



Food and Agriculture
Organization of the
United Nations

Automation and social impacts: winners and losers

Background paper for
The State of Food and Agriculture 2022

FAO AGRICULTURAL DEVELOPMENT ECONOMICS
WORKING PAPER 22–09

▶
ISSN 2521-1838

November 2022

Automation and social impacts: winners and losers

**Background paper for
*The State of Food and Agriculture 2022***

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Rome, 2022

Required citation:

Charlton, D., Hill, A.E. & Taylor, J.E. 2022. *Automation and social impacts: winners and losers*. Background paper for *The State of Food and Agriculture 2022*. FAO Agricultural Development Economics Working Paper 22-09. Rome, FAO.
<https://doi.org/10.4060/cc2610en>

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ISSN 2664-5785 [Print]

ISSN 2521-1838 [Online]

ISBN 978-92-5-137074-2

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Abstract

Agricultural production is changing rapidly. The adoption of labour-saving technologies, from tractors in low-income countries to high-tech artificial intelligence (AI) solutions found mostly in high-income countries, is occurring in the context of a global agricultural transformation and evolving agrifood systems. Understanding the social implications of automation in agriculture requires viewing technology change on farms within the broader context of the agricultural transformation and agrifood systems, as well as changing economic incentives to develop and adopt labour-saving technologies.

This study overviews the social implications of automation in agriculture, focusing on labour and employment. Based on the available literature, it finds that, contradictory to the beliefs that automation creates unemployment and depresses wages, automation can stimulate employment by allowing producers to expand production and by creating jobs at other nodes along agrifood systems (e.g. storage, processing, transport).

The study further reviews the impacts of automation on employment, which will depend on the driving factors. If automation is driven by rising wages and labour scarcities, then it is unlikely to create unemployment; if forcibly promoted, for example through government subsidies, it could lead to rising unemployment and falling or stagnant wages. However, in both scenarios, the literature suggests that automation is likely to have positive indirect effects via job creation at other nodes in agrifood systems. Governments should take caution in creating market distortions that encourage automation of tasks with an ample workforce, particularly when skillsets of those workers are unlikely to transfer to other employment opportunities in agrifood systems. For example, public investment in automating harvesting – despite an abundance of harvesters – may be problematic because the skillsets of harvesters likely differ from the skills required by newly-created jobs from automation. Government policy should therefore focus on fostering innovation, improving human capital, and building the capacities of agricultural producers, particularly youth, so that they can navigate automation technologies and access higher-skilled jobs. Investing in infrastructure (e.g. internet connectivity) is also a key enabler to adoption.

Keywords: digital technology, automation, labour, income distribution.

JEL codes: D10, Q18, I32, O54.

Acknowledgements

This paper has been written as a background paper for *The State of Food and Agriculture 2022*.

The authors are thankful to Andrea Cattaneo (Senior Economist, Agrifood Economics Division [ESA], FAO), Ahmad Sadiddin (Economist, ESA, FAO), Sara Vaz (Economist, ESA, FAO), Laurence Dynes (Junior Economist, ESA, FAO), as well as other members of *The State of Food and Agriculture* writing team, and all the colleagues who provided comments during the review seminars for the valuable support on the development of this paper.

We also would like to thank the ESA Working Paper Review Board and, in particular, Christian Morales Opazo (Senior Economist, ESA, FAO), Ana Paula de la O Campos (Economist, ESA, FAO) and Marco V. Sanchez (Deputy Director, ESA, FAO) for their reviews and inputs.

Finally, we would like to thank Daniela Verona (Publishing Coordinator, ESA, FAO) for her valuable support for the formatting and layout of the publication.

1 Introduction

Agricultural production is changing rapidly. The adoption of labour-saving technologies, from tractors in low-income countries to artificial intelligence (AI) solutions found mostly in high-income countries, is occurring in the context of a global agricultural transformation and evolving agrifood systems. A basic premise of this paper is that understanding the social implications of automation in agriculture requires viewing technology change on farms within the broader context of agricultural transformation and agrifood systems, as well as changing economic incentives to develop and adopt labour-saving technologies.

This study offers a comprehensive overview of the social implications of automation in agriculture, focusing on labour and employment. It begins with an overview of labour in agrifood systems and agricultural transformation. It then reviews social implications of automation, with a focus on labour and employment. Why farmers automate can shape social outcomes in complex ways. Automation incentives as well as social impacts are likely to vary at different stages of the agricultural transformation and in different agrifood systems.

Automation on farms naturally implies a smaller agricultural workforce, but also a different workforce. Skillsets of farmers as well as farm workers must match the skill demands of new and more sophisticated agricultural technologies. The study then focuses on this often-overlooked aspect of agricultural automation and offers some insights into who is most likely to benefit from automation and who is not, as well as new educational challenges given increasingly complex agricultural technologies. The study concludes by recapping key findings and policy implications.

2 Understanding agrifood systems

Understanding the dynamics of agrifood systems is critical when analysing and predicting effects of automation at any node in the system. Both upstream and downstream responses are equally important in understanding partial equilibrium implications for agricultural production, prices, trade flows, and employment.

To exemplify the importance of thinking about automation across entire agrifood systems, consider the invention of the mechanical tomato harvester in California, United States of America. Between the 1950s and 1960s, Gordie (Jack) Hanna, a plant breeder, and Coby Lorenzen, an agricultural engineer, both at the University of California, Davis, developed a mechanical tomato harvester and genetically engineered tomatoes that could be picked with it. They successfully bred a tomato that ripened uniformly on the vine and had a tough skin that would not break even when handled roughly by a machine. This tomato breed allowed for the successful use of an automated harvester that pulls tomatoes from the ground, separates them from their vine and collects them without breaking the skin (Taylor and Charlton, 2018). This was a significant breakthrough, combining biology and agricultural engineering in new ways. The first commercial harvesters were used in California in 1961, two years before the Bracero Program – which allowed Mexican workers to come to the United States of America on short-term contracts as agricultural workers – ended, on which processing tomato growers relied. By 1967, approximately 80 percent of California’s processing tomato acreage was mechanically harvested (Schmitz and Seckler, 1970).

Early work on the social implications of this invention focused on welfare gains for farmers and consumers from increased production efficiency and welfare losses for agricultural workers (most of whom were immigrants) from reduced farm job opportunities (Schmitz and Seckler, 1970). However, studies that considered the increased demand for workers in cannery and assembly line jobs concluded that the effects in upstream and downstream markets can offset much, if not all, of the welfare losses from reductions in demand for seasonal farm labour on farms, as employment shifts toward higher-skilled and higher-paid jobs off-farm (Brandt and French, 1983). Over the past 35 years, the mechanical tomato harvester and its improvements reduced field labour requirements for processing tomatoes by 92 percent per ton (Huffman, 2012). Long-run increases in production led to more employment in (upstream) equipment production and maintenance and (downstream) food processing and manufacturing that helped fuel the fast-food revolution in the United States of America. However, as the required skillsets differed for jobs across the agrifood value chain, new jobs did not appear immediately, and after more than three decades, the winners and losers from this technological breakthrough are not immediately clear. Because of the large sunk cost, adoption of the mechanical tomato harvester remains concentrated among commercial farms in developed countries, with unclear implications for the welfare of smaller farms in both developed and developing countries.

This section provides an overview of upstream and downstream markets in agriculture. We make a distinction between three different types of agricultural production – subsistence farming, family commercial farming, and corporate commercial farming – and document the upstream and downstream market linkages for each. We also take note of the different types of labour needed within each market. The goal is to establish forward and backward linkages across agrifood systems that shed light on how effects from automation technologies can permeate across distinct labour markets. Within that overall structure, we then discuss key

heterogeneities in worker attributes that employers demand and prevalent in the labour pool across these labour markets. In particular, we focus on differences in gender roles, labour types (e.g. migrant/local or seasonal/non-seasonal workers), and skillset. The goal is to shed light on labour markets across agrifood systems that workers can transition between without incurring high switching costs. Finally, we discuss implications from globalization in terms of potential job creation that might occur in agrifood systems.

