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ENGINES OF GROWTH:
FARM TRACTORS AND TWENTIETH-CENTURY U.S. ECONOMIC WELFARE

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ABSTRACT

The role of twentieth-century agricultural mechanization in changing the productivity, employment opportunities, and appearance of rural America has long been appreciated. Less attention has been paid to the impact made by farm tractors, combines, and associated equipment on the standard of living of the U.S. population as a whole. This paper demonstrates, through use of a detailed counterfactual analysis, that mechanization in the production of farm products increased GDP by more than 8.0 percent, using 1954 as a base year. This result suggests that studying individual innovations can significantly increase our understanding of the nature of economic growth.

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The mechanization of agriculture in the twentieth century, propelled by the development and universal adoption of the gasoline or diesel tractor, has significantly and permanently changed the economic and physical landscape of the United States. The number of people working on farms has dropped from a peak of 13 million in 1910 to about 6 million today, during which time the country's population has more than tripled, from 92 million to almost 310 million. Horses and mules, the dominant source of farm power at the turn of the century, have all but disappeared from the scene. The average size of a farm has more than tripled, driven by economies of scale. Numerous small towns, their economic viability weakened by decreases in population density in the surrounding areas, have almost ceased to exist.

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

This paper quantifies some of these benefits from mechanization, through the use of a counterfactual analysis. Using the year 1954 as a base, we estimate a direct social savings of $29.2 billion, equivalent to 8.0 percent of GNP, when compared to a hypothetical economy at the same date using farm power technology available in 1910. Although this contribution is a small part of the doubling of real per-capita GNP between these two dates, it nonetheless is large enough to be considered a significant growth factor. This analysis calls into questionan assumption often cited by growtheconomists: that individual technological improvements are too minor to be studied in isolation.

BACKGROUND

In his influential work on United States railroads, Robert Fogel used the emerging techniques of the New Economic History to attack a popular belief among historians that railroads were indispensable to American economic growth.[1] His counterfactual analysis of commodity transportation yielded a social savings estimate which suggested that railroads made only a small contribution to national income in the year 1890 (about 1.0 per cent if adaptations were permitted). Fogel used his results to support Simon Kuznets' assertion that no single innovation was important enough to be worthy of study in isolation. Technological progress, although a key factor in promoting economic growth, was, in his view, made up of a large number of individual improvements, none large enough by itself to be significant.

Professor Fogel defended his data and analysis against a number of critics many years ago, and his critique of the 'hero theory' has been largely accepted. The belief that technological change consists of countless small innovations has become embedded in much of current growth theory in economics. Many of the currently popular macroeconomic models use a technology-improvement parameter that grows exponentially over time, without any exogenous stimulus other than random shocks. Even more recent work in endogenous growth theory still models new technologies as 'arriving' at a steady rate, rather than being created and developed.

We contend that this emphasis seriously undervalues the contribution of the inventors, entrepreneurs, and firms that were and are the drivers of much technological change. The work of Nathan Rosenberg and Joel Mokyr, among others, convincingly portrays invention and innovation as critical to growth of income and wealth over the long term.[2] A large literature has emerged over the past 30 years attempting to relate research & development to growth, almost exclusively by econometrically relating R&D spending with total factor productivity increases. This work consistently shows strong correlation between the two factors, but convincing evidence demonstrating causation is lacking.

PREVIOUS WORK

There have been relatively few attempts to quantify the direct economic impacts of new technology, however. Zvi Griliches' early work on hybrid corn and Schmitz and Seckler's research on the mechanical tomato harvester are two of these related to agriculture.[3] Spurred on by the early work of Fogel and Albert Fishlow, scholars have investigated the impact of railroads on growth in a number of different countries, often finding direct social savings far greater than that measured by Fogel.[4] Especially notable are the work of John Coatsworth and William Summerhill, who quantified social benefits in excess of 10 percent for Mexico and Brazil, respectively.[5]

Alan Olmstead and Paul Rhode have explored some of the economic benefits from adoption of the tractor, work which has arisen out of their interest in diffusion of agricultural technologies.[6] Olmstead and Rhode acknowledge that economic historians have largely ignored the impact of mechanization on society, and set about to remedy the situation. They choose to model tractor adoption as a capital replacement problem, with benefits arising from lower input costs, and include land augmentation as well.

Citing estimates of labor, machine, and other inputs from a number of USDA farm studies from the 1930s and 1940s, Olmstead and Rhode derive an estimate of labor savings from mechanization equal to 1.7 billion effort-hours per year by 1944. Because their estimates include primarily field efficiency improvements, the authors find savings of 850,000 workers, or about 8% of total agricultural requirements. In the present work, a detailed counterfactual model and more comprehensive approach yields substantially higher social savings estimates.

Although improvements in transportation, industrialization in general, R&D spending, and investments in education and other human capital are widely recognized as supporting economic growth, agriculture has been considered a laggard or even a hindrance. Upon finding that agricultural productivity measured in value terms was lower than that of manufacturing, and had increased at a slower rate over the past half-century, Denison and other pioneers of growth accounting proposed that rapid transfer of resources out of agriculture was a necessary condition for countries to grow.[7] An entire generation of development economists encouraged third-world countries to abandon agriculture and focus their energies on manufacturing or other inherently 'high-growth' activities.

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

Second, the period during which the growth accountants were gathering their data was one of massive adjustment of resources out of agriculture. The mechanization described in this paper led to the movement of more than eight million workers from farms to other employment, creating a large and long-lasting disequilibrium. In finding that wages in agriculture were well below that in other sectors, even after controlling for education and other differences, Theodore Schultz (among others) concluded that the labor market had failed to adjust optimally; growth in the United States could be speeded up by accelerating the move out of agriculture.[8] It is important to understand the true implications of this finding. Labor and other resources devoted to agriculture were not inherently less productive; they had become so due to massive technological change and a failure to adjust quickly enough. This point will be revisited in the conclusion to the paper, after enumeration of the social savings.

