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Mechanized Agriculture: Machine Adoption, Farm Size, and Labor Displacement

Andrew Schmitz and Charles B. Moss
University of Florida

Mechanization in such countries as the United States and Canada has dramatically reshaped the agricultural landscape since the time of early settlement. The introduction of new technologies—such as the mechanical tomato harvester, grain combines, and large four-wheel-drive tractors—has resulted in an increase in both farm size and agricultural output, a decrease in the demand for farm labor, and the demise of rural comunities. The adoption of new technologies results in losers and gainers; a debate centers around whether losers should be compensated. Agricultural labor includes workers that are employed in packing and processing plants in which wages are generally low (somewhere near the minimum wage) and working conditions are less than desirable.

Key words: labor demand, technical innovation, rural communities.

Introduction

Mechanization in such countries as the United States and Canada has dramatically reshaped the agricultural landscape since the time of early settlement. However, in some parts of the world, agriculture is still highly labor intensive. Mechanization has had a major impact on the demand and supply for farm labor; the profitability of farming; and the change in the rural landscape, including rural communities. The introduction of new technology usually results in losers and gainers. For example, the introduction of the mechanical tomato harvester in California created considerable controversy, primarily due to farm workers not being compensated for lost wages (Schmitz & Seckler, 1970).

In this article, we highlight several mechanical innovations that include the tomato harvester, cotton stripper and picker, sugarcane harvester, grain combine, lettuce harvester, orange harvester, zero-tillage air seeder, high-clearance sprayer, small farm equipment (e.g., Leon dozer blade, balers and handlers, and rock pickers), concentrated livestock operation equipment, and greenhouse nursery operations. There are others not included, such as tobacco harvesting.

Factors Affecting Farm Labor Demand

We focus on the demand for labor at the farm and at packing and processing levels. We do not discuss the demand for workers employed in other sectors of agriculture (e.g., machine, fertilizer, and chemical manufacturers).

There are two general types of agricultural labor in the United States and other developed countries: owner-operator (or farm household labor) and hired labor. Mechanization affects both sources of labor but in slightly different ways. Mechanization tends to expand the reach of owner-operator labor, resulting in larger farms (i.e., exploiting economies of scale). Mechanization that replaces hired labor focuses on replacing labor in high-valued crops such as fruits and vegetables. At the beginning of the 20th century, this replacement led to debates about labor-push or labor-pull where agricultural labor was used in the growing industrial sector.

Since a major issue is the displacement of labor as a result of agricultural mechanization, we highlight the economic theory behind the choice to adopt agricultural mechanization. In this context, we hypothesize two types of agricultural labor. The first type of agricultural labor is labor hired by the farm. These individuals are paid a fee for service. While a variety of agricultural labor contracts are available (e.g., hourly wages or piecemeal rates), hired workers do not have an equity share in the output.[1] The second type of labor is that of the owner-operator. This labor earns a residual return instead of an hourly wage rate. The complication is that this residual return also includes the return to other factors provided by the sole-proprietor (i.e., capital invested, management, and risk-bearing capital). In general, the supply of either hired or household labor is dependent on the tradeoff between the marginal utility of income versus the marginal utility of leisure.[2]

The demand for hired agricultural labor is affected by policies such as minimum wage rates and immigra-

1. *A discussion of labor contracts can be found in several sources, including Moretti and Perloff (2002), Polopolus and Emerson (1991), and Roka (2009).*

tion policies (i.e., the Bracero program initiated in 1942 and ended in 1964 that provided immigrant labor primarily from Mexico and the Simpson-Mazzoli Act of 1986 which made it illegal to knowingly hire illegal immigrants). On the other hand, the supply and demand for owner-operator labor is affected by factors such as agricultural programs, credit policies, and tax incentives. Different policies have different impacts on the incentives for mechanization. Policies that affect the cost of hired labor such as changes in minimum wages[3] or immigration policies lead to mechanization in higher-valued crops (typically replacing harvest labor such as in the case of the tomato and citrus harvester) while policies that affect farm household labor impact mechanical innovations affecting farm size (i.e., tractor size, tillage and planting efficiency).

Tractors, Tillage Equipment, and Related Technologies

Some of the earliest mechanical innovations in agriculture involved the replacement of draft animals with the steam engine power, which was replaced by the internal combustion engine. Today, agricultural mechanization includes information technologies such as those used in precision agriculture.

Olmstead and Rhode (2008) refer to 1840-1910 as the “great period” of US farm mechanization.

> The adoption of new farm technologies was closely tied to the adoption of horses and mules, as opposed to oxen or human labor for power on US farms. They suggest that a common definition of farm mechanization is the adoption of a machine that allows farmers to substitute animal (horse) power for human labor, thereby enabling a farm worker to cultivate more area … per day or week…. [I]n a sample of 628 Illinois farmers in 1860, mechanical reaper owners possessed 5.9 horses and mules and 0.43 working oxen—twice the ratio of equine to bovines found in the sample area of Illinois in the general population of farmers…. [F]rom 1850 to 1910, farm acres per worker increased as horsepower per worker increased” (Huffman, 2014, p. 111).

Tractors

Prior to the industrial revolution, farming was exclusively hand-and-horse-powered. Eventually, this led to the advent of steam power and later gas and diesel engines. The use of gasoline farm tractors was central to long-term mechanization (Figure 1). Innovative advances in farm tractor technology between 1910 and 1940 dramatically improved efficiency. According to Olmstead and Rhode (2008), early tractors included the Bull (1913), the first small and agile tractor; the Fordson (1917), the first mass-produced tractor; and the Farmall (1924), the first general purpose tractor capable of cultivating row crops such as corn and cotton. The latter was

2. *The basic formulation of the Becker (1965) household production model assumes that the household uses labor to produce a collection of goods consumed by the household (x) using purchased inputs (z) and labor (l_1). In addition to being used in the production of household consumption, labor can also be allocated to earning a wage rate (l_2) or agricultural production (l_3). Any labor not used in household or farm production or used to earn a wage is consumed as leisure. The complete household production model can be formulated as*

$$\max_{x,z,l_1,l_2,l_3} U(x, L-l_1-l_2-l_3)$$
$$\{x,z,l_1\} \in T$$
$$z'\mathbf{p} \le Y_F + wl_2 + \pi(p^*, w^*, l_3, \mathbf{k}),$$

