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Reshaping the Landscape: The Impact and Diffusion of the Tractor in American Agriculture, 1910–1960

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This article analyzes the revolutionary impact the tractor had on rural America and examines the economic, technological, and institutional factors governing the machine's diffusion. Our simultaneous-equation regression model helps decipher the complex relationship between farm scale and diffusion. In addition, analyzing diffusion as a capital replacement problem reveals that the shift to the new technology was far more rapid than what has generally been thought and provides a new perspective on the long co-existence of both horses and tractors on farms.

The farm tractor was undoubtedly one of the most revolutionary technological innovations in the history of modern agriculture, vastly increasing the supply of farm power, raising productivity, and reshaping the rural landscape. But, as with many great inventions, the tractor's emergence generated considerable controversy, as contemporaries both lauded it as a symbol of progressive agriculture and condemned it for destroying a traditional way of life centered around the horse. Given the tractor's importance, scholars have long pondered such issues as the evolution in tractor design, the long coexistence of the animal and mechanical modes of production, regional variations in adoption patterns, the impact of farm scale on diffusion, and the tractor's effect on farm structure and productivity.[1]

[1] Ankli, "Horses Vs. Tractors," pp. 134–48; Ankli and Olmstead, "Adoption," pp. 213–30; Clarke, *Regulation*; Musoke, "Mechanizing," pp. 347–75; Sargen, *"Tractorization"*; and Whatley, "Institutional Change."

This article offers a fresh perspective on the tractor's economic impact, its diffusion pattern, and the factors governing its spread. The existing literature offers many conflicting claims about the determinants of tractor diffusion and the impact of the tractor on farm scale and production relationships. To help disentangle these claims, we model the tractor adoption and farm scale in a simultaneous-equations framework. Our econometric analysis suggests that farm scale had a positive and significant effect on tractor adoption and that tractor adoption had a significant, albeit smaller, positive effect on scale. In addition, we show that numerous variables that typically have been treated as exogenous, such as the prices of horses and feed, were in fact endogenous to the diffusion process. Recognizing this point leads us to model tractor diffusion as a capital replacement problem. This analysis helps explain why many previous studies found little difference in the relative costs of the tractor and horse modes and why the two modes coexisted for several decades. Our work suggests a dramatically different picture of both the tractor's competitive advantage and of the timing of the tractor's ascendancy in American agriculture. Finally, our work adds to the understanding of the complex workings of rural America by showing how markets and institutions evolved to facilitate diffusion.

THE IMPACT OF THE TRACTOR

Most of the literature on tractors by economic historians has focused on their diffusion and all but ignored the issues of the machine's impact on the American economy. Agricultural historians have not been so remiss. Here we complement the more general history literature by adding new data and perspectives pertinent to our understanding of the impact of the tractor. In doing so, we focus on the macro issues that shaped the very structure and character of American development.[2]

One of the hallmarks of the American experience over the nineteenth century was the westward march of commercial agriculture. This process symbolically ended in 1890 with the closing of the frontier. As newly settled areas matured, the acres of cropland harvested continued to increase until 1920 and then reached a plateau. But, by allowing farmers to convert land used to feed draft animals to the production of food and fiber for human consumption, the tractor essentially continued the process of land augmentation for another four decades. Given the crop yields prevailing over the late nineteenth and early twentieth centuries, a mature farm horse required about three acres of cropland for feed each year. In aggregate, farm draft animals

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[2] For an analysis of a number of important farm-level and sociological issues, such as the tractor's effect in reducing the drudgery and the intensity of farm work, an excellent entry point is Williams's three chapters on the tractor's impact. *Fordson*, pp. 131–90.

consumed the output of roughly 22 percent of all cropland harvested over the 1880 to 1920 period; draft animals in cities and mines consumed the output of another 5 percent. The cropland used to feed horses and mules peaked in 1915 at about 93 million acres; 79 million acres for maintaining work animals on farms and 14 million acres for those off farms. From 1915 on there was a steady decline. In 1930, 65 million acres of cropland were used to feed horses and mules, with all but 2 million acres devoted to farm stock. By 1960 only 5 million acres were needed. The released land was roughly equal to two-thirds of the total cropland harvested in 1920 in the territory of the Louisiana Purchase.[3]

There were also significant changes in the use of pasture that hitherto have not been fully appreciated. Circa 1910 farm horses and mules consumed the product of roughly 80 million acres of pasture. By 1960 most of this pasture land was freed, chiefly for the use of dairy cows and beef cattle. The impact of the tractor on the *effective* crop and pasture land base almost surely depressed crop and livestock prices and contributed to the great upheavals of the interwar years and to pressure for government farm programs. In addition to increasing the effective stock of land, the tractor also was land augmenting via its effect on increasing yields. The timeliness of work could be crucial in many operations, from plowing to the harvest.[4]

Rivaling the importance of changes in land use was the tractor's impact on farm labor. The decline in the farm population after 1940 represents one of the great structural shifts in American history, yet the economic history literature examining the diffusion of the tractor is all but silent on the machine's role in this transformation. United States Department of Agriculture (USDA) authorities estimated that in 1944 the tractor saved on net roughly 940 million man-hours in field operations and 760 million man-hours in caring for draft animals relative to the 1917–1921 period. The combined savings of 1.7 billion man-hours per year represented about 8 percent of the total agricultural labor requirements in 1944, and translates into about 850 thousand workers.[5]

[3] U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 537.

[4] Baker, *Graphic Summary*, p. 52; and Williams, *Fordson*, p. 150.

[5] Cooper, Barton, and Brodell, *Progress*, esp. p. 62. Autos and trucks also had an enormous impact, saving an additional 1.5 billion man-hours in hauling and travel time in 1944 relative to the 1917–1921 level. Finally, there was a saving of roughly 1.1 billion man-hours because farmers no longer had to raise as much feed for horses and mules. Taken together, the tractor, motor vehicle, and feed saving equaled about 23.8 percent of the 1944 labor requirements. These calculations hold the land base constant and do not account for the increase in worker and land productivity due to the increase in net output resulting from no longer having to devote a sizable portion of the acreage to feeding draft animals.

The conversion of man-hours into the number of workers assumes a 2000-hour farm work year. This should be viewed as a lower-bound estimate of the number of workers displaced because the farm work year (as measured by the ratio of USDA estimates of the man-hours of labor required on farms to total farm employment) reached 1977 hours at its peak in 1944, and typically varied between 1640–1790 hours over the 1910–1960 period. See series K 174 and K 410 in U.S. Bureau of the Census, *Historical Statistics*, pp. 467–68 and 498.

Unfortunately, the USDA offers no comparable assessment of the impact of the tractor after it was fully diffused. Estimating the tractor's savings of labor is extremely difficult in the post–World War II period because the adoption of the new generation of harvest equipment—combines, corn pickers, field forage harvesters, cotton pickers, and hay balers—was closely intertwined with the existence of the tractor. These machines operated more efficiently in tandem with a tractor (driven by the power takeoff) than if towed by horses; moreover, tractors increasingly became embodied in the harvesting equipment as farmers opted for self-propelled units. Calculating the 'independent' contribution of the tractor becomes somewhat arbitrary. Nevertheless, it is possible to rein in the estimates by making explicit assumptions. We know that using the 1944 land-to-labor ratios, cultivating and harvesting the 1959 acreage of major field crops would have required about 3.67 billion more man-hours than were actually used. Of this total, 1.55 billion hours would be devoted to preharvest operations and 2.12 billion to the harvest. Taking the conservative assumption that tractors accounted for 75 percent of the saving in preharvest operations and none in the harvest operations yields a total savings (including reduction of hours for animal care) of roughly 1.74 billion man-hours annually between 1944 and 1959. Taking the more liberal assumption that tractors accounted for all of the preharvest saving and 25 percent of the harvest saving yields an estimate of 2.65 billion man-hours. The lower-bound estimate represents 18 percent of the total reduction in man-hours in U.S. agriculture between 1944 and 1959; the upper-bound estimate, 27 percent. It is important to note that even our lower-bound estimate of labor savings for the post-1944 period exceeded the USDA estimate for the pre-1944 period.[6]

The upshot is that by 1960 the tractor reduced annual labor use by at least 3.44 billion man-hours of field and chore labor from the level required using the horse power technology. (The 3.44 billion figure combines the USDA estimate of annual labor savings before 1944 and our lower-bound estimate of saving between 1944 and 1959.) This was the equivalent of approximately 1,720 thousand workers, which represented 24.3 percent of farm employment in 1960 and 27.3 percent of the decline since 1910.[7]

Associated with the decline in the farm workforce was a dramatic decrease in the number of farms. We can perform a crude calculation to gain a better handle on the impact of the tractor on this key structural change. We begin with the observation that the ratio of workers (including both family

[6] Hecht, *Farm Labor Requirements*; and McElroy, Hecht, and Gavett, *Labor*. According to the USDA, the number of man-hours devoted to the care of horses fell from 792 million in 1944 to 109 million in 1960. Offsetting this decline was a roughly 100 million increase in the hours required for repairing and maintaining tractors and related equipment.

[7] For estimated labor requirements over the 1910–1960 period, see U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 577. These estimates deal only with the direct impact of the tractor. The machine also promoted structural changes such as the growth in farm size and an increase in specialization. To the extent that these changes saved labor, it would enhance the tractor's overall impact.

and hired labor) per farm was remarkably stable over the 1910–1960 period, hovering between 2.1 in 1910 and 1.7 during World War II.[8] Based on the 1960 ratio of 1.8 workers per farm, the labor savings estimated previously suggests that there would have been at least 956 thousand more farms in 1960 in the absence of the tractor.[9]

Historians have often bemoaned that the purchase of a tractor exposed farmers to more of the vagaries of the market. Where once farmers could "grow" their own power and fuel, they now had to buy these from farm machine and oil companies. Antitractor forces such as the Horse Association of America argued that the tractor-induced loss of self-sufficiency caused many of the farm bankruptcies of the early 1920s.[10] To date, the discussion of the loss of self-sufficiency has been long on rhetoric and short on analysis and precision. Just how serious was the problem? In 1955 farmers spent roughly $2.2 billion on tractors, of which $0.7 billion was for the net cost of new purchases, $1.1 billion for fuel and lubrication, and $0.4 billion for repairs and maintenance. The total represented only about 6 percent of all farm production and living expenses and only about one-quarter of farm expenditures for motor vehicles and machinery in that year.[11] This seems a modest price compared to the extra freedom, flexibility, and productivity that farmers and their families gained from owning a tractor. In addition, one must remember that the effects of the tractor were not all one-sided because it significantly increased the farmer's self-sufficiency in the labor market. Numerous USDA studies show that one of the main attractions of the tractor was that it allowed farmers to do work in a timely fashion without relying on hired help, thus saving the transactions costs and uncertainty associated with the highly imperfect rural labor market.

[8] This tight relationship between the farm labor force and the number of farms is borne out in the state-level dataset introduced later in the article. The results of an OLS regression of the log of number of farms in a state on the log of the number of male farm workers (including family and hired labor) and a time trend using decadal data over the 1910 to 1960 period yields the following (where the standard errors are in the parentheses)

$$\log(farms) = -23.49 + 1.059 \log(male\ labor) + 0.01056\ year, \quad R^2 = 0.966$$
$$(1.601)\ (1.196*10^{-2}) \qquad\qquad (8.145*10^{-4})$$

The constancy of this relationship reinforces the interpretation offered by Brewster, "Machine Process"; and Kislev and Peterson, "Prices" regarding the central role of labor supervision in the internal organization of the farm.

[9] This implies, assuming a constant land base, that in the absence of the tractor, the average size of U.S. farms in 1960 would have been 239 acres (instead of the true value of 297 acres). It further implies that 37 percent of the growth in farm size since 1910 was due to the tractor.

[10] There is a valid point here. Clearly, the tractor added to the country's stock of land producing a marketable output. But this change in output represented the gross savings to farmers and society. To obtain the net savings one must subtract out the costs of the fuel and other off-farm inputs associated with mechanization. See also Olmstead and Rhode, "Controversy."

