel Cost per Acre - T	Total VC w/ Tractor	Total VC w/ Horses	Threshold (acres)
1923	\$505.89	\$427.85	\$0.94	\$0.42	\$3.01	\$2.38	\$1.12	\$3.93	\$3.95	3545.32
1924	\$495.40	\$426.68	\$0.94	\$0.42	\$3.16	\$2.50	\$0.65	\$3.57	\$4.10	129.80
1925	\$509.84	\$455.93	\$1.03	\$0.46	\$3.16	\$2.50	\$0.65	\$3.61	\$4.19	93.15
1926	\$499.02	\$434.48	\$0.96	\$0.43	\$3.31	\$2.62	\$0.64	\$3.69	\$4.27	111.70
1927	\$479.26	\$423.18	\$0.93	\$0.42	\$3.31	\$2.62	\$0.63	\$3.67	\$4.24	98.28
1928	\$480.48	\$440.57	\$0.97	\$0.44	\$3.31	\$2.62	\$0.61	\$3.67	\$4.28	65.09
1929	\$465.64	\$442.90	\$0.97	\$0.44	\$3.31	\$2.62	\$0.62	\$3.68	\$4.28	37.65
1930	\$391.00	\$390.11	\$0.82	\$0.37	\$3.16	\$2.50	\$0.47	\$3.34	\$3.98	1.38
1931	\$302.78	\$283.35	\$0.57	\$0.26	\$2.41	\$1.91	\$0.34	\$2.50	\$2.98	41.10
1932	\$256.72	\$221.28	\$0.43	\$0.19	\$1.81	\$1.43	\$0.45	\$2.07	\$2.24	214.20
1933	\$251.72	\$224.17	\$0.46	\$0.21	\$1.51	\$1.19	\$0.40	\$1.80	\$1.97	159.15
1934	\$287.74	\$284.50	\$0.60	\$0.27	\$1.81	\$1.43	\$0.41	\$2.11	\$2.40	11.07
1935	\$322.12	\$335.06	\$0.72	\$0.32	\$1.96	\$1.55	\$0.44	\$2.31	\$2.67	n. m.
1936	\$337.22	\$359.77	\$0.75	\$0.34	\$1.96	\$1.55	\$0.48	\$2.38	\$2.70	n. m.
1937	\$356.29	\$387.29	\$0.81	\$0.36	\$2.26	\$1.79	\$0.48	\$2.63	\$3.06	n. m.
1938	\$315.13	\$325.92	\$0.64	\$0.29	\$2.26	\$1.79	\$0.47	\$2.54	\$2.90	n. m.
1939	\$305.75	\$316.01	\$0.63	\$0.28	\$2.26	\$1.79	\$0.46	\$2.53	\$2.89	n. m.
1940	\$303.77	\$320.82	\$0.66	\$0.30	\$2.26	\$1.79	\$0.45	\$2.53	\$2.92	n. m.

- Notes: 1. Tractor repairs and chore labor estimated at 2% of tractor purchase price.
2. Premium for tractor implements versus horse implements maintained at \$10 per year.
3. Interest rate 7% from 1923-1932; 6% from 1933 onward.
4. Annual feed costs based on Clarke's 1929 value, adjusted for changes in crop price index.
5. Hourly labor rate, annual horse care costs based on Clarke's 1929 values, adjusted for changes in wage index.
6. Fuel cost per acre is based on Clarke's 1929 value, adjusting by ratio of wholesale fuel price to 1929 value (\$.07)
7. n. m. = not meaningful - calculated threshold is below zero, indicating tractor is fixed- and variable-cost saving.

Starting with 1923, a meaningful threshold can be calculated. The near parity between variable costs in the two modes produced a very high threshold in that year, but for the next four years, the number averaged about 108 acres. Beginning in 1928, the threshold fell rapidly, and by 1930, it appears that all sizes of corn farms should have been making plans to mechanize. Price changes during the Great Depression cause a dramatic reversal up to 1933, but within two more years, the continually falling hedonic price of the tractor has once again eliminated the threshold. By 1935, the tractor was fixed- and variable-cost saving according to this analysis; complete adoption should be expected to occur from that point onward.

The stability of the annual thresholds from 1924 to 1927 is quite intriguing. If one were to use 110 crop acres as the threshold for 1929, based on a 2-3 year lag due to vintage capital effects and farmers' hesitation to make a 'bet-the-farm' decision on a tractor, the adoption gap almost disappears. With crops making up about two-thirds of the land of a typical corn-belt farm, this 110 crop-acre farm would contain 165 total acres. According to data presented by Clarke, the farmer would cultivate, on average, 52 % of the acres in corn and 23% in oats, with the remaining cropland split among wheat, hay, and soybeans.⁶³

Two census sources can help evaluate how this new threshold compares with the tractor purchase experience of the corn belt states. In the 1925 and 1930 agricultural censuses, farms were sorted by size class, with the closest breakpoint to the 1925-28 threshold at 175 total acres.⁶⁴ The 1935 census featured detailed data on corn cultivation

⁶³ Clarke, *Regulation and the Revolution*, p. 276.

⁶⁴ Bureau of the Census, *United States Census of Agriculture: 1925* (Washington: USGPO, 1927), pp. 7-8.

- the farms in this year were also sorted into classes based on the acreage of corn raised.⁶⁵

A breakpoint at 55 corn acres is almost ideal for the current purpose. Table 17 compares the previously seen tractor adoption data to the 1925 and 1935 census farm statistics. It can easily be seen that there is no longer an adoption gap for 1929, as ownership of tractors exceeds the threshold levels in four out of the five corn-belt states.

Table 17. Tractor Adoption vs 1924-27 Threshold Levels.

State	% of farms with tractor - 1929	% of farms > 175 acres, 1925 Census	% of farms > 55ac corn, 1935 Census
Ohio	23.1	9.6	2.9
Indiana	22.3	13.4	8.1
Illinois	30.9	26.2	24.8
Iowa	29.4	31.3	31.9
Missouri	9.3	21.0	8.1

Source: Bureau of the Census, *United States Census of Agriculture, 1925* (Washington: U.S. Department of Commerce, 1927), pp. 6-13; Bureau of the Census, *United States Census of Agriculture 1935*, (Washington: U. S. Department of Commerce, 1936), p. 313.

Once again looking at the late 1920s threshold values, one is cheered by the fact that the 108 acre average is within the realm of the size of farms studied by the original USDA surveys. One of the problems with Clarke's conclusions is that she arrived at a threshold of 67 crop acres, which as I have demonstrated would have been about half that had she used a reasonable number for the tractor's purchase price. The threshold farm, then, was considerably smaller than any of the actual general purpose tractor farms surveyed, which

⁶⁵ Bureau of the Census, *United States Census of Agriculture 1935* (Washington: USGPO, 1936), p. 312-3.

were all greater than 100 crop acres. In effect, she was evaluating a farmer's decision to use either six horses or four horses and a tractor, and the threshold she came up with was too small to support either of the two options considered. In the USDA survey, tractorless farms with 60-99 crop acres used only four horses on average. With the annual thresholds calculated in this section, I have no concerns that citation of the USDA corn belt studies is appropriate.

