Adoption of Labor-Saving Technologies in Agriculture

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Abstract
Labor-saving technologies in agriculture have been fundamental to the advancement of the agricultural industry, and in general, the economies of nations. This article presents a review of several economic theories that form the basis of the economics of labor-saving technologies, including the theory of induced innovation and subsequent theories developed from it. The review also includes empirical application studies and classifies existing literature into ex ante and ex post analyses of technology adoption. It also presents a thorough review of economic studies on the most successful labor-saving technology adoptions in agriculture, including crops and livestock. Finally, we discuss the future of labor-saving technologies in agriculture and their implications for new societal and economic structures.
1. RESEARCH BACKGROUND

Technological innovation is important for the advance of agricultural productivity, and ultimately, the economic prosperity of nations. The modern global agricultural industry is more efficient than at any time in the past, mainly due to labor-saving technologies (Edan et al. 2009). Different from other industry sectors, labor-saving technologies in agriculture must be advanced given the complex, highly variable, and loosely structured agricultural environment. Also, the implementation of a systems approach is specific to agriculture, which involves the confluence of different disciplines, in most cases, biology/agriculture-related fields along with engineering (Rasmussen 1968). Moreover, labor-saving technologies in agriculture must overcome the challenge of risky and lower returns on the investment, given that the agricultural output is usually lower in price and seasonal throughout the year. Nonetheless, results of the technological revolution in agriculture have led to increased productivity, including lower production costs, reduced dependence on labor, increased quality of agricultural output, and improved environmental control (Edan et al. 2009).

Labor-saving technologies exhibit a considerable impact on labor demand and supply and therefore usually have significant policy implications. From a policy perspective, mechanization technologies might lead to decreased demand for labor and increased concentration among firms. Considering the impact on economic agents, labor-saving technologies are adopted because they can potentially increase revenues and reduce labor input costs and related risks (Sunding & Zilberman 2001). However, to ensure adoption, labor-saving technologies must be economically viable. Once a technology has proven feasible, several factors can impact diffusion patterns, including the inherent risks associated with the agriculture activity, investment costs, uncertainties around the innovation’s performance and reliability, appropriateness for a specific agricultural operation, and environmental conditions. Macroeconomic aspects also influence the adoption and diffusion of labor-saving technologies. For example, institutional arrangements such as labor supply structures, labor contracting, and stock of human capital have been identified as factors deterring adoption of labor-saving technologies in the US South before the introduction of the cotton machine harvester (Whatley 1985, Alston & Ferrie 1993, Heinicke & Grove 2008).

The development of labor-saving technologies has not been consistent across agricultural industries. Labor-saving machinery adoption and diffusion were successful for most annual crops (e.g., grains, cotton), but the same cannot be said for specialty crops (e.g., fresh fruits and vegetables). Productivity increases stemming from systems approach technological innovations (i.e., improvements in seeds, fertilizers, pest management) have led to an increased need for labor, but labor-saving technologies for specialty crops have not been fully developed or widely adopted. In the livestock sectors—primarily dairy—technological advances have led labor to be replaced by increasingly less costly capital, especially in regions where labor is relatively scarce and its cost has been further increased by government regulation.

2. THE HISTORY OF CAPITAL REPLACEMENT OF LABOR

In the post–World War II era in the United States, farm labor declined by at least two-thirds, and the ratio of machinery to labor doubled. The prevailing view was that obstacles to migration out of agriculture depressed rural wages, inducing farmers to substitute capital and intermediate inputs for cheap labor (Rosenzweig 1988). In fact, Manuelli & Seshadri (2014) provided evidence on the impact of low labor costs on the slow rate of tractor adoption in US agriculture between 1910 and 1940.

As countries developed and capital per worker increased, the agricultural sector reacted strongly to the increase in the ratio of wages to rental rates, shifting away from relatively more expensive
labor into relatively cheaper capital. As a result, agricultural capital to labor ratios increased faster with development than did nonagricultural ratios. Herrendorf et al. (2015) found that labor-augmenting technological progress happened faster in agriculture compared to other sectors such as manufacturing and services in the post–World War II period in the United States. This was attributed to the fact that capital share in agriculture is larger compared to other sectors owing to the intensive use of physical capital and land in agriculture. Herrendorf et al. estimated the elasticity of substitution between capital and labor in US agriculture at 1.58. Alvarez-Cuadrado et al. (2017) observed that agriculture lost importance in the share of employment as it became more capital intensive relative to the rest of the economy.

Technological changes in agriculture have also led to studies of labor pull or push. Labor pull suggests that capital accumulation raised urban wages and attracted surplus labor out of the agricultural sector (Gylfason & Zoega 2006), whereas Peterson & Kislev (1986) concluded that technological change in agriculture induced labor to be pushed in rather than pulled out of the sector. However, Alvarez-Cuadrado & Poschke (2011) concluded that both the pull and push phenomena occurred at different periods in time. Improvements in industrial technology pulled labor out of agriculture until the 1920s; after 1960, improvements in agricultural technology pushed resources into agriculture.

Other studies went further, concluding that improvements to agricultural productivity are central to a country’s economic development (Gollin et al. 2007). Other authors claimed that a country’s economic development is often characterized by substantial reallocations of resources out of agriculture (Alvarez-Cuadrado et al. 2017). In sum, improvements in agricultural productivity, including labor-saving technologies, are closely related with advancements in a country’s economy.

2.1. Labor Availability and Immigration

For centuries, US agriculture has depended on a migrant labor force (Martin 2009). Currently, Mexico is the number one source for migrant labor, accounting for 75% of hired farm workers in the United States (Calvin & Martin 2010). This has been driven by a number of factors. One factor is the relatively slow economic growth in Mexico, especially the 1994 economic recession in which one-tenth of Mexican workers in the formal sector lost jobs; in addition, real wages fell, and inflation increased by 50% (Martin 2009). Second, US economic growth in the late 1990s with unemployment rates below 4% resulted in the nonfarm economy pulling much of the US citizenry off the farm. Third, large water storage projects in the West during the second half of the twentieth century accelerated the growth of farms, thus increasing the demand for workers, as proprietors could not harvest crops themselves given the available technology.