[11] U.S. Department of Agriculture, *Farmers' Expenditures*, pp. 1, 6. The previous estimates overstate the actual loss in self-sufficiency because many farmers who used horses spent considerable sums buying animals and supplies. Animals, feed, harnesses, and stud and veterinary services for the most part were internal to the farm sector, but not necessarily to individual farmers.

The impact of the tractor was not limited to the farm. The new machine also revitalized and transformed the agricultural equipment industry. Economic historians have long recognized the importance of the agricultural implement industry in the nineteenth century, not only for supplying the tools that increased farm productivity, but also for its backward linkages to the machine-tool industry and other modern sectors. Clearly, as the nation's industrial base broadened, the relative importance of the agricultural implement industry declined. Nevertheless, it remained a world leader through the twentieth century.

What is not generally recognized is the extent to which the tractor came to dominate this sector. By 1939 the tractor industry employed more wage-earners and produced greater value added than the remainder of the agricultural equipment industry.[12] Even in the latter sector, much of the output was "tractor-driven" as implement manufacturers produced larger, more durable equipment better suited to the machine. Given the tractor's characteristics, one might surmise that motor vehicle firms would capture the industry. However with the exception of Ford, the successful tractor manufacturers had their origins in the agricultural equipment industry. This simple observation offers a valuable clue to understanding the sources of comparative advantage in the equipment industry. Evidently it was easier for agricultural equipment firms to learn to make engines than it was for auto firms to learn to serve the farm. Marketing networks and the two-way flow of ideas linking equipment producers with farmers, which was so important for secondary innovations, provided key advantages to the equipment companies. Understanding the role of secondary innovations and the resulting evolution of tractor productivity is crucial for understanding the machine's acceptance.

THE EVOLUTION AND SPREAD OF THE TRACTOR

The early gasoline tractors of the 1900s were behemoths, patterned after the giant steam plows that preceded them. They were useful for plowing, harrowing, and belt work but not for cultivating fields of growing crops nor powering farm equipment in tow. Innovative efforts between 1910 and 1940 vastly improved the machine's versatility and reduced its size, making it suited to a wider range of farms and tasks. At the same time, largely as a result of progress in the mass-production industries, the tractor's operating performance greatly increased while its price fell.

Several key advances marked the otherwise gradual improvement in tractor design. The Bull (1913) was the first truly small and agile tractor, Henry Ford's popular Fordson (1917) was the first mass-produced entry, and the revolutionary McCormick-Deering Farmall (1924) was the first

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[12] U.S. Bureau of the Census. *Sixteenth Census, Manufactures*, pp. 415–22.

general-purpose tractor capable of cultivating amongst growing row crops. The latter machine was also among the first to incorporate a power-takeoff, enabling it to transfer power directly to implements under tow. A host of allied innovations such as improved air and oil filters, stronger implements, pneumatic tires, and the Ferguson three-point hitch and hydraulic system greatly increased the tractor's life span and usefulness. Seemingly small changes often yielded enormous returns in terms of cost, durability, and performance. As an example, rubber tires reduced vibrations thereby extending machine life, enhanced the tractor's usefulness in hauling (a task previously done by horses), and increased drawbar efficiency in some applications by as much as 50 percent. The greater mobility afforded by rubber tires also allowed farmers to use a tractor on widely separated fields. Developments since World War II were largely limited to refining existing designs, increasing tractor size, and adding driver amenities.[13]

We know of no attempt to formally measure the actual productivity effects of these improvements in tractor design, but knowledgeable observers placed great stock in their importance.[14] As an example, Roy Bainer, who as a young man was an early tractor adopter and later became one of the deans of the agricultural engineering profession, noted that without improved air filters his machines lost power and needed a valve job within a year of entering service. He and other agricultural engineers also maintained that the Ferguson hitch revolutionized the tractor's capabilities and efficiency in towing implements. The extraordinarily rapid diffusion of some of the changes lends credence to Bainer's informed view. The standard wheeled models went from about 92 percent of all tractors sold for domestic use in 1925 to about 4 percent in 1940. Conversely, general-purpose tractors, which were first introduced in 1924, comprised 38 percent of sales in 1935 and 85 percent by 1940. In a similar fashion, within six years after Allis-Chalmers first introduced pneumatic tires on its new models in 1932, 95 percent of the new tractors produced in the United States were "on rubber." By 1945 about 72 percent of the stock of all wheeled farm tractors had rubber tires.[15]

A summary picture of the replacement of the animal mode by the mechanical mode is offered in Figure 1. It charts the number of tractors and draft animals in the United States between 1910 and 1960. The total number of farm horses and mules reached its maximum of 26.7 million head in 1918. Workstock (animals aged three and over) peaked in 1923 at 20.7 million

[13] Fox, *Demand*, p. 33; USDA, *Agricultural Resources*, p. 1. For the general evolution of the tractor, see Gray, *Development*; and Williams, *Fordson*.

[14] The recent unpublished work of W. White, "Unsung Hero," promises to provide better measures of the value of improvements in tractor quality and their impact on the diffusion of the machine.

[15] McKibben and Griffen, *Changes*, p. 13; U.S. Bureau of the Census, *Census of Agriculture: 1945*, p. 71; and interviews with Roy Bainer, Davis, CA, 1982–1984.
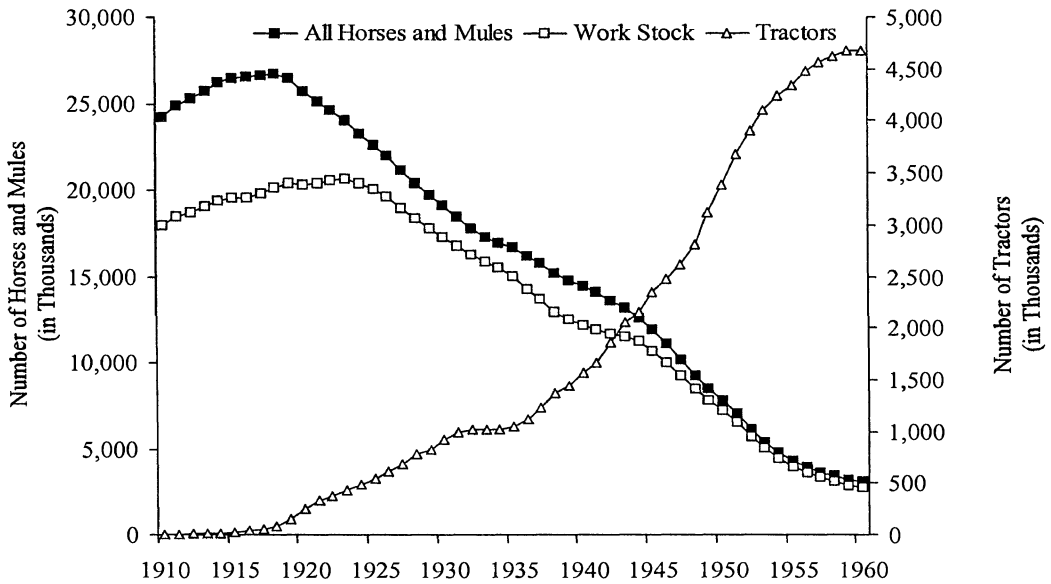
FIGURE 1
NUMBER OF DRAFT ANIMALS AND TRACTORS IN THE UNITED STATES, 1910–1960

Sources: Brodell and Jennings, *Work*, p. 10; U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 432; and U.S. Bureau of the Census, *Historical Statistics*, p. 469.

head; this was roughly the level that would have been required over the 1920–1960 period to maintain the 1910 ratio of workstock-to-cropland-harvested. After 1925 draft animal numbers steadily declined, falling below 3 million by 1960.[16] The stock of tractors began to expand rapidly during World War I, rising to a plateau of about one million machines in 1929. A second burst of growth began in the late 1930s, leading the tractor stock to climb above 4.5 million units by 1960.

The diffusion of the tractor exhibited significant regional variation as indicated in Table 1 showing the proportion of farms reporting tractors and draft animals. The Pacific and West North Central regions led the way with roughly 8 percent of farms reporting tractors in 1920. The development of the general-purpose tractor in the mid-1920s quickened the pace of diffusion in the East North Central and, to a lesser extent, in the three southern regions. All regions experienced a slowing of diffusion during the Great De-

[16] The population of horses and mules off farms began to decline well before the population on farms. There were some 3.45 million horses off the farm in 1910. This number fell to an estimated 2.13 million by 1920 and to 380,000 by 1925, according to C. L. Harlan of the USDA Bureau of Agricultural Economics as cited in Dewhurst and Associates, *America's Needs*, pp. 1103 and 1108. Of course, the "horseless" age never truly arrived. A recent National Agricultural Statistics Service survey of the nation's equine inventory on 1 January 1999 stood at 5,317.4 thousand head, up by 1.3 percent from the 1998 levels. Of this number, over 3.2 million were on farms, a greater level than in 1960. Almost all of these animals, both on farm and off, were kept for recreational purposes. USDA, *U.S. Equine Inventory*.

TABLE 1
PERCENTAGE OF FARMS REPORTING TRACTORS, HORSES, OR MULES, 1920–1969

	U.S.	NENG	MALT	ENC	WNC	SALT	ESC	WSC	MTN	PAC
Tractors										
1920	3.6	1.4	3.1	5.1	8.4	0.9	0.5	1.8	6.5	7.5
1925	7.4	4.6	11.3	13.5	13.7	2.6	1.3	2.9	7.7	13.4
1930	13.5	10.5	21.5	24.7	26.5	4.2	2.1	5.7	17.9	20.8
1935	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
1940	23.1	19.2	33.0	39.9	44.7	5.6	3.6	14.9	28.3	27.6
1945	34.2	31.1	49.7	56.4	61.2	11.1	7.7	25.3	44.3	38.4
1950	46.9	44.9	63.6	69.4	71.8	23.2	18.8	38.4	64.8	56.8
1954	60.1	60.2	77.4	82.6	83.3	38.6	31.8	50.0	74.6	67.3
1959	72.3	74.2	86.4	88.8	88.0	55.8	47.2	62.7	82.1	76.8
1964	76.6	74.8	88.1	90.3	90.4	63.2	56.3	67.4	83.4	73.8
1969	80.8	81.0	89.4	87.6	88.0	74.0	70.7	75.1	82.6	76.0
Horses or Mules										
1925	84.2	74.0	81.6	87.8	92.2	79.9	81.2	85.9	89.2	65.5
1930	79.9	66.3	74.6	84.3	89.0	77.7	73.8	83.5	81.9	55.4
1935	73.4	54.3	70.4	77.9	83.8	68.0	70.1	76.1	78.1	48.9
1940	71.5	46.6	66.5	74.4	79.3	71.6	69.1	74.8	75.5	43.5
1945	63.8	37.2	56.0	61.8	77.1	65.3	64.2	63.5	69.2	35.5
1950	54.0	35.4	40.9	39.6	57.8	62.8	64.5	57.5	59.3	27.4
1954	37.6	26.0	23.9	20.9	32.8	49.3	50.8	42.9	49.6	21.8
1959	30.6	22.2	20.2	16.4	23.1	40.6	44.6	37.6	48.6	22.7
1964	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
1969	20.0	20.1	20.4	15.6	18.6	16.0	19.8	25.0	40.8	22.5
Horses										
1900	79.0	84.8	88.6	91.6	93.1	55.5	62.6	78.7	91.8	87.3
1910	73.8	79.3	85.3	90.7	93.0	48.2	52.8	72.8	87.2	84.2
1920	73.0	81.4	87.1	91.2	93.6	46.1	53.6	69.1	90.8	78.2
1935	51.9	54.0	67.6	74.8	79.6	23.2	25.6	46.6	76.9	45.5
1940	51.6	46.4	63.4	71.3	75.4	24.7	29.8	50.0	74.6	40.6
1945	48.3	37.4	53.6	60.9	74.5	25.3	31.4	49.0	69.5	33.2
1950	39.4	35.1	39.4	38.1	55.8	26.4	31.6	45.5	58.7	26.5
Mules										
1900	25.8	0.3	4.0	7.9	18.5	36.1	48.5	49.0	7.2	8.5
1910	29.4	0.5	4.6	9.1	21.1	41.2	50.4	52.5	8.9	8.1
1920	35.0	0.8	6.8	10.9	24.9	52.1	55.1	60.5	12.6	9.2
1935	33.1	0.5	7.1	9.8	17.4	50.4	57.8	55.8	8.8	7.0
1940	30.3	0.4	6.8	7.6	13.4	53.1	54.6	48.6	6.3	5.3
1945	25.4	0.3	4.7	5.2	10.2	47.0	50.3	36.7	4.4	3.2
1950	20.5	0.5	2.6	2.6	4.6	41.6	46.3	24.8	2.9	2.0

Sources: U.S. Bureau of the Census, *Census of Agriculture 1950*, pp. 382–91, *Census of Agriculture 1959*, pp. 214–17, 506–09, and *Census of Agriculture 1969*, ch. 2, p. 23, ch. 4, p. 14, and ch. 5, p. 32.

pression and an acceleration during and immediately after World War II. The postwar spread of tractors was especially rapid in the South.[17]

The decline in the proportion of farms reporting draft animals shown in Table 1 was nearly the mirror image of the rise in the share reporting trac-

[17] Brodell and Ewing, *Tractor Power*, pp. 5–11; U.S. Bureau of the Census, *Historical Statistics*, pp. 510 and 519–20.