HISTORY AND TECHNOLOGY

Agriculture in 1910

The decade between 1910 and 1920 marked the peak of animal-powered farming in the United States.[9] With the frontier closed and population expanding through rapid immigration, farmers employed more than 21 million horses and 5 million mules to produce the nation's crops. Of the total land area in the continental United States in 1910, farmland comprised almost half, representing 879 million acres. Slightly more than a third of this, or 310 million acres, were used for growing crops, the remainder being woodland, pasture, land for structures, and unimproved areas. Agricultural output was sufficient to provide an exportable surplus of cotton, tobacco, grains, and animal products totaling $900 million, slightly exceeding farm product imports.[10]

A summary of the leading crops is shown here as Table 1.[11] Corn was the most important agricultural commodity, both in terms of acreage planted and value. Then, as today, about four-fifths of the corn raised was fed to animals, including draft animals such as horses and mules, as well as hogs, cattle, chickens, and other food animals. Hay, was likewise fed to both types of animals, but not of course to people. Oats, the fifth most valuable crop, was also fed mostly to animals and made up a significant proportion of horse and mule feed. Wheat was grown almost exclusively for human consumption and made up the third largest crop by acreage. Cotton, although not grown as widely as wheat or oats, was a more valuable crop and a major source of export revenue: more than 70 percent of the 10.6 million bales grown in 1909 were exported.

Nearly all of these crops were grown, cultivated, and harvested using animal power or manual labor. Although steam-powered traction engines had been in use for plowing since the 1870s and gasoline tractors had been commercially available for a few years, neither had made a major impact on farming. Their massive size and weight made them usable only for threshing grain and plowing, and even then only in areas with hard, dry ground. Before 1910, only about 58,000 steam traction engines and 2,500 gas tractors had ever been produced, and U.S. Department of Agriculture (USDA) estimates showed only about 1,000 gasoline machines in use in 1910.[12] As such, we consider 1910 to be essentially *pre-tractor* and are using its input-output structure as the basis for the counterfactual 1954 economy considered later.

The 1910 census places the value of horses and mules on farms at $2.6 billion, or about 6 percent of all farm property. With implements and machinery valued at $1.27 billion, U.S. farms had almost $3.9 billion in 'crop-growing' capital. Capital intensity can be calculated at $12.52 per acre, a number that remained constant in real terms through the first half of the century. This surprising finding will be considered in the counterfactual analysis later in the paper.

In 1910, more than 32 million people lived on the nation's farms, comprising 35 percent of the total population. Of these, the census records 12.1 million as farm workers, or about one-third of the total work force of 38 million. Some pertinent statistics on agricultural employment are shown here in Table 2. In a separate estimate, the UDSA calculated that a total of 22.55 billion hours of labor were expended in farming in 1910[13]; this ties in reasonably well with the census work force number, indicating an average of about 1,860 hours per worker per year.

Development of the tractor and related technologies

This section presents an abbreviated developmental history of the tractor and other closely related machines.[14] The idea for gasoline-powered traction engines emerged shortly after the introduction of the internal combustion engine in the 1880s. The first working model was introduced in 1892, and commercial models were sold beginning in 1902. The first tractors shared similar traits to the steam traction engines that had emerged 20–30 years earlier. Weighing between 20,000 and 30,000 pounds, with huge steel wheels or tracks, these models were large and expensive.

Driven by intense competition, the major manufacturers worked to reduce both size and cost, and by the time Ford introduced its Fordson model (the first successful small tractor) in 1917, average weights were down to 2,000–6,000 pounds, and prices were under $1,000. International Harvester led the next round of innovation, introducing a general purpose (GP) tractor, the Farmall, in 1925. This model, with high ground clearance, small front wheels, and modest weight, was designed for cultivating, as well as for plowing and cutting. By the mid-1930s, GPs had replaced the standard Fordson-type tractor in most applications.

Three other improvements were critical in completing the technology base for the tractor. Deere released a power lift for its models beginning in 1927. This device allowed the implement to be raised before every turn by pulling a lever. Rubber tires first became available for tractors in 1932, and by 1938 had largely replaced steel wheels. The pneumatic tires not only did less damage to fields, they allowed a higher forward speed, due to reduced friction. Finally, the development of diesel engines beginning in the mid-1930s gave farmers access to a lower-cost fuel for their machines, eventually replacing kerosene and gasoline engines for most tractors.

By about 1934, the technology of tractor development had achieved a 'dominant design'. The Farmall-type general purpose tractors would change little over the next 30 years. Beginning in 1935, and despite the ongoing depression in the United States, tractor sales increased rapidly. As is shown by the trends in farm use of tractors and draft animals in Figure 1, the process of diffusion was essentially complete by 1960. With the exception of the cotton South, the increase in the percent of farms with tractors from year to year had stopped.

Self-propelled implements, which integrated a tractor engine and operator's compartment within the implement itself, were the next logical development in the mechanization of agriculture. Combine harvesters, or 'combines' for short, were first released during World War II and were soon universally adopted in dry grain growing areas; a team of combines harvesting a huge field of wheat is one of the most recognizable images in modern U.S. agriculture. Later introduction of self-propelled corn and cotton pickers allowed complete mechanization of these technically more-complicated tasks during the 1950s and 1960s. As all of these devices are critically dependent for their operation on internal combustion engines, self-propelled combines and mechanical pickers as considered here as products of 'tractorization'.