*where $\{x,z,l_1\} \in T$ denotes the household production technology, Y_F denotes the fixed income (i.e., possibly transfer payments or income to capital invested in financial assets), **p** is a vector of prices for purchased household inputs, π(.) is the profit function for agriculture (e.g., the dual profit function convex in output prices p^* and concave in input prices w^*), and **k** is a vector of quasi-fixed inputs whose level cannot be instantaneously varied. In this formulation, the vector of quasi-fixed variables includes investment in agricultural mechanization. In this formulation, some households will choose to hire out as laborers [i.e., $l_3 = 0 \Rightarrow \pi(p^*, w^*, l_3, \mathbf{k}) = 0$] while others choose to be part or full time farmers.*

3. *Schuh (1962) estimates a model of the supply and demand for hired agricultural labor. He finds that agricultural labor may function as a residual labor demand (i.e., employment in the farm sector increases when the non-farm demand for labor is soft). Gardner (1972) analyzed the impact of minimum wage provisions on the demand for hired labor in agriculture. He finds that the initial minimum wage provisions increased the supply of agricultural labor because these provisions excluded farm labor uses. Later when agricultural labor uses were brought under the minimum wage rules, the quantity of hired labor in agriculture declined. Support for Gardner’s results on farm labor was provided by Gallasch (1975). Lianos (1972) finds that both hired and farmer labor declined with the introduction of minimum wage. Following the model from Footnote 1, the shadow price of farm labor used in agricultural production must be consistent with the market price of hired labor: $[\partial \pi(p^*, w^*, l_3, \mathbf{k}) / \partial l_3] \ge w$. If the market price for hired labor increases due to minimum wage regulations, the amount of family labor used in agriculture will decrease until this equilibrium is restored.*

Figure 1. Early gas farm tractor.
Source: Authors

Figure 2. Modern tractor with hydraulic front-end loader.
Source: http://static.wixstatic.com/media/7c998a_ef6be35f971331a566065086a30830d9.jpg_1024.

Figure 3. Modern tractor with Leon dozer blade.
Source: Revegetation Equipment Catalog

Figure 4. Automated rock picker.
Source: Degelman

the first gasoline-powered tractor that incorporated a power takeoff system.

In 1910, there were negligible numbers of tractors on US farms and approximately 24 million draft animals (Olmstead & Rhode, 2008). In 1925, in Kansas, 39% of farms with acreage between 200 and 360 acres had tractors, whereas 68% of farms with acreage between 380 and 600 acres had tractors (Grimes, Kifer, & Hodges, 1928). By 1943, there were equal numbers of draft animals and tractors—approximately 13 million. By 1960, tractors almost totally replaced draft animals as a source of power to run farm operations. The implementation of tractors decreased the time needed for production activities and allowed farmers to sow and harvest large acreages with less manpower (Hurt, 2002; O'Dell, 2007).

With the advent of large four-wheel-drive tractors, along with their accompanying equipment such as the air drill, individual farmers were able to plant, harvest, and maintain a sizable acreage (Hurt, 2002). It is often suggested that since 1945, farm size in many areas of North America has increased by at least a factor of 10 because of this technology.

Small Machinery and Equipment

As tractors evolved, so did small machinery and equipment that worked in concert with tractors. These technologies allowed for a further decrease in labor demand from individual farmers. Figures 2, 3, and 4 illustrate examples of labor-saving technology in the small machinery market such as the front-end loader, Leon Dozer Blade, rock pickers, skid-loaders, balers and bale handling equipment, grain carts, and grain truck hydraulic lifts. Some of the equipment has complementary features in that it can be used for both livestock and crop production enterprises. This has enabled producers to diversify into both livestock and grain operations.

With many of the new technological innovations, hydraulics played a major role. For example, with respect to zero-tillage technology (discussed below), large machines can be moved easily due to hydraulic systems. The 80-foot air drill can be winged to make it

Figure 5. Horse-drawn one-way.
Source: The Encyclopedia of Saskatchewan

Figure 6. US dust bowl era (1930s).
Source: North Carolina State University's climate education for K-12

transportable on highways. Therefore farmers are not limited to expanding farm size by buying adjoining properties, as distance is no longer a factor. This provides much more scope for expanding farm size.

Like hydraulics, welders have had a major impact on agricultural efficiency. Welders have allowed farmers to engage in many activities, such as redesigning farm equipment.

Zero Tillage

Prior to zero-tillage technology, farmers used summer fallow as a risk-management strategy (McClinton, 2006). Early methods of fallowing included the use of horse-drawn one-ways (Figure 5), discers, and cultivators, while later methods included zero tillage through chem fallowing. Generally, summer fallowing increases soil erosion due to bare fields, depletes soil organic matter over the long term due to minimal fertilizer inputs, and increases soil salinity due to rising groundwater levels (McClinton, 2006). These practices generally are no longer used in dry-land farming, as most farmers have replaced summer fallowing with continuous cropping

Figure 7. Zero-till air seeder.
Source: Central Header Parts website

practices. As a result, the possibility of another agricultural "Dust Bowl" (see Public Broadcasting Service [PBS], 2014, for a historical perspective) occurring is remote (Figure 6).

A major breakthrough in the seeding of crops was the advent of zero-tillage air seeders, which were designed for large acreages and are currently the main grain and oilseed planting equipment (Figure 7). No-till air drills allow for continuous cropping in the absence of summer fallow because this reduces soil erosion and increases soil moisture retention. Accompanying this technology was the introduction of high-clearance sprayers—as opposed to ground-level sprayers—that improve efficiency in the application of fungicides and pesticides.

The widespread adoption of zero-tillage technology in western Canada has been one of the factors that transformed prairie agriculture. The transformation from a tillage-dominated cereal crop and fallow agriculture economy in the 1960s and 1970s to the diversified direct-seed crop production of the first decade of the 21st century has been dramatic (Schmitz, 2014).

There are significant monetary and non-monetary benefits accruing to farmers, farm equipment manufacturers, herbicide and pesticide suppliers, and society from the use of zero-tillage equipment (Nagy & Gray, 2012). Benefits from zero tillage include increased carbon sequestration and reduced nitrous oxide emissions, soil erosion and salinity, fuel and labor use, and tractor hours.