TABLE 2
PERCENTAGE OF FARMS REPORTING

	U.S.	NENG	MALT	ENC	WNC	SALT	ESC	WSC	MTN	PAC
Horses/Mules and No Tractors										
1940	53.0	34.9	41.5	40.3	40.4	66.9	65.8	65.3	53.6	29.5
1945	38.8	22.5	24.3	22.9	24.1	56.3	57.5	47.9	34.9	18.9
1950	30.5	21.2	15.8	13.4	15.5	47.8	51.5	38.9	20.3	11.1
1954	17.4	11.8	6.6	4.7	5.3	29.5	34.1	23.8	11.5	6.3
Horses/Mules and Tractors										
1940	18.6	11.7	24.9	34.1	38.9	4.7	3.3	9.5	21.9	14.0
1945	25.0	14.7	31.7	38.9	52.7	9.0	6.7	15.6	34.3	16.6
1950	23.7	14.7	25.3	26.2	42.7	15.3	13.2	18.9	39.1	16.6
1954	20.4	13.9	17.2	16.2	27.7	19.7	17.3	19.3	38.1	15.5
Tractors and No Horses/Mules										
1940	4.5	7.5	8.1	5.8	5.8	0.9	0.3	5.4	6.4	13.6
1945	9.5	16.9	18.4	17.4	9.0	2.2	0.9	10.0	11.1	22.6
1950	23.2	30.2	38.3	43.2	29.2	7.9	5.6	19.4	25.7	40.2
1954	37.6	39.6	55.8	63.8	54.7	16.6	13.5	29.4	34.5	44.8
No Tractors or Horses/Mules										
1940	23.9	45.8	25.4	19.8	14.9	27.5	30.6	19.8	18.1	42.9
1945	26.8	45.8	25.6	20.8	14.2	32.5	34.9	26.5	19.7	41.8
1950	22.6	33.9	20.6	17.2	12.6	28.9	29.7	22.7	14.9	32.1
1954	24.7	34.7	20.4	15.2	12.4	34.2	35.2	27.6	15.9	33.5

Sources: U.S. Bureau of the Census, *Census of Agriculture 1954*, pp. 220–21, and *Census of Agriculture 1940*, pp. 30–35, 82–93.

tors.[18] But it would be a mistake to interpret one series as simply the reflection of the other. There was substantial overlap between the two power sources as is demonstrated in the 1940–1954 data displayed in Table 2. As an example, 18.6 percent of farms in 1940 reported both draft animals and tractors; this was roughly four-fifths of the farms reporting tractors and about one-quarter of those reporting horses. Over this period, the fraction of farms reporting only animals decreased whereas the share reporting only tractors rose.[19] The farmers in the Pacific states led the way in converting to tractor-only operations, but even there, animals were common place. In 1940 only about 14 percent of the farms sampled in that region reported tractors and no draft animals.

[18] The comparison is made more difficult because the data for 1900, 1910, and 1920 treat farms reporting horses and mules separately whereas those for 1925 and 1930 combine the two. Data for the period 1935 to 1950 confirm the suspicion that a substantial fraction of farms (approximately 10–15 percent of farms reporting draft animals) possessed both mules and horses. If we are bold enough to extrapolate on the basis of the 1935 data, then we find that approximately 93 percent of the nation's farms possessed draft animals in 1920. This would imply a 20 percentage point decline in the proportion of farms over the 1920 to 1935 period, closely in line with a reduction of the share of farms reporting horses. (There was little change in the share of farms reporting mules over this period.)

[19] Totals derived from the statistics reported in Table 2 differ slightly from those appearing in Table 1 due to sampling variations. In addition to the trends noted in the text, the percentage of farms with two or more tractors climbed in the post–World War II period.

■ Animals, No Tractor   ■ Animals and Tractor   ▨ Tractors, No Animals   □ No Animals or Tractor
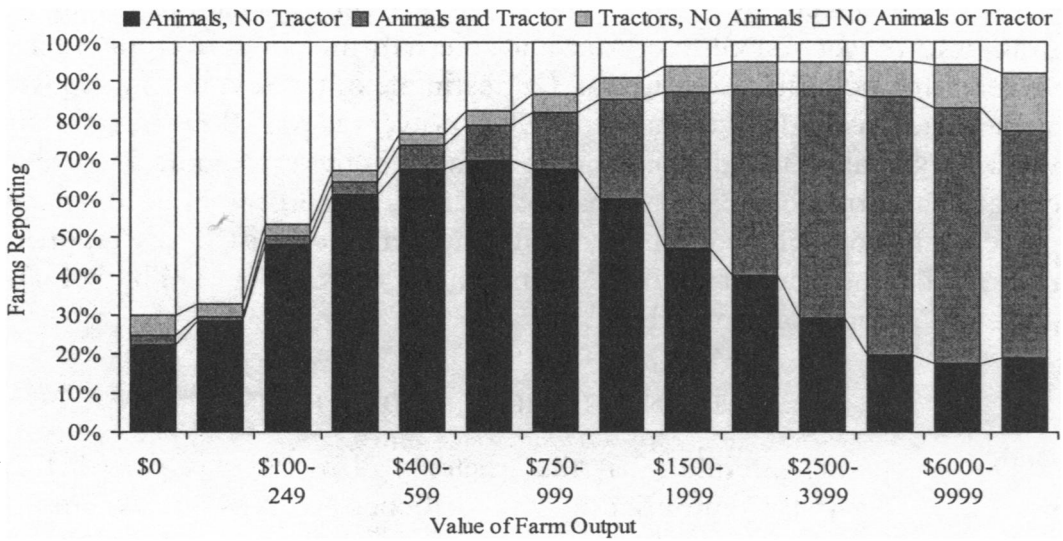
FIGURE 2
FARM SCALE AND POWER, 1940

Source: U.S. Bureau of the Census, *Census of Agriculture 1940*, pp. 82–84, 91.

Interestingly, the national data indicate that roughly one-quarter of sample farms reported neither tractor nor draft animals. This represented a significant increase over the levels prevailing in the 1920s, implying that the spread of the tractor was accompanied by a rise in the fraction of farms without internal sources of draft power. In many areas the increase in the proportion of "powerless" farms likely reflected an increase in professional contractors who managed or at least supplied tractor services to neighboring farms. The tractor's speed and surplus power helped encourage this increase in the division of labor.

Further evidence on the breakdown of farms by class of power is displayed in Figure 2. Using 1940 data, the figure shows how the share of farms in each power class varied with farm scale, as measured by the value of farm output. As the value of output increased, the percentage of farms without power fell markedly, whereas the share of farms with machines and the share with animals both increased. The proportion of farms reporting tractors, which started low, rose rapidly and peaked above 76 percent in the $6,000 to $9,999 revenue range. The fraction reporting animals rose over lower output classes, peaking at around 88 percent in the $2,500 to $3,999 range, and then declined slightly. The share with both power modes followed a similar pattern, but the decline was slight and at a larger scale. This evidence suggests that the class of farms with both power modes was an important, evolutionary stage between all-horse farms and all-tractor farms.

Ultimately, the spread of the tractor represented far more than just the replacement of the horse; rather it signaled a dramatic increase in total

horsepower capacity available on the farm. Between 1910 and 1960 national farm draft power soared over four-and-one-half times while cropland harvested remained roughly constant. Our estimate of the relative horsepower capacity (measured in terms of drawbar power) supplied by tractors and workstock (Table 3) indicates that tractors accounted for about 11 percent of national farm horsepower capacity in 1920, 64 percent in 1940, and 97 percent in 1960. Thus, compared with the percentage of farms reporting tractors, the measure of diffusion using power capacity started higher, and grew faster and more smoothly.[20]

MARKETS, INSTITUTIONS, AND DIFFUSION

The economics literature on the tractor's diffusion has two distinct branches. The first, exemplified by Zvi Griliches and Austin Fox, empirically estimates the demand for tractors using national time series. The second, employing the threshold model, analyzes cost and engineering data to determine the break-even acreage at which farmers in different regions should have been indifferent between the tractor and horse modes. This latter branch has been the dominant approach employed by economic historians with contributions from Nicholas Sargen, Robert Ankli, Alan Olmstead, Sally Clarke, Byron Lew, and Warren Whatley.[21]

The threshold approach suffers from a number of serious conceptual problems. To date, scholars have failed even to reach a consensus about whether the horse or tractor was the fixed-cost-intensive mode of production. A common argument is that although its initial cost was higher than that of a comparable team of horses, the tractor actually saved fixed costs because the horses must be fed whether or not they worked. This formulation implied, contrary to conventional wisdom and a large body of empirical observations, that small farms should have adopted the machine and large farms should have stuck with animals.[22]

Most tractor studies find that the cost differentials were small. This makes threshold estimates highly sensitive to changes in factor prices, errors in measurement, and seemingly arbitrary allocations between fixed and variable costs. These problems are magnified because over most of the period in question, the choice was not simply between machines or animals. Rather it was between tractors of varying sizes preferred for one set of tasks, combined with horse teams of varying sizes used for another set of tasks. Instead

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[20] These trends are generally consistent with the finding that larger farms adopted tractors first. The national numbers are also fairly close to Sargen's annual series of the share of tractor horsepower in national horsepower capacity (pp. 32–41, esp. p. 38), adding to our confidence in their use.

[21] David, "Mechanization," pp. 3–39. For early econometric studies of tractor diffusion, see Griliches, "Durable Input"; and Fox, *Demand*.

[22] Jasny, *Research Methods* and "Tractor," pp. 708–23.