Agriculture in 1954

By the mid-1950s, U.S. agriculture had changed dramatically from half a century earlier and was approaching full mechanization.[15] Recent developments in the genetic selection of seed characteristics and increased use of chemical fertilizers had launched the second major productivity revolution of the twentieth century, that of dramatic yield improvement. Several important new crops had emerged and were being widely cultivated, most notably soybeans and sorghum. Two wars, the Great Depression, and several sharp agricultural slumps had alternately boosted and ravaged farm income. The population of the United States had increased by 80 percent to 165 million, while farms had lost more than 40 percent of their people.[16]

Despite these changes, the amount of land used to grow field crops was little altered. The total reported for the census year of 1954 was 329 million acres, a 6 percent increase from 1909, and only 30 million less than the all-time high reached in 1929. Large decreases in corn and cotton acreage were balanced by the 18 million acres of soybeans and 16 million acres of grain sorghum added to the nation's output mix. Exports of farm products totaled $3.1 billion, again dominated by cotton, wheat, and tobacco. Imports were even greater, however, and an overall agricultural products deficit of $650 million was recorded.[17] Data for the most important crops are listed in Table 3.

Although total cropland did not change drastically from 1909 to 1954, there were a number of notable regional and sectoral shifts. The West North Central states added 19 million acres and the Mountain states almost 14 million acres as the last frontiers were filled in, aided considerably by improved irrigation techniques. These states added small grains, such as wheat and barley, as they were abandoned by farms in the east. Corn's net decrease of 20 million acres was almost entirely accounted for by four states: Missouri, Kansas, Oklahoma, and Texas, the last three of which increased land in wheat by 9.5 million acres and sorghum by 13 million acres. Cotton acreage declined in every state in the South, as increasing yields collided with a declining export market. Finally, 15 million acres were taken out of production in the East and Southeast, as urbanization and lower output prices changed these farmers' ability to remain competitive in their markets.

By 1954, tractors were used to plow and prepare nearly all of this land; seed, cultivate, and fertilize the crops; and harvest all of them, except for cotton and tobacco. According to the census of that year, 2.7 million farms reported a total of 4.3 million tractors. There were, in addition, 980 thousand combines and 688 thousand corn pickers.[18] Only about 500 thousand farms had two or more work animals and no tractor; 80 percent of those were in the South. The value of implements and machinery on U.S. farms in 1954 has been estimated at $16.3 billion, including about $4.3 billion of automobiles and trucks, or about 13 percent of the value of total farm property.[19] With slightly more than $230 million in horses and mules added in, the value of 'crop-growing' capital was $12.2 billion, or about $36.70 per acre harvested. It is important to note that capital intensity, when deflated to 1910 dollars, was $12.77 excluding automobiles and trucks, little changed from the $12.52 calculated for the earlier period.

The farm labor force of 1954 was significantly smaller than that of 1910. Not only had the numbers of farm proprietors, unpaid family workers, and hired workers all declined significantly, but a large proportion of the proprietors also farmed only part-time. Aided by productivity increases from mechanization and the growth of rural manufacturing, almost half of the nation's farm operators held paying jobs away from the farm. More than 1 million of these operators worked more than 200 days per year off-farm.[20] In addition, the hired work force worked far fewer days per year, mostly during harvest time, as tractors had replaced the demand for more steady labor.[21] With these complications, and lacking an occupational census of the same year, the labor force calculation for 1954 was relatively involved. The details are not included here, but the results are summarized in Table 4.[22]

THE COUNTERFACTUAL PROPOSITION

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

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

Model of the Physical Inputs to Farming

In this spirit, the model here is based on physical inputs to farm production. Mechanization saved labor directly, both by reducing the number of people involved in farm tasks and by speeding up the performance of each task. By eliminating animal draft power, it also indirectly saved the land and labor that would have been required to raise animal feed. Power farming replaced horse and mule capital with that of tractors, combines, and pickers. Finally, there were minor impacts on other inputs: fuel and lubricants were an added cost, while horseshoes and veterinary care declined. Seed, irrigation, and fertilizer inputs, so important for increasing yields, are not considered within this counterfactual analysis.[23]

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

First, farmers require large numbers of work animals to meet their power needs. Based on the calculations of the previous sections, which showed that real capital intensity did not change appreciably with the switch to tractors, it is assumed that all of the proceeds from the hypothetical tractor purchase would be required to purchase work stock.[124]

Second, tractors are assumed to be unavailable elsewhere in the world. Although the United States was a leader in mechanization, by the 1950s most of the developed world had introduced tractors. In this counterfactual, however, changes in trade flows will only be considered to the extent that land required for animal feed would displace that actually used for exports.

Third, farmers are initially constrained to produce the same amount of crops in the counterfactual 1954 as in the historical year, except that no surpluses need be generated. The switch to horses and mules would require a significant increase in acreage for animal feed. Two

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[1]

output mix options are evaluated in the counterfactual analysis: one in which production of major crops is identical to 1954 output, including sorghum and soybeans, which were not produced in large amounts early in the century; and one that uses the output mix from 1910, scaled up to account for population increase.[25]

Fourth, additional labor required for farm operations is pulled from the goods producing sectors. Labor demand in these sectors is assumed to be perfectly elastic, with wages equal to marginal product; their loss does not affect the productivity of remaining workers. Under these conditions, the social loss from relocating them into agriculture is exactly equal to their wage.

Fifth, welfare losses from this experiment would reduce income enough to impact consumption. However, preferences among all goods are not homothetic; food demand is highly income inelastic. In keeping with a number of estimates made by the USDA, this elasticity is assumed to be 0.2.[26] Output requirements for the counterfactual are reduced proportionately as income falls.