Agricultural Precision Technology

Precision agriculture technology offers farmers opportunities to increase profit by simultaneously decreasing wasted resources and labor costs. Some examples include the addition of GPS auto-steer and guidance to reduce overlap, automatic yield monitors, and variable rate technologies (VRT) for applying liquid fertilizer. These technologies have become more affordable and, hence, are accessible to many farmers (Mandel, Lawes,

Figure 8. Original mechanical tomato harvester.
Source: http://ucanr.edu/repository/a/?get=131081

& Robertson, 2010; Swinton & Lowenberg-deBoer, 2001). For Australian farmers, the annual benefit from cost savings and increased production covered the cost of guidance and auto-steer equipment within three years, while the payback period for yield monitoring and VRT was higher at seven years (Mandel et al., 2010).

Although the use of precision agriculture technology offers significant savings in labor and other costs within a reasonably short payback period, the rate of adoption by farmers has been somewhat uneven both geographically and temporally (Swinton & Lowenberg-deBoer, 2001). Overall, the adoption of agricultural precision technology most often occurs in labor-scarce, land-abundant countries with rates of adoption accelerating when commodity prices are high and interest rates are low (Swinton & Lowenberg-deBoer, 2001).

Mechanical Harvesting Technology

Mechanical harvesting has become widespread. As noted earlier, mechanization can displace or substitute for workers in cases of labor shortages. The most contentious form of mechanization is typically the adoption of harvest technologies for high-valued crops such as fruits and vegetables because of the large amount of agricultural labor involved.

Tomatoes

The mechanical tomato harvester developed and used in California was supported and criticized by many (Figure 8 presents the original tomato harvester). The rate of return from investment in the harvester was high, but there were social costs such as farmworker displacement. Schmitz and Seckler (1970) noted that an integrated public-private approach to mechanical harvesting of tomatoes for canning sharply reduced producers' labor requirements. Gross social returns to aggregate research and development were about 1,000%, and even if displaced labor had been compensated for wage loss, the net social returns were highly favorable.

The issue of labor displacement and compensation has been questioned by some. According to Professor Hartsough, Chair of the University of California (UC), Davis Agricultural and Biological Engineering Department, the mechanical harvesting of tomatoes was controversial because it seemingly displaced human labor. However, by reducing harvesting costs by nearly one-half, the harvester eliminated an economic constraint on the US tomato processing industry, resulting in large increases of tomato acreage and yield. Those increases, in turn, provided additional employment in field work, transportation, and processing that more than offset the displaced harvesting jobs (UC Davis News Service, 2005). Originally, the early tomato industry was 80-90% dependent on immigrant labor.[4]

The study by deJanvry, LeVeen, and Runstein (1980) noted that the adoption of the tomato harvester appeared to be the only alternative when the Bracero program ended in 1964.[5] From the tomato grower's perspective, switching to mechanical harvesting required a large initial investment. Consequently, the adoption of the tomato harvester caused a shift from the variable cost of hand harvest to the high fixed cost of mechanization. Growers were willing to make this investment because of the support from processors in the pricing of toma-

4. *Rapid adoption of the cotton picker in California brought serious labor problems for Central Valley raisin and grape producers. This is because mechanization of one crop can cause labor shortages for other crops that are not mechanized but are grown in the same area (e.g., comparing grape and cotton crops: grapes are harvested earlier than cotton so workers that used to remain to pick cotton left before the harvest season). Therefore, mechanization in one crop leads to mechanization in other crops, albeit indirectly through impacts on labor (Rasmussen, 1968).*
5. *In 1965, California had 63 tomato harvesters operating in 15 counties. The average machine harvester crew picked 0.35 ton of tomatoes per hour, per worker. A good hand picker averaged 0.19 ton per hour. Per machine, 61 man-hours per acre yielded 21.5 tons. By hand, this would have required 113 man-hours per acre. Average machine cost was $9.84 per ton, while average hand cost was around $17 per ton (Rasmussen, 1968).*

Figure 9. Early John Deere cotton stripper.
Source: https://www.pinterest.com/pin/331085010078002317/.

toes. Furthermore, switching to mechanical harvesting yielded an estimated cost savings of between $5.41 and $7.47 per ton to growers. These savings were attributable to machines only requiring one pass through the field and machine sorters being paid less than hand pickers. Due to the larger capital investment required to purchase machinery, growers implemented larger-scale planting to increase yields to offset larger overhead investment costs. Because planting a single crop would have incurred a higher risk due to vulnerability to market fluctuations and weather, only farmers with sufficient land for other crops could afford to take on the risk of growing tomatoes. Consequently, large-scale planting eventually led to fewer growers with larger acreages[6] (deJanvry et al., 1980; Rasmussen, 1968).

Cotton

The cotton picker and stripper[7] (Figure 9) displaced thousands of farm workers in various states, including Alabama, Mississippi, and Oklahoma. Like the tractor, combine, and tomato harvester, it contributed to a significant increase in farm size.

Although sharecropping stifled the South's attempts to mechanize, too many farmers, both tenants and owners, were trying to survive on small, uneconomical farms, trapping themselves in poverty. From 1910 to 1970, the Great Migration…reduced the region's oversupply of small farmers. The mechanical cotton picker played an indispensable role in the transition from the prewar South of over-population, sharecropping, and hand labor to the capital-intensive agriculture of the postwar South (Holley, 2003).

While the first patent for a cotton picker was made in 1850, it was almost a century later that a mechanical picker was commercially produced. The Rust picker, patented in 1933, could do the work of 50 to 100 hand pickers, thereby reducing labor needs by 75%. Steel shortages in the 1940s delayed full-scale production of a mechanical cotton picker until after World War II (Holley, 2003).

A controversial issue of the mechanical cotton harvester was the role it played in the Great Migration of the 20th century (Holley, 2003). The popular opinion is that mechanization eliminated jobs and forced farm families to switch to urban employment. In actuality, emigration from the South in the United States was a product of the desire for higher-paying industry jobs in the North rather than an enclosure movement motivated by landowners who were opposed to sharecroppers mechanizing as quickly as possible. Southern cotton farmers were often hesitant to transition from manual labor to machinery due to the expense and unfamiliarity of the technology (Holley, 2003).