TABLE 3
TRACTOR, DRAFT ANIMAL, AND TOTAL HORSEPOWER, 1910–1960

	1910	1920	1930	1940	1950	1960
			TOTAL			
New England	353,934	332,472	330,033	531,216	809,953	1,188,908
Middle Atlantic	1,153,129	1,204,349	1,575,492	2,365,736	4,091,126	5,522,786
E. N. Central	4,101,843	4,689,929	5,625,324	9,281,516	14,034,349	20,699,336
W. N. Central	6,398,505	7,796,298	9,492,163	12,665,453	18,914,699	27,774,760
South Atlantic	1,416,321	1,768,780	1,783,219	2,197,258	4,999,308	7,964,718
E. S. Central	1,436,523	1,648,072	1,622,070	2,068,429	4,350,231	6,278,099
W. S. Central	2,536,437	2,976,497	3,556,166	4,781,519	7,975,266	9,511,322
Mountain	1,152,587	1,910,865	2,041,315	2,404,402	4,069,596	5,165,660
Pacific	969,208	1,198,602	1,447,010	2,277,134	3,401,699	5,225,766
United States	19,518,486	23,525,863	27,472,790	38,572,663	62,646,227	89,331,354
			ANIMAL			
New England	353,934	309,604	188,943	149,584	85,309	34,168
Middle Atlantic	1,153,129	1,105,066	695,238	668,385	319,959	128,505
E. N. Central	4,101,843	4,168,478	2,901,720	2,581,751	976,824	353,717
W. N. Central	6,398,505	6,656,491	5,402,036	3,831,723	1,862,265	559,493
South Atlantic	1,416,321	1,665,793	1,300,127	1,337,670	1,093,216	422,250
E. S. Central	1,436,523	1,586,567	1,370,818	1,430,652	1,222,510	451,422
W. S. Central	2,536,437	2,760,631	2,607,480	2,051,264	1,140,384	444,482
Mountain	1,152,587	1,735,691	1,363,345	1,040,929	730,988	426,522
Pacific	969,208	995,910	642,753	489,452	299,257	183,306
United States	19,518,486	20,984,231	16,472,459	13,581,410	7,730,711	3,003,865
			TRACTOR			
New England		22,867	141,090	381,632	724,644	1,154,740
Middle Atlantic		99,283	880,254	1,697,351	3,771,167	5,394,281
E. N. Central		521,451	2,723,604	6,699,765	13,057,526	20,345,619
W. N. Central		1,139,807	4,090,127	8,833,730	17,052,434	27,215,267
South Atlantic		102,987	483,092	859,588	3,906,092	7,542,468
E. S. Central		61,506	251,252	637,777	3,127,721	5,826,676
W. S. Central		215,866	948,686	2,730,255	6,834,882	9,066,839
Mountain		175,174	677,970	1,363,473	3,338,609	4,739,138
Pacific		202,692	804,258	1,787,683	3,102,442	5,042,460
United States	NA	2,541,632	11,000,331	24,991,253	54,915,516	86,327,489
	TRACTOR'S SHARE OF TOTAL (percentages)					
New England	6.9	42.8	71.8	89.5	97.1	
Middle Atlantic	8.2	55.9	71.7	92.2	97.7	
E. N. Central	11.1	48.4	72.2	93.0	98.3	
W. N. Central	14.6	43.1	69.7	90.2	98.0	
South Atlantic	5.8	27.1	39.1	78.1	94.7	
E. S. Central	3.7	15.5	30.8	71.9	92.8	
W. S. Central	7.3	26.7	57.1	85.7	95.3	
Mountain	9.2	33.2	56.7	82.0	91.7	
Pacific	16.9	55.6	78.5	91.2	96.5	
United States	10.8	40.0	64.8	87.7	96.6	

Sources: U.S. Bureau of the Census, *Fourteenth Census*, pp. 540–41, *Sixteenth Census*, pp. 589–93, and *Census of Agriculture 1959*, pp. 214–15, 508–09. Horsepower per tractor and animal by regions were estimated based on Kinsman, *Appraisal*; Hurst and Church, *Power*, pp. 16–17; Brodell and Cooper, *Fuel*; Brodell and Jennings, *Work*, pp. 18–19; and Brodell and Kendall, *Fuel*.

of a single break-even point, farmers (and later economic historians) were confronted with myriad possible thresholds.

The existence of capacity constraints and the value of "timeliness" in farm work further complicate the analysis. A two-horse team might plow at a lower cost per acre than a small tractor, but might not be able to complete as many acres during the plowing season. In many studies, capacity constraints, not cost conditions, were the crucial determinants of the reported thresholds. The existence of capacity constraints implies that other inputs could be more fully utilized if the binding constraints were loosened. To make meaningful comparisons between techniques in this case, one needs information about a farm's entire range of production activities, not just those requiring power.[23]

The insights of A. V. Chayanov are directly relevant here.[24] In Chayanov's view, the Russian peasant farmer had difficulty hiring outside labor and faced capacity constraints for specific tasks performed by family labor. Mechanization of the peak load constraint permitted farmers to increase the area planted in high-value crops, utilize their family labor more intensely, and raise total net income. One key insight is that if the new technology allows a farmer to increase the acreage worked (as the tractor did), it can raise farm income even if the new technology has a higher per acre cost than the old technology. A second key insight is that the profitability of mechanization depends crucially on the nature and "quality" of rural markets and institutions, and in particular the workings of the labor market.

The institutional conditions common in the American North, where non-family laborers were scarce and family laborers had to be fed whether or not they worked, suggest that the relevant "wage rate" jumped discontinuously when the labor requirement rose above the family's labor supply.[25] This could explain why larger farms tended to adopt the more timely, labor saving tractor whereas smaller farms continued to use the horse. Recognizing imperfections in the credit market could also help explain the stylized facts that smaller farms were slower to adopt the more capital-intensive technology and that cash-flow considerations influenced the tractor purchase decision.[26]

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[23] Similar issues arise due to the interactions between the draft power mode and other farm technologies. For example, Sargen found that the profitability of the tractor in the wheat-belt during the 1920s and 1930s depended on whether or not combined harvesters, which employed tractors as their power source, were also adopted. Whatley and Musoke found similar interactions with other types of equipment that affected the profitability of using a tractor. Under these conditions, the threshold approach loses some of its simplicity and elegance.

[24] Chayanov, *Peasant Economy*.

[25] Fleisig, "Slavery," pp. 572–97.

[26] This is suggested in Clarke's analysis. We would expect large-scale operators could most likely obtain credit on better terms than smaller and more marginal producers. In addition, there were significant differences in credit availability for different modes of production. Tractor manufacturers had access to national credit markets and were known to carry paper on new purchases. Furthermore, horse advocates complained that local banks readily accepted tractors as security, while refusing to accept

An exhaustive reading of USDA and state-experiment-station power studies reveals that during the crucial decades of diffusion, farming practices and institutions evolved in ways that promoted tractor adoption. For example, the studies show many farmers significantly increased their acreage (through renting or purchasing land) and changed their cropping patterns after acquiring a tractor. In Illinois (1916), about one-third of the tractor owners who stated that their tractors were profitable increased the acreage which they were farming, the increase averaging about 120 acres per farm.[27] In North and South Dakota, 44 percent of the adopters added acreage with the "average increase being 139 acres."[28] Numerous other studies tell a similar story of tractor adopters increasing their farm size to facilitate mechanization. This implies that it is inappropriate to treat acreage as an exogenous explanatory variable.

To help disentangle the interactions between farm scale and tractor adoption, we will formally investigate their empirical relationship using a simultaneous-equations regression framework. Our analysis required the construction of several new datasets, assembled from a variety of USDA and Census of Agriculture sources. These state-level panel datasets include the proportion of farms reporting tractors, the acreage of cropland harvested per farm, the share of cropland in field crops, farm wage rates, fuel prices, and the rental costs of land and tractors, among other variables. The data cover the years 1920, 1925, 1930, 1940, 1945, 1950, 1954, and 1959. Unfortunately, the Census did not inquire about tractor ownership in 1935. (See the Appendix for details.)

To measure diffusion, we employ a variant of the conventional measure of diffusion, the percentage of farms reporting tractors. Specifically, we use the log odds ratio, that is, the log of the number of tractor farms over the number of nontractor farms. To measure farm scale, we employ cropland harvested per farm rather than the more conventional farm size because the numerator of the latter statistic includes nonarable land, which is not directly relevant for tractor adoption. Using state-level data has both obvious advantages and disadvantages for investigating the relationship between tractor diffusion and farm scale. The chief advantages are the geographic and temporal scope of coverage. The relevant data are available for every region in the country over almost the entire period of the tractor's spread. Although

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horses. It is also doubtful that the availability of information was scale neutral. Farmers with large operations and more wealth likely had more education and more access to technical literature, and they were more likely to associate with peers who were also experimenting with new methods.

[27] It is unclear whether this additional acreage resulted entirely from the purchase of nearby land or also reflected rented land. For our purposes, this distinction does not matter. Yerkes and Church, *Economic Study*. Other Illinois studies, including Yerkes and Church, *Tractor Experience*, p. 7, and *Dakotas*, p. 8; and Tolley and Reynoldson, *Cost*, pp. 56–57, found similar results.

[28] Yerkes and Church, *Dakotas*, pp. 7–8.

far superior to using national data, the level of aggregation in state-level data does not provide a clear picture of the individual farmer's decision-making process. Unfortunately, a comprehensive micro-level dataset showing the detailed characteristics of individual farmers does not exist to our knowledge. With this important objection in mind, we now analyze the state-level data to identify the major patterns of the diffusion of the tractor and the changes in farm scale.

Our model adopts a simple simultaneous-equations regression framework

$$Scale = a_t \, Tractor + a_x X_s + a_z Z$$
$$Tractor = b_s \, Scale + b_x X_t + b_z Z$$

where *Scale* is the farm scale as measured by the log of cropland per farm; *Tractor* is the extent of diffusion as measured by the log of the odds ratio; X_s is the vector of independent variables that affect farm scale directly; X_t is the vector of independent variables that affect tractor adoption directly; and Z is the vector of independent variables directly affecting both farm scale and tractor adoption.

Making the exclusion restrictions that define X_s and X_t is obviously a matter of economic judgment. We include two variables in X_s: the "rental" rate on farmland relative to the agricultural wage and the date of settlement of the state, which reflects the regime in which the state's farms were formed. In X_t we use measures of tractor "rental" rates and farm gasoline prices relative to the agricultural wage. These costs affect adoption directly, and arguably influence farm scale solely or rather principally through tractor adoption. Included in Z are the share of cropland in field crops (barley, buckwheat, oats, rye, and wheat) and a set of year and regional dummies that help account for temporal and geographical fixed effects in the panel dataset.[29] Table 4 reports the summary statistics of the data used in the analysis.

We estimate the relationships using weighted two-stage least squares regressions run on the pooled time-series cross-section sample. Throughout the analysis, we use bootstrap techniques to correct the standard errors for heteroscedasticity.[30] Table 5 reports the results of the reduced form and structural analysis.

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[29] The fixed-effect model allows for separate intercept terms for the USDA's ten main agricultural regions: Northeast, Lake, Corn, Northern Plains, Southeast, Appalachia, Delta, Southern Plains, Mountain, and Pacific states. In the regressions, the Pacific region is the excluded category. We use the USDA regions rather than the nine Census regions because the former better reflect the relevant cropping systems and yield a slightly better fit. We also include year dummies, using 1920 as the default. Note that the use of regional and year fixed effects discards some potentially valuable information provided by cross-sectional and temporal variations, but this procedure is desirable because it helps prevent spurious correlation from clouding the causal relationships between scale and adoption.

[30] See Efron and Tibshirani, *Bootstrap*. We used the number of farms as weights in the scale regressions and the product of the number of tractor farms times the number of nontractor farms divided by the total number of farms as weights in the log odds regressions.

TABLE 4
DESCRIPTIVE STATISTICS OF REGRESSION VARIABLES

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
LODDS	384	−1.072	1.908	−6.118	2.876
LCRFM	384	10.845	0.723	9.493	12.771
LPGWG	384	−2.757	0.517	−3.658	−1.320
LTRWG	384	2.824	0.671	1.364	4.440
LLRWG	384	4.445	0.870	1.560	6.623
SETTLE	384	1840.63	47.56	1790	1960
FIELD	384	0.268	0.207	0	0.778
NEAST	384	0.229	0.421	0	1
LAKE	384	0.063	0.242	0	1
CORN	384	0.104	0.306	0	1
NPLAIN	384	0.083	0.277	0	1
SEAST	384	0.083	0.277	0	1
APPAL	384	0.104	0.306	0	1
DELTA	384	0.063	0.242	0	1
SPLAIN	384	0.042	0.200	0	1
MOUNT	384	0.167	0.373	0	1
PACIFIC	384	0.063	0.242	0	1

Notes: Series definitions: *LODDS* is the log of the number of tractor farms over the number of non-tractor farms; *LCRFM* is the log of cropland harvested per farm; *LPGWG* is the log of the ratio of the farm gasoline price to the wage rate; *LTRWG* is the log of the ratio of the tractor "rental" rate to the wage rate; *LLRWG* is the log of the ratio of the land "rental" rate to the wage rate; *SETTLE* is the year of the state's settlement; *FIELD* is the share of field crops in acres of cropland harvested; and *NEAST* through *PACIFIC* are regional dummy variables.
Sources: See the text and the Appendix.