2.1 Overview of upstream and downstream agricultural markets

Figure 1 depicts agrifood systems. The figure separates upstream, midstream, and downstream markets, listing key activities undertaken in each market. The figure shows linkages across markets and highlights differences in the common market activities for three distinct categories of agricultural producers – subsistence, family commercial, and corporate commercial farms. At the bottom of the figure we list major types of labour used in each market and indicate (with upward and downward arrows) how automation technology impacts each labour type. We discuss these labour impacts in the following section. Here we provide background on the market linkages within agrifood systems that is useful to clarify the labour market implications from automation technology adoption.

We consider production of the raw agricultural commodity as central to the system, and thus the midstream market consists of three types of agricultural producers. Subsistence farms are operations that engage in farming activities as part of a household livelihood strategy; few inputs are purchased and agricultural products are consumed by the producing households (Morton, 2007). Subsistence farms are most common in developing countries but can also describe small homesteads in rural areas in high-income countries (Davidova *et al.*, 2012). While subsistence farms are characterized as producing food for their own consumption, this does not necessitate that households produce all their food. In fact, households engaged in subsistence farming rely heavily on purchased foods (Frelat *et al.*, 2016; Sibhatu, Krishna and Qaim, 2015; Sibhatu and Qaim, 2017). Family commercial farms are operations engaged in farming activities as part of a household income strategy; most inputs are purchased and agricultural products are sold in local, national, or global markets. Family commercial farms include smallholder farms in developed and developing countries as well as mid- and large-scale operations in developed countries that are owned and operated by a household. Corporate commercial farms engage in farming activities as part of a business strategy and are not run by members of the same household; all inputs are purchased, and agricultural products are sold primarily in national and global markets. Corporate commercial farms are more common in high-income countries, consisting of large-scale agricultural producing businesses, but they also exist in developing countries in the form of plantations and large-scale estates (Hall, Scoones and Tsikata, 2017). Activities undertaken at this node in agrifood systems consist of all actions directly associated with crop and livestock production. For crop production these include soil maintenance and preparation, planting, weeding and plant care, and harvesting. For animal husbandry these include breeding, raising, and daily care and health monitoring.

Upstream activities consist of all activities related to providing inputs for agricultural production. These vary by type of agricultural production, but broadly include the production and distribution of seeds, fertilizers, equipment/machinery, animal feed, irrigation/wells, insurance, and financing/loans. Subsistence farms rely primarily on non-purchased inputs including saved seeds, animal feeds from cultivated crops, and rainfall rather than irrigation (Barnett, 1996).

Depending on their size, location, and other defining characteristics, family commercial farms might use non-purchased or purchased inputs, or some combination of the two. For example, smallholder farms in developing countries might use saved seed (Kraft, de Jesús Luna-Ruiz and Gepts, 2010) or purchase seeds from local markets (Mcguire and Sperling, 2016), manure from the farm or purchased fertilizers. Corporate commercial farms in developing and developed countries rely almost entirely on purchased inputs. Purchased inputs used by family and corporate commercial farms include fertilizers, improved seeds and feeds, equipment and technology, irrigation, young livestock (e.g. calves), and financing and insurance. In this representation of agrifood systems, what we commonly think of as agricultural technological innovation occurs on the input side, through the availability of improved (or less costly) seeds, fertilizers, equipment, feeds, and irrigation systems. In an economist's eyes, it implies a change in the agricultural production function, which describes the technology that transforms inputs into output. Automation technology is modelled as new equipment purchased in this upstream market, together with a change in the production function on the farm.

Downstream activities begin where the harvest leaves off. They include packaging farm output and the logistics entailed in transporting, storing, and processing agricultural products post-harvest. For subsistence farms, logistics activities take place in the household or village and consist of preparing the product for storage (e.g. bagging grains, slaughtering livestock, cleaning, drying) and storing the product. Consider the production of grains by subsistence farms. Logistics activities commence with drying, which can begin before harvest by leaving the crop in the field for several weeks after maturity (Mendoza *et al.*, 1982) and continues after harvest, most typically by sun drying (Proctor, 1994).¹ For family commercial farms, logistics activities can take place in the household or village, using local intermediaries, or with global intermediaries. Local intermediaries consist of traders or middlemen who travel farm to farm purchasing agricultural products, producer cooperatives, direct sales at local marketplaces, and government or state-run marketing boards (Barrett and Mutambatsere, 2008). Local intermediaries handle logistics activities related to storage and initial transportation, e.g. transportation off-farm, to and from storage facilities, and to and from processing facilities or local markets. Global intermediaries consist of traditional exporters and importers, e-intermediaries, or other buyers who procure products on an international scale. E-intermediaries consist of organizations involved in logistics activities who operate on a digital platform; this emerging category of intermediaries typically offer improved price transparency and greater market access than is normally feasible for family commercial farms (Ferreira, Goh and Valavi, 2017; Goyal, 2010). Global intermediaries handle logistics activities from initial farm purchases to storage, transportation, and distribution. Initial farm purchases at this level can be contracted in advance or based on spot market prices. Corporate producers may also be distributors, procuring produce from other farms – including in other parts of the world – to fill contracts with large supermarket chains and other buyers. Storage on this scale typically occurs in large, designated warehouse spaces; transportation occurs in all modes, including ocean, air, rail, and road freight; and distribution involves bulk deliveries of agricultural commodities to processors or wholesalers.

Technological innovation can also occur in the logistics sector, often in response to new technologies in upstream markets. Automation technologies can stimulate production while

¹ A variety of alternative drying methods exists; however, these are not common among subsistence farms. For an overview of available drying technologies, see Proctor (1994).

increasing storage and intermediary logistical needs. For example, in the United States of America, productivity gains in the grain industry led to increased demand for grain storage (Swearingen and Janzen, 2020) as well as increased trade and a new need for innovations in storage technology (Fornari, 1982). In developing countries, improved storage technologies, particularly those targeting on-farm storage for subsistence farms, have trickled down from more developed countries to address enduring storage challenges, rather than addressing new storage needs from increased production. Indeed, the Food and Agriculture Organization (FAO) of the United Nations estimates that post-harvest storage loss is as high as 40 percent in developing countries (FAO, 2011). The availability of these storage technologies for subsistence farms in developing countries improves storage efficiency and capacity, leading to reduced food waste, increased food consumption, and overall improved producer livelihood (Bokusheva *et al.*, 2012; Omotilewa *et al.*, 2018; Rabé, Ibrahim and Baributsa, 2021; Ridolfi and Dubois, 2019). Adoption decisions in developing country agriculture are endogenous, driven by a variety of characteristics of farms and farmers, including education, household size, and type of production (Conteh, Yan and Moiwo, 2015).

Next, the commodity undergoes processing and packaging. This can take the form of primary food processing to create ready-to-sell foods and ingredients (e.g. cleaning, drying, slaughtering), secondary processing to create ready-to-eat unprocessed foods (e.g. cooking, fermenting, grinding, preserving), or tertiary food processing to create ready-to-eat processed foods (e.g. combining and preparing foods for frozen meals). For subsistence farms, these activities are typically undertaken by the household or locally and consist of only primary food processing activities. Subsistence farms engage in these activities to prepare and store food for their own consumption. For family commercial farms, these activities can be undertaken by the household or locally, by small commercial firms, or by large commercial firms. For corporate commercial farms, these activities are undertaken by small or large commercial firms. Small commercial firms handle primary and secondary processing in designated processing facilities with the end goal of distributing the prepared foods for commercial distribution, purchasing, and consumption. Large commercial firms handle primary, secondary, and tertiary processing in food and beverage manufacturing facilities. The final products from large commercial firms are designed to have long shelf lives and are distributed globally.

The processing node in agrifood systems has its own research and development aimed at improving processing and packaging efficiency and developing new products (processed foods). Technological innovations in the processing and packaging sector can both drive and be driven by technological innovations in upstream markets. Innovations in this sector can influence demand for upstream and midstream products by reducing production costs (and thus prices for the end consumer) or by increasing demand for a raw commodity that is an input in a new processed food. Alternatively, innovations in this sector can be in response to improved production efficiency in midstream markets. For example, the mechanical tomato harvester increased availability and decreased prices of processing tomatoes. This, in turn, enabled food processors to develop new tomato-based products and improve the efficiency of the processing line, ultimately feeding the fast-food revolution (de la Peña, 2013). Improving access to food processing technologies is a priority initiative in many developing countries, because these technologies can reduce waste from current production and increase future production, with the potential to increase trade, foster upstream technology adoption, create jobs, and reduce hunger and poverty (Annan, Conway and Dryden, 2015; Hussein and Suttie, 2016; Nair and Landani, 2020).