When considering 1929 and 1930, where the thresholds are substantially lower, I would be much less willing to rely on crop studies done on 100+ acre farms. Unfortunately, I have not seen surveys or studies of small farms, with the wealth of data collected in the 1929-1930 efforts. A farmer that might have replaced one or two out of four horses with a tractor would likely have substantially different productivities, costs, and even cropping patterns than the large-scale farmers. Extrapolating the data from large farms could produce fairly large errors, and with the sensitivity of the threshold analysis to small changes in cost components, would very likely lead to erroneous results.

It seems entirely possible that on a very small farm, between 20 and 40 crop acres, perhaps, that a tractor could not completely replace any horses until the dominant design emerged in the mid-1930s. Horses were retained on farms until tractors were thought capable of taking over all farm tasks, including not only plowing and harvesting which had been available for a number of years, but also for cultivating and planting, which were newly possible with the general purpose tractors of the late 1920s. Planting or seeding was considered especially difficult, as early tractors had tended to compact the soil, thus reducing yields. The switch to rubber tires during the 1930s finally allowed tractors to

compete with horses in planting tasks; rubber-tired tractors could also travel on roads, allowing tractors to replace horses in off-farm wagon transport.

Once these capabilities were established, a small farm could eliminate its last or only team of horses, replacing them with a small tractor. It is no accident that manufacturing firms began selling so-called one-plow tractors in about 1934; these units were marketed for farms too small to use a standard-sized tractor efficiently, and sold for between \$500 and \$600 during this period. These small tractors had their own diffusion pattern which was substantially different than that of the tractors used on larger farms.

Conclusions

There are three conclusions which emerge from my re-evaluation of tractor adoption in light of the changing quality and technology of the 1920s and 1930s. First, the tractor diffusion studies published over the past 20 years, including Sally Clarke's carefully crafted and thoroughly researched work, fall short of providing convincing explanations due to their failure to adequately consider the quality factor. This paper has shown that Clarke's New Deal Regulation thesis loses much of its empirical support once properly comparable tractor purchase prices are used in the threshold analysis.

Secondly, I have attempted to answer Olmstead's challenge of diffusion models in general by demonstrating that threshold models can be a useful tool in attempting to understand the process of technological diffusion. By constructing and examining a series of annual thresholds for the use of tractors on large corn-belt farms, I have shown that the pattern of tractor adoption seen in a number of states closely matches that predicted by the

model. The disruptions caused by the Great Depression and output limitations imposed during World War II delayed the eventual complete tractorization of the Corn Belt until the post-war years.

Finally, it is imperative for anyone who attempts to use threshold models to explain diffusion to adequately consider the impact of changes in the product's own cost and quality. During the time that old and new technologies are competing, entrepreneurs, engineers, and production workers invest large amounts of effort in cost reduction, performance improvement, and provision of new and better features. The nature of the competition often induces improvement in the threatened technology, as well as forcing the prices and costs together. It is not surprising that fixed and variable costs are quite close, and therefore that the calculated thresholds are sensitive to small changes in one or more of these costs.

The implications of this work go far beyond tractors, reapers, and other agricultural machines. The huge set-up and shutdown costs and large amount of indivisible fixed capital in process industries such as chemicals, basic materials, and even pharmaceuticals indicate that threshold models should have a great deal of applicability across these industries and over time. Threshold models are one of the important techniques that researchers can use in attempting to understand the process of diffusion.

CHAPTER 6

EXTENSIONS AND APPLICATIONS

There are several important implication of this work that I explore in this final chapter. First, the example of the gasoline tractor should cause us to change the way we understand and model technological change. Doing so correctly, and in a way that will provide useful and provable conclusions about our economic world, will require considerably more complexity and generality than economists have achieved to date. Secondly, my work shows that studies of technological diffusion must consider quality and performance change over time in modeling the adoption process.

Thirdly, the mechanization of agriculture in the United States has not been copied or adapted in much of the world. Far too many countries today are inefficiently producing the food they consume, with negative impacts on their welfare and growth potential. A brief consideration of the elements of this successful transition in the United States may be useful in assessing the prospects for global progress in raising agricultural efficiency. I conclude with a discussion of my future research interests in these three important areas.

Implications for Understanding Technological Change

The preceding chapters have shown that the farm tractor made an important contribution to the growth of the United States during the middle part of the 20th century. However, the welfare benefits were generated quite slowly, mostly through releasing key resources such as labor to other productive uses. This process, in turn, followed increases in adoption, which were driven by improvements in performance, quality, and cost of the machines themselves. A similar analysis to the one detailed in Chapter 3, but covering the period only up to World War II, would show significantly lower social savings.

This example has important implications for the study of technology's role in driving economic growth. Assuming that the gasoline tractor arrived fully formed, like Athena springing from the brow of Zeus, is clearly inappropriate. Both Mokyr and Rosenberg have detailed the large and variable lags between the initial invention and widespread adoption of scores of new technologies throughout recent economic history.⁶⁵ Even if an appropriate date could be found for the tractor innovation, modeling it as a 'technology shock', an instantaneous change in farming's production function, would lead to erroneous conclusions in interpretation of relevant empirical data.

The alternative extreme, often called technological drift, is equally unsuitable in describing the tractor experience. The large number of important new inventions and technologies introduced in the early years of the 20th century and their steady rate of improvement led Simon Kuznets to conclude that no single invention or innovation was worth studying in isolation. In his view, technological change was a series of uncountable

⁶⁵ Examples can be found in Nathan Rosenberg, *Perspectives on Technology*, (Cambridge, England: Cambridge University Press, 1976), pp. 66-75; Mokyr, *The Lever of Riches*, p. 178-9.

small improvements, which together created the impressive increases in output, income, and consumer welfare that he spent years quantifying. Robert Fogel echoed the conclusion of his mentor in his critique of the indispensability of the railroad. He warned against "a hero theory of history applied to things rather than to persons"⁶⁶.

Although it is true that many large and small innovations combined to create the tractor's 'dominant design' of the late 1930s, there were not an uncountable number of them, nor were all of equal importance. The tractor was one of the most important applications of the internal combustion engine, a macro-invention by Mokyr's standards, perhaps even deserving the distinction as a technological hero.⁶⁷ In fact, the social savings in Chapter 3 could be interpreted as arising from the internal combustion engine; additional counterfactuals on the automobile and truck, which are largely separable, could lead to a realistic calculation of the welfare benefits from this key technological leap forward.

Within the developmental history of the tractor, a few key events, decisions, and micro-inventions were critical in moving the technology ahead:

1. The invention of the magneto around 1900 made it possible to start an internal combustion engine easily and reliably, and made automobiles and tractors alike usable by people without the specialized training that had been needed for previous modes of power, such as steam engines.

⁶⁶ Robert W. Fogel, *Railroads and American Economic Growth: Essays in Econometric History*, (Baltimore: The Johns Hopkins Press, 1964), p. 236.