A set of consistent and largely sensible findings emerge, findings which are in line with the suppositions of most of the authors of USDA and experiment-station power studies and of other informed contemporary observers, yet contrary to much of the recent work on tractor diffusion by economic historians. The coefficient on the fitted scale variable reveals a positive and statistically significant effect (0.798) of farm size on tractor adoption, specifically a 10 percent increase in cropland per farm would increase the odds ratio by about 8 percent. To put this into context, this implies the increase over the 1920–1960 period in the log of national cropland per farm (which grew by 0.425 points) would explain about 8 percent of the increase in the log odds ratio (which grew by 4.260 points). The combined effects of the fall in tractor "rental" rates and fuel prices relative to the farm wage rates would account for another 22 percent of the increase in the log odds ratio. Time effects, which capture among other variables the spread of information and unmeasured quality improvements in the machine, account for the bulk of the increase. These results are consistent with the emphasis that most contemporary observers placed on the importance of the improvements in tractor design. What is more notable for our current purposes is that in the farm-scale regressions, tractor adoption had a positive,

TABLE 5
SIMULTANEOUS-EQUATION MODEL OF THE SCALE-ADOPTION RELATIONSHIP

Dependent Variable:	Reduced Forms		Structural Equations	
	LODDS	LCRFM	LODDS	LCRFM
LCRFMFIT			0.7962	
			(0.3121)	
LODDSFIT				0.2416
				(0.0637)
LPGWG	0.1666	0.5017	−0.4937	
	(0.3711)	(0.1553)	(0.3641)	
LTRWG	−1.7748	−0.8359	−0.7694	
	(0.5031)	(0.1698)	(0.5398)	
LLRWG	0.3273	0.0843		−0.0089
	(0.0813)	(0.0408)		(0.0424)
SETTLE	0.0036	0.0068		0.0061
	(0.0017)	(0.0011)		(0.0012)
FIELD	0.3689	0.3443	0.0005	0.2449
	(0.2044)	(0.1251)	(0.2156)	(0.1187)
NEAST	0.5539	0.2981	0.3582	0.2086
	(0.1977)	(0.1218)	(0.1708)	(0.1418)
LAKE	0.8902	0.3880	0.5406	0.2092
	(0.1252)	(0.0879)	(0.1422)	(0.1133)
CORN	0.6314	0.6015	0.2711	0.4956
	(0.1663)	(0.0758)	(0.1505)	(0.0940)
NPLAIN	1.1757	1.1755	0.0555	0.9056
	(0.1355)	(0.0615)	(0.3636)	(0.1009)
SEAST	−0.0881	0.2235	−0.2736	0.3488
	(0.2411)	(0.1159)	(0.2297)	(0.1129)
APPAL	−0.3209	−0.1135	−0.1402	0.0765
	(0.1981)	(0.1137)	(0.2411)	(0.1106)
DELTA	−0.5294	−0.0753	−0.4697	0.1401
	(0.2151)	(0.0991)	(0.2160)	(0.1064)
SPLAIN	0.2952	0.5749	−0.3373	0.4990
	(0.1634)	(0.0669)	(0.2172)	(0.0591)
MOUNT	0.5898	0.3702	−0.0911	0.2646
	(0.1788)	(0.0936)	(0.1924)	(0.0780)
D1925	1.1831	0.0765	1.1509	−0.2464
	(0.1626)	(0.0575)	(0.1663)	(0.0623)
D1930	2.2174	0.2442	2.0627	−0.3756
	(0.2273)	(0.0906)	(0.2533)	(0.0979)
D1940	2.3486	−0.1720	2.4866	−0.5919
	(0.1380)	(0.0676)	(0.1478)	(0.1579)
D1945	1.1452	−0.6509	1.5734	−0.6828
	(0.4051)	(0.1598)	(0.5041)	(0.2203)
D1950	2.5988	−0.2169	2.6842	−0.7906
	(0.1911)	(0.0797)	(0.2262)	(0.2436)
D1954	2.8927	−0.2648	3.0997	−0.8852
	(0.2273)	(0.0882)	(0.2641)	(0.2799)
D1959	3.6608	0.0663	3.6052	−0.8363
	(0.1767)	(0.0738)	(0.1777)	(0.3090)
Constant	−6.0663	1.4462	−10.9339	0.0539
	(4.4306)	(2.3739)	(5.0519)	(2.5164)
N	384	384	384	384
R²	0.940	0.902	0.936	0.899
Weights*	T(F−T)/F	F	T(F−T)/F	F

* where F is the number of farms and T is the number of tractor farms.
Note: Standard errors are in parentheses.

statistically significant effect (0.242) on the log of cropland per farm. Thus, these simultaneous-equations regressions reveal that greater scale induced greater tractor adoption and, independently, greater tractor adoption led to greater scale. These findings reinforce the conclusions that farm scale did matter (positively) for tractor adoption but that treating it as an exogenous variable is inappropriate.

Besides assuming that farm scale is an exogenous explanatory variable, much of the existing literature also assumes that custom tractor services were of negligible importance, thereby dismissing another means that tractor owners had to spread their fixed costs. This assumption is at sharp variance with actual practice during the initial period of diffusion.[31] Data for 1905–1909 show that custom work accounted for about 44 percent of the plowing done by gasoline tractors and over 50 percent of the plowing performed by steam tractors in the western United States and Canada.[32] All of the power studies pertaining to the 1915–1922 period show that custom tractor work was common, with 40 percent or more of the tractors engaged in some custom service. But such aggregate figures mask the importance of custom work for marginal adopters, because tractor owners with small farms were far more likely to offer custom services to spread the fixed costs of the machine. [33]

In addition to market adjustments, diffusion depended crucially on a stream of secondary innovations that enhanced the versatility and reliability of tractors. In this regard, the story of the tractor was like that of most inventions. In the first decades of diffusion, animal and mechanical power modes were imperfect substitutes. The power studies suggest that limitations in tractor versatility meant that horses were still required (or in some cases preferred) for many tasks.[34] This helps account for the long co-existence of the two modes. Improvements in the tractor and its accoutrements step-by-step permitted farmers to replace draft animals in specific tasks. As examples, rubber tires allowed tractors to perform hauling chores; the power take-off made the tractor more competitive in towing harvesting equipment; and general-purpose designs gradually eliminated the need for horses in cultivating and other tasks. The culmination of these and numerous other changes meant that by the early 1940s, horses were no longer required on most farms.

Our reading of the contemporary power studies indicates that changes in institutions and in the markets for custom services, land rental, and so on

[31] As examples see Clarke, *Regulation*, p. 90; and Sargen, *"Tractorization,"* p. 100.

[32] Ellis, *Traction Plowing*, pp. 22–23.

[33] For example, "such outfits [large tractors] frequently are bought principally for custom work, in which case the size of farm becomes less important." Yerkes and Church, *Economic Study*, p. 7.

[34] Handschin, et al., "Horse," pp. 202–09. The problem that farmers faced with needing both horses and tractors was similar to the tractor-labor trade-off in cotton production analyzed by Whatley. In this case, cotton farmers using a tractor and releasing labor in nonharvest operations might have jeopardized the ability to obtain workers to pick the cotton.

helped to adjust the machine-to-land ratio for a large number of marginal adopters thereby playing an important role in the early years of diffusion. At the same time, an ongoing process of technological change transformed tractors, making them more versatile and efficient in an ever-increasing set of tasks. The coexistence of both draft animals and tractors on the same farm may, in some instances, have been due to inertia, but in most cases it reflected the prevailing state of the technology that confined tractors to a limited number of tasks.[35]

FACTOR MARKETS, COEXISTENCE AND DIFFUSION

In addition to the tractor's technical shortcomings, the smooth working of factor markets offers a second important reason for the long coexistence of the two modes of production. Viewed from the perspective of the agricultural sector as a whole, many of the key variables in the tractor adoption decision were endogenous. The old technique was embodied in the horse, a durable capital good with an inelastic short-run supply and a price that could adjust to keep the animal mode competitive. Figure 3 graphs movements in the real prices (discounted by the GNP deflator) of medium-size tractors, mature horses (age two and older) and hay over the 1910–1960 period. Real tractor prices fell dramatically over the 1910s and early 1920s, but what is notable is that the horse prices nearly kept pace. The real value of mature horses in 1925 was less than one-half of their 1915 value. Besides lowering horse prices through direct competition, advances in the mechanical technology and the diffusion of the tractor increased productivity and shifted out the supply of agricultural products. Given a downward-sloping demand function for agricultural products, this led to lower crop prices and reduced the major expense of the animal mode: feed. Thus, via its effects on both horse and feed prices, the tractor by its very nature made its major rival more competitive in the short run.[36]

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[35] In addition to pointing to the technical limitations of early tractors, the large equine stock remaining on farms reflected the value that many humans placed on their bonds with horses. Such ties undoubtedly affected the diffusion process. For example, many farmers retained their old stock even after adopting machines and, at least up through the 1940s, relatively few of the displaced horses and mules were sent to slaughter. A 1959 U.S. Agricultural Research Service study indicates that only 19 thousand, or 6 percent, of the 314 thousand horses and mules disappearing off farms in 1940 were slaughtered in federally inspected meat plants. (A further irony is that the chief use of horsemeat was for dog and cat food.) The number and share slaughtered rose over the late 1940s and early 1950s, but at the peak less than one-half of the disappearing animals met their end in this way. That more farmers did not avail themselves of this option must have slowed the replacement of animals by machines. Csorba, *Use of Horses*, pp. 8 and 14.

[36] Given the diversity of crop requirements and the integration of the national markets of horses and feed, crop-specific technological changes that increased the tractor's competitiveness in one region could reduce horse and feed prices, thereby increasing the horse's competitiveness in another region. In this way, the rapid spread of tractors in the Great Plains induced a delay in the South.
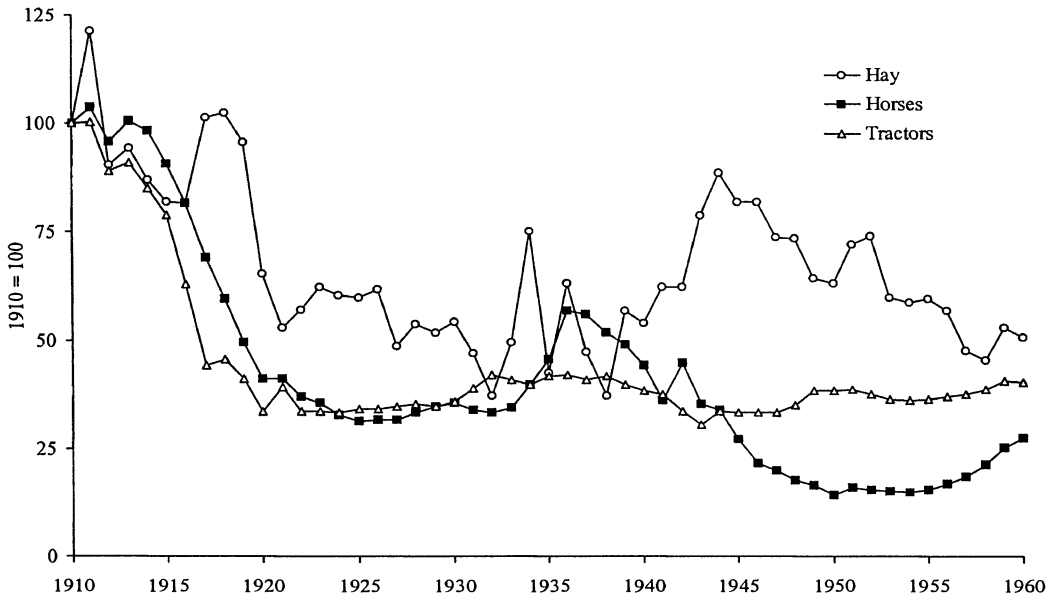
FIGURE 3
REAL PRICES OF HAY, HORSES, AND TRACTORS

Sources: The prices for horses two years and over are from U.S. Department of Agriculture, *Crops and Markets*, 12:2 (Feb. 1935). p. 34, up to 1935, and spliced to Series K 571 from U.S. Bureau of the Census, *Historical Statistics*, thereafter. The hay prices are from *Historical Statistics* Series K 552. The tractor price series is based on "medium tractors" from U.S. Bureau of Agricultural Economics, *Income Parity, Prices Paid*, p. 50, up to 1939, spliced to the U.S. Department of Agriculture series for 20–29 belt hp tractors reported in *Agricultural Prices*, 29 March 1950, p. 34; *1956 Agricultural Statistics*, p. 468; and *1962 Agricultural Statistics*, p. 563. All of the prices are deflated by a GNP deflator derived from the Balke-Gordon series, "Estimation," pp. 84–85, before 1929 and the official series (F 5 in *Historical Statistics*) thereafter.