The distribution and retail sector, wherein the food product reaches the end consumer, constitutes the final node in agrifood systems. It consists of household consumption, and local and global sales. For subsistence farms, all agricultural products produced are consumed by the household. For finished agricultural products that originate from family commercial farms, some are consumed by the household, some are sold locally (e.g. in rural village markets in developing countries or farmers markets in urban areas in high-income countries), and some are widely dispersed on the global market. Most agricultural products that originate from corporate commercial farms are distributed and sold on the global market, although some are sold in local and regional markets (Angelsen and Kaimowitz, 2001; Walkinshaw, Quinn and Otten, 2019). Global markets consist of wholesalers, retailers, supermarkets, restaurants, food service, and e-commerce.

Technological innovations enter this node of agrifood systems primarily via the global market. For wholesalers, retailers, restaurants, and food service providers, recent automation technologies have reduced labour needs (Gazzola *et al.*, 2022) and increased sales and productivity (Rudd, 2019). However, the most substantial technological advancements in the global distribution sector in recent years are concentrated in e-commerce (FMI and Hartman Group, 2021; Reinartz, Wiegand and Imschloss, 2019), with potential to drive technological innovation upstream in agrifood systems. Environmental concerns are at the forefront of issues induced by food e-commerce growth. New industry demands include organics, sustainable packaging (Spruit and Almenar, 2021), managing complex and sometimes uncertain transportation services (Gee *et al.*, 2020; Hesse and Rodrigue, 2004), and in developing countries, improvements in a variety of supporting industries including transportation infrastructure, logistics, and online services (Cai *et al.*, 2015; Zeng *et al.*, 2017; Zhang and Huang, 2015).

2.2 Labour supply and demand throughout agrifood systems

A key consideration in understanding winners and losers from farm automation is to recognize how effects from automation at one node in the agrifood chain permeate through the system. In the framework shown in Figure 1, farm automation technologies are invented through research and development in the upstream, input, markets. This research and development leads to new, cost-saving, risk-reducing, and productivity-enhancing technologies that are purchased by agricultural producers or supplied to farms by contracted service providers. Once purchased, automation technologies reduce labour demands for the tasks they automate but increase them for new tasks, such as equipment maintenance and operation. Often, automation technologies lead to increased production that applies pressure on downstream markets in the agrifood chain. Ultimately, this might lead to expansion, growth, and technological innovation in the logistics, processing, and distribution sectors.

How midstream adoption of automation technologies impacts labour demand in other nodes along agrifood systems is a key determinant of net labour market impacts from the technologies. At the bottom of Figure 1, we highlight key types of labour needed in each sector and indicate (with upward and downward arrows) how the adoption of automation technologies by agricultural producers is expected to (directly) impact each of these labour types.

Two salient points emerge from this figure. First, the impacts of automation on midstream farm employment are mixed. Demand for family and hired workers performing manual tasks as well as labour supervisors is likely to decrease with less labour-intensive methods – that is,

unless automation, by resolving labour bottlenecks in some tasks, enables farmers to expand their production (the extensive margin effect). Meanwhile, the demand for relatively skilled workers who complement the new technologies increases on farms. Second, the overall impacts of farm automation on employment in agrifood systems are likely to be very different from the impacts on individual farms. Automation could easily decrease low-paying seasonal employment on farms but increase higher-paying and less seasonal employment upstream and downstream.

New technologies tend to be more intensive in purchased inputs. For example, high-yielding seed varieties were engineered during the green revolution to efficiently transform soil nutrients into grain. Thus, their effective use requires purchasing fertilizer in addition to new seeds, and it creates new labour demands to apply the fertilizer, manage weed growth (which increases with fertilizer use), and harvest the additional output. It also requires having secure access to water, without which fertilizer application and high-yielding seed use is likely to be counterproductive. Where farm workers are not widely available and farm wages are high, high-yielding varieties can create new demands for automation. Tractors require fuel, replacement parts, and servicing. More sophisticated labour-saving solutions, like weeding and thinning machines, require an assortment of inputs, including cameras and software, chemical herbicides, and information technology (IT) management. Because of this, the adoption of new technologies on farms is likely to increase employment – both technical and non-technical – in upstream input-supplying markets. Assuming new technologies, including automation of selected farm tasks, enable farms to maintain or increase food output, this creates forward linkages downstream from the farm. Downstream activities, including transportation of farm produce, packing and sorting, processing, and distribution, will also experience increased demand for most types of workers, to handle the higher volume of farm products.

Expansion of input and logistics markets requires more drivers to acquire materials needed to create the technology, deliver the technology to agricultural producers, deliver the agricultural products to processors, and deliver the product to retailers or directly to consumers. The input, logistics, and distribution markets require warehouse workers to assemble, package, and ship the technology and agricultural product. The input and processing markets require machine operators and mechanics to operate and maintain new farm automation equipment² and handle increased demands on processing equipment. All upstream and downstream markets require more office workers and salespeople to manage increased logistical and sales needs of the new technology and higher volume of the agricultural product. Each of the markets additionally require specialists, including financial specialists to aid farms in accessing credit, logistics specialists to handle increased shipping and storage needs, quality assurance specialists to monitor product quality, and technology specialists to handle increased computing, tracking, and data needs as processing and distribution companies grow and develop new e-commerce solutions.

These labour demands create employment opportunities for a variety of workers. Drivers and warehouse workers require little formal education and vary in pay, job security, and required experience (Bonacich and De Lara, 2009; Gittleman and Monaco, 2020). These types of jobs are somewhat seasonal, though less so than field jobs in agriculture, and the vast majority are

² Some farms will contract with input providers to use the new technology with the aid of the input provider, i.e. removing the farm from responsibilities for operating and maintaining the equipment. In other cases, the farm may purchase the technology and hire their own operators and mechanics.

filled by men (England, 2010; Scott and Davis-Sramek, 2021).³ Machine operators and mechanics require little formal education but more experience than drivers and warehouse workers. Input market jobs have an element of seasonality but less than farm jobs; for example, machine maintenance tends to be year-round, whereas crop worker demands fluctuate sharply across the seasons. Most machine operator and mechanic jobs are filled by men (Zippia, 2021). Office workers, sales, and specialists require more formal education, training, and experience. Of the jobs in the upstream and downstream markets, these are the highest paid, require the most formal education, and typically employ a higher proportion of females (US BLS, 2022).

On the farm, implications for labour demand depend on the labour and operation type. Subsistence farms are owned and operated by family labour. If these farms adopt automation technology, they can reduce demand for family labour (increasing the allocation of labour hours to non-farm employment) or expand their operation (potentially becoming a family commercial farm) or both. Expansion of non-farm job opportunities and affordable food for purchase through improved labour efficiency in the farm sector can lead some subsistence farms to exit agriculture entirely. Family commercial farms are also owned and operated by family labour, but they often use some hired labour, including hired field workers, labour supervisors and contractors. When these farms adopt automation technologies, they can sometimes reduce their demand for all three types of labour, expand their operations, or both. On corporate farms, family labour plays a relatively small role, and the demand for skilled managers, automated technologies, mechanics, and IT workers who skilfully interpret data feedback from digital technologies can be significant. Adoption of advanced technologies increases the demand for machine operators and mechanics who operate and maintain the new equipment, farm managers and sales personnel who have greater responsibilities due to increased production volume, and technology specialists who are needed to handle computing, data collection, and data processing as farm production expands.

Note that our discussion of labour market impacts thus far does not include the potential *indirect* effects from adoption of automation technologies. For example, automation requires researchers and scientists upstream to develop and improve technologies as companies compete on price or product quality. This can lead to new labour-saving technology adoption at other nodes in agrifood systems, in an effort to counteract heightened labour needs. Indirect effects from automation technology have the potential to reduce demand in the long-run for off-farm jobs within agrifood systems with more easily automated tasks, including drivers, warehouse workers, and machine operators, while increasing the demand for more highly skilled workers like scientists, engineers, and data analysts.