However, since the 2008 US economic recession, conditions have changed in the direction of having fewer workers available to work in agricultural fields throughout the United States. Indeed, the estimated number of unauthorized Mexican immigrants living in the United States has decreased by 7% to 11.3 million in 2016 since peaking at 12.2 million in 2007 (Krogstad et al. 2017).

The general economic growth and productivity in Latin America of both the farm and nonfarm economies have started to accelerate relative to the United States. Second, fertility rates in Mexico started dropping around 1980, which can be attributed to a number of cultural and economic factors. This demographic shift is now starting to affect the working-age population. Third, increased spending on border enforcement has increased migration costs for potential workers (Taylor et al. 2012). Fourth, the agricultural labor force is gradually aging, and with older workers exiting from agriculture, the US farm labor supply is likely shrinking (Zahniser et al. 2012). Whereas the supply of farm labor appears to be decreasing, demand for farm labor has remained relatively constant, with 1 million workers as the annual average since 2007. Nonetheless, a widespread
shortage of agricultural labor has not yet happened (Zahniser et al. 2012, Hertz & Zahniser 2013). In this scenario, labor-saving and labor-enhancing technologies appear as a promising alternative. Besides mitigating labor dependency, these technologies could add other benefits such as the improvement of working conditions in the field.

3. ECONOMICS OF LABOR-SAVING TECHNOLOGY ADOPTION

3.1. Economic Theories on Technological Change

Labor-saving technology adoption research stems from the general economic theories on technological change. A number of such theories have emerged during the twentieth century. In his seminal work *The Theory of Wages*, Hicks (1932) postulated the induced innovation theory, generating a series of related theories. During the 1960s, the growth theories of technological change emerged and focused on the impact of input-relative prices on the rate and direction of technological change. These theories were supported by the work of Fellner (1961, 1962), Mansfield (1962), Kennedy (1964), and Nordhaus (1973). Another group of theories aimed to explain the impact of input-relative prices using a microeconomic approach. Main proponents of this body of literature were Samuelson (1965), Ahmad (1966), Binswanger (1974), and Hayami & Ruttan (1970, 1971), the last of which includes an application to technological change in agriculture.

During the 1970s, the evolutionary theory of innovations was developed and postulated that firms decide to invest in an innovation based on a set of decision rules responding to an environmental stimulus. Nelson & Winter (1973, 1974, 1975, 1977; Nelson et al. 1976) were the main proponents of the evolutionary theory of innovations. The path dependence theory was developed in the 1980s and was centered on the dynamics of resource allocation, in which increasing returns could cause the economy to gradually lock into an outcome less superior to the plausible alternatives in a process that was not easily changeable or predictable (Arthur 1983, 1989).

The integration of factor- and demand-induced models was identified as a need in developing a general theory of innovation (Binswanger & Ruttan 1978, Christian 1993). Ruttan (1997) believed that, besides integrating the factor- and demand-induced models, the development of a more general theory of innovation would integrate other theories, including the induced technological change, evolutionary, and path-dependence models and international trade theory.

3.2. Economics of Labor-Saving Technology Adoption

The economic literature on the adoption of new technologies, including labor saving, could be classified according to the time at which adoption decisions are made: ex ante (before adoption) or ex post (after adoption). Such classification helps us understand the factors that affect the adoption of new technologies.

3.2.1. Ex ante. Ex ante studies are those centering on net present value and expected profit maximization models with risk and uncertainty approaches.

3.2.1.1. Net present value. Net present value (NPV) analysis is the most basic approach to evaluating investment decisions. Given that profits and investment decisions occur at different time periods, all financial activities must be discounted to the present using a discount factor. An NPV greater than zero would indicate a profitable investment worth considering (Dixit & Pindyck 1994). However, the application of NPV suffers from limitations associated with disregarding uncertainties surrounding the investment decision and the decision maker (Dixit & Pindyck 1994).
3.2.1.2. Expected profit maximization models, including risk and uncertainty. Typically, investment decisions involve uncertainty, which is usually related to productivity efficiencies, the reliability of the technology, and output and input prices, among other factors. There are two approaches to analyzing risky investment choices: (a) an adoption decision at a given moment of time (i.e., should they invest in labor saving), emphasizing the decision maker’s risk aversion (Marra et al. 2003); and (b) an adoption decision that changes over time, developing decision rules that establish critical values of key random variables that trigger adoption. Both approaches were designed to explain underinvestment in technologies that appeared worthwhile using traditional NPV.

The models that introduce risk considerations at a given moment in time rely on an expected utility framework (Just & Zilberman 1983, 1988; Koundouri et al. 2006). Because of variations in their degree of risk aversion, individuals could make either discrete choices (adopt or not) or continuous choices (at the level of adoption). Yet the criterion for adopting a new technology is that the NPV of the expected gain be greater than the NPV of the cost of bearing risk. This cost can be represented by the variance of the risk-aversion coefficient of the decision maker. This approach suggests that more risk-averse individuals are less likely to adopt a specific technology, and when adopting, they will make a smaller investment.

In advancing the complexity of investment models, Arrow & Fisher (1974) incorporated the timing of the investment decision, because the uncertainty about the future value of an investment and its irreversible costs could affect the timing of the investment, especially for investments with the potential to be more profitable in the future (Marra et al. 2003). This approach emphasized the value of delaying the investment or the option value.