⁶⁷ Mokyr adopted Goldschmidt's distinctions between macro- and micro-mutations in evolutionary biology in coining the term macro-invention. The phrase general-purpose-technology (GPT) is appearing more often in the current growth literature. Mokyr, *The Lever of Riches*, pp. 289-90.

2. Henry Ford's vision of a small, affordable tractor to free up horses for use in the First World War led to the first great boom in tractor sales. His entry into the tractor business shocked the agricultural implement companies that seemed a natural to dominate this emerging market. The intense competition forced them to completely change their approach to design, manufacture, and sales of their products, creating a much more cost-effective and efficient industry.

3. The row-cropping International Harvester Farmall introduced in the mid-1920s launched tractors into planting, cultivating, and fertilizing tasks long considered too delicate for machines to handle. This advance ultimately made it possible to eliminate animal power from farming completely, a situation not even considered by the agricultural experts of the 1920s. A special report of the 1930 Census even warned that the tractor had created such a massive decline in work horse breeding that animal stocks would not be able to recover when the inevitable expansion in demand arrived, driven by increases in population and crop cultivation.⁶⁸

4. The development of rubber tires to replace steel wheels on tractors had two important effects. Reduction in rolling friction without loss of traction meant that a far greater proportion of the engine's power was available at the drawbar for pulling loads. On steel wheeled tractors, the drawbar horsepower averaged 75% of the belt value; the same machine on rubber tires would be rated by the Nebraska tests at up to 95% of the belt horsepower.

⁶⁸ Bureau of the Census, *Fifteenth Census of the United States, 1930, Agriculture, Special Report: The Farm Horse*, (Washington: U. S. Government Printing Office, 1933).

In addition, rubber tires made it possible to drive tractors on paved roads. As manufacturers began providing a fifth gear for travel at 15-20 mph, tractors could be driven between remote fields or even haul products to town. This increase in the mobility and versatility of the farmer was an important enabling factor in the expansion in the size of farms, a notable change in the post-WWII era.

Extensions to Other Technologies

More generally, this tractor experience is typical of the adoption pattern in many important new technologies. As any reasonably aware adult (or child) knows, computers have increased incredibly in speed and capability in the 75 years of their existence. No macroeconomist would ever attempt to describe their emergence as a single technology shock, followed by a re-adjustment to long-run equilibrium. Within this developmental period, however, a few major innovations mean that the rate of technological improvement has been quite uneven. The integrated circuit, CRT screen, personal computer, internal hard disk drive, and CD-Rom are all arguably advances that disrupted any underlying gradual changes.

In much the same way, optical fiber for communication has continually evolved since its commercial launch in the late 1970s.⁶⁹ A technology invented by Thomas Edison in the 1870s, optical fibers were long limited by an inability to make glass pure enough to transmit light long distances. Two related advances, the laser and vapor-phase glass

⁶⁹ This next section is based on the author's personal experience in the fiber optic industry and his unpublished Master's thesis, *The Strategic Evolution of the Fiber Optics Industry*. Details are available upon request.

deposition, served as enabling inventions for the technical and commercial development of optical communication.

Initial manufacturing efforts by AT&T and Corning Glass Works, were fairly disappointing. Low production yields and poor performance meant that conventional sound transmission through copper wires was still lower cost for most applications. Fiber had a competitive advantage only in areas where electromagnetic interference raised the cost and degraded the performance of copper wire.⁷⁰

Substantial research and development effort, led by engineers and scientists both in laboratories and in the production facilities, created a series of innovations that produced better performance and lower cost. Yields of fiber meeting specifications on attenuation (loss of signal) and tensile strength were increased from less than 20% to more than 90% in a period of less than two years. In other words, with no increases in any of the inputs (aside from the development of a large stock of human capital), output increased by almost 500%!⁷¹ Clearly a model that provided for these non-convexities without insisting on exogenously determined increases in technology or stochastic probabilities of success would be a significant step forward in our understanding of actual technological change.

Implications for Modeling of Diffusion

The analysis in Chapters 5 and 6 challenged the threshold models most often used to describe the adoption of new technologies. The failure of tractor researchers to

⁷⁰ Optical transmission through glass is immune to electromagnetic interference; for example, cross-talk is not experienced in all optical networks.

⁷¹ This same experience was typical of early microprocessor fabrication, as yields of 'good' chips increased from less than 2% to more than 10%.

adequately account for changes in the product's own price and performance led to erroneous conclusions about the functioning of markets and impacts of policy initiatives. This result also can be broadened beyond the example of farm tractors.

Paul David's celebrated study of the reaper includes a similar assumption of unchanging quality.⁷² In his analysis, David describes a lag of 20 years from McCormick's invention of the reaper in 1831 to its widespread adoption in the 1850s, suggesting that it was an invention ahead of its time. Upon construction and analysis of a threshold model, David concludes that increases in farm size combined with changes in factor prices to create the 'delayed' adoption.

A closer look at reaper availability, cost, and performance casts doubt on this diffusion story. The twenty-year lag was an artifact, not of inadequate demand, but of the lack of a producing firm! Cyrus McCormick tinkered with his new invention for 15 years after its initial demonstration, struggling to make changes that he thought would improve its performance.⁷³ He sold his first units in 1840, but was not sufficiently pleased with them to make a significant investment in production until his decision to relocate from Virginia to Chicago in 1847.⁷⁴

Armed with a new and better design, McCormick constructed a factory in Illinois in 1848 with working capital borrowed from a few friends, and began selling reapers in

⁷² David, "The Mechanization of Reaping".

⁷³ Cyrus McCormick, *The Century of the Reaper*, (Boston: Houghton Mifflin, 1931).

⁷⁴ McCormick's great rival and court opponent, Obed Hussey, was an Ohio minister and part-time reaper manufacturer. He didn't make a commitment to large-scale production during that period either, selling about 400 units from 1840-49. Source is Leo Rogin, *The Introduction of Farm Machinery in its Relation to the Productivity of Labor in the Agriculture of the United States during the Nineteenth Century*, University of California Publications in Economics: Volume 9, (Berkeley: University of California Press, 1931), pp. 73-4.

earnest. The factory seems to have reached full operation in 1850, just the time David notes that reaper sales began to increase in the Mid-west. Within a few years, the factory had expanded several times to meet demand, and imitators had built plants to compete with McCormick.

With much of the 'lag' accounted for by the lack of a product of sufficient quality to sell, the diffusion in the 1850s is related to cost and quality factors also not considered by David. Olmstead has suggested that the expected life may have increased from 5 to 10 years during this period, with a major impact on the threshold calculations.⁷⁵ In a notorious case, an implement magazine publisher who entered the production arena made a number of reapers out of green wood and sold them to an unsuspecting public. When the wood dried out, the resulting warping rendered the units inoperable. Farmers demanded refunds, and the publisher was driven into bankruptcy.⁷⁶

Implications for Mechanization in other Countries

Much of the developed world has mechanized its agriculture to the same extent as the United States. Even in Japan, with considerable topographical barriers to large machines and a tradition of labor-intensive farming, small tractors have replaced much of the manual labor common even 20 years ago.⁷⁷ Still, there are large parts of the world consuming

⁷⁵ Olmstead, "The Mechanization of Reaping and Mowing."

