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Innovations for a Shrinking Agricultural Workforce

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Recent studies provide evidence that the farm labor supply in the United States is becoming less elastic. Charlton and Taylor (2016) find that rural Mexico, the primary source of U.S. farm workers, is transitioning out of farm work, just as the United States did in the mid-twentieth century and as economies around the globe typically do as they develop. Fan et al. (2015) show that the U.S. agricultural workforce became less migratory in the 1990s, limiting farmers' ability to adjust to short-term shocks by drawing workers from other regions. Richards (2018) finds evidence of persistent labor shortages for harvest workers in California, given a marginal value product of labor insufficient to support higher wages that might attract additional workers. Hertz and Zahniser (2013) document that local farm labor shortages were pervasive throughout the United States in 2011. As the labor supply to U.S. farms continues to contract, farmers will have to invest in labor-saving technologies if they wish to remain competitive in a global economy.

Evidence from previous mechanization events in agriculture indicates that innovation and adoption of labor-saving agricultural technologies is a long process. The cultivation and harvest of the most delicate farm products, like fresh fruits and vegetables, are difficult to mechanize. Successful innovation will require substantial up-front investments in interdisciplinary research combining horticultural and engineering expertise. Farms should anticipate making increased investments in labor-saving technologies, which typically require large up-front costs but can pay off in the long run through reduced labor costs and less dependence on seasonal labor. At the same time, they will need to invest in human capital, learning to work with new technologies and manage a "teched-up" farm workforce.

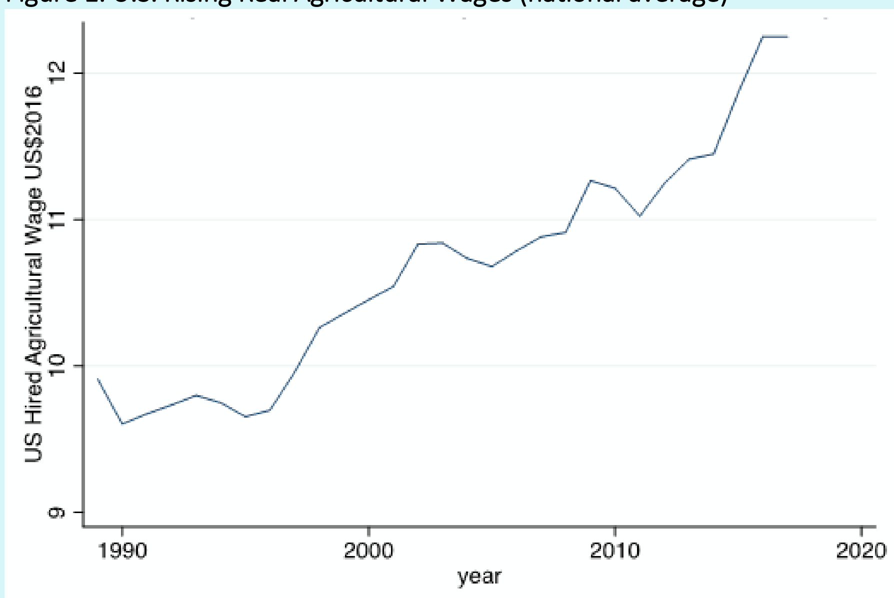
In this article, we examine a producer's decision to adopt a labor-saving technology with potentially high up-front adoption costs and document the expected labor savings associated with several innovations, many of which are not yet in commercial use. Most successful innovations are feasible only with advancements in cultivars, mechanical engineering, and information and technology (IT), highlighting the need for interdisciplinary coordination. Adopting labor-saving technologies can require changing plant varieties, orchard and vineyard layouts, cultivation practices, and machinery, entailing significant start-up costs. New on-farm investments can be high in terms of both financial outlays and learning, but they are increasingly profitable in the face of rising wages and labor shortages. As agricultural technologies become more IT-intensive, investments in infrastructure (e.g., bringing the Internet to the field) and education (preparing the farm workforce of the future) and research and development (R&D) will require a greater role for state and local governments and public–private partnerships to solve the farm labor problem.