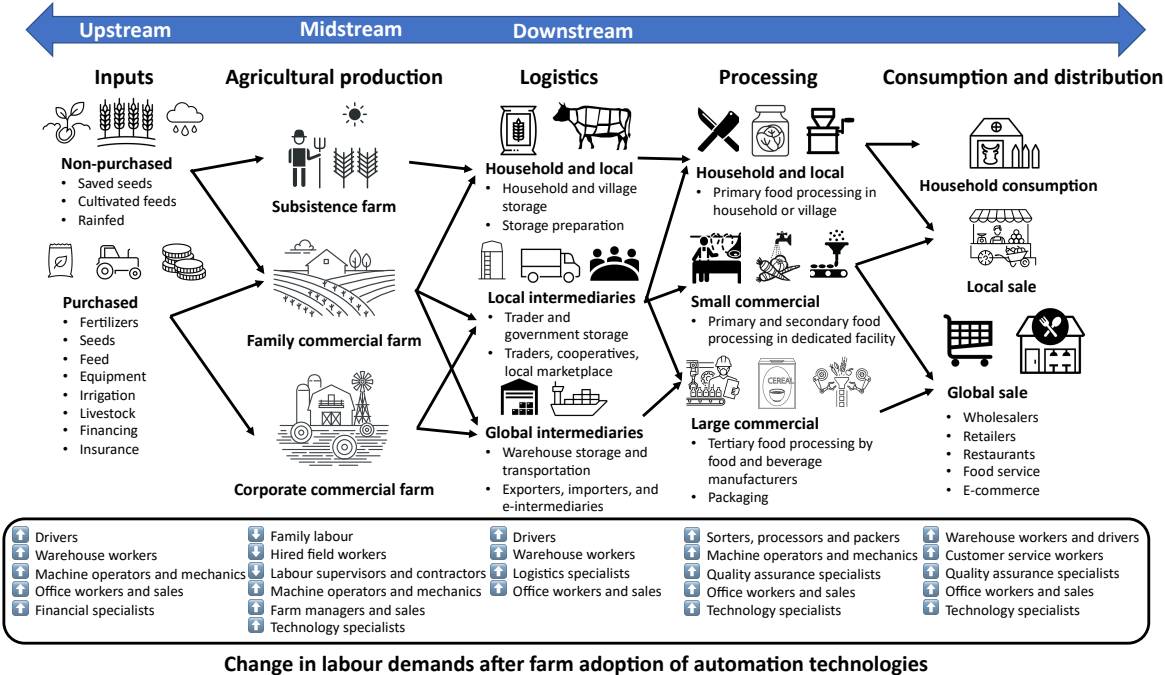
The adoption of automation solutions has potential implications for worker bargaining power, or the capability of workers to bargain over terms and conditions of employment. Worker bargaining power can be (simplistically) modelled as a function of the institutional setting (e.g. the existence of unions⁴ and government policies that protect worker rights) and attributes

³ In recent work, Scott & Davis-Sramek (2021) estimate that 3.2 percent of truck drivers in the United States of America are female, and show that this proportion has risen significantly in the past decade.

⁴ In addition to shaping worker bargaining power, the existence of unions can influence whether an organization adopts a new technology, but this may increase or decrease the likelihood of adoption based on the type of technology and types of worker protections negotiated by unions (Lommerud and Straume, 2012; Tauman and Weiss, 1987).

of the worker or job (e.g. the number and types of tasks the worker performs) (Bivens and Shierholz, 2018; Cazes *et al.*, 2019; Lamarche, 2015; Wilmers, 2020). Historically, farm worker unionization in the United States of America has been difficult due to the abundance of young farm workers migrating from Mexico throughout most of the twentieth century (Taylor and Charlton, 2018). However, there was a brief period following the termination of the Bracero Program between Mexico and the United States of America in which farm labour unions exercised a great deal of negotiation power using tactics that included consumer boycotts and farm worker strikes. However, as unauthorized immigration increased in the subsequent decades, union influence declined. Given that automation technologies can most easily replace jobs that consist of a few, specific tasks, the jobs that remain on farms are likely to involve the performance of a larger variety of tasks and tasks that involve higher skill or training. These types of jobs are also associated with increased worker bargaining power (Wilmers, 2020), suggesting that remaining on-farm workers might be able to negotiate higher wages or improved working conditions. Labour scarcity also improves worker bargaining power, so if the number of workers willing to hand-pick crops declines, the bargaining power of these workers will also likely increase (absent a perfect mechanical substitute). Throughout agrifood systems, however, implications for worker bargaining power are mixed. Drivers and warehouse workers typically have low bargaining power, whereas machine operators, mechanics, office workers, sales and specialists are likely to have higher bargaining power. Taken as a whole, increases in demand for all of these job types might increase wage inequality within agrifood systems (Wilmers and Aeppli, 2021).

Figure 1. Illustration of farms in the context of agrifood systems



Source: Author's own elaboration.

2.3 The agricultural transformation and agrifood systems

Adam Smith (1776) argued in the *Wealth of Nations* that the division of labour and subsequent specialization of labour into specific tasks and professions is essential for increasing prosperity and economic growth. Specialization allows workers to produce goods more efficiently and trade with one another, thus increasing overall social welfare. This gives rise to what is commonly known in economics as the agricultural transformation. As economies develop, labour-saving innovations in agriculture push workers off the farm while profitable activities in the non-farm sector simultaneously pull workers away (Gollin, Parente and Rogerson, 2002; Lewis, 1954; Michaels, Rauch and Redding, 2012). At the same time, as country incomes rise, fertility declines and schooling increases, and the combination of these and expanding non-farm jobs reduces the supply of workers available for agriculture. Because of this combination of labour-demand and labour-supply trends, as an economy develops the share of the population working in agriculture declines. Agricultural automation can help spur the agricultural transformation, by reducing the need for labour on farms while releasing workers to other sectors. However, automation is also a result of the agricultural transformation, as producers seek ways to maintain or even expand agricultural production as workers leave the farm. The agricultural transformation gives rise to increased innovation, technological developments, and capital investment, all of which are critical components of economic growth.

In the classic dual-economy model in development economics (Lewis, 1954), agricultural labour prior to the agricultural transformation is abundant and the marginal value of labour on farms negligible. Workers survive with subsistence production, and there is insufficient land and capital to improve the productivity of the marginal worker. By expanding opportunities into the non-farm sector, marginal (low-productivity) workers can migrate out of the agricultural sector. Expanding capital and production capabilities in both the non-farm and farm sectors eventually leads to a relative scarcity of labour. Wages, which in theory equal the marginal value product of labour (the additional value added from the last unit of labour) in both sectors, rise. This transformation generates prosperity throughout the economy in both farm and non-farm sectors. A pivotal component of this theory is that there is adequate investment in agricultural production while the transformation is underway. Otherwise, the movement of labour off-farm could result in rising food prices that push up non-farm wages and stunt economic growth (Johnston and Nielsen, 1966; Lele and Mellor, 1981).

Rapid technological advances around the world, including mechanical advances from the Industrial Revolution and advances in agronomy from the green revolution, have enabled food production to expand with fewer labour inputs and limited expansion of farmland (Johnson, 2000). Government investments in agricultural production, research and development, extension, infrastructure, and market integration in the early stages of the agricultural transformation are imperative for a smooth transition to increased industrialization (Timmer, 1988). Absent adequate infrastructure for transporting and marketing goods, the nascent urban sector will be unable to purchase food or provide capital and textile goods to the rural sector.

Access to road infrastructure and transport is necessary to enable the farm sector to access adequate agricultural inputs, including physical and human capital, and to sell harvested products at a good price. Road infrastructure in northern United Republic of Tanzania is poor. Paved road density is 2.2 kilometres per every 100 square kilometres of space in the region of Kilimanjaro and 0.15 kilometres in the region of Manyara (compared to 134 kilometres for the countries of the Organisation for Economic Co-operation and Development [OECD]).

Research shows that a one standard deviation increase in their measure of a farm's remoteness in northern United Republic of Tanzania is associated with a 9–20 percentage point decrease in the probability that the farm uses fertilizer and a 4–9 percentage point decrease in the probability of selling maize (Aggarwal *et al.*, 2018). The effects of expanding road networks in rural agricultural regions on agricultural productivity are mixed (van de Walle, 2009). For example, India's national rural road construction programme, which was launched in 2000 and cost roughly USD 40 billion, had no discernible impact on agricultural outcomes, income, or assets, but did accelerate labour migration out of agriculture (Asher and Novosad, 2020). Nevertheless, access to improved road infrastructure combined with access to agricultural extension services that provide farmers with improved information, technology, and resources has been shown to increase the probability that farmers in rural Ethiopia use agricultural advice, credit and modern inputs. Farmers were also more likely to trade across villages and specialize in crops for which they had a comparative advantage. However, improved access to extension services or roads in isolation had no effect on agricultural production (Gebresilashe, 2018). These findings suggest that impaired market access, including access to productive inputs and information, can have drastic effects on agricultural productivity.