Dixit & Pindyck (1994) synthesized the option-value approach, stating that the model was based on a stochastic dynamic framework that analyzed investment decisions in the presence of uncertainty, irreversibility, and the flexibility to postpone investment. A large body of research in agricultural economics uses the option-value model (e.g., Chavas 1994, Purvis et al. 1995, Zhao 2001, Isik et al. 2001, Carey & Zilberman 2002, Isik et al. 2003, Baerenklau & Knapp 2007, Livingston et al. 2015). Early option-value models considered only one source of uncertainty—such as input price, output price, yield, etc.—but more recent modeling has incorporated multiple sources of uncertainty. For example, Torani (2014) developed a framework in which the decision to invest in a new technology follows a threshold decision rule under the effect of two stochastic processes.

Both the risk-aversion and option-value approaches suggest that investments should be taken when they are, on average, profitable, underscoring the risk costs and the value of delaying the investment. Understanding the uncertainties about new technologies is crucial to making sound decisions. The decision to adopt labor-saving technologies involves many types of uncertainties, including technology performance, future price of labor, future price of output, energy costs, and availability of cheaper technologies in the future. The decision maker must weigh risk aversion, improved information, and future expectations to justify delaying the investment decision.

3.2.2. Ex post. Ex post studies are those on the diffusion of new technologies, with different levels of sophistication ranging from adoption surveys, to diffusion models embedding heterogeneity in diffusion, to threshold models.

3.2.2.1. Diffusion models. Diffusion models focus on a novel technology’s level of penetration in a specific market. Griliches (1957) introduced the concept of diffusion models with his econometric study of the commercial introduction and diffusion of hybrid maize, characterizing the diffusion phenomena with the length of introduction lag, speed of innovation’s adoption, and terminal extent (i.e., the S-shaped function; David 2015). Mansfield (1961) advanced Griliches’s work by
developing the “contagion” model of diffusion. Information imperfections could gradually be eliminated as long as information about the innovation was disseminated. Following technology-diffusion patterns, Rogers (1976) distinguished between early adopters, followers during a period of higher rates of adoption, and laggards during a saturation stage. Such a pattern is sometimes followed by a period of decline in which the technology is replaced by another.

A branch of the technology-diffusion literature includes studies that try to understand the individual adoption process and the resulting diffusion process, as well as identify the socioeconomic, structural, or demographic variables affecting the decision to invest in a new technology. Decision makers consider profit and risk when evaluating new technologies. The new technology tends to improve temporal profits but entails fixed costs. Due to heterogeneity among decision makers and dynamic processes of learning and improvement in technologies, the time of adoption varies among decision makers, resulting in the S-shaped diffusion curve. There are two ways to measure the path of diffusion, by estimating either the share of the number of producers or the share of the area of production adopting the new technology (Feder et al. 1985, Sunding & Zilberman 2001, Jaffe et al. 2002, Foster & Rosenzweig 2010).

3.2.2.2. Heterogeneity in diffusion. Labor-saving technologies often involve a large amount of investment; hence, the firm size is one major source of heterogeneity affecting the timing of adoption. In general, it is believed that larger farms tend to be early adopters. However, Olmstead & Rhode (2001) proved that custom services and renting could overcome the scale barrier to adoption. Lu et al. (2016) supported this finding by observing that large farms that have adopted a new technology rent the use of it to smaller farmers. Over time, the rate of ownership increases as technology prices decline. Another source of heterogeneity may be differences in resource availability and quality. Caswell & Zilberman (1986) showed that the adoption of modern irrigation technologies was more likely to occur when water-holding capacity was low. Their analysis suggested that labor-saving technology adoption might occur in locations with unreliable labor availability.

3.2.2.3. Threshold models. David (1969) developed the threshold model, in which heterogeneity in the population of potential adopters was critical to the adoption decision. David & Olsen (1984, 1986) introduced the concept of “capital-using automation of production methods” in the transition to the new technology. This generalized approach also introduced the concept of a “learning process,” in which the novel capital good could be improved over time, and these improvements would be based on accumulating experience and would reduce the cost of the innovation.

Threshold models vary in their analysis of adoption by individual decision makers. Several models use static models emphasizing risk considerations (e.g., Jensen 1982), whereas others use dynamic models. McWilliams & Zilberman (1996) determine the timing of adoption using the trade-off between the gain from early adoption versus the decreased fixed cost of the technology by delay. The literature suggests that dynamic processes resulting in changes in key variables have higher explanatory power compared to static approaches (Feder et al. 1985, Karshenas & Stoneman 1993, Sunding & Zilberman 2001, Koundouri et al. 2006).

One branch of the literature that reconciles the threshold and imitation models of diffusion focuses on multistage process models, which emphasize that adoption involves multiple stages, including awareness, assessment, decision, purchase, use, and reevaluation (Kalish 1985, Zilberman et al. 2012). Other models include learning as a risk-reducing strategy (Chatterjee & Eliashberg 1990). There are studies that focus on sequential learning across countries (Ganesh et al. 1997), the importance of referrals of previous adopters (Schmitt et al. 2011), and the effect of social networks on the adoption of new agricultural technologies (Goldenberg et al. 2007).
In general, the literature suggests that adopters of new technologies are concerned about uncertainty related to the properties and performance of the new technology and how these uncertainties affect various aspects of agricultural performance. This is precisely the case of labor-saving technologies. To diminish risks associated with performance and malfunctions, insurance and system backups could be an alternative. Mechanisms to protect against risks associated with the performance of a novel technology include warranties, responsive technological support, educational hands-on demonstrations, and arrangements such as money-back guarantees, experimentation with new technology, and short-term renting (Sunding & Zilberman 2001).

4. CUTTING-EDGE LABOR-SAVING TECHNOLOGIES

4.1. Labor Saving in Crops

Labor-saving mechanization has been successful in the agricultural crop industry since the 1800s. During that century, three major labor-saving machines were developed: John Deere’s steel plow, Cyrus McCormick’s reaper, and John Appleby’s grain binder. Early in the 1900s, gasoline engines were adapted to existing machines, and a wide variety of mass-production harvesting machines became available, including the self-propelled wheat combine, the hay baler, and cotton and corn pickers. By the 1960s, grains and almost all roots and tubers were harvested entirely through mechanized methods (Kelly 1967). Tractors, combines, and other farm machinery were continuously improved during the second half of the twentieth century to maximize efficiency, productivity, and ease of use (Edan et al. 2009). Since the 1960s, advancements in the field of mechatronics—a combination of mechanics, electronics, and computer systems—have facilitated the development of sensors and vision-guided devices that were added to the existing machines improving automation and intelligence (Edan et al. 2009).