⁷⁶ In a future work, I will explore the details of changes in the cost structure of reapers, in a manner similar to the effort on tractors in Chapter 5.

⁷⁷ Yujiro Hayami and Vernon W. Ruttan wrote an influential book, *Agricultural Development: An International Perspective*, (Baltimore: The Johns Hopkins Press, 1971), which claimed that there were two equally productive paths to agricultural productivity; the optimal choice depended on relative prices of labor and capital. They ignored the fact that increasing incomes must raise the reservation wage of agricultural workers. 'Cheap' labor is incompatible with high incomes and living standards.

food that is produced with rudimentary techniques, often involving neither animal nor machine power. The U. S. experience detailed in this dissertation details offers some rationale and direction for improving this situation.

Firstly, there are great gains to a nation from consuming food that is produced efficiently. By replacing draft animals that consumed one-quarter of the output they helped to produce, the productivity of U.S. agriculture increased sufficiently to raise incomes in the entire nation by almost 9%. If this type of productivity increase can be achieved by a developing country through mechanization, it should prove well worth the investment.

If soil, climate, and/or infrastructure is insufficient to yield efficient food production, perhaps the nation should purchase its food from an area of the world that is growing and harvesting food productively. Transport costs will certainly reduce the net benefit, but city-states like Honk Kong and Singapore have benefited significantly from this practice.⁷⁸ It is, of course, imperative that the local work force be capable of producing goods or services of sufficient value in trade to pay for the imported food.

In a similar vein, mechanization can only achieve its full benefits if alternative employment can be found for the resources freed up. Regional and distributional impacts are inevitable with such a large transfer of economic activity. In the case of labor, the reallocation proceeded very smoothly in the United States. With few alternative employment, horses (and pasture land) did not fare as well.

⁷⁸ In this respect, the Asian city-states of today are much like Rome, Athens, or Paris in the past, relying on extensive hinterlands to grow the food eaten by those in the city.

One of the hidden advantages in the U.S. experience was that the farmers were rather well educated, except in some parts of the South. The skills which made a Mid-western farmer successful created good job prospects when they were released from agriculture: financial experience from managing a farm business; mechanical know-how from repairing binders, mowers, and other complicated equipment; formal education at least through eighth grade, facilitated by leisure time in the winter months. It is not a coincidence that branch manufacturing plants sprang up all over the Mid-Atlantic and North Central states in the 1950s and 1960s. The available local work force was hard-working, loyal, and highly skilled.

Finally, government programs which prop up marginal farmers or otherwise distort market signals often do much more harm than good. The diffusion analysis in Chapter 5 shows that Clarke's claim that New Deal programs promoted tractorization is not supported by the data. In fact, by providing loans to farmers who otherwise would have left agriculture, by preventing prices from falling to the free-market level, and by artificially promoting exports through subsidies, government programs more likely delayed mechanization. This is in sharp contrast to the beneficial effects of the agricultural experiment stations' work shown by Griliches in his analysis of corn hybridization.⁷⁹

Future Research Interests

There are several natural extensions of this work that I plan to pursue in future research. I would like to develop alternate methods for calculating welfare benefits from

⁷⁹ Griliches, "Hybrid Corn."

adoption of the tractor, as has been done for several other innovations by empirical researchers. In addition, by breaking out the social savings by region within the United States, I should be able to shed additional light on factors that promoted or hindered tractor diffusion. Finally, the social savings methodology developed here can likely be applied to estimate the impact of other significant technological advances.

Researchers attempting to assess the importance of discrete innovations have calculated consumer surplus directly from available data by estimating supply and demand functions. The best known of these efforts are that of Zvi Griliches for hybrid corn and Schmitz and Seckler for the tomato harvester.⁸⁰ The degree of governmental distortion in farm prices since the Depression period of tractor diffusion makes such a calculation problematic in the case of the tractor, however. Fortunately, Manuel Trajtenberg has provided an alternate means of estimating consumer surplus in his study of CT scanners.⁸¹

In this work, Trajtenberg obtained not only technical information and sales quantities, but also a complete record of all purchases, including the actual price paid. With this data, he was able to use a 'characteristic' approach to calculate welfare benefits directly. A price index based on the change in consumer surplus fell far more rapidly than a hedonic index which was also estimated, especially in the early years of production when the hedonic regressions failed to capture much of the benefits from new and unique features.

The hedonic literature indicates that welfare assessments through the characteristic approach succeed only if the data-set is essentially complete; if significant producers or

⁸⁰ Griliches, "Hybrid Corn" and Schmitz and Seckler, "Mechanized Agriculture and Social Welfare."

⁸¹ Manuel Trajtenberg, *Economic Analysis of Product Innovation: the Case of CT Scanners* (Cambridge, Massachusetts: Harvard University Press, 1990).

models are missing, the results can be seriously misleading. In order to use a modification of Trajtenberg's approach to analyze tractor adoption, I will need to improve the completeness of my data in the years immediately after commercial introduction, 1902-18.

A second opportunity for future work is in analyzing regional variations in social savings and tractor diffusion. In his hybrid corn study, Griliches attempted to explain regional differences in the rate of adoption through economic factors such as profitability of farms and the quantity of agricultural extension effort. My work suggests that similar factors might have had an impact on the rate of mechanization, in addition to the magnitude of the social savings generated in the region. Data are available to perform this same analysis at the state or census-region level. Such an undertaking could help to definitively decide the equilibrium vs. disequilibrium debate started by David and Griliches almost 40 years ago.

Lastly, it is likely that the same type of counterfactual estimate as in Chapter 3 could be extended to the Green Revolution in the United States, which began before World War II and was not complete until almost 1980. A reduction of labor inputs of roughly equal magnitude to mechanization, along with a vast decrease in land usage per unit of output, would likely lead to social savings estimates as large as that calculated above. With this effort, the adverse social consequences from land and town abandonment would require explicit calculations, as ultimate adjustments are not complete even today.

In similar fashion, the 19th century mechanization of U. S. agriculture, involving the adoption of reaper, mower, thresher, and many horse drawn cultivating implements brought about the first significant shift out of agriculture. These devices allowed farmers

to grow enough crops above subsistence level so that, once transportation costs were driven down, large numbers of city dwellers could afford to work in commerce and industry, and buy their food at the market. Although data availability and accuracy would be quite challenging, I believe that census information should be sufficient to develop an order-of-magnitude estimate of social savings from these technologies.

This type of analysis, if its basic approach is accepted, should be a useful way to evaluate the effects of a numbers of general purpose technologies: the electric motor and/or dynamo, the internal combustion engine, the use of steam engines in transport, as opposed to Fogel's counterfactual on railroads alone. As the consumer needs met by these devices are not as fundamental (or as inelastically demanded) as food, I expect that there will be additional challenges in correctly specifying both the production technology and the nature of demand substitution. Nonetheless, the effort should pay benefits in increasing our understanding of the 'lumpiness' of innovation, and thus the value of the contribution of individual inventions, inventors, and entrepreneurs.