World War II brought many changes to agriculture in the South; the number of farms declined steadily and the size of farms increased[8] (Holley, 2003). With the introduction of the mechanical cotton picker, the South was no longer dependent on cotton as its major crop. Cotton acreage was replaced with mechanized crops such as rice and soybeans, thus creating a more diversified agricultural economy. The mechanization of cotton also signaled the end of sharecropping, as more people moved to urban areas (Holley, 2003). Advances in cotton harvesting continued with the modular technology, which reduced the time bottleneck at the cotton gin. Figure 10 presents the newest technology, which integrates the modular technology into the cotton stripper.

6. *For harvesters to be economical, large acreages of tomatoes are required. In 1964, there were 1,072 farmers growing tomatoes on 143,000 acres. The average farm size was 132 acres. By 1975, the number of tomato farmers had decreased to 845, with fields averaging 354 acres (deJanvry et al., 1980).*
7. *The difference between cotton pickers and cotton strippers involves the internal action of the machine. Cotton strippers use rows of spindles to pull the cotton fiber from the cotton boll; the cotton stripper removes the boll in the harvesting process. Cotton stripping tends to be a one-pass activity, but cotton harvested with a stripper requires the separation of the boll from the cotton at the gin.*

Figure 10. Cotton stripper with bailer.
Source: John Deere website

Figure 11. Hand harvesting of sugarcane.
Source: Okinawaology Blog website

Sugarcane

Domestic Sugarcane. Sugarcane was introduced to the continental United States through Louisiana in the 1750s and was a major crop in both Florida and Louisiana by the 1800s. Over much of the history of sugarcane production, much of the planting and harvesting was labor intensive (Figure 11). It was not until the 1940s in the United States (and 1960s in Australia) that mechanization of the sugarcane harvest became feasible (Figure 12; Barker, 2007; Burrows & Shlomowitz, 1992).

Figure 12. Sugarcane harvester.
Source: CNH International website

In contrast, the mechanization of Florida sugarcane harvests was not prevalent until the 1980s (Baucum, Rice, & Schueneman, 2002). While Louisiana implemented mechanical sugarcane harvesters soon after they were developed due to labor shortages and the ease of implementation in Louisiana fields, Florida did not do so until the 1980s (Baucum et al., 2002). This is because Florida sugarcane growers had access to a burgeoning Caribbean immigrant labor force, and it was more difficult to use mechanization in Florida fields. By using cheap illegal laborers, foreign labor quickly became a core part of the Florida sugarcane industry. The illegal labor force in Florida displaced many legal resident agricultural workers who required higher wages and employment costs. Furthermore, the large wage differential between the displaced legal workers and immigrant labor allowed the Florida sugar industry to become unprecedentedly profitable. With labor so cheap and land difficult for machines to harvest, there was little incentive for sugarcane harvesters in Florida to adopt a mechanized harvest scheme. Indeed, it was not until 1986, with the passage of the Simpson-Mazzoli Act, that mechanization in Florida sugarcane harvesting was implemented. The Simpson-Mazzoli Act placed stringent restrictions on the use of illegal immigrant labor, forcing sugarcane growers to either hire legal workers and pay full wages or find some other alternative (Barker, 2007; Baucum et al., 2002; Hill, 1963; Iwai & Emerson, 2008).

8. *In 1954, the average picking cost of cotton was $3,355 per machine. The average cost per bale with machine picking was $25.76 versus $45 per bale for handpicking. The average machine yield was 1.5 bales per acre, which was 1-3% less yield than handpicking; however, that was easily mitigated by different planting strategies. Additionally, even if wages were lower, machine picking would still yield substantial savings (Hedges & Bailey, 1954). Based on data from the 1949 harvest, in a machine harvest season with two pickings, the first picking averaged 1,701 pounds per acre, per hour, yielding about 7 bales per day. The second picking averaged 505 pounds per acre, per hour, yielding about 2.3 bales per day (Hedges, 1950). The average cost of machine picking was $8.25 per hour of operation. However, cotton costs by machine harvest on a second picking were only $0.91 per hundredweight of seed cotton, compared to $4 per hundredweight for handpicking. Moreover, overall harvester efficiency at 96.5% was comparable to handpicking at 97.6% (Hedges, 1950).*

Figure 13. Potato harvesting.
Source: Authors.

Table 1. Wheat data, 1925, Meade County, Kansas.

Number of farms (of 748 total surveyed)	210 farms	127 farms
Acres per farm	200-360	380-600
Farms with tractors	29 (39%)	87 (68%)
Farms with combines	41 (20%)	47 (37%)

Source: Grimes, Kifer, and Hodges (1928)

In addition to the loss of cheap illegal labor, many legal migrants chose less arduous jobs outside of the sugarcane fields. The increasing labor costs forced sugarcane growers to adopt mechanical harvesting. By 1987, 30% of Florida's sugarcane was mechanically harvested and 100% by 1993. In all instances, while mechanization required large initial capital investments, it was subsequently met with increased production and significantly diminished labor requirements and costs (Baucum et al., 2002).

Potato Harvester

For many years, potatoes were hand harvested. During the 1950s and 1960s, the number of mechanical potato harvesters increased fivefold in the United States. Note the similarity between the sugarcane harvester, for example, and the potato harvester. Both of these use a conveyer-belt system in the field for unloading the product from the harvester to the loading wagon (Figure 13).

Grain Combines

The introduction of the grain combine replaced the early technology where grain was harvested with threshing machines driven by steam engines. Today, the grain combine has been adapted for many more commodity crops, such as canola, lentils, and peas.

The grain combine was first developed in the 1920s and was readily adopted by large farms. In 1925, 37% of farms between 380 and 600 acres had grain combines, while only 20% of farms between 200 and 360 acres had combines (Table 1).

Prior to the advent of the combine, small grains at harvest were first made into sheaves by the use of binders (Figure 14) and then "stooked" before being threshed separately using steam-powered threshing machines (Figure 15). The labor used was a mix of migrant, local, and family. Farmers tended to own their harvest machines, while custom operators owned threshers (Isern, 2004).