A major challenge of automation systems is the capacity to adapt to heterogeneity over space and time. This requires the ability to precisely monitor various factors, assess situations, and determine the course of action and then execution (e.g., a weeding system needs to identify a noxious weed, determine how to eliminate it, and then accomplish this). The range of agricultural activities that can be automated is increasing with the improvement of information technology and the emergence of Big Data and methods to utilize it in agriculture (Weersink et al. 2018).

4.1.1. Auto-guidance systems. Automated vehicle navigation systems are classified according to the level of human involvement and include operator-assisted steering systems, automatic steering systems, and complete autonomous steering systems (Edan et al. 2009). The development of the global positioning system (GPS) in the late 1980s revolutionized this field and promoted the widespread adoption of automatic guided vehicles (Edan et al. 2009). In general, considerations that prove the feasibility of this technology include initial investments, labor costs, speed, work hours, energy consumption, and surveillance/control costs. Challenges affecting the successful implementation of autonomous vehicles in agriculture include large operating areas, uneven and changing ground surfaces, cultivation operations, environmental conditions, low-cost output, and safety guarantees (Mousazadeh 2013).

Commercial development of auto-guidance systems in North America began in the early 1990s. For example, GPS guidance systems help the driver to steer a vehicle in the field. Another successfully adopted example is the auto-steering systems that steer the vehicle alongside a path, leaving the driver the task of turning at the end of a crop row (Edan et al. 2009). Autonomous vehicles are capable of working without a human operator and would manage steering, detect and avoid unknown objects, ensure a safe speed, and perform tasks while driving. To estimate
the return on the investment of autonomous vehicles, it is important to assess the degree of the human operator’s involvement that could range from drive assistance, to automatic steering, to autonomous vehicles. Several economic studies, such as those by Goense (2003), and Pedersen et al. (2006), have compared the economic feasibility of autonomous with conventional manned field vehicles. All of these authors concluded that autonomous vehicles are economically feasible subject to considerations, including the number of hours per day the vehicle is working, the price of the GPS navigation system accompanying the vehicle, and the cost of labor. The adaptability of the vehicle to carry a diverse array of implements is also related to the number of hours per growing season the vehicle is in use. This aspect is related to precision agriculture methods, such as chemical sprayers, tree canopy shakers harvesters, and others. In general, efficiency-related aspects are of top priority for autonomous vehicles. A study by Sørensen et al. (2010) investigated the top user requirements for plant nursing robots and found that adjustability to field planting, profitability, minimization of damage to crops, and reliability of the machinery were among the top priorities considered for this technology.

Ensuring safety is important for autonomous vehicles. Several technologies are being studied, including ultrasonic sensors, binocular stereo cameras, and laser rangefinders. For the successful implementation of these technologies, the initial cost is of prime importance. For example, ultrasonic sensors are relatively low cost, but their detection range is short compared to a laser rangefinder; however, the cost of the latter technology would prevent widespread adoption in its current form (Edan et al. 2009).

4.1.2. Irrigation systems. An increase in water scarcity has led to improvements in irrigation technology over time. Traditional (gravitational) irrigation technologies have low water-use efficiencies (percentage of applied water actually utilized by crops), especially on lands with low water-holding capacity (sandy soil). Technologies like drip irrigation and sprinkler systems require extra investment but increase water-use efficiency by improving water holding capacity of the soil and the timing of irrigation. Drip irrigation has been used to apply chemicals (chimigation). It thus tends to increase yield, reduce drainage and chemical residues, and frequently save water. Adoption of drip irrigation tends to save irrigation labor compared to flood protection, but it requires significant human capital for design and management (Taylor & Zilberman 2017). Adoption of drip irrigation in developing countries may have private and public benefits (Kumar & Palanisami 2011). By 2015, drip irrigation was used on 40% of the land in California after a long diffusion process during which private sector efforts were mostly responsible for the improved performance of the technology. Public and private collaboration has led to adopting crop systems to utilize the drip system most effectively, increase the range of crops on which it is applied, and increase automation of irrigation systems (Taylor & Zilberman 2017).

The precise determination of the agricultural crops’ water needs is at the center of irrigation automation devices. A large body of literature has covered the effect of insufficient or excessive irrigation for crops, concluding that either could have a destructive or obstructive effect on yields (Nikolidakis et al. 2015). To determine the optimal crop water balance, one must quantify inputs such as irrigation and rainfall and outputs such as transpiration, evaporation, and drainage. The equipment used to assess such balances includes soil sensors, agroclimatic stations, and lysimeters, the latter of which is a standard tool for measuring evapotranspiration (Ruiz-Canales & Ferrández-Villena 2014). The progress in irrigation technology has been fostered by advancements in the field of wireless sensors and precision agriculture. Such sensors enable controlling the irrigation flow rate and duration in response to local conditions. Water-saving technologies are of primary importance in an era when savings in water usage and production costs are central to guarantee environmental and economic sustainability of the agricultural industry (Goumopoulos et al. 2014).
4.1.3. Seedling production. Seedling production is mainly represented by the grafting of herbaceous seedlings of fruits and vegetables crops. This is an ancient labor-intensive practice that originated in Asia and that has spread throughout Europe and North America, as it enables farmers to overcome limitations in accessing arable land (Kubota et al. 2008). Other reasons for seedling production include procuring plants with improved disease resistance, yields, and product quality. Semi- or fully automated grafting robots have existed in North America since the 1990s. However, these machines are not widely commercialized owing to their lack of flexibility and low productivity compared to manual grafting (Kubota et al. 2008). Recent advancements in robotic systems include improvements in machine vision and leaf removal, whereas planting and cutting devices have emerged as a promising alternative to the automatization of seedling production (Edan et al. 2009). Although they are not directly applicable to seedling production but are relevant to labor-saving technologies in plant propagation, the advancements of Big Data in agriculture will help to save time and costs in developing new plant varieties, thus leading to labor savings in seedling production (Weersink et al. 2018).