Lastly, the 1910 production technology is assumed to use inputs in fixed proportion. The farmer's decision was essentially to choose an area of land to cultivate. Given that choice, a certain number of operations had to be performed, each requiring a specific amount of labor and capital. Feed for the work animals required an additional amount of land to be cultivated, using inputs in the same proportion. The output yield, which was largely out of the control of the farmer, simultaneously determined the absolute return to the three factors.[27]

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

$$Y = \sum_{i=1}^{I} \sum_{j=1}^{J} \Psi_{ij} \min\{R_{ij}; L_{ij} / \alpha_i; H_{ij} / \beta\} \tag{1}$$

where: ψ_{ij} is the 1954 yield, in bushels per acre, of crop i in state j; R_{ij} is acreage, L_is labor, and H_{ij} the horses used for crop i in state j; α_i is the labor requirement per acre in state j, assumed the same for all crops;[28] and β is the work stock requirement per acre, for all crops and states. Production is utilized for consumption (C), animal feed (Y^H), exports (X), and surplus (S):

$$Y = C + Y^H + X + S \quad \text{for each crop i.} \tag{2}$$

Animal feed requirements can be expressed as

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

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

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

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

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

$$C = \sum_{i=1}^{I}\sum_{j=1}^{J}(\Psi_{ij}R_{ij}) - (\gamma_{corn} + \gamma_{oats} + \gamma_{hay})\beta\sum_{i=1}^{I}\sum_{j'1}^{J}R_{ij} - X - S \ . \tag{5}$$

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

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

Minimize $R^T = \sum_{i=1}^{I}\sum_{j=1}^{J} R_{ij}$, subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(\Psi_{ij}R_{ij}) - (\gamma_{corn} + \gamma_{oats} + \gamma_{hay})\beta\sum_{i=1}^{I}\sum_{j'1}^{J} R_{ij} - X - S \geq C$$

$$R_{ij} \leq \overline{R_{ij}} \quad \forall\, i,\ j$$

$$\sum_{i=1}^{I} R_{ij} \leq \overline{R_j} \quad \forall\, j\,.$$

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

$$L_{ij} = \alpha_i R_{ij} \tag{6}$$

$$H_{ij} = \beta R_{ij}\,. \tag{7}$$

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

The Counterfactual Data

With this framework in place, the experiment is straightforward. The first step is a determination of the effect of horses on the net output of a given acreage. A number of studies by the USDA and other government agencies early in this century provided information on optimal feeding of horses and other work animals. One USDA study widely cited in the diffusion literature reported that work horses were fed, on average, 49 bushels of oats, 31 bushels of shelled corn, and 4,980 lbs of hay annually, in addition to six months of pasturing.[29]

Depending on availability of feed, the proportion of corn and oats could be varied, with a bushel of corn replacing about 1.8 bushels of oats. At yields prevailing in 1954, then, maintaining a horse for a year would require 1.3 acres of oats, 0.75 acres of corn, and 1.7 acres of hay. If insufficient land existed to grow the required amounts of oats (as is the case here), then an alternative scenario would use 0.3 acres of oats, 1.25 acres of corn, and 1.7 acres of hay.[30]

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

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

The next step is to apply feed requirements to the 1954 production data, which is reproduced here in the first column in Table 5. Raising crops on the 329 million acres shown would require an additional 9.2 million acres of oats, 38.3 million acres of corn, and 52.1 million acres of hay, based on the low-oats feeding regime discussed above.[31] The resulting total acreage appears in the second column of the table. Unfortunately, this amount of cropland is well above the maximum levels utilized in the historical experience of the United States. It is possible that this acreage could not even be farmed or would have resulted in substantially higher inputs or lower yields than for land areas actually cultivated.

To answer this concern, a detailed breakdown of cropland use by state and by crop was constructed, using the historical levels from 1909 to 1954 as denoting a feasible region. Land denoted by the 1954 census as ‘cropland harvested’ or ‘cropland used only for pasture’ was deemed to be usable for the counterfactual, whereas crop failure and summer fallow areas were not considered potentially available.[32] Permanent pasture and woodland areas were also not included in the calculation, mostly due to the impossibility of determining their suitability for crop agriculture. The details of this effort are not included here, but the results suggest that just less than 400 million acres could be utilized for crops, although the yields on the additional land would be slightly lower than the national averages for the major crops considered. The 432 million shown as the total for the counterfactual could not be supported within the existing farmland use patterns.

Fortunately, there were two sources of ‘excess’ production in 1954 for which the value is known, and which can be eliminated in calculating social savings. The early 1950s were times of surpluses, as the combination of farm programs, yield improvements, and an export slump following the Korean War created an imbalance of supply over demand. Large stocks of unsold farm products accumulated in storage, and the level of stocks of several important crops was still increasing in 1954. Clearly, stock accumulation can be eliminated from the counterfactual without any difficulty. Despite the slump, U.S. exports were still a significant user of cropland, especially for wheat and cotton.

By eliminating the build up of stocks and releasing the land devoted to exports of corn, wheat, and other small grains, a significant decrease in required acreage is achieved. Not surprisingly, the cotton areas that could be freed up are not nearly as useful. The small grains do not grow well in the warm climates where cotton is grown, and corn yields in Texas and the deep South were among the lowest in the country. As a result, it is unlikely that even extreme land pressures as envisioned by this counterfactual would cause abandonment of cotton acreage. The third column of figures in Table 5 shows the net requirements after elimination of surpluses.

Finally, the impact of the movement of labor out of manufacturing needs to be considered. A rough calculation of the social savings with this level of agricultural activity suggests that hypothetical income in 1954 would have been slightly more than 9 percent lower than it actually was.[33] With an income elasticity of food consumption of 0.2, food purchases by consumers could be expected to drop by 1.8 percent. This, in turn, would reduce the land requirements by the same amount. The fourth column of Table 5 shows the results of this adjustment.