Background

Until fairly recently, U.S. farms had access to an elastic immigrant labor supply, and there was little incentive to invest in the development or adoption of labor-saving technologies. U.S. fruit, vegetable, and horticultural production expanded even as wages remained relatively steady throughout the late twentieth century. At times, there has been outright opposition to the development of labor-saving technologies. The University of California was sued in 1979 for using public funding to develop the mechanical tomato harvester (introduced in 1962) on the grounds that the harvester put people out of work and benefited only large producers. The impacts of this innovation on the farm labor market are unknown, inasmuch as the rapid adoption of the tomato harvester simultaneously increased demand for workers in tomato processing plants and at other stages of production. Schmitz and Seckler (1970) estimated gross social gains from the development of the tomato harvester at around 1,000%, well exceeding potential losses to workers who were laid off and small farms that went out of business after the introduction of mechanized harvest. Consumers gained from lower prices, as rapid expansion of the fast-food industry increased the demand for machine-picked tomatoes. The distributional issue remained, inasmuch as those who lost because of the new technology were not compensated and, in most cases, not even identified.

The farm labor situation looks different today than it did in the 1960s, and potential losses will be smaller in today's agricultural labor market than they were previously. Fewer people are willing to work in agriculture today, so rather than replacing workers, agricultural labor-saving innovations are expected to make farmers more competitive while making the workers who remain in agriculture more productive, potentially supporting higher wages and reducing some of the physical risks and discomforts associated with farm work.

Figure 1. U.S. Rising Real Agricultural Wages (national average)



Source: U.S. Department of Agriculture, "Quick Stats" (https://quickstats.nass.usda.gov [Accessed November 26, 2018]). Deflated using All Urban Consumers Price Index, Bureau of Labor Statistics (https://data.bls.gov [Accessed November 29, 2018]).

Rising real farm wages suggest that the farm labor supply is indeed becoming more inelastic (Figure 1). As farm workers become less migratory, seasonal shortages are likely to become more frequent while wages rise (Fan et al., 2015). One suggested solution to the farm labor problem is to improve the efficiency and utilization of the H-2A agricultural guest worker program. The number of H-2A workers certified to work on U.S. farms grew 250% between 2007 and 2018, even though producers raise concerns regarding the complexity and expense of contracting workers through H-2A.[1] Farmers often face uncertainty about how many workers they should contract at the start of the season, before weather outcomes and yields are realized, so contracting guest workers prior to harvest entails risks. Furthermore, filing for H-2A, recruiting, transporting and housing workers, and complying with all regulations pertaining to the H-2A program (like investing in new agricultural technologies) is costly. While guest workers might seem like a plausible solution to the diminishing farm labor supply in the short-run, the number of workers willing to migrate from Mexico to U.S. farms via seasonal work visas is expected to shrink in the long run. Charlton and Taylor (2016) find that rural Mexico is transitioning out of farm work, and although higher U.S. farm wages slow the movement of rural Mexican workers out of agricultural work, they do not reverse it. Mexico's rural population exceeds that of Central America, and contracting and transporting sufficient numbers of workers from