4.1.4. Automatic sprayers. Automated chemical sprayers are important for several reasons, such as reducing humans’ exposure to chemicals. Moreover, applying the precise amount of chemicals can protect the crop, as over-application could damage the environment, pollinators, and the plant itself, as well as increase the plant’s resistance to the chemical (Esau et al. 2014). They also have the potential to reduce labor costs. One way to determine the precise rate of application for automated sprayers is to use aerial spectral imaging converted into geographic information system (GIS) coordinates obtained by a receiver in a tractor, which is used with computer-controlled nozzles. The system is sensitive to positional error caused by the GIS; in addition, the updated aerial imaging is expensive, its quality is variable, and data processing is difficult (Michaud et al. 2008). Recent advancements in this field include the reliance on wireless sensors to provide real-time detection information that is used to dispense the precise chemical rate. Ultrasonic sensors are mounted in the sprayer boom, connected with solenoid valves, and variable rate controllers are connected wirelessly to a PC (Zaman et al. 2011, Reyes et al. 2012). Further advancements in the technology include the use of digital color cameras with custom software capable of providing real-time information in the field (Esau et al. 2014). Variable rate sprayer technology is also being studied and specifically applied to fruit trees and vines (Escola et al. 2013, Gil et al. 2013). Typically, canopies vary from tree to tree, which makes it difficult to apply a uniform dosage for the entire orchard block. Orchard sprayers that provide variable rate algorithms to adapt the rate and duration of chemical application according to the canopy volume of each tree or vine plant in real time are under study and thus far have yielded promising results (Escola et al. 2013, Gil et al. 2013).

4.1.5. Weed control automation. Automated weed control has the potential to reduce both production costs due to fewer labor hours dedicated to weed removal and the herbicide application, thus having a positive impact on the environment. Automated weed control is feasible, as demonstrated by advancements in the fields of guidance using GPS, weed detection and identification using technologies such as hyperspectral imaging, precision in row weed control using microspray cutting and thermal electrocution, and mapping (Slaughter et al. 2008, Bakker et al. 2009). The design of methods for intrarow weed removal, which differs from removal between crop rows, presents particular challenges. Recently developed weed control systems are yet not widely adopted because of the constraints of cost, low capacity, low selectivity, and extended time to perform adjustments (Pérez-Ruiz et al. 2014). Co-robots, or machines that could work beside or cooperatively with humans to jointly perform a task, are seen as an alternative for automated
control of intrarow weed removal. Co-robots are being tested, and the main emphasis of prototype development is in the precision of detection of intrarow weeds, which is done by miniature hoes located in intrarow zones between plants; the initial cost of the system is also important. The system still needs human labor to manually locate the hoes in between row crops. After testing in experimental plots, a 57% reduction in labor hours to remove weeds was achieved using co-robots (Perez-Ruiz et al. 2014).

4.1.6. Crop harvesting. Crop harvesting machines date from the eighteenth century with the invention of the cotton gin by Eli Whitney. In the 1920s, the Rust brothers developed a cotton picker prototype that was successfully adopted along with an improved cotton cultivar more adaptable to the machine (Kelly 1967). Another widely adopted mechanical harvester device was the tomato harvester that was facilitated by the confluence of several disciplines, including plant breeding, horticulture, and engineering (Rasmussen 1968). The tomato harvester led to cost savings of 40% compared to hand harvesting (Rasmussen 1968, Schmitz & Seckler 1970). Despite positive net gains to society, the tomato harvester led to labor displacements affecting vulnerable farm workers (Schmitz & Seckler 1970). Increased industry concentration was suggested as a solution, as greater initial capital investments were required to purchase the harvester compared to manual labor. In addition, larger operations consisting of more cultivated area were more likely to gain efficiencies because they could use the harvester to its fullest capacity (Rasmussen 1968).

Early attempts to mechanically harvest fruits included the development of tree shakers, in which the movement detached fruit from the tree without damaging the tree, and catching devices that would prevent damage to the fruit. These machines proved successful in harvesting deciduous fruit trees with robust trunks and fruit surfaces that could withstand impact—such as plums—and for fruits destined for the processing market but not the fresh market, such as apples, cherries, or peaches (Karkee et al. 2017). Another type of harvesting includes the pick-and-place method involving robotic individual fruit picking. This process includes locating the target fruit, approaching it, detaching it, and placing it in a container. In general, robotic harvesting of fruits has not achieved commercial success due to limitations in the detection accuracy, speed, and machine robustness (Karkee et al. 2017).