Finally, I have a great deal of interest in working to develop models which can mathematically describe the evolutionary process described in this work. Perhaps with growth theorists working from the direction of equilibrium-based convex models, and technological historians such as Mokyr and Rosenberg bringing insights from evolutionary biology and engineering, there will be a meeting somewhere in the middle with a rich model that adequately describes reality. I would like to be a part of that process.

Final Thoughts

I conclude with a few final thoughts. If the endogenous growth theorists are correct and innovations arrive in large numbers at a steady rate, then perhaps it does not make sense to study any one particular technology. The focus on human capital accumulation, encouragement of government-sponsored basic research, and provision of incentives for spending R&D capital may be all that governments and their economic advisors can do. If, on the other hand, technological innovation is lumpy, with some advances clearly more important than others, and especially if entrepreneurs are the primary agents of change, then there may a role for studying the more important inventors and inventions of the past. In his critique of the historians who believed the railroad to be indispensable, Fogel attempted to eliminate the hero worship that he feared would invade economic history. Although it appears he was correct in disputing the railroad's right to claim superiority in its day, I believe that I have found, in the farm tractor, an unsung hero.

LIST OF REFERENCES

- Abramovitz, Moses, "Resources and Output Trends in the United States Since 1870," *American Economic Review, Papers and Proceedings* 46:2 (May, 1956) pp. 5-23.
- Aghion, Phillipe and Peter Howitt, "A Model of Growth through Creative Destruction," *Econometrica* 60 (March, 1992), pp. 323-51.
- Aghion, Phillipe and Peter Howitt. *Endogenous Growth Theory*. Cambridge, Massachusetts: MIT Press, 1998.
- Ankli, Robert E., "Horses vs. Tractors on the Corn Belt," *Agricultural History* 54 (Jan. 1980), pp. 134-148.
- Ankli, Robert E. and Alan L. Olmstead, "The Adoption of the Gasoline Tractor in California," *Agricultural History* 55 (July 1981), pp. 213-30.
- Antle, John M. *World Agricultural Development and the Future of U. S. Agriculture*. Washington: American Enterprise Institute, 1988.
- Berardi, Gigi M., and Charles C. Geisler, editors. *Social Consequences and Challenges of New Agricultural Technology*. Boulder, Colorado: Westview Press, 1984.
- Berck, Peter, "A Note on the Real Cost of Tractors in the 1920s and 1930s," *Agricultural History* 59:1 (January, 1985), pp. 66-71.
- Boskin, Michael J., E. Dulberger, R. Gordon, Z. Griliches and D. Jorgenson. *Toward a More Accurate Measure of the Cost of Living: The Final Report of the Advisory Committee to Study the Consumer Price Index*. U. S. Senate Committee on Finance. Washington: Government Printing Office, 1996.
- Bresnahan, Timothy F, and Robert J. Gordon, editors. *The Economics of New Goods*. Chicago: The University of Chicago Press, 1997.
- Brodell, Albert P. and R. A. Pike. *Farm Tractors: Type, Size, Age, and Life*. Washington: U. S. Department of Agriculture, Bureau of Agricultural Economics and Agricultural Marketing Service, 1942.
- Brodell, Albert P. and Albert R. Kendall. *Life of Farm Tractors*. Washington: U. S. Department of Agriculture, Bureau of Agricultural Economics, 1950.
- Broehl, Wayne G., Jr. *John Deere's Company*. New York: Doubleday, 1984.

- Bureau of the Census. *Thirteenth Census of the United States: Agriculture*. Washington: U. S. Department of Commerce, 1911.
- Bureau of the Census. *Census of Manufactures, 1923*. Washington: U.S. Government Printing Office, 1923.
- Bureau of the Census. *United States Census of Agriculture 1925*. Washington: U. S. Department of Commerce, 1927.
- Bureau of the Census. *Fifteenth Census of the United States, 1930, Agriculture, Volume II, Part 1*. Washington: U. S. Department of Commerce, 1932.
- Bureau of the Census. *Fifteenth Census of the United States, 1930, Agriculture, Special Report: The Farm Horse*. Washington: U. S. Government Printing Office, 1933.
- Bureau of the Census. *United States Census of Agriculture 1935*. Washington: U. S. Department of Commerce, 1936.
- Bureau of the Census. *Sixteenth Census of the United States: Agriculture*. Washington: U. S. Department of Commerce, 1941.
- Bureau of the Census. *United States Census of Manufactures 1954*. Washington: U. S. Department of Commerce, 1955.
- Bureau of the Census. *United States Census of Agriculture 1954*. Washington: U. S. Department of Commerce, 1955.
- Bureau of the Census. *Historical Statistics of the United States, Colonial Times to 1970. Volume I*. Washington: U. S. Department of Commerce, 1975.
- Changes in Farm Production and Efficiency*. Statistical Bulletin No. 233, Revised. Washington: U. S. Department of Agriculture, 1961.
- Clarke, Sally, "New Deal Regulation and the Revolution in American Farm Productivity: A Case Study of the Diffusion of the Tractor in the Corn Belt, 1920-1940," *The Journal of Economic History*, 51(Mar. 1991) 101-123.
- Clarke, Sally H. *Regulation and the Revolution in United States Farm Productivity*. Cambridge: Cambridge University Press, 1994.
- Coatsworth, John H. *Growth Against Development: The Economic Impact of Railroads in Porfirian Mexico*. DeKalb, Illinois: Northern Illinois University Press, 1981.
- Court, Andrew, "Hedonic Price Indexes with Automotive Examples," in *The Dynamics of Automobile Demand*, General Motors Corporation, ed. New York: General Motors Corporation, 1939, pp. 99-117.
- Csorba, Julius J. *Farm Tractors: Trends in Type, Size, Age, and Use*. Agricultural Information Bulletin No. 231. Washington: U. S. Department of Agriculture, 1960.
- Danbom, David B. *Born in the Country: A History of Rural America*. Baltimore: The Johns Hopkins University Press, 1995.