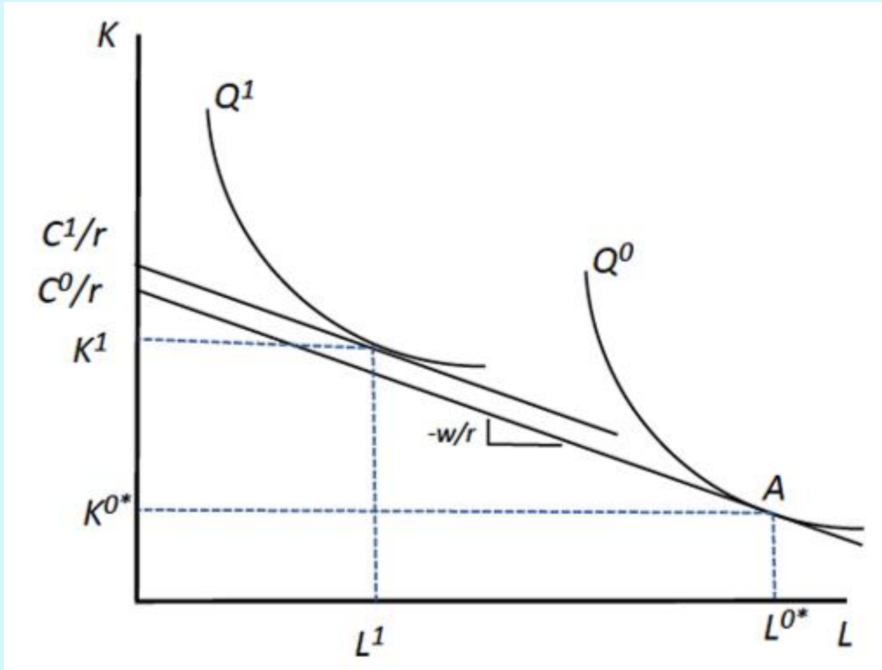
[1] U.S. Department of Labor, Office of Foreign Labor Certification (OFLC). "Disclosure Data." (https://www.foreignlaborcert.doleta.gov/performancedata.cfm [Accessed November 1, 2017 and November 27, 2018]).

more distant countries may be politically or logistically infeasible. In the long-run, agricultural producers will have to find alternative production practices that are less labor-intensive.

Modeling Technology Adoption

The tighter farm labor supply and rising real wages put pressure on agricultural producers to invest in labor-saving technologies and more efficient labor management practices. Production technologies in agriculture often entail high start-up costs, including replanting orchards, retrofitting trellis systems, purchasing new equipment, and learning new practices. A producer who maximizes profit (or expected profit) will invest in a new technology only if the discounted stream of profits from technology adoption is greater than those of continuing to produce using traditional technologies, accounting for the amortized start-up costs.

Figure 2. Optimal Technology Selection When Wages Are Low

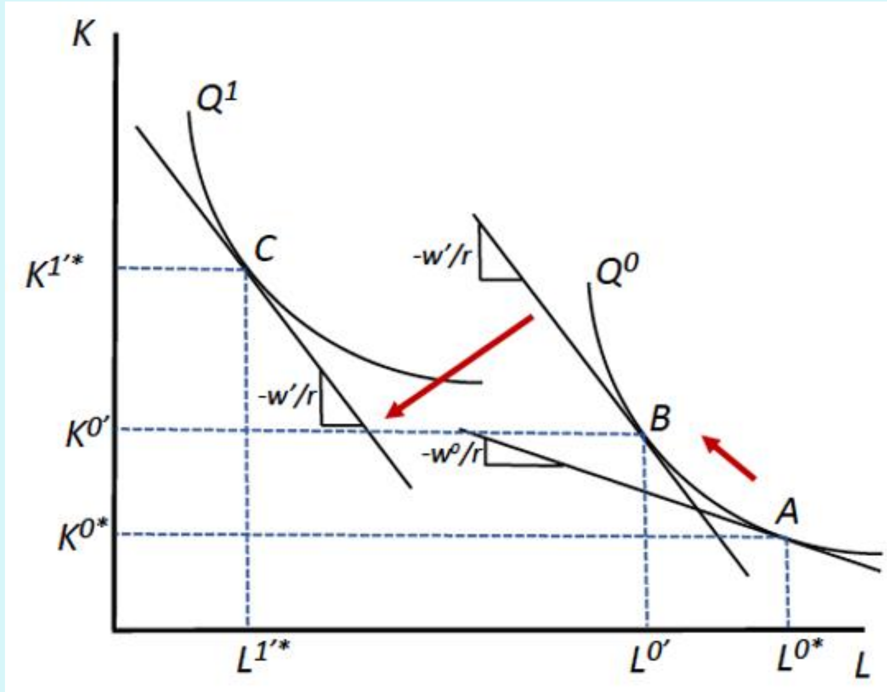


Note: The profit-maximizing farmer produces at point *A* with technology depicted by isoquant Q^0, employing L^{0*} units of labor and K^{0*} units of capital. The cost of production is C^0. The producer has no incentive to invest in the new technology (isoquant Q^1) since, at the optimal point, the cost of production would be greater with the new technology than with the original technology.