To this point, all of the calculations regarding land use for each crop in the counterfactual have been at the national level. In an attempt to simulate the local optimization that would have occurred and in hopes of avoiding gross distortions that could be caused by this high-level analysis, a 'feasible allocation' has been constructed using state-level data from the census.[34] In essence, the heuristic used adds additional production to each state's output level based on the average yield of the land already in use for that crop. Constraints are included to prevent individual crop acreage from rising above levels supported by historical experience or statewide totals from exceeding the sum of available cropland harvested and cropland pastured. The results of this feasible allocation are included as the last column in Table 5.

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

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

Table 7 summarizes the data and results from this second counterfactual. Actual 1909 production of the major crops is shown in the first data column. As this paper stated earlier, exports were significant for many crops, especially cotton and wheat. It is necessary to subtract out these exports prior to adjusting for population and yield increases, the results of which appear in the second column. The next two columns record the effect of these population and yield adjustments. The last column presents the results of a state-level allocation of land identical in technique to that performed for the first counterfactual. This analysis concludes that 397 million acres would have been needed to produce the 1909 crop mix with horse and mule-powered cultivation, an amount of land that was actually available in 1954.

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

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

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

Social Savings Calculations

Having assembled reasonable cropland numbers for a hypothetical 1954 horse-powered agriculture sector, constructing labor savings estimates is the next step. For simplicity, it is assumed that labor is used in fixed proportion to land input, with the factor set equal to its value in the base year of 1909. Earlier in this paper, it was stated that 12.1 million workers were required to farm the 310.4 million acres harvested in 1909. This produces a figure of 0.039 workers per acre, or about two full-time workers for an average-sized farm with 50 crop acres. However, labor intensity in 1909 varied considerably from state to state. The counterfactual economy, by changing the relative amounts of the various crops grown, would also impact labor utilization. To improve the precision of this allocation, hypothetical labor requirements were estimated on a state-by-state basis for both of the counterfactuals detailed above. Producing the 1954 crop mix with the 1909 technology would be expected to employ 14.4 million workers, and the alternate 1909 crop mix economy would use 15.0 million laborers.[35]

Earlier in this paper, ecalculations were presented of the effort hours and number of full-time equivalent workers for the actual, tractor-using farm sector of 1954. A total of 11,962 million hours were expended in agricultural labor, representing 5.98 million full-time equivalent workers. In addition to forcing the farm operators with substantial off-farm employment and part-time wage workers to return to essentially full-time work, several million additional workers would have had to be retained in agriculture, preventing them from moving into the rapidly expanding manufacturing sectors of the 1940s and 1950s. Using the average hourly wage in good-producting sectors of $1.65 in 1954, the direct labor savings compared to the 1954 crop mix scenario are estimated at $27.8 billion, and $29.8 billion compared to that required by the 1909 crop mix.[36]

Although labor makes up the bulk of the social savings, contributions from exports and stock building, the use of grazing land, and a deduction for fuels used by tractors also need to be included. In order to make the acreage allocations feasible, all exports except cotton and increases in crop inventories were eliminated. In effect, these products were eaten up by the hypothetical horses. The inventory increases 'lost', if valued at the current price of crops sold, were worth $575 million in 1954. Lost exports for that year had a value of $1.039 billion.

Likewise, about 53 million acres of pasture land is converted to growing animal feed under the first counterfactual. Had it not been needed for crops, it would likely have been used for feeding cattle, as was the bulk of the nation's pasture land in the real 1954. Using the 1954 census data on cattle production and value, the contribution of this land to grazing can be estimated at $3.16 per acre, or about 12.5 percent of the total value of the cattle sustained on it. The resulting social savings of $167 million is another part of the total contribution of the tractor.[37]

Finally, tractor operating costs should be deducted from the social savings previously calculated, to the extent that they would exceed out-of-pocket expenses for maintaining work stock. As stated previously, capital cost per acre, when adjusted for changes in the price level, was approximately the same for tractors as for horses. Tractors, in addition, required fuel and lubricants to operate, and on occasion repair parts or shop maintenance were needed. In the case of horses, shoes, harnesses, and veterinary care were the major expense items incurred, in addition to feed, which has been extensively covered above. Of all of these factors, the only one of significant magnitude is fuel purchase. Based on a USDA estimate of consumption of various fuels by tractors in 1953 and 1955, total fuel expense for 1954 is estimated at $416 million.[38]

The social savings results are simmarized in Table 8. Total savings for the year 1954 are $29.2 billion under the most reasonable and thoroughly developed scenario. With total output in that year measured at about $365 billion, the tractor and its related machines are shown to have contributed savings worth 8.0 percent of total U.S. GNP.

DISCUSSION

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

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

Not all of the yield increases were due to scientific knowledge alone, however. The higher speeds in plowing and harvesting facilitated by tractors eliminated time constraints in both spring and fall of the year. Faster planting meant that the farmer could wait to sow until the risk of a late frost was minimized. Quicker harvests allowed the operators to wait until the crop had reached peak ripeness, then rapidly bring in the entire crop. A horse-drawn combine or binder, for instance, operated at less than half of the speed of the tractor-drawn or self-propelled models. A horse-powered farmer on a large plot who began harvesting when the crop was not quite ripe might not finish before the last of the crop dried out and became difficult to cut and thresh. As a result, mechanization contributed to yield improvement by cutting losses due to weather-related causes and by increasing the quality of the crop harvested.