- David, Paul A., "The Mechanization of Reaping in the Antebellum Midwest," in Henry Rosovsky, ed. *Industrialization in Two Systems: Essays in Honor of Alexander Gerschenkron*. New York: Wiley, 1966, pp. 3-39.
- Deere & Company. *John Deere Tractors: 1918-1994*. St. Joseph, Michigan: American Society of Agricultural Engineers, 1994.
- Denison, Edward F. *Accounting for United States Economic Growth 1929 – 1969*. Washington: The Brookings Institution, 1974.
- Erb, David and Eldon Brumbaugh. *Full Steam Ahead: J. I. Case Tractors & Equipment 1842 – 1955*. St. Joseph, Michigan: American Society of Agricultural Engineers, 1993.
- Farm & Implement News 52:26 (July 2, 1931).
- Farm Employment: Monthly by States 1950-57, United States by Years 1910-57, by Months 1940-57*. Statistical Bulletin No. 236. Washington: U. S. Department of Agriculture, 1958.
- Farm Labor*. U. S. Department of Agriculture, Agricultural Marketing Service. Washington: U. S. Department of Agriculture, July 1955.
- Federal Trade Commission. *Report of the Federal Trade Commission on the Causes of High Prices of Farm Implements*. Washington: U. S. Government Printing Office, 1920.
- Federal Trade Commission. *Report on the Agricultural Implement and Machinery Industry*. Washington: U. S. Government Printing Office, 1938.
- Federal Trade Commission. *Report of the Federal Trade Commission on Manufacture and Distribution of Farm Implements*. Washington: U. S. Government Printing Office, 1948.
- Fettig, Lyle P. *Price Indexes for New Farm Tractors in the Postwar Period*. PhD Dissertation, University of Chicago Department of Economics, 1963.
- Fishlow, Albert. *American Railroads and the Transformation of the Ante-bellum Economy*. Cambridge: Harvard University Press, 1965.
- Fite, Gilbert C. *American Farmers: The New Minority*. Bloomington, Indiana: Indiana University Press, 1981.
- Fogel, Robert W., "A Quantitative Approach to the Study of Railroads in American Economic Growth: A Report of Some Preliminary Findings." *The Journal of Economic History* 22:2, June 1962, pp. 163-97.
- Fogel, Robert W. *Railroads and American Economic Growth: Essays in Econometric History*. Baltimore: The Johns Hopkins Press, 1964.
- Fogel, Robert W., "Notes on the Social Saving Controversy." *The Journal of Economic History* 39:1, March 1979, pp. 1-54.
- Fraser, Colin. *Tractor Pioneer: The Life of Harry Ferguson*. Athens, Ohio: Ohio University Press, 1973.

- Fulton, Craig V., Earl O. Heady, and George E. Ayres. *Farm Machinery Costs in Relation to Machinery and Farm Size*. Ames, Iowa: Iowa State University, 1978.
- Gordon, Robert J. *The Measurement of Durable Goods Prices*. Chicago: University of Chicago Press, 1990.
- Gray, R. B. *The Agricultural Tractor: 1855 - 1950*. St. Joseph, Michigan: American Society of Agricultural Engineers, 1954 (revised, 1975).
- Gregor, Howard F. *Industrialization of U. S. Agriculture: An Interpretive Atlas*. Boulder, Colorado: Westview Press, 1982.
- Griliches, Zvi, "The Demand for a Durable Input: Farm Tractors in the United States, 1921-57," in Arnold C. Harberger, ed., *The Demand for Durable Goods*. Chicago: The University of Chicago Press, 1960.
- Griliches, Zvi, "Measuring Inputs in Agriculture: A Critical Survey" *Journal of Farm Economics* 42:2 (May 1960), pp. 1411-33.
- Griliches, Zvi, "Hybrid Corn and the Economics of Innovation." *Science* (July 19, 1960) pp. 275-280.
- Griliches, Zvi, "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in *Price Indexes and Quality Change: Studies in New Methods of Measurement*, Zvi Griliches, ed. Cambridge, Massachusetts: Harvard University Press, 1961.
- Griliches, Zvi, "The Sources of Measured Productivity Growth: United States Agriculture, 1940-60," *Journal of Political Economy* 71 (July, 1963), pp. 331-46.
- Griliches, Zvi and Irma Adelman, "On an Index of Quality Change," *Journal of the American Statistical Association* (September 1961), pp. 535-548.
- Grossman, Gene M. and Elhanan Helpman. *Innovation and Growth in the Global Economy*. Cambridge, Massachusetts: MIT Press, 1991.
- Haessel, Walter W., Earl O. Heady, and Leo V. Mayer. *A Five Sector Model of Agricultural Development, Industrialization, and Food Aid in a Dual Economy*. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, 1972.
- Harberger, Arnold C., "A Vision of the Growth Process," *American Economic Review* 88:1 (March, 1998) pp. 1-32.
- Hayami, Yujiro and Vernon W. Ruttan. *Agricultural Development: An International Perspective*. Baltimore: The Johns Hopkins Press, 1971.
- Heady, Earl O., "Extent and Conditions of Agricultural Mechanization in the United States," in J. L. Meij, ed. *Mechanization in Agriculture*. Chicago: Quadrangle Books, 1960, pp. 63-97.
- Heady, Earl O., ed. *Economic Models and Quantitative Methods for Decisions and Planning in Agriculture*. Ames, Iowa: The Iowa State University Press, 1971.
- Heady, Earl O. and John L. Dillon. *Agricultural Production Functions*. Ames, Iowa: Iowa State University Press, 1961.

- Heady, Earl O., Edwin O. Haroldsen, Leo V. Mayer, and Luther G. Tweeten. *Roots of the Farm Problem*. Ames, Iowa: The Iowa State University Press, 1965.
- Heady, Earl O., Glenn L. Johnson, and Lowell S. Hardin, eds. *Resource Productivity, Returns to Scale, and Farm Size*. Ames, Iowa: The Iowa State College Press, 1956.
- Higbee, Edward. *Farms and Farmers in an Urban Age*. New York: The Twentieth Century Fund, 1963.
- The Hired Farm Working Force of 1954*. Agricultural Marketing Service #103. Washington: U. S. Department of Agriculture, 1956.
- Hopkins, John A. *Changing Technology and Employment in Agriculture*. Washington: U. S. Department of Agriculture, Bureau of Agricultural Economics, May, 1941.
- Hot Line Farm Equipment Guide – Quick Reference Guide*, 14th Edition. Fort Dodge, Iowa: Heartland Ag-Business Group, 1995.
- Hurst, W. M. and L. M. Church. *Power and Machinery in Agriculture*. U. S. Department of Agriculture Miscellaneous Publication No. 157. Washington: U. S. Government Printing Office, 1933.
- James, John A. and Mark Thomas, eds. *Capitalism in Context: Essays on Economic Development and Cultural Change in Honor of R. M. Hartwell*. Chicago: The University of Chicago Press, 1994.
- Jasny, Naum. *Research Methods on Farm Use of Tractors*. New York: Columbia University Press, 1938.
- Johnson, D. Gale and Robert L. Gustafson. *Grain Yields and the American Food Supply*. Chicago: University of Chicago Press, 1962.
- Johnson, A. N., "The Impact of Farm Machinery on the Farm Economy," *Agricultural History* 24:1 (January, 1950), pp. 58-62.
- Johnson, Paul C. *Farm Inventions in the Making of America*. Des Moines: Wallace-Homestead, 1976.
- Johnson, Paul C. *Farm Power in the Making of America*. Des Moines: Wallace-Homestead, 1978.
- Jones, Fred R. *Farm Gas Engines and Tractors*, 4th edition. New York: McGraw-Hill, 1966.
- Kelley, Allen C., Warren C. Sanderson, and Jeffrey G. Williamson, eds. *Modeling Growing Economies in Equilibrium and Disequilibrium*. Durham, North Carolina: Duke Press Policy Studies, 1983.
- Karolevitz, Robert F. *Old Time Agriculture in the Ads*. Aberdeen, South Dakota: North Plains Press, 1970.
- Klancher, Lee. *Farmall Tractors*. Osceola, Wisconsin: Motorbooks International, 1995.