Agricultural production is foundational to economic development since everyone must eat for sustenance. Thus, migration of labour out of agriculture is only an effective development tool when accompanied by improved agricultural productivity. Prior to the Industrial Revolution, most of the labour force in countries throughout the world lived in agrarian societies where agricultural households often consumed at least part of what they produced. In many countries today agricultural households are still common in the rural countryside. For example, throughout rural China, India, and much of sub-Saharan Africa there are millions of smallholder farms, many of which consume at least part of what they produce. Men and women often contribute specific roles or manage individual plots, thus contributing to the total household production (Andrews, Golan and Lay, 2015; Baudron, Nazare and Matangi, 2019; Jacoby, 1991; Udry, 1996). However, in the United States of America, only 1.4 percent of the workforce was employed directly on farms in 2020 (USDA Economic Research Service, 2022). Other developed countries similarly have a small share of their population directly employed on farms. Decreasing fertility rates, increasing rural education, and improving job opportunities in the non-farm sector are reducing farm labour supply even in low- and middle-income countries around the world. Secondary school construction in rural Mexico is accelerating the agricultural transformation by reducing the probability that boys living in a village with a secondary school when school-aged grow up to work in the farm sector when of working age (Charlton and Taylor, 2020). In Viet Nam, the rural economy is diversifying into more non-farm work and education, rather than land, which is associated with improvements in household welfare (Liu *et al.*, 2020).

The agricultural transformation does not evolve from two isolated industries but involves the transformation of entire agrifood systems. To provide sufficient food to urban workers, investments are needed, not only in agricultural production, but also in transport, storage, food processing, and other physical and market infrastructure. Backward and forward linkages connect the agricultural sector to the non-farm sector, and new jobs are formed throughout the system as the economy develops. As incomes rise, the share of income individuals spend on food purchases generally declines, as stated in Engel's Law. Nevertheless, total expenditures for food usually increase with wealth since individuals and households typically demand higher

quality and greater variety of food. Increasing labour force participation in the urban sector, particularly among women, often places binding time constraints on urban families. Households thus purchase more processed foods that can be prepared quickly as the labour force becomes more urbanized. Since processed foods have value-added characteristics, the increasing demand for processed foods and variety of foods generates opportunities for rent-seeking behaviour in carving out niche food markets downstream of the farm gate.

The agricultural marketing infrastructure that includes processing, logistics, and wholesale is often referred to as the hidden middle (Reardon, 2015). Although this portion of the agrifood value chain has received relatively little attention in the economic literature, it constitutes an estimated 20–40 percent of the value added and costs in food value chains in developing countries. Each node in the chain, including the farm, depends on every other. Transport of agricultural goods from rural to urban sectors or trade across rural regions requires investments in transportation infrastructure, cold storage, preservation, processing, wholesaling and retailing (Barrett *et al.*, forthcoming). The private sector typically initiates changes along the agrifood value chain. Given heterogeneous preferences for value-added characteristics in agrifood systems, firms downstream from the farm often have opportunities to exert market power, as seen, for example, in rural Africa. Consumers in rural Africa received only 18 percent of the total surplus generated from subsidies randomly distributed to agrifood traders, and intermediaries retained the remainder (Bergquist and Dinerstein, 2020).

Policies that increase market competition could theoretically improve consumer welfare and help generate increased investments in productive capital and technologies throughout the agrifood value chain. For example, poor access to well-functioning markets, where farms can sell excess production, may inhibit farmers from investing in productive technologies that would increase production and reduce local farm-gate prices. Poor communication and transport infrastructure, rule of law, and access to commercial finance can all limit market competition (Moser, Barrett and Minten, 2009). In Kenya, it was found that poor access to financial credit prevented small-scale farmers from storing and selling grain during the lean season when grain prices typically rise by 25–40 percent. A field experiment that provided farmers with timely access to credit, thus permitting them to buy inputs in seasons when prices were lower and to sell grain in seasons when prices were higher, had a 29 percent return on investment (Burke, Bergquist and Miguel, 2018). This experiment demonstrates the potentially large gains that might be possible from improving market competition in rural developing economies. The number of supermarkets is increasing rapidly in developing countries (Minten *et al.*, 2016). The presence of few large supermarkets might create the necessary conditions for monopsonistic buying power, in which they become the major purchaser of agricultural goods, and therefore control the market. Even so, numerous studies show positive welfare effects for small-scale farmers contracting with supermarkets, inasmuch as supermarket contracts guarantee a steady buyer for higher value products (Chege, Andersson and Qaim, 2015; Ogutu, Ochieng and Qaim, 2020). Supermarkets often contract directly with farms to ensure timely supply of high-quality fresh fruits and vegetables, and thus might reduce the need for an intermediary.

Concurrent with the supermarket revolution, farmers in developing countries are increasingly producing commodities for export. The introduction of foreign trade can have myriad effects on rural communities. Some observers postulated that an abundance of natural resources with access to foreign trade can trap developing countries in the production of low-value commodities, thus stunting economic growth in what is commonly referred to as the Dutch

disease. Nevertheless, rapid introduction of palm oil processing factories in Indonesia led to increased urbanization, and individuals living near factories were 8 percent more likely to work in the non-farm sectors and 20 percent more likely to be employed in the formal sector, and per capita household expenditures were 10 percent higher (Edwards, 2019). Furthermore, foreign standards often require agricultural producers and other market participants along the agricultural supply chain to invest in technologies that ensure adequate throughput and quality. When countries open up to foreign direct investment, capital intensity tends to increase at all stages of the agrifood value chain. This causes labour productivity to increase, including on the farm (Barrett *et al.*, forthcoming; Lagakos, 2016; Liu *et al.*, 2020). Foreign direct investment has transformed processing, logistics, and storage from small- to large-scale in China and Viet Nam (Reardon, 2015). The scale of businesses in the agrifood value system is growing more slowly in India and in the Philippines, which implemented laws to prevent foreign direct investment in the retail food sector (Barrett *et al.*, forthcoming; Reardon, Timmer and Minten, 2012).

Changes in global trade relations, including foreign trade expansion and adoption of new trade standards, can be driven by or drive automation technology adoption. New automation innovation in one country can increase that country's relative advantage in producing an agricultural product, leading to increased productivity and naturally an expansion of trade. Trade can also drive automation technology adoption as trade in the inputs market creates potential for global diffusion of new technologies. Given the interconnection between automation and trade, considering the welfare impacts of trade expansion and adoption of new trade standards is an important component of assessing overall welfare impacts from innovation.

Evidence of welfare impacts of foreign trade and adoption of trade standards are mixed. For example, Asfaw *et al.* (2010) find that the adoption of trade standards from the European Union in rural Kenya had significant positive effects on farmers' health, presumably by reducing use of harmful pesticides. However, some contend that small-scale and marginal farmers are excluded from foreign trade because they do not have the economies of scale to adopt foreign standards. Furthermore, trade liberalization can often generate abrupt changes in prices and profitability. Labour does not migrate as readily as capital, sometimes leading to large wage disparities across sectors and regions following rapid trade liberalization. For example, trade liberalization in Brazil led to large declines in formal sector employment and wages in regions that specialized in crops with greatest tariff reductions. Earnings in negatively impacted regions lagged behind earnings growth in other regions for more than 20 years, illustrating how slowly labour might respond to changes in agricultural prices and economic opportunities that arise from opening up to world trade (Dix-Carneiro and Kovak, 2017). Despite interest in foreign agrifood supply chains, domestic value chains still hold the majority share of agricultural output in most low- and middle-income countries. Locally-owned supermarkets constitute substantial shares relative to foreign supermarkets in much of the developing world: 38 percent in Latin America, 52 percent in Africa, and 64 percent in Asia (Barrett *et al.*, forthcoming).