Although no attempt was made to separate out the impacts of science versus technology on yield improvements for all crops, an example with corn should suffice as an illustration. Johnson and Gustafson estimated that mechanization was responsible for one-third of the increase in corn yields this century.[39] With this as a basis, the counterfactual can be recalculated, using the same process as described in the previous section. With lower corn yields, an additional 11.5 million acres would have to be cultivated to produce the output required by the population and by work animals. This, in turn, would require an increase of 500,000 in the farm labor force, bringing the total to 14.9 million full-time workers. The resulting social savings calculation raises the benefit to 8.5 percent of 1954 GNP, versus the 8.0 percent determined above. Clearly, the contribution of tractors to yield improvements of other crops would raise the social savings even further.

A second factor related to yields is more difficult to quantify. The use of chemical fertilizers, herbicides, and pesticides had already become widespread in the years after the second World War. In most parts of the country, these chemicals were applied *by tractor*. In addition, the fast speed and low out-of-pocket cost of tractor operation meant that farmers conditioned their soil more with tractors than they had with horse teams. An extra disking or pass with a harrow just prior to planting made the soil more resilient and encouraged the growth process. While soil conditioning and chemical application could have been done by horse or mule teams, the added labor expense and time requirements meant that this was seldom done. These considerations also indicate that the true social savings from mechanization are higher than what has been presented.

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

With the development of general-purpose tractors, hydraulic implement lifts and weight levelers, and the power take-off, farmers entered the era of 'fingertip farming'. Although field operations were still time-consuming and could be monotonous, the tremendous physical strain had been eliminated. Related mechanical inventions such as the corn picker/sheller, the cotton picker, pickup hay baler, and field forage harvester, all dependent on the tractor engine for their power, eliminated the more physically demanding of the laborer's tasks.[40] No attempt has been made to measure these benefits in a way that would allow them to be added to social savings, but the benefits to the farmers and farm workers seem clear.

CONCLUSIONS

In this paper we show that agricultural mechanization as embodied in the tractor and related equipment made a significant contribution to the growth of U.S. output. The social savings is calculated at $29.2 billion, or 8.0 percent of U.S. GNP in 1954, an amount several times as large relative to the size of the economy than Fogel's best estimate for railroads in 1890. Why should such an unheralded technology prove to be more important than the mighty railroads, which united the country and captured the bulk of the country's stock investment for half a century?

It is likely that the answer lies in two aspects of tractors that differ considerably from the railroad experience. In the first place, waterways and canals were a fairly good substitute for railroads in the transportation of commodities at the end of the last century. The geography of the United States is such that most of the population lived close to a navigable waterway; railroads were efficient enough to capture much of the shipment volume, but their costs were not radically lower than that of water transport.[41] In the case of tractors, however, horses were *not* a very good substitute. Once the dominant design emerged in the 1930s, tractors were able to deliver mobile power with a far lower cost in terms of labor, at a comparable expenditure of capital, and without consuming a large portion of the output in the process. It is interesting to note that shipment of goods by water is still common today, whereas horses and mules have completely disappeared from commercial agriculture.

A second important aspect of the tractor is that it is used to produce food, consumption of which is vital to sustaining life. In any economy producing insufficient food, if imports cannot be increased, resources quickly flow back into agriculture. The mechanism can be described as follows: an inelastic demand for food leading to rising food prices, which induces higher factor returns in agriculture, leading to a flow of factors out of manufacturing or services and a consequent expansion of agricultural output.[42] The productivity improvements from mechanization and yield improvements lead to the opposite result. Food surpluses brought about by the productivity improvements, if exports cannot be increased, cause low returns in agriculture, leading to a flow of factors out into manufacturing and services, which allows agriculture to contract output to bring it back into balance with demand.

In most pre-industrial economies, the food supply imperative causes almost the entire economy to be devoted to agriculture. Any improvement to farm productivity will have a huge impact on the wealth of the population, as long as there is alternate employment for the resources released from agriculture. The United States, in its first century as a nation, although well on its way to industrialization, had a large proportion of its population engaged in agriculture. If data could be found to analyze the impact of the nineteenth-century inventions of the reaper and thresher, a proper social savings calculation should show significant social savings. In the case of the tractor, its adoption allowed the U.S. to reduce farm employment from 33 percent of the work force in 1909 to 10 percent in 1954.

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

This paper concludes with a few words about the process of technological change in general. If the endogenous growth theorists are correct and innovations arrive in large numbers at a steady rate, then perhaps it does not make sense to study any one particular technology. The focus on human capital accumulation, encouragement of government-sponsored basic research, and provision of incentives for spending R&D capital may be all that governments and their economic advisors can do. If, on the other hand, technological innovation is lumpy, with some advances clearly more important than others, and especially if entrepreneurs are the primary agents of change, then there may be a role for studying the more important inventors and inventions of the past. In his critique of the railroad's presumed indispensability, Fogel argued against "a hero theory of history applied to things rather than to persons."[43] Although it appears he was correct in disputing the railroad's right to claim superiority in its day, perhaps the tractor needs to be considered an unsung hero of the twentieth century. Certainly, the tractor deserves study as one of the nation's important engines of growth.

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TABLES

Table 1

1909 U.S. Agricultural Output—Major Crops (Acreage, production, and value data in millions)

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

Source: U.S. Bureau of the Census, 1911, pp. 581, 590, 600, 605, 640, 653, 659, 676, 681.

Table 2

The Farm Work Force in 1910

(All figures in thousands)

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

Source: U.S. Bureau of the Census, 1911. Occupation Statistics, p. 91, 96–139.

Table 3

1954 United States Agricultural Output—Major Crops

(Acreage, production, and value in millions)

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

Source: U.S. Bureau of the Census, 1955.

Table 4

Estimate of the 1954 Agricultural Work Force

(All figures in millions)

	Total People	FTE Workers	Hours per Year
Farm operators	4.78	3.44	6,880
Family workers	1.80	1.35	2,694
Hired workers	3.01	1.19	2,388
Total	9.59	5.98	11,962

Source: USDA, *Farm Employment*; USDA, *The Hired Farm Working Force of 1954*; U.S. Bureau of the Census, 1955; and authors' calculations.