- Klancher, Lee. *International Harvester Photographic History*. Osceola, Wisconsin: Motorbooks International, 1996.
- Leffingwell, Randy. *John Deere Farm Tractors*. Osceola, Wisconsin: Motorbooks International, 1993.
- Leffingwell, Randy. *Classic John Deere Tractors*. Osceola, Wisconsin: Motorbooks International, 1994.
- Leffingwell, Randy. *Farm Tractors, A Living History*. Osceola, Wisconsin: Motorbooks International, 1995.
- Letourneau, Peter. *John Deere General Purpose Tractors, 1928-1953*. Osceola, Wisconsin: Motorbooks International, 1993.
- Ling, Peter J. *America and the Automobile: Technology, Reform, and Social Change*. Manchester (UK): Manchester University Press, 1990.
- Loomis, Ralph A. and G. T. Barton. *Productivity of Agriculture in the United States: 1870 - 1958*. Technical Bulletin No. 1238. Washington: U. S. Department of Agriculture, 1961.
- Major Statistical Series of the U. S. Department of Agriculture*. Agricultural Handbook No. 118. Washington: U. S. Department of Agriculture, 1957-60.
- Mann, Jitendar S. and George E. St. George, *Estimates of Elasticities for Food Demand in the United States*. Technical Bulletin 1580. Washington: U. S. Department of Agriculture, 1978.
- Margo, Robert A. "The Rental Price of Housing in New York City, 1830-1860," *The Journal of Economic History* 56 (1996), pp. 605-25.
- Margo, Robert A. and Georgia C. Villaflor, "The Growth of Wages in Antebellum America: New Evidence," *The Journal of Economic History* 47 (1987), pp. 873-95.
- McCormick, Cyrus. *The Century of the Reaper*. Boston: Houghton Mifflin, 1931.
- McInnis, R. M., "Output and Productivity in Canadian Agriculture, 1870-71 to 1926-27," in *Long-Term Factors in American Economic Growth*, Stanley L. Engerman and Robert E. Gallman, editors. Chicago: The University of Chicago Press, 1986, pp. 737-78.
- McKinley, Marvin. *Wheels of Farm Progress*. St. Joseph, Michigan: American Society of Agricultural Engineers, 1980.
- Meij, J. L., ed. *Mechanization in Agriculture*. Chicago: Quadrangle Books, 1960.
- Mills, Robert K., ed. *Implement & Tractor*. Overland Park, Kansas: Intertec Publishing, 1986.
- Mokyr, Joel. *The Lever of Riches: Technological Creativity and Economic Progress*. New York: Oxford University Press, 1990.
- Mokyr, Joel. *Twenty-Five Centuries of Technological Change: An Historical Survey*. Chur, Switzerland: Harwood Academic Publishers, 1990.

- Mokyr, Joel. "Progress and Inertia in Technological Change," in John A. James and Mark Thomas, eds. *Capitalism in Context: Essays on Economic Development and Cultural Change in Honor of R. M. Hartwell*, (Chicago: The University of Chicago Press, 1994), pp. 230-54.
- National Tractor and Farm Implement Blue Book*, 1951 Edition. Chicago: National Market Reports, Inc., 1951.
- Neufeld, E. P. *A Global Corporation: A History of the International Development of Massey-Ferguson, Limited*. Toronto: University of Toronto Press, 1969.
- Nevins, Allan and Frank Ernest Hill. *Ford: Expansion and Challenge: 1915 – 1933*. New York: Charles Scribner's Sons, 1957.
- Nevins, Allan and Frank Ernest Hill. *Ford: Decline and Rebirth: 1933 – 1962*. New York: Charles Scribner's Sons, 1962.
- North, Douglass C. *Structure and Change in Economic History*. New York: W. W. Norton & Co., 1981.
- Olmstead, Alan L. "The Mechanization of Reaping and Mowing in American Agriculture, 1833-1870," *The Journal of Economic History* 35 (June 1975), pp. 327-52.
- Olmstead, Alan L. and Paul W. Rhode. "Beyond the Threshold: An Analysis of the Characteristics and Behavior of Early Reaper Adopters," *The Journal of Economic History* 55 (March 1995), pp. 27-57.
- Peterson, Walter F. *An Industrial Heritage: Allis-Chalmers Corporation*. Milwaukee: Milwaukee County Historical Society, 1976.
- Peterson, Willis L., "Returns to Poultry Research in the United States." *Journal of Farm Economics* 3 (1967), pp. 656-69.
- Platt. *Platt's Oil Price Handbook and Oilmanac*, 63rd edition, 1986. New York: McGraw-Hill, 1987.
- Pripps, Robert N. *Farmall Tractors*. Osceola, Wisconsin: Motorbooks International, 1993.
- Pripps, Robert N. *Illustrated Ford and Fordson Tractor Buyer's Guide*. Osceola, Wisconsin: Motorbooks International, 1995.
- Pripps, Robert N. *Illustrated International Harvester Tractor Buyer's Guide*. Osceola, Wisconsin: Motorbooks International, 1995.
- Pripps, Robert N. *Vintage Ford Tractors*. Stillwater, Minnesota: Voyageur Press, 1996.
- Pripps, Robert N. and Andrew Morland. *Oliver Tractors*. Osceola, Wisconsin: Motorbooks International, 1994.
- Raff, Daniel M. G., and Manuel Trajtenberg. "Quality-Adjusted Prices for the American Automobile Industry: 1906 – 1940," in Timothy F. Bresnahan and Robert J. Gordon, eds., *The Economics of New Goods*. Chicago: The University of Chicago Press, 1997, pp. 71-101.

- Rasmussen, Wayne D. *Agriculture in the United States: A Documentary History. Volume 3.* New York: Random House, 1975.
- Reynoldson, L. A. *Utilization and Cost of Power on Mississippi and Arkansas Delta Plantations.* U. S. Department of Agriculture Technical Bulletin No. 497. Washington: U. S. Government Printing Office, 1935.
- Reynoldson, L. A., W. R. Humphries, S. R. Speelman, E. W. McComas, and W. H. Youngman. *Utilization and Cost of Power on Corn Belt Farms.* U. S. Department of Agriculture Technical Bulletin No. 384. Washington: U. S. Government Printing Office, 1933.
- Rogin, Leo. *The Introduction of Farm Machinery in its Relation to the Productivity of Labor in the Agriculture of the United States during the Nineteenth Century.* University of California Publications in Economics: Volume 9. Berkeley: University of California Press, 1931.
- Romer, Paul M., "Increasing Returns and Long-Run Growth," *Journal of Political Economy* 94 (October, 1986), pp. 1002-37.
- Romer, Paul M., "Are Nonconvexities Important for Understanding Growth?," *American Economic Review* 80 (May, 1990), pp. 97-103.
- Rosen, Sherwin, "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition," *Journal of Political Economy* 82 (January, 1974), pp. 34-55.
- Rosenberg, Nathan. *Technology and American Economic Growth.* New York: Harper & Row, 1972.
- Rosenberg, Nathan. *Perspectives on Technology.* Cambridge: Cambridge University Press, 1976.
- Rosenberg, Nathan. *Inside the Black Box: Technology and Economics.* Cambridge: Cambridge University Press, 1982.
- Rosenberg, Nathan. *Exploring the Black Box: Technology, Economics, and History.* Cambridge: Cambridge University Press, 1994.
- Rosenberg, Nathan, ed. *The Economics of Technological Change.* Harmondsworth, England: Penguin Books, 1971.
- Royal Commission on Farm Machinery. *Farm Tractor Production Costs: A Study in Economies of Scale.* Ottawa: Queen's Printer for Canada, 1969.
- Salter, W. E. G. *Productivity and Technical Change*, 2nd edition. Cambridge: Cambridge University Press, 1966.
- Sanders, Ralph W. *Vintage Farm Tractors.* Stillwater, Minnesota: Voyageur Press, 1996.
- Sargen, Nicholas Peter. *"Tractorization" in the United States and its Relevance for the Developing Countries.* New York: Garland Publishing, 1979.
- Schmitz, Andrew and David Seckler, "Mechanized Agriculture and Social Welfare: The Case of the Tomato Harvester", *American Journal of Agricultural Economics* 52:4 (November, 1970), pp. 569-77.