A common finding in the existing literature is that cost differentials be-tween the machine or animal modes were small. But rather than reflecting long-run conditions, this merely represented a transitional phase in the ad-justment process. As in the debate over the profitability and viability of slavery, the real question answered by such static micro-economic compari-sons is whether the market for durable capital goods (here, the horse) was working properly. Apparently, it was.[37]

[37] Tractor prices might also respond to changes in demand, creating further issues of endogenity. Any deviation from a competitive cost-returns world (where the supply of tractors was perfectly elastic and the machine's price fell due to exogenous technical progress) would require changing the way diffusion is normally modeled. We know that the structure of the tractor industry evolved substantially over time. The industry began the twentieth century as one of the hot, new business opportunities, attracting a wave of startups. The number of tractor manufacturers rose from six firms in 1905 to 15 in 1910 and to 61 by 1915. During the World War I boom, the number of firms making tractors exploded, skyrock-eting to 186 by 1921. The sector was poised for one of the classic shakeout episodes in American industrial history. Among the causes were the collapse in machinery sales following the agricultural downturn of the early 1920s and, specifically, the January 1922 decision by Henry Ford to slash prices

To address how viable the horse mode remained, we adopt a fresh approach by viewing the diffusion process as a capital replacement problem. The key is to understand how horse breeders responded to changing economic conditions. It is important to recognize that there already existed a well-functioning and sophisticated market for the provision of draft power before the tractor was introduced. Although horses and mules were bred in every state, Missouri and neighboring areas emerged as the center of the interregional equine market by the late nineteenth century. Centrally located and favored by low feed prices and a pool of skilled breeders, this region shipped horses and mules throughout the United States. By 1910 breeding rates in the North and South Atlantic and Gulf Coast states were well below the replacement rates needed to sustain the draft animal population.

Breeding activity and parentage were not left to nature. There was an active market for stallion services, which were often provided by stallioners with prized animals. In 1920 only 1.5 percent of all U.S. farms reported having stallions compared to 73 percent reporting horses. Because stallions were hard to handle, most male horses were gelded. Nationally there were over 8 million geldings and only 129 thousand stallions. In all of New England there were well under 3,000 breeding males. The market valued a horse's breeding potential with the price of geldings averaging slightly less than that of mares and only one-fifth that of stallions. Horse breeding also represented one of the common, if lesser known, arenas for government intervention into agriculture in the early twentieth century. After 1900 roughly one-half of the U.S. states, including virtually all of the Midwestern states, enacted laws to register studs available for public service and to regulate the operation of the market for breeding services.[38] (In what follows

on his best-selling Fordson machine from $625 down to $395. Between 1921 and 1924 roughly two-thirds of the manufacturers exited from the business. By mid-decade, the number of makers returned to the level prevailing before the outbreak of World War I and even Ford had exited the industry. R. Gray, *Development*; and R. Williams, *Fordson*, p. 53.

The 1920s saw the share of the tractor market controlled by the eight full-line farm-implement manufacturers rise dramatically and the industrial structure assume a more stable, oligopolistic form. In 1921 the full-line equipment firms accounted for only about 26 percent of the sales of wheeled tractors. By 1929 their share increased to 96 percent, with International Harvester holding a 60 percent market share and Deere a 21 percent share. And by 1937 the full-line firms made up 98.6 percent of the market. The industry remained highly concentrated in the post–World War II period. In 1958 the four largest tractor companies accounted for 72 percent of the value of shipments, the eight largest companies for all but 4 percent. With these changes, it appears the tractor industry moved away from the sharper forms of price competition. In contrast to the experience in the 1920–1922 recession, nominal tractor prices changed little during the more severe 1929–1933 contraction. Real tractor prices rose, slowing diffusion. Temporary National Committee, *Monograph No. 36*, pp. 246–47; and U.S. Bureau of the Census, *1967 Census of Manufacturing*, SR2-66.

[38] U.S. Bureau of the Census, *Fourteenth Census*, pp. 534–38. U.S. state laws typically involved licensing breeding horses for public service, instituting inspection procedures, and standardizing contract forms, especially with regard to liens on the prospective colt. Government involvement in horse breeding in America never reached the extent prevailing on the European continent, where, for exam-

we explore how the number of licensed studs changed over the 1910–1945 period.) Note that well before the arrival of tractors, horse breeders responded in a predictable fashion to market signals. As an example, a decline in horse prices in the mid-1890s resulted in a marked reduction in breeding activity. And there is strong evidence for the existence of a well-integrated national market for draft animals. Although there were substantial and persistent differences in regional prices for draft animals (with prices rising as one moved away from Missouri), prices in every region tended to move together over time. Finally it is important to understand that the draft animal mode of power was not technologically stagnant: over the late nineteenth and early twentieth centuries the average weight and pulling power of farm horses increased as a result of selective breeding.

In 1912 the U.S. Bureau of Agricultural Economics collected detailed estimates from its extensive network of crop reporters on the cost of raising horses from birth to age three.[39] The figures reveal that colt-rearing costs were closely related to the price of mature horses and generally declined from east to west (with the exception of the Pacific Coast).

The cross-sectional data on rearing costs combined with information on input prices allow us to construct two sets of time-series estimates for the horse-rearing cost. The first uses a cross-sectional regression of rearing costs on a set of input prices to derive the horse-rearing cost function. The second is formed as a Laspeyres index from the average weights of the key inputs (grain, hay, labor, land, and interest rates) in overall costs and the relevant price changes over time.

The key variable of interest is the ratio of the price of mature horses to the cost of rearing colts. Conceptually, this ratio is obviously related to "Tobin's q": defined as the ratio of the market price of an asset to its reproduction costs. (Indeed, we are tempted to refer to our ratio as "Dobbin's q".) As is well known in finance/investment literature, if "Tobin's q" exceeds unity, then it is advantageous to invest in new capital equipment. A ratio of less than one discourages new investment because it is cheaper to acquire additional capital through the purchase of existing assets.[40]

The trends in the price-reproduction cost ratio and the extent of horse and mule breeding, as measured by the ratio of colts under age one to total animal stocks, are displayed in Figure 4. Their correspondence is striking. The breeding rate and price-cost ratios moved sharply down together over the

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ple, the French, Belgium, and Austrian states established national stud farms to improve their draft stock. USDA, *Progress*, pp. 19–22; and Gay, *Horse Husbandry*, pp. 179–88.

[39] USDA, "Cost of Raising Horses," p. 28. The correspondents were instructed "[i]n estimating the different items of cost, in terms of money, the amount should be such as you would charge a neighbor, or as a neighbor would charge you for such service. Let the figures given represent your estimate of cost under normal conditions of recent years."

[40] For an entry point into the investment literature, see Abel, "Consumption," pp. 763–67.
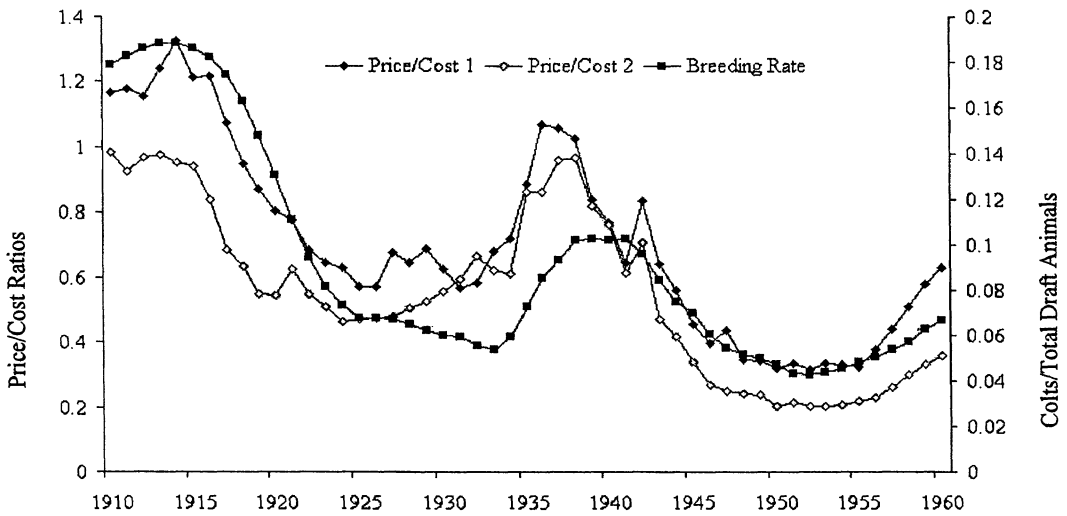
FIGURE 4
DOBBIN'S Q AND BREEDING RATES

Sources: The underlying cost data are from U.S. Department of Agriculture, "Cost of Raising Horses," p. 28; prices for horses two years and over (up to 1935) are from U.S. Department of Agriculture, *Crops and Markets*, p. 12:2 (Feb. 1935), p. 34; and land values, farm wages, interest rates, and prices for oats, hay, and horses (after 1935) are from U.S. Bureau of the Census, *Historical Statistics*, Series K 15, 179, 371, 513, 552, and 571 respectively. Breeding rates are from data in Brodell and Jennings, *Work*, p. 10; and U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 432.

early-1920s, recovered slightly in the mid-1930s, and then fell again after the late-1930s. We can formalize the relationship by regressing the log of the breeding rate on the log of the price-to-reproduction cost ratio. Statistical analysis reveals that these series appear nonstationary. (Using augmented Dickey-Fuller tests, we cannot reject at the 5 percent significance level the hypothesis that each of the original series contains a unit root.[41]) The differenced series, however, meet the standard criteria for being stationary. Table 6 displays the results of regressing the change in (the log of) the breeding rate on contemporaneous and lagged changes in (the logs of) the price-to-reproduction cost ratios (for index 1 and index 2, respectively) over the 1914 to 1960 period. For each price-cost series, including three lags fits best. Given the long period of production in horse rearing, such a lag structure appears well justified on economic grounds. Taken together, these results suggest breeding activity was closely related to the "Dobbin's q" measures. A permanent 10 percent reduction in the price-to-reproduction cost ratio led to a roughly 6.8 to 9.2 percent reduction in the colt-to-horse ratio. This analysis indicates that breeders swiftly responded to the new economic conditions, sharply reducing the number of colts foaled in the late

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[41] We can reject (at a 5 percent level) the hypotheses that the series contain more than one unit root or that either of the price-cost series co-integrate with the breeding series.

TABLE 6
REGRESSION ANALYSIS OF THE RELATIONSHIP BETWEEN BREEDING ACTIVITY
AND THE PRICE-TO-REPRODUCTION COST RATIO, 1914–1960
(dependent variable: *DLBREED*)

	Index 1	Index 2
Constant	–0.00227	–0.00179
	(0.00378)	(0.00466)
DLPC(0)	0.2584	0.2248
	(0.0744)	(0.0833)
DLPC(–1)	0.1819	0.1079
	(0.0749)	(0.0823)
DLPC(–2)	0.2740	0.1310
	(0.0758)	(0.0830)
DLPC(–3)	0.1906	0.2177
	(0.0764)	(0.0846)
	0.620	0.437
N	47	47

Note: Standard errors are in parenthesis. Series definitions: *DLBREED* is the difference in the log of the ratio of colts under age 1 to the total horse population. *DLPC* is the difference in the log of the price-to-reproduction cost ratios.
Sources: See the text.