Opening up to foreign markets also exposes farmers to new farm inputs, which has important implications for technology diffusion and local, regional, and global labour demand. For example, John Deere and AGCO have begun marketing tractors and services to smallholder farms in Africa. This might lead to concerns that large multi-national businesses could take advantage of smallholder farmers, and second, that mechanization might lead to rural unemployment. However, there is also evidence that market-driven mechanization increases employment by expanding overall production and thus total labour demand.

For example, Zambia is one of the least densely populated countries in Africa, and the introduction of tractors increased rural employment by expanding agricultural land and increasing hired labour hours on farms (Adu-Baffour, Daum and Birner, 2019). This is an example of how mechanizing some tasks (e.g. ploughing) can maintain or increase employment in other tasks (e.g. weeding, thinning, and harvesting) on the same farms. Unlike state-planned mechanization programmes that have failed to significantly increase mechanization in Africa, the market typically adjusts to location-specific preferences more quickly and thus is better equipped for transitioning agriculture to more mechanization (Diao *et al.*, 2014).

The agricultural transformation, including expansion of the agrifood value chain, eventually evolves from an economy of excess agricultural labour to an economy with farm labour shortages. Developed countries throughout the world now rely primarily on immigrants to work on their farms (Christiaensen, Rutledge and Taylor, 2021). Immigrants are not always well received by domestic workers. Some residents might perceive that immigrants are taking jobs, even though domestic workers tend to find more year-round, higher-paying jobs in the non-farm sector. Residents in agricultural communities of California have often objected to building temporary farmworker housing for non-immigrant guest workers because they feared that it would reduce the value of their homes and increase crime rates. Nevertheless, rigorous analysis shows that seasonal, labour-intensive agricultural activity is associated with a reduction in monthly crime rates within counties of the United States of America (Charlton, James and Smith, 2022). However, as seasonal farm workers began to settle in the United States of America with their families, increased agricultural employment was shown to increase immigrant shares in rural areas and vice versa, while both immigration and increased agricultural employment increased local poverty rates (Martin and Taylor, 2003). This illustrates that impacts of agricultural production and immigration on local economies is multi-faceted.

Farmers in developed countries are well aware that increased automation and technological advances are needed to maintain their competitiveness given a diminishing supply of agricultural workers. Developed countries traditionally have relied on immigration to meet their farm labour demands. Immigration, however, is not a solution if people in migrant-sending countries transition out of agricultural work (Charlton and Taylor, 2016). Martin (2017) summarizes farmers' options to adjust to labour shortages using four S's: satisfy, stretch, substitute and supplement. Farmers satisfy workers by offering them higher wages and improved benefits. They stretch the farm labour supply by increasing worker productivity through technological advances or improved labour management practices. They substitute for workers by adopting labour-saving technologies like automated harvesters, and they supplement labour by hiring foreign guest workers.

Examples of all four S's can be seen in more developed countries today. Real farm wages in the United States of America increased steadily throughout the first few decades of the twenty-first century (Charlton *et al.*, 2019). Some farm employers, like FirstFruits Farms in Washington State, seek to provide more generous benefits including management training programmes, continuing education, low-rent housing near the farm, access to childcare, investment in a local health clinic, and access to community health educators who serve farm workers (First Fruits Farms, undated). Farms are stretching their workforce by adopting harvest aid technologies, such as strawberry harvesting aids that help workers transport filled trays to the end of field rows more quickly or improve workers' posture so that they do not have to stoop over the rows hour after hour. Employers can even strategically arrange workers into crews to maximize

positive peer effects across workers (Hill and Burkhardt, 2021). Automation of labour-intensive tasks typically increases as wages in the farm sector rise, thus making mechanization more profitable (Charlton *et al.*, 2019; Pingali, 2007). Mechanical harvest of raisin grapes required not only mechanical innovation, but also the breeding of a raisin grape that ripens earlier in the season and can be dried on the vine (Charlton *et al.*, 2019). Engineers are currently seeking robotic solutions that would permit mechanical harvest of strawberries, one of the most labour-intensive crops grown in the United States of America. Finally, developed countries throughout the world bring guest workers from countries that are not as far along in the agricultural transformation.

In the United States of America, guest workers are hired, primarily from Mexico, to work in fields through its H-2A programme that allows temporary agricultural employment of foreign workers. Farms in the northern Great Plains of the United States of America bring guest workers from even further abroad, hiring H-2A workers largely from South Africa to help harvest grains and drive combines. The high degree of mechanization in grain harvest makes it profitable for farmers to pay the relatively high cost of transporting few workers from as far as Africa since the marginal value product of labour in mechanized grain harvest is high. New Zealand hires agricultural guest workers from nations throughout the Pacific Islands; western European nations primarily hire agricultural guest workers from Poland, Romania, and other eastern European nations; and Canada from Mexico and nations in the Caribbean (Taylor and Charlton, 2018). Countries that are currently in transition from having an abundance of farm labour to more industrialized employment might provide guest workers to foreign farms even as they also hire agricultural guest workers from less developed countries. For example, South Africa recruits agricultural workers from Zimbabwe even as South Africans travel to grain farms in the United States of America to work. Mexico has a guest worker programme to hire farm workers from Guatemala even as many rural Mexicans migrate to farms in the United States of America where the daily farm wage is significantly higher than in their home country.

A decrease in the share of the workforce employed in agriculture does not necessarily imply a decrease in the absolute farm workforce. For example, in sub-Saharan Africa, the population is growing at such a rate that the agricultural workforce on farm is actually increasing in absolute terms even though the farm share of national employment is declining. Productivity gaps between the non-farm and farm sectors will continue to pull workers off the farm. However, if the gap is sufficiently small, or only present during the slack season between harvesting and planting or planting and harvest, then efforts to increase labour migration off the farm might only lead to more intense farm labour shortages during peak seasons of labour demand (Christiaensen, Rutledge and Taylor, 2021).

3 Labour-saving technology adoption

To understand the social and employment impacts of automation technologies, it is fundamental to first understand what drives the development and adoption of these technologies. Two scenarios bracket the extremes. We call these the endogenous and exogenous technology development and adoption scenarios.

3.1 Endogenous technology development and adoption

More than fifty years ago, seminal studies by Hayami and Ruttan (1971) and Hicks (Hicks, 1932) showed how labour and/or land scarcity can induce technology adoption through their impact on relative factor prices. For example, the green revolution in South Asia and parts of South-eastern Asia in the 1960s increased wages and harvest volumes, making the adoption of small threshers profitable (Pingali, 2007). In South America, plantations adopted more capital-intensive technologies after the Great Mississippi Flood of 1927 displaced black agricultural workers who then migrated to the north. There was no such technology adoption in counties not affected by the flood, which did not experience a sudden exodus of workers (Hornbeck and Naidu, 2014). Similarly, county-level implementation of more stringent immigration enforcement policies in the United States of America from 2005 to 2012, which decreased the immigrant population within the counties, led to increased equipment use per acre and increased labour expenses (Ifft and Jodlowski, 2016) and, in the dairy industry, to greater labour-efficiency per farm (Charlton and Kostandini, 2021).

Even in less developed countries, where population and labour force growth are generally higher than in high-income countries, seasonal or generalized labour shortages can lead farmers to adopt mechanized technologies. For example, the agricultural industry in Bangladesh is both highly mechanized and labour-intensive (Biggs, Justice and Lewis, 2011). Following major flooding and cyclones in the late 1980s, the government facilitated imports of Chinese diesel pump-sets, as these would help Bangladeshi farmers recover productivity after the loss of substantial draught power. Combined with other market liberalizing activities prompted by the World Bank, Bangladesh began importing small engines, tillers, and pumps. Consequently, agriculture became more mechanized even though it remained relatively labour-intensive. Opening to international trade simultaneously created numerous labour-employing linkages along the food supply chain. Seasonality of labour demand can also create bottlenecks in labour availability that induce technology adoption. Even when wages are low, farmers sometimes experience major productivity gains from technology use during peak labour seasons. Labour scarcity during peak seasons is often exacerbated when farmers multi-crop, growing more than one crop on a single field each year. Peak labour for harvesting one crop bleeds into the peak season for land preparation and seeding of another crop (Pingali, 2007). Mechanization may not be the only available type of technology for reducing strains on labour supply. Technologies like herbicides typically reduce labour requirements for weeding, which are often performed by women and children, and might free family time for other important tasks (Baudron *et al.*, 2019).