Figure 14. Grain binder.
Source: Authors.

Figure 15. Steam-powered stationary threshing machine.
Source: The Pietist Schoolman website

Figure 16. Harvesting with horses.
Source: Julie Punishill website

Once combines were introduced, their use lowered harvesting costs, shortened the harvesting season, and increased the acreage of wheat that one farmer could

Figure 17. Early combine.
Source: Authors.

Figure 18. Modern rotary combine.
Source: Authors.

grow. Many of the early combines were pulled through the field with horses (Figure 16). Subsequently, self-propelled combines were introduced (Figures 17 and 18). As farm size increased, production costs decreased (Grimes et al., 1928). For example, in Oklahoma, the number of wheat farmers had decreased from 11,296 in 1921 to 165 in 1932 (Taylor, 1937). Migratory labor also decreased as few laborers were needed for harvest (Isern, 2004).

"Between 1870 and 1890, a number of large wheat farms existed, some exceeding 50,000 acres" (Allen & Lueck, 2002, p. 185). These farms were generally owned under a factory corporate organization form, where owners organized their farms along the lines of manufacturing firms and used a specialized wage labor force. Later, these types of farms gave way to the family farm structure. For example, the well-known Cass-Cheney Farm, on only 4,000 acres of wheat planted, employed 26 breaking plows, 40 plows for turning sod, 21 seeders, 60 harrows, 30 self-binding harvesters, 5 steam-powered threshers, 80 horses, and 30 wagons,

Figure 19. Grain-hauling semi truck.
Source: Authors.

Figure 20. Loading semi trucks.
Source: Authors.

along with a seeding crew of 50 and a harvest crew of 100 (Allen & Lueck, 1998). On the Cass-Cheney Farm, "Oliver Dalrymple managed a harvest crew of 1,000 men and 30 threshing machines spread over 30,000 acres of wheat" (Allen & Lueck, 1998, p. 367). This is a far cry from the modern farms of 2015, where a single family farm can easily manage the planting, spraying, and harvesting of 4,000 acres of wheat.

One of the major breakthroughs in harvesting was not only the introduction of the grain combine, but also the use of trucks with hydraulic grain box lifts in moving the grain from the combine to storage through a grain auger system. In addition, semi trucks are used to haul grain whereas grain carts are used to haul grain from the combine to the trucks (Figures 19 and 20). These semi trucks can be unloaded with the same type of auger used to unload standard trucks where as grain boxes are lifted by hydraulics. This greatly reduces the need for shoveling grain by hand.

Rice Mechanization

After 1940, rice—along with corn and other grains—began being combined using grain harvesters. The rate of adoption was very rapid. Prior to 1930, rice was harvested by hand. As such, labor was intensive and costly, averaging 4.5 labor hours per ton of rice (Thomp-

Figure 21. Planting rice by hand.
Source: Nolathe's Blog website

Figure 22. Rice setting machine.
Source: xoomclips.com

Figure 23. Planting rice with an airplane.
Source: Louisiana State University Ag Center website

Figure 24. Lettuce harvester.
Source: Ramsay Highlander website

son & Blank, 2000). By the 1950s, combines were self-propelled and could be operated by a single person. From the 1940s to the 1980s, yields increased from 2 tons per acre to 4 tons per acre, with labor at only 0.4 hour per ton (Thompson & Blank, 2000).

Once the stripper header began to be used in conjunction with the combine in the 1990s, combines were able to move two to three times more efficiently through a field, which caused labor necessities to decrease to 0.15 hours per ton. Overall, from the beginning of combine use, harvest costs decreased from 67% to only 18% of total costs, while production increased from 0.2 million tons per year to 2 million tons per year (Thompson & Blank, 2000).

The traditional grain harvester is used for harvesting rice. In the early years, like other grains, rice was harvested with threshing machines. Rice was first planted by hand and then later by machines (Figures 21 and 22). As the technology improved in the 20^{th} century, rice growers began using airplanes to plant rice, which made it a capital-intensive crop (Figure 23). To reduce production costs, researchers have developed new rice varieties that allow rice to be planted using ground broadcasting methods such as drills.

Lettuce Mechanization

The development of the lettuce harvester has a long history. Even today, problems remain in the use of the harvester because of the uneven ripening of lettuce. Generally, head, leaf, and romaine lettuce are individually wrapped for the fresh market and are hand harvested using a harvest platform for workers. While this platform has reduced labor costs, further labor-saving innovations are possible. One of the main challenges is that the crop does not mature evenly, so there is a large loss in the amount of lettuce that can be mechanically harvested. One type of lettuce suited to mechanical harvesting is baby lettuce (Figure 24; Calvin & Martin, 2010).

In the 1960s, similar to the tomato industry, the lettuce industry was concerned about the labor situation due to the end of the Bracero program. At this point, research began on a mechanical lettuce harvester that could identify mature heads and selectively harvest them (however, efforts were halted following a lawsuit against the University of California concerning the mechanical tomato harvester). For the most part, modern research has focused on once-over harvest rather than selective harvest (Calvin & Martin, 2000). The first once-over baby leaf lettuce harvester was implemented in the 1990s, and by 2008, 70-80% of it was harvested mechanically. This technology caused a rapid expansion of baby leaf lettuce production.[9] Since the 1990s, the lettuce industry has become significantly more concentrated. By 2007, 8% of lettuce farms controlled 97% of lettuce. Large firms are able to invest in new technology (Calvin & Martin, 2000).

A relatively modern result of technological investment is the Lettuce Bot, a field thinner that is pulled behind a tractor to take pictures of lettuce plants and then utilizes an algorithm to determine if a plant is a healthy lettuce, weed, or another lettuce plant encroaching upon another plant. It kills offenders with a direct spray of highly concentrated fertilizer, which then diffuses into the soil to nourish other plants (*The Economist*, 2012).