1910s and early 1920s. These individual investment decisions helped ensure the ultimate victory of the tractor mode of production.

Another sign of the quick adjustment of horse breeders to the changing demand for animal power was the rapid reduction in the number of licensed stallions and jacks. Figure 5 graphs the number of registered studs in six important breeding states, California, Illinois, Indiana, Iowa, Kansas, and Wisconsin, between the early 1910s and the early 1940s.[42] (Sporadic data available for Kentucky and Missouri paint a largely similar picture.) As Figure 5 reveals, the licensing activity peaked around 1915, and by the mid-1920s the numbers of registered stallions and jacks were typically less than one-third of the levels of a decade before. Given that the registration fees were nominal in most states, the rapid and steady decline in licensing after World War I undoubtedly reflects the withdrawal of many breeders from the business. (The moderate upsurge in licensing in the 1930s indicates that the trend was not inexorably downward.)

The decline in breeding was sufficiently rapid that it soon raised alarms. By the mid-1920s, USDA authorities began to express concerns about impeding problems in articles entitled "Horse Production Falling Fast in US" and "Shortage of Work Animals in Sight." The 1931 USDA *Yearbook* followed suit; under the headline "Horses and Mules Now Raised Are Much Fewer than the Replacement Needs" it noted that breeders were producing only one-half of

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[42] California, *Monthly Bulletin*, pp. 725–27; Purdue, *Indiana Stallion*; Illinois, *17th Annual Report*, p. 25, and *29th Annual Report*, p. 167; Iowa, *1941 Yearbook*, p. 185; Kansas, *Stallion Registry*, p. 6; Wisconsin, *Biennial Report 1935–36*, pp. 194–95, and *Biennial Report 1939–40*, p. 9; and USDA, *Horses, Mules, and Motor Vehicles*, pp. 9–10.
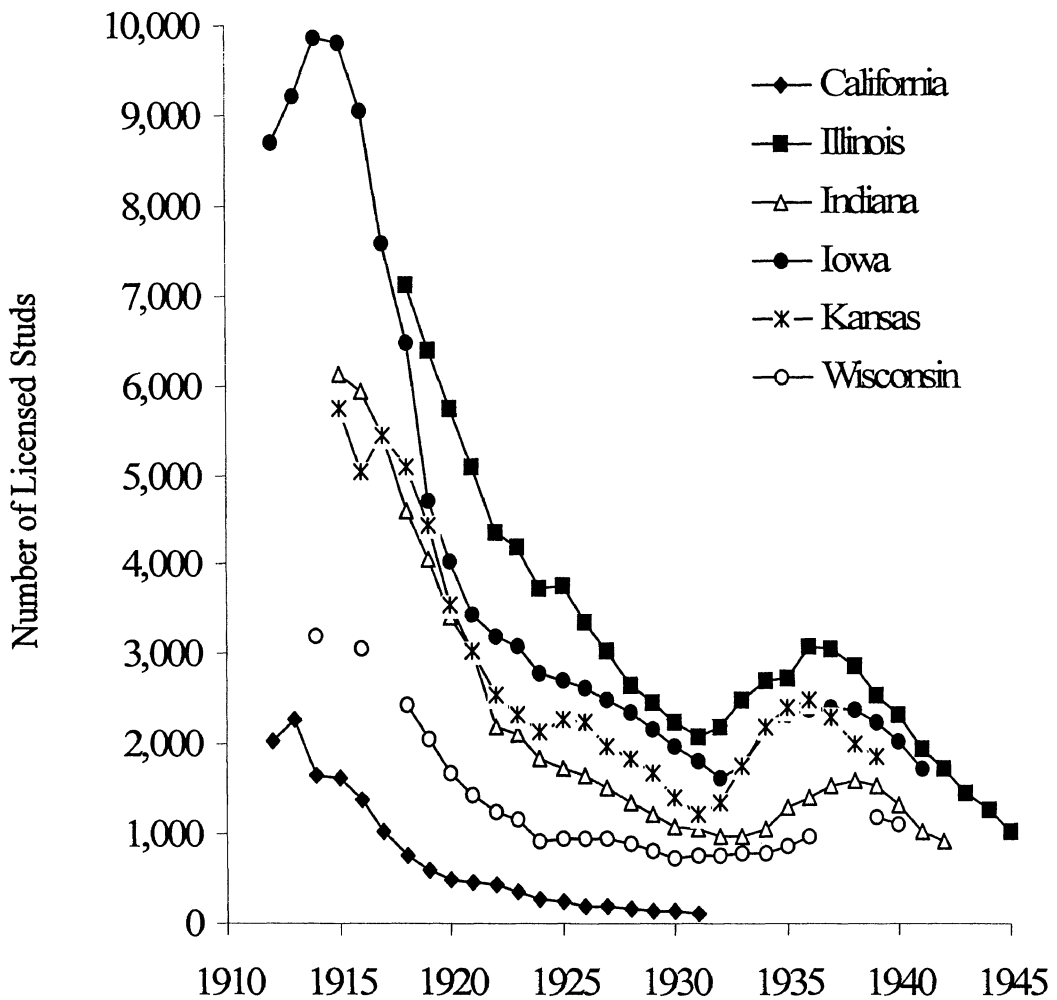
FIGURE 5
STALLION AND JACK REGISTRATION IN SELECTED STATES

Sources: California, *Monthly Bulletin*, pp. 725–27; Purdue, *Indiana Stallion*; Illinois, *17th Annual Report*, p. 25, and *29th Annual Report*, p. 167; Iowa, *1941 Yearbook*, p. 185; Kansas, *Stallion Registry*, p. 6; and Wisconsin, *Biennial Report 1935–36*, pp. 194–95, and *Biennial Report 1939–40*, p. 93.

the 1 million horse colts and 300,000 mule colts needed annually to sustain the animal population.[43] Clearly the people whose livelihood depended on horse and mule breeding saw the handwriting on the wall: the horse age was coming to an end.

As a result, the U.S. population of horses and mules aged significantly after the early 1920s. Figure 6 displays estimates of the average age of the

[43] USDA, *Yearbook of Agriculture 1931*, pp. 328–31, "Shortage," pp. 108–09, and *Agriculture Yearbook 1926*, pp. 437–39.
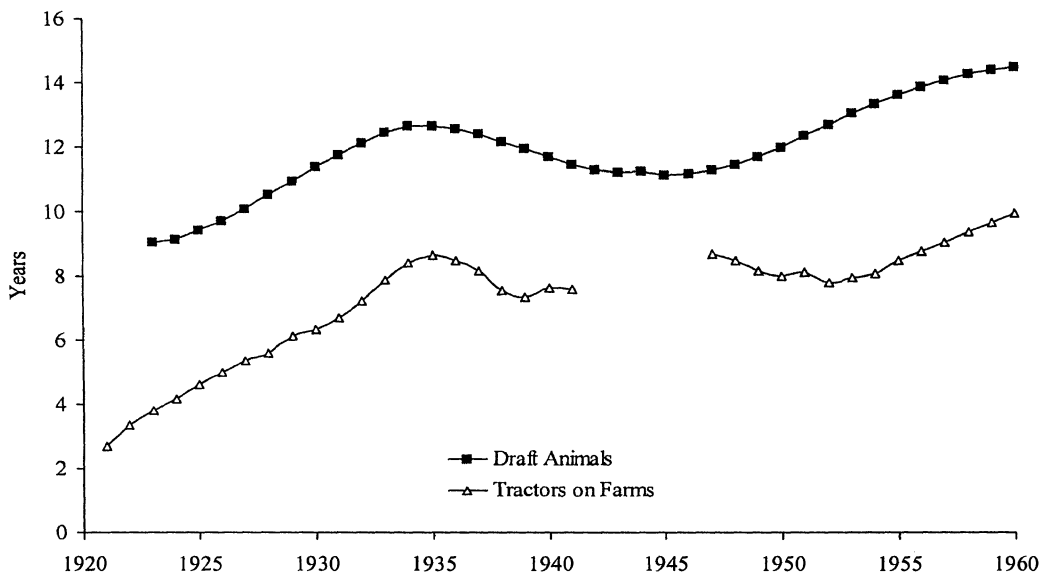
FIGURE 6
AVERAGE AGE OF U.S. DRAFT ANIMALS AND TRACTORS

Sources: The equine series estimates are from annual data on the numbers of horses and mules aged under one year, one–two years, two–three years, and three years and older, reported in U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 432; detailed 1925 figures on the animal population's age distribution are from U.S. Department of Agriculture, "Shortage," pp. 108–09; and a life table for draft animals was constructed from Brodell and Jennings, "Work." The tractor series are from Fox, *Demand*, p. 33.

draft animal and tractors on farms from the early 1920s to 1960. As the figure shows, the average age of horses and mules climbed dramatically over the 1920s and early 1930s, rising from about 9 years in 1923 to over 12.5 years by 1935. The average age declined briefly during the late 1930s and early 1940s as a result of the depression era up-tick in breeding activity and the passing of the bulge of animals born in the late 1910s. After 1943 the average age of draft animals began to climb again. The average age of tractors on farms also generally increased, rising from roughly three years in the early 1920s to about 8.5 years in the mid-1930s. Comparing the series for draft animals and machines highlights an important point about durable capital goods: as the new technology replaces the old, the average age of both stocks may be expected to increase.[44]

[44] We constructed the estimates of the average age of the horse and mule population from annual USDA data on the numbers of horses and mules age under one year, one–two years, two–three years, and three years and older, detailed 1925 figures on the animal population's age distribution, and a life table for draft animals. USDA, "Shortage," pp. 108–09. The series match closely independently derived figures for the average ages in 1933 from Harlan, "Farm Power Problem," pp. 5–9; and for 1943 from Brodell and Jennings, "Work," p. 13. The estimates for the post–World War II period could not be checked against other independent sources, and should not be treated as secure. The tractor series are from Fox, *Demand*, p. 33.
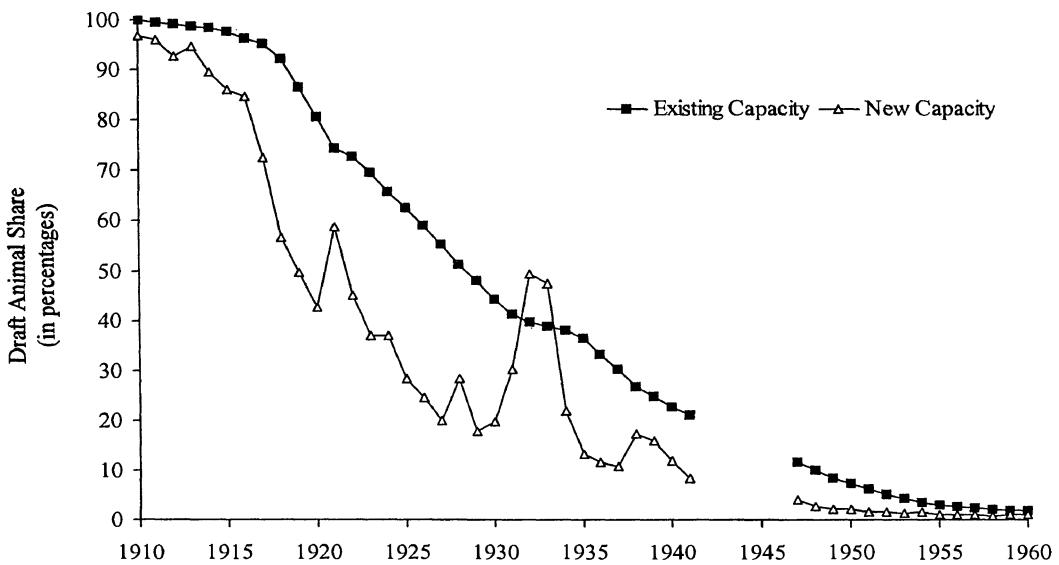
FIGURE 7
DRAFT ANIMAL POWER AS A SHARE OF NEW AND EXISTING CAPACITY

Note: For the 1910–1920 period, the average belt power for tractors is estimated to be 20 horsepower. *Sources*: Brodell and Jennings, *Work*, p. 10; U.S. Department of Agriculture, *1962 Agricultural Statistics*, p. 432; Fox, *Demand*, p. 33; and U.S. Bureau of Agricultural Economics, *Income Parity, Expenses*, p. 56.