Power-intensive tasks (like tilling, grinding, milling, and threshing) are typically the first to mechanize. Tasks that require more dexterity or discernment (such as weeding, sifting, winnowing, and harvesting tea, coffee, or apples) are much slower to mechanize. Even countries with high population density like Bangladesh, India and the Philippines have seen the mechanization of high-power agricultural tasks. Mechanization helps ensure that tasks are

performed in a timely manner, which is imperative when farms begin contracting with large supermarkets or foreign markets. Mechanization of tasks that require more dexterity or discernment does not occur unless wages rise (Pingali, 2007).

Rising farm wages are one of the primary outcomes of the agricultural transformation. As farm labour becomes scarcer, wages rise, and farms seek out automation as an alternative to high-cost labour inputs. In this scenario, labour is already relatively scarce and work opportunities in the non-farm sector are typically growing. A declining labour supply creates demands for labour-saving solutions on farms as well as other nodes of agrifood systems. By adopting automated farming technologies, farm managers can increase the marginal product of labour in step with exogenously increasing market wages. In this automation demand-driven, or endogenous technology, scenario, automated technology does not displace farm labour, but rather replaces labour that is already disappearing from the farm.

3.2 Exogenous technology development and adoption

Changes in relative factor prices are demand-side factors driving the development and adoption of labour-saving technologies, a la Hayami and Ruttan (1971) and Hicks (1932). On the supply side, major advances in biological and mechanical engineering as well as artificial intelligence and machine learning have vastly expanded the potential for technological breakthroughs to automate farm operations. Research and development can seem to take on a life of its own that is independent of demand-side considerations like changing relative factor prices. This raises the possibility that new automation can exogenously appear at low cost and displace workers on farms, instead of being an endogenous response to farm labour shortages as they arise. When farms adopt these technologies, automation replaces labour. On smallholder family farms, automation might free up time for women and family labourers to take more leisure or devote time to other productive activities (Pingali, 2007). In particular, post-harvest activities, like milling, are power-intensive and relatively easy to mechanize. Since these activities are traditionally performed by women, mechanizing milling, threshing, and other post-harvest activities can have major impacts on time allocation of women. However, automation might also displace hired workers, who are forced to seek employment elsewhere, possibly putting downward pressure on wages.

Investment in research and development of new automated technologies usually only occurs when demand for those technologies is high. However, government sponsored research can bring about new automated technologies before there is excess demand. The development of the processing tomato harvester mentioned above, which took place at the University of California, Davis, a public institution, is one broadly viewed example. Researchers from the University of California, Davis acquired government-sponsored grants to support their research and development. It was assumed by many that the adoption of the tomato harvester caused a rapid decline in farm labour demand and put many field workers out of a job. Employment on tomato farms indeed decreased after the introduction of the tomato harvester, but it is unknown how many new jobs were simultaneously created in downstream tomato processing industries (Schmitz and Seckler, 1970). Another issue of concern was the subsequent consolidation of tomato farms, as many small farms did not have the economies of scale required to make large capital investments in harvesters. Numerous small tomato farms ceased operation as a result of the tomato harvester. A multi-million-dollar lawsuit was brought against the University of California for using public funds to develop a technology that put small farms out of business, and the university lost the suit. However, with respect to subsequent

changes in farm employment, adoption of the tomato harvester did not occur in isolation from other labour market pressures. Rapid rise in the demand for the automated harvester can likely be attributed, at least in part, to grower anticipation that the Bracero Program, which had facilitated the migration of guest workers from Mexico to farms in the United States of America for several decades, would soon come to an end. The programme was terminated in 1964, just five years after the tomato harvester became commercially available, and many farmers sought out labour-saving investments because they were concerned that farm labour shortages would follow after the programme ended. One of the primary outcomes of the termination of the Bracero Program was increased capital intensity of agricultural production. Counties that had a higher concentration of workers from the programme prior to 1964, experienced the largest increases in capital-to-labour intensity on farms (Clemens, Lewis and Postel, 2018). Some of the capital-intensive technologies were relatively new, like the tomato harvester. Other crops, including cotton and sugar beets also had advanced automated technologies available for adoption when the Bracero Program came to an end. Although production of these crops declined temporarily after the programme ended, they rebounded quickly relative to other crops that required large shares of Bracero Program's workers to harvest, such as lettuce, celery, and strawberries.

The example of the tomato harvester in the United States of America illustrates that new agricultural technologies can drastically alter labour demands on farms, but it may be difficult to decipher technology-driven versus labour supply-driven changes in agricultural employment. Unless the introduction of the agricultural technology coincides with rising farm wages, anticipated labour shortages, or promises large expected gains in productivity, take-up of the technology will likely be low. For example, there were numerous attempts to increase capital intensity of agricultural production in Africa through the provision of tractors. The abundance of land in Africa appeared ideal for agricultural mechanization. Many expected that introducing labour-saving technologies, like tractors, to African countries could improve agricultural productivity and expand productive acreage. There were three major waves of tractor provisions in Africa from 1945 to 1981. The first wave provided tractors to Kenya, Malawi, Zambia and Zimbabwe using funds from the Marshall Plan following the Second World War. The second wave was sponsored by governments of newly independent countries from 1958 to 1970 (Côte d'Ivoire, Ethiopia, Ghana and the United Republic of Tanzania), and the third wave was funded from new state wealth sourced from oil and other natural amenities from 1970 to 1980 (Nigeria, Cameroon and the Democratic Republic of Congo). Despite state provision of tractors, relatively few farmers adopted tractors throughout the twentieth century (Pingali, 2007). Farm wages were low and lack of international markets for agricultural goods or domestic demand for more consistent agricultural production deterred automation despite the relative abundance of land (Norman *et al.*, 1988). A survey in Nigeria revealed that tractor rental services provided by entrepreneurs who purchased a tractor through the private market were more efficient than owners who obtained a tractor by government assistance. They provided more services, covered more land, provided equipment more specific to the soil type in the regions where they operated, provided more services in seasons of low demand, and were more efficient at obtaining spare parts by visiting multiple suppliers (Takeshima *et al.*, 2015). Thus, even when a labour-saving technology becomes available, there must be adequate market returns from the use of the technology for farmers to adopt.

In rural China, following rural land reforms in the 1980s that redistributed large collective farms to small households, tractor use declined. Furthermore, tractor use declined more in locations

with larger populations, which suggests that availability of labour was a primary factor in whether tractor use continued. Small tractors, which are less expensive and better suited for small landholdings, became more common after the reforms (Chen and Lan, 2020). This shows that agricultural mechanization depends in large part on factor endowments and suitability of the technology in question.

Along with upstream and downstream market conditions, the appropriateness of mechanized technologies and equipment for the size of typical farms in the region is critical in determining rate of adoption. For example, many countries in Eastern and South-eastern Asia are still predominately farmed by smallholder farmers even after undergoing the agricultural transformation (Rigg, Salamanca and Thompson, 2016), and consequently, agricultural mechanization in these countries involved the use of small (single-axle) tractors rather than larger (two-axle) tractors (Biggs, Justice and Lewis, 2011). Similarly, in Ghana, the development of rental services whereby large producers hire out their tractors to small-scale farmers shows promise for connecting smallholder farms to more productive technology (Diao *et al.*, 2014). Power-intensive activities typically mechanize first in developing countries. Mechanization of power-intensive activities can reduce operation costs and prompt more timely completion of fundamental tasks, though equipment generally has to match the regional needs for adoption to occur. In contrast, control intensive operations, like weeding, harvesting, sifting, and winnowing, in which human discernment is an asset, tend to mechanize only when wages are relatively high (Pingali, 2007). In addition to mechanizing tilling and seeding in developing countries, there is also large scope for mechanizing tasks in post-harvest activities such as threshing, shelling, and milling. These activities mechanized rapidly in many developing countries, even those with high population densities like India, Bangladesh, and the Philippines.

3.3 Digital technologies

Digital technologies have found their way into agricultural production in developed as well as developing economies. These technologies consist of mobile devices and social media, precision agriculture and remote sensing technologies, big data and analytics, blockchain, and intelligent learning systems (e.g. deep and machine learning algorithms) (Trendov, Varas and Zeng, 2019). As one example, Hello Tractor in Nigeria is an app that enables farmers to schedule custom tractor work, and mitigates risks involved with investing in tractors by improving access to rental markets for tractor owners (Christiaensen, Rutledge and Taylor, 2021).