Currently, both academia and the private sector are intensively investigating the development of a successful mechanical and automated harvester device for tree fruits. Publicly funded research of mechanized fruit harvesting declined in the United States during the late 1970s. By the mid-1980s, researchers recognized the need to adapt the canopy and the horticultural management of the tree to make it more conducive to mechanical harvesting; that is, they adopted a systems approach (Karkee et al. 2017). In the 2010s, only five US tree fruit industries used some form of labor-saving mechanical harvesting, all of which diverted the product to the processing market; those products included oranges, tart cherries, olives for canning, tree nuts, blueberries, and apples. The degree of commercial utilization of mechanical harvesting varies from complete mechanization (processing blueberries and tart cherries) to semimechanical harvest aid platforms (processing fresh market apples). Most published economic analyses related to mechanical harvesting in specialty crops center on the Florida citrus industry (Searcy et al. 2007; Blanco & Roka 2009; Iwai et al. 2009a,b; Moseley et al. 2012; Searcy et al. 2012). There is one published study each on mechanical harvest of tart cherries (Wright et al. 2006), sweet cherries (Seavert & Whiting 2011), olives (Klonsky et al. 2012), and blueberries (Gallardo & Zilberman 2016). Most of these studies use NPV to estimate the economic potential of mechanical harvesting compared to hand harvesting. Mechanical harvesting is more likely to be adopted when its NPV is greater than that of hand harvesting. In some industries such as blueberries, the price differential between the fresh and processing market would determine the adoption of a mechanical harvesting system. Wright et al.
(2006), Iwai et al. (2009a), and Moseley et al. (2012) use different methodologies to demonstrate that labor-saving technologies are profitable in the long run compared to hand harvesting under strong assumptions of efficiencies and economies of scale. Overall findings are that mechanical harvesting is more feasible for industries producing crops for the processing market than for the fresh market and that a total systems approach is most suitable.

The absence of available robotic systems for harvesting fresh market fruits is mainly owing to the unstructured orchard structure, variable outdoor environmental conditions, complex tree structures, fruit clusters and occlusion, inconsistencies in fruit shape and size, and fruit sensitivity to damage (Karkee et al. 2017). Improvements in fruit detection and localization, the duration of the cycles, prevention of fruit bruising, and most importantly, prevention of fruit detachment are needed to make automated harvesting systems commercially successful (Karkee et al. 2017).

4.2. Labor Saving in Livestock

4.2.1. Dairy. The dairy industry has undergone a profound transformation worldwide, moving toward intensive large-scale production units. Technology adoption in dairy production allows for higher milk yield and lower per-unit costs, mainly through labor-saving innovations. Numerous technological advances have provided economic incentives for dairy farm consolidation and herd expansion. Major innovations have been achieved in breeding technology, milking systems, feeding, and herd management. The second half of the 1950s witnessed far-reaching changes in breeding strategies and methods (i.e., new selection mechanisms). In the 1970s, dual-purpose cows had been widely replaced by pure dairy cow breeds, mainly Holstein-Friesian. Revolutionary developments in cattle breeding occurred simultaneously with major technological changes in dairy farming itself (Bieleman 2005). A process of mechanization and rationalization brought in milking machines, milk tanks, herringbone milking parlors, cubicle cow houses, and new foddering systems. The driving force behind this process was the inevitable need to boost labor productivity in dairy farming, as labor costs increased at a much faster rate than the price of the farm’s dairy products.

The most important twentieth-century innovation in dairy farming, however, was the milking machine. This new technology was the springboard to what would eventually lead to the introduction of the herringbone milking parlor, which made substantial savings on labor possible and allowed the farmer to reduce the number of cowmen he employed or to work less himself. However, the introduction and spread of these innovations clearly had a scale-increasing effect of their own (Bieleman 2005). Eventually, the nearest to the ideal of a house that needed little bedding, in which the animals could walk around freely while staying reasonably clean, was found in a British model, the cubicle stall.

As the use of cubicle cow houses spread, the use of the milk-cooling tank also became more general, especially with the introduction of bulk collection. Tank milk was of a better bacteriological quality than churn milk, and it could be brought to dairy factories more regularly, which made the processing of milk in factories more efficient. Transport costs were also lower, and the mobile milk tanker, with its greater collecting area, allowed an increase in scale in the milk-processing industry. The 1970s and 1980s were typified not only by the introduction of cubicle stalls and the milk cooling tank but also by the introduction of the earliest forms of computerization. Process computers took over a number of the farmer’s tasks, such as distributing concentrates and the registration of milk yields. In the 1990s, this development culminated in the introduction of the milking robot.

In roughage production, silaging eventually replaced traditional methods of hay making completely. Crucial for this technology was the application of PVC sheeting to cover the silos,
introduced in the 1950s, as well as the introduction of the self-loader. Meanwhile, unwalled clamps (or a walled horizontal silo if it had a concrete floor and concrete walls) covered with black plastic became a familiar feature in the yards of dairy farms. Their success was assured by their low cost, the low input of labor, and the quality of the product. More or less parallel to the shift from hay to silage was the replacement of the classic cutter bar by the rotary mower for harvesting grass. As grassland management became more and more intensive, the rotary mower was shown to be especially suitable for farmers who chose to use their grassland as intensively as possible.

Rising labor costs in the mid-1970s were one of the main reasons for increasing automation in the milking sector. A complete robotic milking system (RMS) was first developed in the Netherlands in the 1980s, and the first commercial automatic milking system (AMS) was produced there in 1992. Today, AMS is in use on more than 6,000 dairy farms worldwide. More than 90% of dairy farms using AMS are located in northwestern Europe, where investments are driven by high labor costs, a continuous increase in average herd size, and the ongoing dominance of the family farm structure (Meijering et al. 2000). Originally, AMS targeted small family farms with up to 150 cows, but continuous technological progress and increased management skills have allowed AMS to be installed on larger farms, including some with more than 500 cows per herd.

Two great advantages to AMS include reducing the workload per milking and the ability to milk more than twice daily without incurring extra labor costs (Dijkhuizen et al. 1997). On average, a 10% reduction in total labor demand is reported compared to conventional milking systems with two milkings per day (Sonck 1995, de Koning et al. 2003). Furthermore, milking frequencies of more than twice daily can be reached under automatic milking, which is desirable for high-yielding cows because three milkings a day are expected to enhance lactation milk yield by 10–15% on average (Svennersten-Sjauña et al. 2000, Billon & Tournaire 2002, Speroni et al. 2002, Wagner-Storch & Palmer 2003).