Figure 2 illustrates the costs and inputs necessary to produce a fixed quantity of output using two different technologies on a given farm. For simplicity, assume that there are two inputs to production, labor (L) and capital (K). A unit of capital costs r in rent and a unit of labor costs w in wages, so the cost of production is $C=wL+rK$. Let Q^0 be the isoquant for the original labor-intensive technology, such that the selected quantity of production can be efficiently produced using any combination of labor and capital along Q^0, and let Q^1 be the isoquant for the same quantity of production using the new technology. The producer maximizes profits (minimizes costs) for a given technology by producing where the slope of the tangent is the negative ratio of wages to capital rents ($-w/r$). This tangent is an isocost line, since the producer can employ any combination of labor and capital along this line at the same cost. The intercept of the tangent isocost line is equal to the ratio of the total cost of production to capital rents, C/r. Since the intercept of the tangent to Q^1 is greater than the intercept of the tangent to Q^0, the producer minimizes costs by using the original labor-intensive technology. The producer will produce at point *A*, using L^{0*} units of labor and K^{0*} units of capital.

Now suppose that wages rise, making labor more expensive relative to capital. Figure 3 illustrates the effects of increasing wages on optimal production. The isocost lines become steeper when wages rise from w^0 to w'. Maintaining the original technology, isoquant Q^0, the optimal combination of labor and capital changes from point *A* to point *B*. At point *B*, the producer uses more capital and less labor. However, the producer can reduce the amount of labor required for production even more by adopting the labor-saving technology. The optimal combination of labor and capital using the new technology is at point *C*. Since the intercept of the isocost line tangent to Q^1 is less than the intercept of the isocost line tangent to Q^0, we can see that the cost of production using the new technology is less than the cost of production using the old technology. If the up-front cost of adopting the new technology were 0, the producer would clearly minimize costs (maximize profits) by adopting. In reality, there are usually additional up-front costs of adoption that are not depicted in our simplified graph of labor and capital. If the up-front costs amortized over years of production plus the annual cost of employing $K^{1'*}$ units of capital and $L^{1'*}$ units of labor are less than the cost of employing $K^{0'}$ and $L^{0'}$ under the old technology, the producer will invest in the new labor-saving technology. Because large farms can spread the fixed portion of up-front costs across many acres, adoption of most capital-intensive technologies is sensitive to farm size. This explains the concentration of processing-tomato production on fewer farms after the introduction of the tomato harvester.

Figure 3. Labor-Saving Technology Adoption Is Optimal When Wages Are High



Note: When wages rise, optimal production using the original technology moves from point *A* to point *B*, employing more capital and less labor. Labor required for production declines even more if the producer adopts the new technology. The producer will adopt the new labor-saving technology, producing at point *C*, as long as the per period cost of production with the new technology plus the cost of adoption amortized over the life of the technology is less than the cost of production at point *B*, using the original technology.

With this model of technology adoption in mind, in the following section we review several labor-saving agricultural technologies and their adoption paths over time.

Agricultural Innovations

Mechanical Raisin Harvest Required Conducive Market Conditions for Adoption

Agricultural innovations are complicated by the delicate interplay of biological and mechanical design. Adoption of agricultural technologies, once available, is further complicated by changes in the markets for inputs and outputs.