Table 5

Actual and Counterfactual Acreage Requirements, Using 1954 Crop Mix

(All numbers in millions of acres)

Crop	Actual 1954 Production	Add in Feed Acreage	Eliminate Stock Build, Exports	Adjust for Income Effect	'Feasible' Allocation
Corn	78.5	116.8	105.3	103.3	101.9
Sorghum	17.3	17.3	14.9	14.5	14.7
Oats	37.9	47.1	44.4	43.6	41.6
Wheat	51.4	51.4	36.0	35.0	37.7
Other grains	19.7	19.7	18.1	17.7	19.9
Soybeans	17.8	17.8	17.8	17.5	17.6
Hay	69.9	122.0	116.3	114.3	117.7
Cotton	18.9	18.9	17.1	16.8	16.8
Minor crops	17.8	17.8	14.1	13.8	14.0
Total	329.2	428.8	384.0	376.5	381.9

Source: U.S. Bureau of the Census, 1955; and authors' calculations, discussed in the text.

Table 6

Actual and Counterfactual Acreage Requirements by Region

(All numbers in millions of acres)

Region	1909 Cropland Harvested	1954 Cropland Harvested	Feasible Allocation	1954 Total Cropland
New England	4.6	2.4	4.5	3.3
Mid Atlantic	17.2	11.5	15.2	14.3
E N Central	59.7	59.2	67.5	70.1
W N Central	114.5	133.5	140.1	146.6
S Atlantic	30.2	23.0	26.3	28.9
E S Central	25.7	19.6	30.6	30.9
W S Central	39.0	43.5	54.5	57.8
Mountain	8.8	22.5	24.8	26.7
Pacific	10.6	14.1	18.3	20.4
U.S. Total	310.3	329.3	381.8	399.0

Source: U.S. Bureau of the Census, 1911; U.S. Bureau of the Census, 1955; and authors' calculations.

Table 7

Actual and Counterfactual Acreage Requirements, Using 1909 Crop Mix

(All numbers in millions of acres)

Crop	Actual 1909 Production	1909 for Domestic Consumption	Adjusted to 1954 Population	Adjusted to 1954 Yields	Feasible Allocation
Corn	98.4	97.0	174.3	115.6	114.2
Oats	35.2	35.1	63.1	52.1	48.9
Wheat	44.3	37.5	67.3	58.7	61.0
Other grains	13.6	13.3	23.9	19.3	21.1
Hay	72.3	72.2	129.8	118.2	121.4
Cotton	32.0	9.0	16.2	7.9	12.2
Minor crops	14.7	14.2	23.4	18.9	18.7
Total	310.5	278.3	497.9	390.6	397.4

Source: U.S. Bureau of the Census, 1911; and author's calculations.

Table 8

Social Savings from the Farm Tractor in 1954

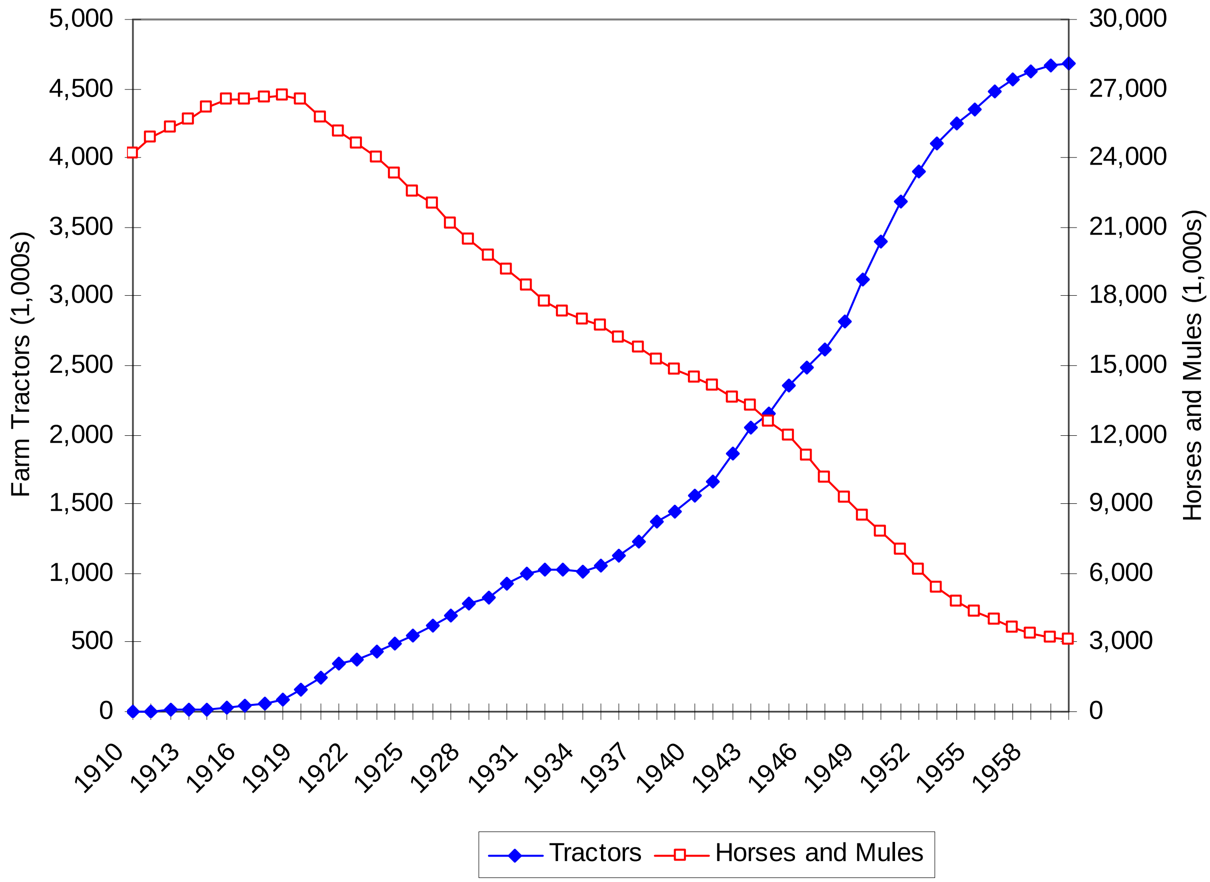
(All values in millions of dollars)