AMS result in fundamentally different management systems. For the decision to adopt such systems, several authors stress the importance of noneconomic factors, such as lifestyle choices, including avoiding labor management (e.g., Mathijs 2004, Hyde et al. 2007), in addition to economic factors. Various studies document the causal importance of such nonpecuniary benefits with respect to other agricultural technologies, for example, reduced management effort and work time, equipment savings, improved operator and worker safety, improved environmental safety, and overall convenience (e.g., Marra & Piggott 2006, Zilberman et al. 2010). More recent studies show that adopting management-saving technologies frees operators’ time for off-farm employment, which leads to higher off-farm income (e.g., Fernandez-Cornejo et al. 2005). Finally, Meijering et al. (2000) name some key factors for the successful implementation of such AMS: realistic expectations; consultancy support before, during, and after implementation; effective system control; computer skills; appropriate barn layout and functioning cow traffic; technological functioning; and regular maintenance.

Several studies empirically investigate factors and effects for the adoption of AMS under various policy contexts and production conditions (e.g., Sauer & Zilberman 2012 for Denmark; Butler et al. 2012 for the United Kingdom; Hyde & Engle 2002 and Hyde et al. 2007 for the United States; de Koning et al. 2003 for the Netherlands). In general, studies find a significant reduction in labor needs and the creation of freedom and flexibility for the farmer; however, in practice, farmers found their work routines to be changed rather than lessened after implementing AMS. Results also underscore the importance of risks faced by the agents, the effects of network externalities and peer-group learning, and the positive influence of previous dairy farm–specific innovation experiences. With respect to the decision to adopt AMS as a new milking technology, empirical studies in general suggest the following most important attributes: (a) labor cost savings; (b) the requirement of a minimum herd size to work profitably; (c) an expected output increase due to higher
milking frequencies; (d) animal health implications leading to reduced veterinary expenses, higher milk quality, and hence, increased output; (e) the significance of previous innovation experiences, especially with respect to organic milk production; and (f) nonpecuniary factors.

Performance in dairy production increased enormously as a result of these interlocking technological improvements and the comprehensive process of mechanization and rationalization. Once milk quotas came into effect as part of the EU common agricultural policy (CAP) regime, they led to a striking decrease in production. In practice, the quantity of milk a farmer was allowed to deliver was now fixed; for him to reduce his costs and maintain his income meant he had to achieve his quota with as few cows and the least amount of labor possible. As fodder costs made up a large part of total operating expenses, fodder conversion became an important topic. Efficiency in milk production had to be improved in this sense, which meant that breeding strategies now concentrated on higher production, in relation to a lower weight of the cow and hence a lower consumption of feed (Bieleman 2005).

Precision dairy farming involves a diverse array of technologies, including physiological, behavioral, and productivity indications for individual animals through milk yield recording, milk component and cow activity monitoring, rumination behavior, as well as milk conductivity and heat detection indication (e.g., Bewley 2010, Bewley & Russell 2010, Dolecheck & Bewley 2013). These technologies mainly focus on the way in which dairy cows are managed by monitoring factors such as rumen pH, jaw movements, feeding behavior, heart rate, and sleeping time. Therefore, they aim to maximize individual animal performance, detect and cure diseases in a timely way, and thus minimize the use of medication and labor through adequate and cost-effective prevention methods. However, the adoption of such technologies has been rather slow so far, mainly due to unfamiliarity with available technologies, profitability concerns, learning difficulties, and previous negative experiences (Dolecheck & Bewley 2013). Nevertheless, given the increasing price of labor relative to the development of farm gate prices for milk, it can be expected that more and more producers will realize the labor-saving opportunities offered by these technologies, regardless of the size of the dairy operation. In addition, wider societal benefits such as reduced environmental impact and improved animal health and well-being render these technologies highly attractive for future dairy farming.

4.2.2. Pork. Pig production developed incrementally in the twentieth century. Government involvement was mainly through feed markets, marketing subsidies, and cropland market interventions. Production units were small, especially with respect to hog production. However, since about 1990, the US hog industry (but also in EU countries, especially Denmark, the United Kingdom, and Germany) has seen major restructuring. High feedstuff prices had increasingly undermined profitability. The increasing cost competitiveness has led the industry toward larger scales of production, increasingly specialized production, and production based on the most cost-effective technology.

A set of alternative production techniques—such as breeding and nutrition systems, genetics, feeds and feeding programs, housing conditions, and animal health—have to be considered (Whittemore & Kyriazakis 2006). There is a particular interest by research and development departments in the optimal feeding ratio (composition of ingredients, percentage of vitamins and micronutrients, etc.), the origin of genetic material (genotypes provided from breeding stock or from finishers), as well as the insemination method to improve the herd’s quality characteristics (Galanopoulos et al. 2006). These technological choices, of course, have a crucial impact on the economic and sustainable performance of the individual farm.

In the European Union, increasing consciousness about excess production and the induced burden on the CAP budget—the main point of concern for the industry and related...
stakeholders—has shifted from output growth to input-efficient farm management. This also triggered a rapid development of electronic data recording and processing facilities, especially in sow farming. For example, in the Netherlands during the 1980s, manual calculations were almost completely replaced by PC-based systems designed to provide daily production information on individual animal levels that is of essential value in making management decisions (see Boehlje & Eidman 1984). By the 1990s, nearly 40% of Dutch sow farmers used management information systems (MIS) (accounting for approximately 75% of all Dutch sows). Surveys on adoption and use of information systems, conducted in 13 midwestern states, showed that US sow farmers had similar rates of MIS adoption as their Dutch counterparts (Verstegen et al. 1995).

Various empirical studies have investigated the productivity and efficiency effects from labor savings by technological improvements and management innovations in the pork sector. Galanopoulos et al. (2006) found that the choice of the insemination method, origin of genotype, feedstuff preparation system, mortality rate of piglets, and size class have a significant impact on the efficiency of pig production units. Verstegen et al. (1995) investigated the economic benefits of MIS in sow farming by estimating mixed-effects models controlling for self-selection bias and changes over time. Production on farms adopting MIS increased by 0.56 piglets per sow per year, a significant return on investment. Verstegen et al. (1995) conducted a pilot experiment to yield insight into whether laboratory experiments can be used as an alternative to surveys for determining the profitability of MIS in sow farming.