The mechanical raisin-harvesting process offers a prime example of the multifaceted range of factors that affect technology adoption. Until 2000, nearly all of California's 270,000 acres of raisin grapes were harvested manually from the vine and placed in trays to dry on the ground. Average yield was 2 dry tons per acre (Fidelibus, 2014). This is a very labor-intensive task that required approximately 19.2 person-hours per ton of dry raisins (Christensen, 2000; Peacock et al., 2006). Advances in cultivation practices in conventional vineyards (severing canes so that machine harvest does not cause stem-end tearing), combined with innovations in production practices (use of continuous trays) and harvesting machines, reduced harvest labor to 4.4 person-hours per dry ton (Vasquez et al., 2007).

For a new vineyard, the 2006 investment cost for equipment was $124,028 using a traditional manual harvesting system (Peacock et al., 2006) and $257,533 using the continuous tray system (Vasquez et al., 2007). Adoption was very slow, given the high capital cost per acre and the availability of affordable labor (Studer and Olmo, 1974). While labor was relatively inexpensive, there was little incentive for producers to invest in a labor-saving technology, as illustrated in Figure 2. After 2002, following a 56% drop in raisin prices and a tightening labor market, adoption grew rapidly (Fidelibus, 2014); in 2017, an estimated 20% of acreage was harvested using this approach (NASS, 2018).

An alternative mechanized harvesting method called "dry-on-vine" (DOV), developed originally in the 1960s, produces much higher yields (4 dry tons per acre on average) and requires only 3.2 person-hours per dry ton at harvest (another 1.3 person-hours per dry ton are required to remove severed canes after harvest when the labor market is not as tight; Fidelibus et al., 2016). This method entails high up-front costs, including building a new trellis system, planting new vines, and purchasing new equipment. A cost-benefit analysis corresponding to Figure 2 reveals that, at 2016 wages, the labor savings and increased yield justify the $13,994 per acre investment of switching from traditional tray-dried to DOV raisin production (Taylor and Charlton, 2018). Up-front costs have hindered adoption; only about 9% of California acreage was DOV by 2017 (U.S. Department of Agriculture, 2018). Nevertheless, new plantings are now being developed with this approach in mind.

Delicacy and Dexterity: More Challenging Innovations Come at Higher Cost

Tree fruits are some of the most labor-intensive crops grown in the United States today, and viable technologies to reduce labor requirements are on the horizon for only a few varieties. Nearly all fresh-market fruits and vegetables are hand harvested, creating high demand for seasonal labor. Existing mass-harvesting methods such as trunk or canopy shaking result in unacceptable fruit damage and cannot be used selectively to harvest fruits that do not ripen uniformly. Canopy and crop load-management operations, like pruning and flower and fruit thinning, are also manual and labor intensive. These activities require advanced perception and dexterous manipulation capabilities, and they have to be performed reliably in a fast, cost-effective manner.

To address these challenges, engineers from academia and industry are developing "intelligent" robotic solutions for some of the most labor-intensive tasks. Commonly, such solutions need to be combined with changes in cultivars and/or horticultural practices. The up-front costs of adopting robotics in the field will likely be high, and if the robots damage the fruits, the value of the end-product will decline. These barriers would prevent adoption in markets with low wages and an elastic labor supply, but if the farm labor supply continues to tighten and wages continue to rise, robotics will be a critical step forward in keeping U.S. farms competitive in a global market. Some examples of intelligent automated systems that have recently become commercially available or are on the horizon include automated lettuce thinners, integrated weed management systems, and robotic apple harvesters (not yet commercially available).

Thinning lettuce is very labor intensive, and most lettuce fields in California used to be hand-thinned, typically using a hoe. Several companies have introduced automated lettuce thinners that use machine vision and a spray system to remove unwanted plants. Mosqueda et al. (2017) tested four automated thinners and reported that, on average, 2.03 person-hours and 7.31 person-hours per acre were needed to thin the lettuce plots with and without the machine, respectively. The respective labor costs were estimated at $43.40 and $112.70 per acre, accounting for higher wage rates of equipment operators.