- Schultz, Theodore W. *The Economic Organization of Agriculture*. New York: McGraw-Hill, 1953.
- Schultz, Theodore W. *Economic Growth and Agriculture*. New York: McGraw-Hill, 1968.
- Schultz, Theodore W., "Reflections on Agricultural Production, Output, and Supply," *Journal of Farm Economics* 38 (August, 1956), pp. 748-62.
- Shannon, Fred A. *The Farmer's Last Frontier: Agriculture 1860-1897*. New York: Holt, Rinehart and Winston, 1945.
- Siebert, Horst. *Economic Growth in the World Economy: Symposium 1992*. Tübingen, Germany: J. C. B. Mohr, 1993.
- Slicher van Bath, B. H., "The Influence of Economic Conditions on the Development of Agricultural Tools and Machines in History," in J. L. Meij, ed. *Mechanization in Agriculture*. Chicago: Quadrangle Books, 1960, pp. 1-36.
- Solow, Robert M., "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics* 39:3 (August, 1957) pp. 312-20.
- Summerhill, William R. *Railroads and the Brazilian Economy Before 1914*. Ph.D. Dissertation, Stanford University, 1995.
- Summerhill, William. "Transport Improvements and Economic Growth in Brazil and Mexico," in Stephen Haber, ed. *How Latin America Fell Behind: Essays on the Economic Histories of Brazil and Mexico, 1800 - 1914*. Palo Alto, California: Stanford University Press, 1997, pp. 93-117.
- Swinford, Norm. *Allis-Chalmers Farm Equipment, 1914 - 1985*. St. Joseph, Michigan: American Society of Agricultural Engineers, 1994.
- Thomas, Norman F. *Minneapolis-Moline: a History of its Formation and Operations*. New York: Arno Press, 1976 (dissertation, University of Minnesota, 1953).
- Tolley, H. R. and L. A. Reynoldson. *The Cost and Utilization of Power on Farms where Tractors are Owned*. U. S. Department of Agriculture Bulletin No. 997. Washington: U. S. Government Printing Office, 1921.
- Trajtenberg, Manuel. *Economic Analysis of Product Innovation: the Case of CT Scanners*. Cambridge, Massachusetts: Harvard University Press, 1990.
- U. S. Department of Agriculture, Bureau of Statistics. *Imports of Farm Products into the United States, 1851-1908*. Bulletin 74. Washington: Government Printing Office, 1910.
- U. S. Department of Agriculture, Bureau of Statistics. *Exports of Farm Products from the United States, 1851-1908*. Bulletin 75. Washington: Government Printing Office, 1910.
- U. S. Department of Agriculture, Bureau of Statistics. *Imports of Farm and Forest Products, 1909-1911, by Countries from Which Consigned*. Bulletin 95. Washington: Government Printing Office, 1912.

- U. S. Department of Agriculture, Bureau of Statistics. *Exports of Farm and Forest Products, 1909-1911, by Countries to Which Consigned. Bulletin 96.* Washington: Government Printing Office, 1912.
- U. S. Department of Agriculture. *Agricultural Statistics, 1936.* Washington: U. S. Government Printing Office, 1937.
- U. S. Department of Agriculture. *Agricultural Statistics, 1941.* Washington: U. S. Government Printing Office, 1942.
- U. S. Department of Agriculture. *Agricultural Statistics, 1945.* Washington: U. S. Government Printing Office, 1946.
- U. S. Department of Agriculture. *Agricultural Statistics, 1946.* Washington: U. S. Government Printing Office, 1947.
- U. S. Department of Agriculture. *Agricultural Statistics, 1955.* Washington: U. S. Government Printing Office, 1956.
- U. S. Department of Agriculture. *Agricultural Statistics, 1956.* Washington: U. S. Government Printing Office, 1957.
- von Tunzelmann, G. N. *Steam Power and British Industrialization to 1860.* Oxford: Clarendon Press, 1978.
- von Tunzelmann, G. N. *Technology and Industrial Progress.* Aldershot, U.K.: Edward Elgar, 1995.
- Vossler, Bill. *Orphan Tractors.* Osceola, Wisconsin: Motorbooks International, 1996.
- Wendel, Charles H. *150 Years of International Harvester.* Sarasota, Florida: Crestline Publishing, 1981.
- Wendel, Charles H. *The Allis-Chalmers Story.* Sarasota, Florida: Crestline Publishing, 1988.
- Wendel, Charles H. *Minneapolis-Moline Tractors, 1870-1969.* Osceola, Wisconsin: Motorbooks International, 1990.
- Wendel, Charles H. *150 Years of J. I. Case.* Sarasota, Florida: Crestline Publishing, 1991.
- Whatley, Warren C. *Institutional Change and Mechanization in the Cotton South.* PhD Dissertation Stanford University, 1983.
- Wik, Reynold M. *Steam Power on the American Farm.* Philadelphia: University of Pennsylvania Press, 1953.
- Wik, Reynold M. *Henry Ford and Grass-Roots America.* Ann Arbor, Michigan: The University of Michigan Press, 1972.
- Wik, Reynold M. *Benjamin Holt & Caterpillar: Tracks & Combines.* St. Joseph, Michigan: American Society of Agricultural Engineers, 1984.
- Williams, Michael. *Massey-Ferguson Tractors.* London: Blandford Press, 1987.

- Williams, Robert C. *Fordson, Farmall, and Poppin' Johnny*. Urbana, Illinois: University of Illinois Press, 1987.
- Williamson, Jeffrey G. *Late Nineteenth-Century American Economic Development: A General Equilibrium History*. Cambridge: Cambridge University Press, 1974.
- Williamson, Jeffrey G. *Industrialization, Inequality, and Economic Growth*. Cheltenham, UK: Edward Elgar, 1997.
- van Zon, Adriaan. "Vintage Capital and R&D Based Technological Progress." in *New Explorations in the Economics of Technical Change*, Christopher Freeman and Luc Soete, editors. London: Pinter, 1990.