The use of production contracts is generally associated with a significant increase in productivity (McBride et al. 2008). These authors used a treatment-effects sample-selection model to examine the impact that feeding antibiotics has on the productivity of US hog operations. No significant relationship was found between productivity and antibiotics fed during finishing, but productivity was significantly improved when antibiotics were fed to nursery pigs. Miller et al. (2003) identified improvements in average daily gain, feed conversion ratio, and mortality rate from growth-promoting antibiotics in the grower/finisher phase of US pork production. These productivity improvements translated into a 9% improvement in net profits due to growth-promoting antibiotics.

4.2.3 Poultry. There has been a tremendous restructuring of the poultry processing industry in the last 50 years. The industry has changed from one of numerous small plants producing generic whole birds to one consisting of much larger plants producing deboned poultry, tray packs, and further processed products. There have been cost-effective innovations driving structural change: New processed products raised production costs, while new production technologies reduced production costs (e.g., by increasing line speeds, improving yields, and realizing scale economies; see Morrison-Paul et al. 2004). These changes had significant labor-saving effects as well. Powered by rapid consumption growth, production plants had to dramatically increase in size. By adding cut-up and processing lines to the end of existing slaughter lines, poultry plants were able to increase net revenues by selling a variety of products in segmented markets. Organizationally, many poultry slaughter firms adopted an integrated structure in which the integrator owns the slaughter plant, feed mill, and further processing plants and contracts with a number of poultry growers. The integrator provides the grower with essential inputs—chicks, feed, veterinary services, etc.—whereas the grower contributes housing and labor services. Growers frequently maintain long-term relationships with processors based on performance-focused contracts that also cover price risks and area-wide disease and weather risks.

As in the pork sector, the use of antibiotic growth promoters (AGPs) is prominent in the poultry industry, as it is assumed to increase productivity and generate wider economic benefits based on a higher input efficiency, including significant labor savings. Various studies investigate
these assumed productivity effects (e.g., Emborg et al. 2001 for Denmark; Engster et al. 2002 and MacDonald & Wang 2011 for the United States). MacDonald & Wang demonstrated that suspending AGPs would have no statistically significant effect on production in US broiler grow-out operations, after controlling for other factors that might affect production (e.g., labor, capital, and other inputs). However, the authors also found that growers who do not use AGPs receive statistically significantly higher contract fees than growers who use AGPs to compensate for assumed lower selling prices. Others even document a negative effect of using AGPs with respect to chicken production (Graham et al. 2007).

As in the pork sector, the use of AGPs is considered to be more beneficial where animal health has to be maintained, as in older facilities and with less hygiene-efficient management types (MacDonald & Wang 2011). Finally, some studies highlight that antibiotics can decrease the bacterial contamination of animal carcasses and products (e.g., Hurd et al. 2008), whereas others point out that improved biosecurity, better hygiene-management practices, or vaccinations offer the opportunity to control infectious disease in food animals without increasing levels of antibiotic resistance (Teillant & Laxminarayan 2015).

Several empirical studies are worth mentioning with respect to technological innovations in poultry production that also result in potentially labor-saving effects. By 1976, Mann & Paulsen (1976) had already developed an econometric simulation model to evaluate the impact of policy alternatives on costs, prices, and net profits in beef, pork, broiler chicken, and turkey production over a 10-year period. Goodhue (2000) investigated the behavior of processors in the broiler industry with respect to growers’ production contracts using an agency theoretic framework. The study confirms inter alia that processors control inputs to reduce the information rents paid to growers. Ollinger et al. (2005) used a panel provided by the US Census Bureau to empirically examine technological change in the US poultry industry based on a sound production framework and found that substantial scale economies were much greater than those realized in cattle and hog slaughter, implying that consolidation is likely to continue and that optimizing input and output mixes appears to be critical to securing cost competitiveness. Finally, MacDonald & Wang (2011) confirmed earlier evidence that broiler producers (partly) suspending the use of subtherapeutic antibiotics do not experience statistically significant impacts on production given other inputs. However, these producers most likely receive higher contract fees, suggesting that they bear higher costs (including labor) to realize given output levels.

5. FUTURE RESEARCH

During the last century, the agricultural industry has gone through two significant revolutions. First, the Green Revolution involved the adoption of hybridized seeds, mechanized devices, improved irrigation systems, and low-cost chemicals such as fertilizers and pesticides (Weersink et al. 2018). The second ongoing revolution is the digital agricultural revolution, represented by the development and adoption of automated systems, robots, sensor technology, Big Data analytical platforms, and artificial intelligence. Future agricultural systems will rely on robots, sensors, and Big Data analytics that enable principal operators to manage their fields with improved precision on both spatial and temporal scales (Weersink et al. 2018).

The ongoing revolution is further fueled by changes in population aspirations, an aging population, and a growing population that challenge the agricultural industry to ensure food security. In this context, labor-saving technologies aimed at enhancing labor productivity by decreasing the agricultural industry’s dependency on labor are becoming increasingly important. The agricultural industry will be more economically sustainable by automating subminimum-wage jobs. Examples of technological advancements in agriculture yet to be widely adopted include harvesting
robots, driverless tractors, sprayer drones, artificial intelligence to manage chemical and fertilizer application, and precision dairy farming, among others (Ball et al. 2017, Smith 2017).

Contrary to the belief that agriculture automation will displace workers, automation will create better paid jobs requiring different sets of skills. Workers will have the opportunity to move up in the value chain with new job tasks such as managing fleets of robots rather than spraying chemicals or cleaning cow udders. Other types of jobs will be, for example, to analyze and interpret data coming from artificial intelligence, allowing better decisions based on more detailed and high-quality information (Ball et al. 2017, Smith, 2017) and a consideration of wider societal benefits such as environmental impacts and animal health.

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Errata

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