More recently, shifts in migrant labor have been an impetus for renewed interest in further mechanization of all types of lettuce harvest. While many producers are beginning to use the H-2A guest worker visa program to meet labor demand in the production of other crops with relatively short harvest seasons, the H-2A program is not widely used for lettuce. This is mainly because the Central Coast lettuce season in California is 7 months long. For this reason, the H-2A program is not used due to both the availability of US farm workers and the high cost of providing the free housing required by the program for the duration of the season. In Arizona, where the lettuce season is only four months, farm workers have traditionally been migrant alien (green card) commuters. However, border controls are increasing and green-card commuters are aging. Younger workers tend to be unauthorized and rely on false documentation. In turn, this drives the younger workers farther north where they are not as vulnerable to detection. Consequently, the labor that was once used for lettuce is diminishing

Figure 25. Citrus harvester—Tree shaker.
Source: University of Florida, Citrus Mechanical Harvesting website

due to a northward shift into the harvest of other crops (Calvin & Martin, 2000).

While the baby lettuce leaf industry is already highly mechanized, firms are developing prototypes to harvest the remaining lettuce crops.[10] Because the US lettuce industry does not face much import competition, if wages were to rise due to increased mechanization, it could likely pass on some costs to consumers. In turn, "a substantial increase in wages would likely spur increased mechanization, including a nonselective harvester for mature lettuce" (Calvin & Martin, 2000, p. 41).

Mechanical Citrus Harvester

During the 2004-05 harvesting season, more than 36,000 acres of Florida citrus were mechanically harvested (Figure 25), but this is changing due to the increase in citrus greening (Huanglongbin or HLB) in the state. In contrast to the increasing mechanization of many other crops, mechanically harvested citrus acreage has decreased significantly since 2005. During the 2012-13 harvesting season, less than 9,000 acres of

9. *While outputs for different lettuce harvesters vary, one manufacturer estimates their machine can cut 13,000 to 15,000 pounds per hour. This would be equivalent to the output of a 140-person crew. Smaller push machines can cut about 300 pounds per hour (Calvin & Martin, 2000).*

10. *Ramsay Highlander has recently launched a mechanical harvester designed for romaine, green leaf, and iceberg lettuce. This new harvester uses Ramsay's Water Jet cutting method, which allows for adjustment of cutting height for uneven beds. This increases yield and product shelf life while also reducing labor. According to Ramsay's specifications, their new machine can harvest 12,000 pounds of romaine per hour into totes and up to 24,000 pounds per hour with a bulk loader. "This harvesting method is the way of the future because of its increased yield, its natural sanitary cutting method, and its ability to negotiate uneven beds…. If you have unpredictable field conditions, this water jet harvester provides a labor saving harvesting solution" (Ramsay Highlander website: http://www.ramsayhighlander.com).*

Florida citrus were mechanically harvested (Roka, House, & Mosley, 2014c).

Mechanical citrus harvesters were first introduced in Florida in the 1960s to harvest oranges (Roka, Ehsani, Futch, & Hyman, 2014a). These systems reduce the cost of labor compared to hand harvesting (Roka, 2009). While fruit recovery approaches 99% of total crop and yields a tenfold increase of boxes per hour compared to hand harvesters, fewer mechanical citrus harvesters are being used to harvest citrus in Florida (Roka et al., 2014b).

After 2006, HLB became widespread in Florida. HLB-infected trees absorb nutrients less effectively and are often poorly nourished. As such, many growers who were using mechanical harvesters prior to 2006 either stopped or significantly scaled back use to minimize damage to already stressed trees. Additionally, HLB has restrained the efficiency of canopy-shaking systems because of the increased costs of replacing trees that had been mechanically harvested before the HLB outbreak (Roka et al., 2014b). Because of HLB, fruit recovery has fallen from above 90% to below 80%. As such, grower concerns still remain and the number of mechanically harvested acres is rapidly decreasing while costs continue to rise (Roka et al., 2014b).

Moreover, managing HLB-infected trees has significantly increased production costs. “Since 2004, the cost of growing oranges for juice processing has increased from $800 to $1,700 per acre” (Roka et al., 2014c, p. 3). Most of this cost increase is due to surging pesticide use to combat HLB. Additionally, harvesting costs have risen by at least 30% as a result of increased minimum wage and added costs of the H-2A visa program for seasonal agricultural workers. The potential cost savings from mechanical harvesting technologies could aid the economic viability of Florida growers (Roka et al., 2014b). However, before growers are willing to re-implement mechanical harvesting, they will have to be confident that short-term benefits are not offset by long-term losses (Roka et al., 2014c).

Huffman (2014) provides examples of mechanical harvesters for other fruit crops. In general, the development of harvesters depends on the technical difficulty. For example, while there is difficulty in separating citrus fruit from the tree, this is not a problem for other fruit crops such as cherries and plums. Also, there is a tradeoff between the visual attributes of the fruit and the fruit’s peel. Citrus is shielded by a strong peel, other fruits are not. The relative value of the crop helps determine the economic success of harvesters. Fruits used in processed products (i.e., canned) are less valuable than their fresh counterparts. This decline in relative value is related to the economic pressure to reduce the cost and marginal benefit of appearance. These pressures give rise to incentives toward mechanization for certain fruit crops.

Figure 26. Greenhouse nursery hydroponic tomato enterprise.
Source: Ontario Greenhouse Alliance website

Greenhouse Nursery Technology

Over the past several years, there has been a significant increase in the production of crops such as tomatoes and leatherleaf ferns (Figure 26). These developments have had a major impact on international trade in these products. For example, Florida is a major tomato producer, but at the same time, the United States imports a sizable amount of nursery tomatoes from Canada. This is a result of the greenhouse nursery technology in Canada.

Drought and Drip Irrigation

Severe droughts in many parts of the world are likely to continue and perhaps worsen (National Aeronautics and Space Administration [NASA], 2015). Over the years, there has been an increased use of drip irrigation in light of global drought conditions. For example, in Israel, most of the cotton is grown under drip irrigation (Fishelson & Rymon, 1989). The adoption of new agricultural production technologies leads to changes in the distribution of work over a given time period. Because these technologies are labor-intensive, more farm labor is required than for competing technologies.