Source	1954 Crop Mix	1909 Crop Mix
Wage labor freed up	27,800	29,800
Land reallocated	200	200
Exports maintained	1,000	1,000
Crop inventory increased	600	600
Less: Fuels used	(400)	(400)
Total savings	29,200	31,200
1954 U.S. GNP	364,800	364,800
Savings as % of GNP	8.0 %	8.6 %

Source: Authors' calculations. See discussion in text.

Figure 1

Replacement of Horses by Tractors on U.S. Farms—1910 to 1960



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

[1] Fogel, *Railroads*.

[2] Among the many relevant works of these two authors are Rosenberg, *Technology*; Rosenberg, *Inside the Black Box*; Mokyr, *The Lever*; and Mokyr, *Twenty-Five Centuries*.

[3] Griliches, "Hybrid Corn"; Schmitz and Seckler, "Mechanized Agriculture."

[4] Fishlow's research, which was contemporaneous with Fogel's, also considered the railroad's impact on the U.S. economy. See Fishlow, *American Railroads*.

[5] Coatsworth, *Growth* and Summerhill, *Railroads*.

[6] Olmstead and Rhode, "Reshaping".

[7] Denison, *Accounting*.

[8] Schultz, *Economic Growth*.

[9] Except as noted, all of the numerical data in this subsection comes from the 1910 Census (Bureau of the Census, *Thirteenth Census)*.

[10] U.S. Department of Agriculture, *Exports*.

[11] This data from the 1910 Census represents crops grown in the 1909 farm season.

[12] Steam traction engine data is from Wik, *Steam Power*, pp. 100–1. Gas tractor data is from U.S. Department of Agriculture, *Changes*, p. 31 and from William White's dissertation research.

[13] Ibid., p. 20.

[14] Excellent book-length treatments of tractor evolution include Williams, *Fordson* and Gray, *The Agricultural Tractor*. A description of the most relevant information for this study can be found in William White's dissertation.

[15] The only significant exceptions were in the cotton South, where the mechanical picker had not fully replaced hand methods for harvesting, and in cultivation and harvesting of tobacco, which was still done by hand years later.

[16] Except as noted, all of the numerical data in this subsection comes from Bureau of the Census, *United States Census of Agriculture, 1954*.

[17] U.S. Department of Agriculture, *Agricultural Statistics, 1956*, pp. 574–76.

[18] U.S. Department of Agriculture, *Changes*, p. 31.

[19] U.S. Bureau of the Census, *Historical Statistics*.

[20] U.S. Bureau of the Census, *United States Census of Agriculture*, 1954, p. 105.

[21] The 1.9 million hired workers who worked 25 or more days in 1954 averaged only 142 days of work. An additional 1.1 million people worked 1–25 days during the year. Source: U.S. Department of Agriculture, *The Hired Farm Working Force*.

[22] The resulting number of agricultural workers of 5.98 million is very close to that of 6.2 million from the BLS Employment and Earnings reports. Source: U.S. Bureau of the Census, *Historical Statistics of the United States*.

[23] Olmstead and Rhode thoroughly explore these aspects of the 20th century revolution in agriculture in their 2008 book *Creating Abundance: Biological Inovation and American Agricultural Development.* Olmstead and Rhode primarily focus on the tremendous increases in yields, i.e., output of consumable crops per acre cultivated. This paper focuses on the significant reduction in factor inputs needed per acre of consumable crops.

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

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

[26] A somewhat recent study that quotes earlier work is Mann and St. George, *Estimates*. The same 0.2 estimate is found in Heady, "Extent."

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

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

[29] Reynoldson, Humphries, Speelman, et al., *Utilization*, p. 33.

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

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

[32] This data can be found in U.S. Bureau of the Census, *United States Census of Agriculture, 1954*, pp. 8–9,

32–37. "Cropland used only for pasture" included rotational pasture as well as idle cropland; the name indicates that this land had been used for crops at some time in the past.

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

[34] The results of this exercise were, in turn, checked by running an LP optimization model using the equations discussed above. Results from the LP optimization were quite similar to those shown in Table 5.

[35] The calculated value using the nationwide average is about 500,000 higher in both cases; in other words, 14.9 million and 15.5 million workers, respectively.

[36] The average hourly wage for non-supervsory workers in the goods-productng sectors was $1.65 in 1954, according to U.S. Department of Labor*, Employment, Hours, and Earnings, United States, 1909-90, Volume 1, p. 3*. Although service sector wages were somewhat lower, no aggregate date exists for years before 1964.

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

[38] Csorba, *Farm Tractors,* p. 4. Prices of the various fuels are from *Platt's*. Detailed calculations are available upon request from the authors.

[39] Johnson and Gustafson, *Grain Yields*, p. 53.

[40] An exception to this general trend is in the harvesting of tobacco and some fruits and vegetables, which today still involves a good deal of physical labor.

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

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

[43] Fogel, *Railroads*, p. 236.