Integrated weed management (IWM) systems are essential for broccoli and lettuce. A central part of IWM is physical weed removal. Currently, this removal is performed using standard cultivators that remove weeds between rows, followed by labor-intensive manual weeding inside the rows. The cost of hand weeding ranges from $250 to $450 per hectare. Recently, robotic cultivators have been commercialized to mechanize intra-row weeding. These use computer vision to distinguish crop plants from weeds and activate high-speed blades to selectively destroy weeds. Lati et al. (2016) evaluated a robotic cultivator and reported that it removed 18%–41% more weeds at moderate to high weed densities and reduced hand-weeding times by 20%–45% compared with the standard cultivator.

Other innovative robotic systems being developed by startup companies are at a pre-commercial stage. For example, an apple-harvesting robot is being developed that uses computer vision to locate the fruits and a vacuum gripper on a robot arm to pick them. Its developers have tested the robot on V-trellised trees thinned to single fruits inside the robot workspace and pruned to approximately 25 cm wide. They report picking one apple per second with one robot arm (Salisbury and Steere, 2017). Given that one typical worker on an orchard platform picks approximately 1 apple per 1.5 seconds, the robotic arm could replace 1.5 pickers, and multi-farm harvesters could replace small teams of pickers.[[2]]

New Innovations Demand New Skills

Not only will labor demands decrease in response to technological improvements, but the skills required on-farm also will change. Farm workers will increasingly include mechanics and engineers. Our educational system—including high schools, community colleges, and universities—will have to prepare a generation of workers with the skills to manage new crop technologies. Informational resources, including high-speed Internet, will have to reach into the fields. Rather than importing low-skilled farm workers, the United States might import agricultural engineers from Mexico, where universities currently produce twice as many engineers per capita as U.S. universities do.

New technologies make farm workers more productive, making it possible for farmers to pay higher wages to a smaller workforce. Rising wages can benefit farm workers and the communities where they live, but only if workers have the skills that new technologies demand and if lower-skilled workers can shift their labor from newly mechanized crops and tasks to others that are more difficult to mechanize.

Conclusion

Investments in labor-saving capital and technologies will enable farmers to produce more food with fewer workers. Previously, agricultural labor-saving technologies displaced large numbers of farm workers. However, the agricultural labor supply is shrinking, farm wages are on the rise, and workers from regions that traditionally sent migrants to U.S. fields are becoming more educated and more skilled, preferring jobs outside of agriculture that are more comfortable and secure (Charlton and Taylor, 2016; Richards, 2018). Richards (2018) reports that U.S. farms do not have sufficiently large profit margins to pay workers enough to address labor shortages that may arise from reduced farm worker availability due to declining immigration. As workers eschew agricultural work, innovation will be required to keep U.S. agricultural production competitive in the world market. This can occur and is occurring through new forms of R&D and investments in labor-saving technologies.

A diminishing farm labor supply puts pressure on the agricultural sector to adopt new technologies for difficult-to-mechanize tasks. The competitiveness of U.S. agriculture, as well as the welfare of farm workers and the communities in which they live, depends on how we as a society adapt to a new era of farm labor scarcity. Technologies that were relatively inexpensive to develop and adopt have been in commercial use for many years. The tightening of the farm labor supply today creates incentives to develop and adopt more challenging—and more expensive—labor-saving solutions.

Innovations that keep an aging farm workforce employed and productive are needed while researchers develop robots that can perform tasks that are easy for humans but difficult for machines. Some innovations make use of relatively simple technologies, like growing berries on platforms in the fields that save workers' backs or providing workers with power-assisted pruning shears. Nevertheless, R&D investments today should be more proactive, preparing for the not-too-distant future when fewer workers remain in agriculture and immigrants are better educated. As the farm labor supply tightens, wages rise and producers' willingness to pay the up-front costs of technology adoption increase; however, new innovations have to be available "on the shelf" for adoption. Implementing more sophisticated labor-saving agricultural innovations will require training a generation of farm workers capable of working with the new technologies.

[2] A selection of videos illustrating labor-saving technologies can be found at https://farmlabor.ucdavis.edu.

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