Livestock Operations

Most previous studies focused on technologies that included cotton and other mechanical harvesters at the neglect of the transformation that has occurred in the

Figure 27. Hay baler.
Source: John Deere website

Figure 28. Self-propelled bale wagon.
Source: Mascus website

Figure 29. Dairy milking parlor.
Source: Thomas Michael Corcoran website

livestock sectors. The cow-calf sector has benefited from mechanical technologies such as hay balers and loaders (Figures 27 and 28), front-end loaders (Figure 2), and tub grinders, as well as other technologies such as silage for storing feed. As a result, an individual operator can feed more beef cows during the winter months. This number has increased by at least a factor of five to six since the 1950s. Related to the handling of the non-grain component of livestock feed, in the early years, most of the feed was not baled. With the advent of balers, square bales became popular, and large operators adopted the self-propelled bale wagon for hauling square bales (Figure 28). Much later, round balers largely replaced square balers (Figure 27) because they were more economical.

Over time, the US dairy, pork, egg, and broiler industries have become centralized. From 1997 to 2000, there was a large economic and geographic shift from medium-sized livestock farms dispersed over the country to large-scale factory farms concentrated in specific regions.[11] This was partly due to mechanization. For instance, machine milking has replaced hand milking in the dairy industry. The adoption of this technology has influenced the location of dairy production. Dairy production is now more concentrated in California than in Wisconsin, partly because California adopted the large-scale machine milking technology sooner.

Dairy production involves the use of silage, milking equipment, and parlors (see Figure 29). Traditionally, milking of cows has been labor intensive, twice daily, seven days a week. With technologies such as automatic feeding, yield recording, and cluster removal from the cow's udder, it is possible for one operator to milk more than one hundred cows twice a day in a modern milking parlor. The yield of milk per cow is also increased by adopting misters in free-stall barns. Even higher productivity can be achieved with rotary parlors that move cows around on a rotary table as they are milked (McNulty & Grace, 2009). When implemented, the total commercialization of robotic milking offers a vastly reduced labor input and more flexibility in milking times (McNulty & Grace, 2009).

In comparison to the dairy industry, the pork industry centralized very rapidly and fairly recently. Technological change and vertical integration in the swine industry has resulted in fewer farms producing record amounts of pork. For instance, in 1992, less than 33% of hogs were raised on farms with more than 2,000 ani-

11. *Smaller hog operations decreased while larger operations increased. A decline in animal units on very small farms (from 4.4 million in 1982 to 1.6 million in 1997) and on small farms (from 14.9 million to 11.1 million) was more than offset by growth on medium-sized farms (from 4 million to 6.4 million) and on large farms (from 7.4 million to 14.5 million; US Department of Agriculture [USDA], Economic Research Service [ERS], 2001).*

Figure 30. Confinement pork operation.
Source: Epoch Times website

Figure 31. Turkey feeding operation.
Source: Journalstar.com

mals; by 2007, that fraction rose to 95% (Food and Water Watch [FWW], 2010). Furthermore, this rapid concentration occurred mostly in the Southeast, especially in North Carolina, due to lenient zoning and lack of strict environmental regulations. As such, mechanization of certain aspects of hog farming developed alongside the rapid growth of the farms. As more hogs were produced under concentrated feeding, the introduction of mechanical feeding essentially allowed feeding to become more precise. Additionally, technology has been introduced for "mechanical manure handling and disposal, control of the internal pig house environment, heating/cooling systems, and malodor control (Figure 30). Of these applications and systems, those posing the greatest future challenge are concerned with pollution of the external environment (water, air) and animal welfare" (McNulty & Grace, 2009, p. 15).

Another example of the livestock industry becoming increasingly centralized is the layer hen and egg industry. From 1997 to 2007, the number of egg-laying hens on large farms increased by 23.6% while the number of farms decreased (FWW, 2010). Furthermore, in 2012, egg-producing hens produced more than 300 eggs per year per hen, compared to 150 eggs per year per hen in 1947. While the main focus of the layer industry is egg collection and processing, the physical layout of enclosures for laying hens is designed specifically for efficient, concentrated, mechanical feeding and egg collecting.

An example of a large egg-producing operation is Hickman's Family Farms in Arizona, which houses more than 4 million laying hens (Incredibleegg.org, n.d.). This operation is highly mechanized—from egg production through egg sorting and packaging.

Related to the layer hen and egg industry is the broiler chicken industry. From 1997 to 2007, the number of broiler chickens on the largest farms increased by 87% to almost one billion. A remarkable aspect of the broiler industry is the degree to which it is vertically integrated. Large producers and companies (such as Tyson) own and control the majority of the supply chain; production at the farm level is linked to post-production operations, including slaughter of poultry, preparation of meat cuts, and packing of eggs for the supermarket/retail trade. Large-scale chicken and turkey production involves producers who raise baby chicks and poults according to the standards set by the companies and then send back for processing (Figure 31).

As such, farmers have been transformed into virtual subcontractors in that they are compensated for the act of raising the birds, not the actual chickens. This form of compensation in part explains the rapid concentration of the broiler industry because to increase profits, farmers must increase the number of birds in their facility. In addition, much of the care required by the individual farmers is mechanized, allowing them to feasibly care for more birds than ever before (FWW, 2010).

It is estimated that more than 30 billion broiler eggs are incubated annually. Without technology, the poultry industry would be unable to supply the world demand for poultry products (Butcher & Nilipour, 2002).

Concentrated animal feeding operations (CAFOs) represent an area of increased mechanization that has significantly increased the efficiency of feed processing and delivery (Figure 32). In large feedlots, feed trucks deliver feed to cattle pens, which reduces labor expenditures. However, many of the mechanical improvements involve handling production byproducts such as manure, which raises questions regarding the returns

Figure 32. Beef cattle feedlot.
Source: ProCon.org

captured by farmers versus other environmental interests.

There has always been a debate on the environmental impact of concentrated livestock feeding due, in part, to the disposal of animal manure. In the 1980s, many hog farmers in the Midwest adopted a system where the slurry from hog production could be pumped out and spread over cropland as part of a manure management system. The farmers gained from the nutrient value of the manure applied to crops. However, the practice also had significant environmental benefits. In the southern United States, dairies benefited from waste management. One can document specific cases where a large range of agricultural firms are able to deal with negative externalities from concentrated feeding. For example, Hickman's Family Farms uses poultry manure to manufacture fertilizers than are used on golf courses.