Figure 7 provides another perspective on the diffusion process as a capital replacement problem. It shows the horse's share of gross investment in new horsepower capacity (where tractor horsepower is measured in belt units) over the period 1910–1960. For comparison purposes, it also displays the horse's share of existing capacity. By the mid-1920s, horses only represented between 15 and 30 percent of new investments with the exception of the lowest points of the Depression in 1932/33.[45] Thus, in terms of the investment in new power capacity, the shift from the animal to the mechanical mode was substantially more rapid than the existing literature suggests.

Our findings provide insight into a number of important issues. As an example, Whatley and others have noted a variety of reasons, including small farm sizes, unfavorable factor prices, contracting and coordination problems, and the desirability of annual labor contracts to guarantee labor of the peak-load cotton picking requirements, for the South's lag in the adoption of tractors. To this list one must add the workings of the asset

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[45] Using drawbar horsepower instead of belt power would result in a lower initial share for tractor capacity but more rapid growth; the relative movements of investment shares versus capacity shares would be essentially unchanged. Focusing on net investment instead of gross investment would obviously lead to even more skewed results in favor of tractors, given that gross investment in animal stock were below replacement levels by 1923.

market. Although only 1.3 percent of the farms in the East South Central reported tractors in 1925, the nominal prices of horses had already fallen by half since 1920. Thus, the competitiveness of the tractor mode in the South, at the very time when designs suitable for cotton cultivation were just being introduced, was being undercut by the displacement of animals on northern farms and cities. Tractor company policies may have contributed to the South's lag. Records found in the Higgins Archives indicate that Caterpillar dealers in California shipped the horses that it took in trade on tractor sales to the southern market to reduce the local supply.[46]

CONCLUSION

The tractor represented a grand Schumperterian innovation that sent shockwaves throughout the economy, rapidly changing established production relationships and in the process creating new opportunities and destroying old ways of doing business. By focusing almost exclusively on questions dealing with the timing of diffusion, much of the existing economic history literature has ignored other, more fundamental questions.[47] How did the tractor affect farm scale, cropping patterns, the organization of farm work, and internal and external labor markets? In particular, focusing on the horse-tractor trade-off has given short shrift to the tractor's impact on the most important phenomena in twentieth-century American agriculture: the exodus of workers off the farm and the huge reduction in the number of farms. This article has attempted to provide a broader perspective. Table 7 offers a summary of the more important consequences of the spread of the tractor.

Our story of diffusion has a strong supply-side component. Early tractors were unreliable and only suitable to a limited number of tasks. Horses were still required for many jobs. Over the three decades before World War II, a long list of technological improvements made tractors far more reliable and more versatile, and thus more competitive. The rapid adoption of new designs offers silent testimony to their superior worth.[48] As an alternative to past approaches, our account intertwines a story of technological refinement with an analysis of how institutional and market adjustments facilitated adoption. There is a strong tradition for both prongs of our argument; the technological findings are in the spirit of Nathan

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[46] Tractor Files in the F. Hal Higgins Collection on Agricultural Technology, Department of Special Collections, Shields Library, UC Davis.

[47] The analyses of Whatley and Clarke stand apart in their success in integrating the tractor into a more general discussion of regional development.

[48] The actual diffusion pattern was influenced by both World War I, which stimulated adoption, and by the Great Depression, which retarded sales.

TABLE 7
THE IMPACT OF THE TRACTOR, 1910–1960

Replaced about 23 million draft animals.

Increased the effective cropland base by 79 million acres. This represented an increase of about 30 percent and was equal to two-thirds of the total cropland harvested in 1920 in the territory of the Louisiana Purchase.

Increased the effective area of pastureland by about 80 million acres. This land was largely converted from feeding horses and mules to providing food and fiber for human consumption.

Increased the draft-power on farms over four fold.

Increased the timeliness and quality of farm work. Increased crop yields.

Was one of the great labor saving innovations of the twentieth century. By 1960 the tractor had reduced labor requirements by an estimated 1.7 million workers relative to the horse technology that it replaced. This represented 24 percent of farm employment in 1960 and 27 percent of the decline in farm employment between 1910 and 1960.

Accounted for the disappearance of a lower-bound estimate of 956 thousand farms by 1960. This implies that, assuming a constant land base, tractors accounted for an estimated 37 percent of the growth in farm size between 1910 and 1960. The average American farm in 1960 was about 58 acres larger than it would have been without the diffusion of tractors.

Increased labor productivity and allowed farmers more self-sufficiency in the labor market.

Led to a wholesale restructuring of the agricultural equipment industry. By 1939 the tractor industry accounted for over 50 percent of the employment and value added of the agricultural equipment industry.

Sources: See the text.

Rosenberg's work, and our institutional analysis builds on the growing literature on Coasean transactions cost and contracting.[49]

Before the coming of the tractor, horses and mules were the major source of power in rural America. Although there are reams of work analyzing the diffusion and the markets for agricultural machinery, we know of no systematic analysis of how the market for draft power functioned. An analysis of horse breeding is essential to a clearer understanding of tractor adoption. Specifically, we demonstrate that there was a rapid adjustment in expectations regarding the success of the new technology and that by the 1920s the vast majority of new investment in farm power was in tractors, as opposed to horses. In addition, the rapid fall in horse prices helps explain the delay in tractor diffusion, particularly in the southern states.

Beyond helping to better explain the replacement of the horse by the tractor, this article analyzes the applicability of the threshold model to study the diffusion of the tractor and by implication to the study of a wide array of other innovations. In the process we have explained why so many previous studies found little cost advantage for either the horse or the tractor mode of production over the span of several decades. Our regression analysis indicated that farm scale and tractor adoption were co-determined. Larger scale induced greater adoption and greater adoption, larger scale. Given this result

[49] Rosenberg, *Black Box*.

it is inappropriate to treat farm scale as an exogenous variable. These findings complement our earlier work on the reaper and should encourage a re-evaluation of a larger literature dealing with agricultural mechanization. Until our concerns are confronted head on, future threshold estimates should display the warning, *caveat emptor*.

Appendix: Data

The sources underlying our regression variables in our state-level dataset are listed here. The construction of the tractor "rental" and land "rental" series are discussed at the end of this Appendix.

NUMBER OF FARMS AND LAND IN FARMS: Data by state from U.S. Bureau of the Census, *Historical Statistics,* Series K 17–81.

FARMS REPORTING TRACTORS: U.S. Bureau of the Census. *Census of Agriculture 1959,* p. 214.

SETTLEMENT: The date of settlement is the decade that the state's population density first exceeded two persons per square mile, as indicated by Series A 196 of U.S. Bureau of the Census, *Historical Statistics.* States achieving this level by the first census were assigned 1790.

LABOR: As our labor quantity measure, we use the number of male agricultural laborers as reported in the Census of Population and corrected in the 1910 to 1950 period by Miller and Brainerd, "Labor Force Estimates"; the 1960 data are from the U.S. Bureau of the Census, *Census of Population 1960.*

CROPLAND AND FIELD CROP SHARE: The basic data on acreage of cropland harvested for 1920 to 1959 are from the U.S. Bureau of the Census: *Census of Agriculture 1959,* table 21, pp. 53–64. The census's definition of "cropland harvested" changed between 1920 and 1930 to include orchard and other "minor" crops, which were important for selected states. We employed the following sources to construct state-level estimates of acreage in these minor crops for the pre-1930 era: USDA, *Agriculture Yearbook 1921,* p. 463; and U.S. Bureau of the Census, *Fourteenth Census of the United States 1920, Agriculture,* table 127, p. 852. The field-crop share is the proportion of cropland devoted to barley, buckwheat, oats, rye, and wheat.

FARM WAGES: For 1920–1945, we used daily farm wages without board from U.S. Bureau of Agricultural Economics, *Farm Labor,* 12 February 1946, pp. 12–15. The 1950 are from *Farm Labor,* 14 January 1952, p. 12; for 1955, from U.S. Department of Agriculture, *Crops and Markets,* Vol. 33 (1955): p. 127; and for 1960, from *Farm Labor* January 1961, p. 15. Daily wages in the Pacific States are not reported in this period; they were estimated based on hourly wages in the Pacific States and the average of ratio of daily wages to hourly wages in the other 45 states.

LAND PRICES: Value of land per acre from Lindert, "Long-run Trends," with the 1925 and 1955 values interpolated based on the annual data from US Economic Research Service, *Farm Real Estate.*

INTEREST RATES: For 1920–1940, state data from Horton, *Farm-Mortgage Credit*; the 1945–1960 rates based on regional data from U.S. Department of Agriculture, *1962 Agricultural Statistics,* p. 590.

REAL ESTATE TAXES: Tax rates per $100 of value from Bird, *Taxes*; and Stinson, *Revised Estimates.*

GASOLINE PRICES: The gasoline prices paid by farmers for 1919/20 were 1919 state

prices from U.S. Department of Agriculture, *Monthly Crop Reporter*, March 1920, p. 26; those for 1924/25 are April 1924 state prices from U.S. Department of Agriculture, *Crops and Markets*, Vol. 1, Supp. 6, (June 1924), p. 170; those for 1929/30, 1939/40, and 1944/45 were based on the national prices for gasoline purchased by farmers from U.S. Department of Agriculture, *Agricultural Prices*, October 1959, p. 30 and 1934 state relatives reported in U.S. Bureau of Agricultural Economics, "Prices Paid for . . . Household Articles," p. 5; those for 1949/50 are March 1949 state prices reported in U.S. Department of Agriculture, *Agricultural Prices*, 29 March 1950, p 26; for 1954/55 are 15 June 1954 state prices reported in U.S. Department of Agriculture, *Crops and Markets 1955*, Vol. 32, p. 105; and those for 1959/60 are 15 June 1959 state prices reported in U.S. Department of Agriculture, *Agricultural Prices*, November 1961, p. 24. For consistency, the analysis used gasoline prices throughout. This might raise some concerns because tractors shifted between fuels over this period. Fortunately, the prices of the two main fuels, gasoline and kerosene, were highly correlated across regions (the 1924 correlation coefficient was 0.73 across states).

TRACTOR PRICES: Prices of tractors up to 1935 were based on national USDA series for "medium tractors" from U.S. Bureau of Agricultural Economics, *Income Parity, Prices Paid*, p. 50, spliced from 1939/40 on to the USDA series for 20–29 belt horse-power tractors reported in *Agricultural Prices*, 29 March 1950, p. 34; *1956 Agricultural Statistics*, p. 468; and *1962 Agricultural Statistics*, p. 563. State prices were constructed based on 1934 price relatives for three tractors (John Deere 15–30 HP tractors, IHC Farmall, and J. I. Case General Purpose Model CC) reported in US Bureau of Agricultural Economics, "Prices Paid . . . for Farm Machinery," p. 12 and 1954 price relatives from *Crops and Markets* 32 (1955): p. 106.

TRACTOR "RENTAL" RATES: The tractor prices series were converted into a "rental" series by multiplying the tractor price by a cost of capital formed from the state's mortgage interest rates, expected inflation, and tractor depreciation. Based on a reading of USDA and state power studies, we modeled the depreciation rate as follows: 15.8 percent per annum in 1910, 14.3 percent 1920; 13.3 percent 1925; 12.1 percent 1930; 8.3 percent 1940; 7.1 percent 1945; 6.7 percent 1950; 6.1 percent 1955; 5.6 percent 1960. Hurst and Church, *Power*, p. 24; Parsons, *Farm Machinery: Use*, pp. 27–28. Inflationary expectations were based on a centered three-year moving average of the official GNP deflator (Series F 5 in *Historical Statistics*) spliced to the Balke-Gordon series before 1929 from "Estimation," pp. 84–85.

LAND "RENTAL" RATES: The land prices were converted into a rental series by multiplying the land price by a cost of capital formed from the state's mortgage interest rates, real estate tax rates, the expected inflation rate as defined above, and 4 percent depreciation rate.

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