Animal rights movements worldwide are gaining momentum and they are having a major effect on animal agriculture. For example, in 2014, California passed legislation where the number of laying hens that can be housed in a single cage has been severely reduced (Bunge, 2014). Some groups such as the Animal Legal Defense Fund (ALDF) argue that animals—like people—have certain rights and they oppose the "ag-gag" laws that protect factory farming operations.[12] Spiegel (2016) states that Paarlberg argues that the GMO controversy is tame compared to the CAFO controversy.

Beyond the Farm Gate

We have not discussed the labor employed in the farm machinery manufacturing industry. Large companies, such as John Deere and New Holland, employ thousands of workers, including highly skilled engineers.

The focus of this article, up to this point, has been the narrow demand for farm labor. However, what is the picture for agricultural labor that is employed, for example, by the meatpacking industry? The working conditions in the early 21st century often are little better than they were in the early 20th century, as documented in "Meatpacking in the US: Still a Jungle Out There?" on a PBS Now program (PBS, 2006). According to the PBS Now program, because of improved distribution channels and large-scale consolidation, the meat industry has become the largest agricultural sector in the United States, with the top four firms accounting for approximately 50% of all US poultry and pork production and 80% of all beef production. At the same time, consolidation has increased the number of workplace hazards and immigrant workers and decreased workers' income (PBS, 2006). Meatpacking is one of the most dangerous factory jobs in the United States (twice the number of injuries as all US manufacturing jobs) and has a high employee turnover rate due to job stress and low wages (PBS, 2006). With more than 500,000 employees, the average earnings of meatpacking employees is approximately $12 per hour, which is less than the average wage for all other US manufacturing jobs.

Overview

The following is an overview perspective on agricultural mechanization as discussed above, with some additional considerations:

1. Investments in small machinery and equipment (e.g., GPS technology) have resulted in large savings to farmers.

2. Technologies such as the mechanical tomato harvester require very little hand labor, while crops such as lettuce need both mechanical harvesters and hand-labor harvesting crews.

3. Not all mechanical innovations have been successful. For example, because of plant diseases such as citrus greening, sorting problems have arisen that have caused the demand for orange mechanical harvesters to decrease.

4. Many innovations have occurred through investment by the private sector; one of the exceptions is the

12. See http://aldf.org for more information.

Figure 33. Agricultural robotics.
Source: Vision Systems Design website

Figure 34. Steam engine and plow.
Source: Farm Collector website

mechanical tomato harvester, which was developed with both private and public funds.

5. Due to data confidentiality, it is often difficult to estimate the rates of return to investment in agricultural mechanization by the private sector.

6. Even though many of the agricultural technologies are developed by US manufacturers, they are used worldwide, especially in high-income countries. Examples include the adoption of the cotton harvester in Israel and Turkey.

7. A given mechanical harvester, with minimal adaptations, can be used to harvest many different grains and oilseeds (e.g., the same harvester can be used to harvest both wheat and canola). Because of the huge acreage seeded to these crops, machinery manufacturers can capitalize on economies of scale in any given line of machinery production. This is in contrast to the specialized nature of citrus harvesting, where economies of scale are limited due to the relatively small acreage on which citrus is grown.

8. In many cases, it is not profitable or feasible for small farms to adopt large-scale agricultural technologies. In Russia and Ukraine, for example, small, labor-intensive farms operate alongside large, highly capital-intensive farms (Schmitz & Meyers, 2015).

9. The advent of small machinery and equipment technologies—such as hydraulics—has had a profound effect on agriculture. For example, this has enabled individual farmers to engage in several enterprises such as grains and livestock on a large-scale basis.

10. It is common for new mechanical technologies to be coupled with new crop varieties (e.g., tomatoes, rice, and sugarcane). For example, the commercialization of high-yielding sugarcane varieties was possible because of the development and adoption of the mechanical sugarcane harvester that was capable of dealing with lodging associated with the new varieties. Therefore, the payoff to R&D in varietal development may be understated if it does not also include the benefits associated with mechanical harvesting.

11. One cannot over-emphasize the labor component of mechanization (Huffman, 2014). Schmitz and Seckler (1970)—when studying the impact of the mechanical tomato harvester—focused on the concept of Pareto-optimality and the compensation principle. They argued that the adoption of the mechanical harvester resulted in a situation where the compensation principle was met, but not the Pareto principle, since compensation was not paid to displaced workers.

12. Agricultural mechanization has resulted in large, concentrated feeding operations. With this type of animal feeding comes the debate over the violation of animal rights.

13. Agricultural laborers, including workers in packing houses, often receive low wages.

Conclusions

Agricultural mechanical technologies have changed the landscape of farming worldwide. While these technologies have resulted in an increase in farm size, they are

Figure 35. Abandoned farmstead.
Source: Authors.

Figure 36. Dying agricultural community.
Source: Authors.

also often labor displacing. New technologies such as agricultural robotics (Figure 33) will continue the trend toward displacing or replacing farm labor (Boston Consulting Group [BCG], 2014). For example, engineers in California are testing the Lettuce Bot, a machine that can thin a field of lettuce in the time it takes about 20 workers to do the job by hand.

Large-scale agricultural equipment has been around for many years, even prior to large-scale farming. For example, in the early 1900s, steam engines were used to pull large furrow plows to make land suitable for cultivation (Figure 34). Ironically, the continued improvement of large-scale equipment, over time, has resulted in unintended consequences.

The impact of technologies, along with other factors, on the survival of the family farm (Figure 35) and rural communities (Figure 36) has been devastating. In a study for the Economic Council of Canada, Fulton, Rosaasen, and Schmitz (1989) concluded that, for example, in some parts of the Canadian Prairies, the number of rural communities has dropped by a factor of 10 since the 1950s. This has, in part, been brought about by mechanization, which has resulted in increased farm size and the reduction in the need for labor.

> "In the 1960s, farms became larger and the population began to shrink as better highways beckoned people to the city to do more of their business. As in so many small communities, the closing of the school around 1970 marked the beginning of the end….The crumbling old homes and overgrown sidewalks are reminders of the once-thriving community" (Buckmaster, 1993, p. 1).

Unfortunately, economists have not done a good job when dealing with the losers from technological change (Schmitz, Moss, Schmitz, Furtan, & Schmitz, 2010). This is because many of our models focus on only the supply and demand for specific crops along with the needed labor but do not integrate a general accounting of the link to rural communities.

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