Most of these digital technologies are capital-intensive and thus likely reduce manual labour demand on farms. However, like other automation technologies, these might increase demand for the specialized labour needed to operate and maintain the technologies. The scope for digital technologies to improve agricultural productivity and input efficiency is expanding rapidly. Over 40 percent of the global population has internet access, and there are numerous initiatives underway to connect those who still lack internet access (Deichmann, Goyal and Mishra, 2016). Internet access and mobile phone use help farmers overcome information problems, especially as they relate to market conditions; raise on-farm productivity through improved information on efficient use of inputs; and better connect buyers and sellers along the food supply chain through improved logistics platforms. It can also help reduce market power along the food supply chain by reducing the need for middlemen, who often have more market information than the farmers with whom they deal (Deichmann, Goyal and Mishra, 2016).

Digital technologies are a particularly promising technology for smallholder farmers, female farmers, and rural youth. For smallholder farmers in Africa, digital advisory, financial, and market linkage services have been linked with increases in yields from 23–73 percent and increases in income from 18–37 percent (Tsan *et al.*, 2021). Productivity increases are generally attributable to the dissemination of agricultural advice, better financial access, better input access, including seeds, fertilizers, and equipment, and information on more sustainable farming practices. Income increases can be attributed to higher productivity, improved market access for purchasing inputs, access to financial resources, commercial selling, improvements in crop quality, and reduced transaction costs. For example, M-PESA, a mobile money product launched in 2007 in Kenya, increased household consumption and savings, improved household's abilities to cope with health and income shocks, and reduced poverty rates by two percentage points (Jack and Suri, 2014; Suri and Jack, 2016; Suri, Jack and Stoker, 2012). Early adopters of these technologies are likely to be wealthier and more educated, but many attributes of the technologies can drive adoption and foster dispersion of the technology across the income spectrum (Jack and Suri, 2011; Shang *et al.*, 2021; Suri, 2017). For example, easy to use interfaces, affordability, government and institutional support, social factors, including network effects, information access, and improvements in supply chain transparency can increase adoption of digital technologies (Chandra and Collis, 2021; Mas and Radcliffe, 2011; Smidt and Jokonya, 2022).

Initial uptake of digital technologies among women might be low, due to the gender gap in digital technology use – as of 2020, in low- and middle-income countries women were 7 percent less likely than men to own a mobile phone and 15 percent less likely to use mobile internet (GSMA, 2021). However, digital technologies have large potential to aid in narrowing gender gaps in incomes and agricultural productivity as digital technologies become more tailored to unique female needs and equalize access to relevant advice, finances, and agricultural inputs (Tsan *et al.*, 2021). For rural youth, digital technologies have potential to increase interest in future agricultural employment by creating new high-tech employment opportunities in the agrifood sector (Tsan *et al.*, 2021). Rural youth can play a key role in the successful adoption of digital technologies in the agricultural sector as they can combine their insights and expertise in traditional agricultural practices with the digital skills necessary to use the new technologies (Trendov, Varas and Zeng, 2019).

4 Social impacts of technology adoption

Agricultural mechanization is often viewed in a negative light, due to fears that mechanization displaces workers, and thus, can have severe negative welfare impacts for part of society. As shown in the previous section, this is not always the case. Mechanization is adopted most readily in the stages of the supply chain where labour bottlenecks are most severe and thus should have little direct impact on employment. However, mechanization can create or eliminate labour needs upstream and downstream in the supply chain. We often associate mechanization with increased production, which might create greater labour demand in upstream or downstream markets. Mechanization reduces demand for workers performing the now automated task, but increases demand for workers to operate, maintain, and manage the new equipment. To the extent that mechanization can lift worker wages and create job opportunities in other stages of the supply chain, it generally has overall positive welfare impacts. However, this need not always be the case. One unintended consequence of automation is that the economies of scale associated with automation can lead to the consolidation of farms. This can put smallholder farmers out of business if custom service operations for the rental of automation technologies are not economical or not formed. There might be other unintended consequences that differentially affect women, children, or young adults. The welfare impacts of agricultural automation are theoretically ambiguous and differ across individuals and businesses within agrifood systems. Examples are given below.

The employment impacts of farm mechanization can be difficult to measure because mechanization typically is associated with changes across activities on farms, upstream changes in the demand for inputs, and downstream changes from transportation and logistics to food processing and distribution and retail. As the agricultural transformation unfolds, it reshapes how food is produced on farms as well as in other nodes in agrifood systems. When all nodes are changing simultaneously, it is difficult (if not impossible) to ascribe social impacts, like changes in employment, to specific incidents of farm automation. It becomes essential to view mechanization in the context of the collection of tasks performed on farms, as well as in the broader context of agrifood systems.

Mechanization can increase total farm production by expanding cultivated land or improving per-acre yields. This can potentially lead to large welfare increases for agricultural households. However, if there are large economies of scale associated with the mechanized technology, widespread adoption among larger farms can sometimes put smaller farms out of business and precipitate farm consolidation. We consider social impacts for mechanized technology adoption by the agricultural household, the commercial family farm, and the corporate farm separately, though there may be some shared characteristics across farm types.

4.1 Social impacts in agricultural household settings

For the agricultural household that consumes at least part of what it produces, mechanization can reduce farm labour demand, freeing family time for leisure, school, or other productive activities. Mechanization can also improve access to higher-value product markets and qualify agricultural households to form contracts with supermarkets or foreign buyers provided the farm produces yields with consistent quality and quantity of output. Participation in these higher value markets can bring significant welfare gains to agricultural households.

Availability of tractors for small-scale family farms in Zambia led to measurable increases in welfare by allowing farmers to increase production. Land is relatively abundant in Zambia, but farmers do not cultivate all of the available land due to labour constraints. An estimated 95 percent of farms are less than 5 hectares. After the introduction of a tractor sharing private business, farmers who adopted the tractor services more than doubled their incomes on average, primarily by cultivating more land (Adu-Baffour, Daum and Birner, 2019). However, farms who adopted tractor services also purchased more inputs, notably fertilizer, and increased yields by an average of 25 percent.

Even in other regions of Africa, where labour is relatively abundant and fertility rates high, there is evidence that lack of labour on farms limits agricultural production. Mechanization in this context can improve total production and household income. A study of farm-level data from four countries in eastern and southern Africa show that even though agricultural production is extremely labour-intensive, production would increase if farms hired more workers or increased use of tractor or draught-powered equipment (Baudron *et al.*, 2019). Power-intensive agricultural activities experienced rapid rates of automation in labour-abundant countries Bangladesh, India and the Philippines (Pingali, 2007).

Welfare gains from increased productivity in certain stages of production do not necessarily benefit everyone in the household evenly. Nevertheless, in Zambia, tasks like weeding were shared between men and women, and increased cultivation of land did not place a disproportionate added burden on women or children. In fact, even though men traditionally bear the responsibility to plough and prepare the land and women and children typically bear more responsibility to do other activities like weeding, all members of the households that adopted tractor services for land preparation experienced more leisure relative to similar households that did not (Adu-Baffour, Daum and Birner, 2019). This may be due, in part, to increased use of herbicides in households that adopted tractor use. However, it also appears that mechanized households hired more workers to perform non-mechanized activities. There are strong linkages between agricultural tasks, complicating the effects of mechanization on labour demands in other agricultural tasks. For example, labour required for planting and weeding increases if tilling and other land preparation tasks are not performed in a timely manner. Since men typically perform tasks for land preparation, in many instances, labour activities performed by women might be more productive if men's tasks were mechanized (Baudron *et al.*, 2019). In western Kenya, labour-saving technology adoption was shown to free time for both men and women and increase household investment in children's education (Diirro *et al.*, 2021).

One of the most transformative changes that agricultural households might experience through increased mechanization is improved access to higher value output markets, since automated technologies often permit farmers to harvest a more consistent, timely, and thus higher value, product. Supermarkets and foreign buyers of agricultural goods typically have strict quality standards and require minimum quantity of throughput. Although contracts might place additional stress and pressure on farmers to deliver a standard product, large welfare gains have been measured for agricultural households around the world that have participated in contracts with product buyers. For example, supermarket contracts with smallholder vegetable farmers in Kenya increased farmers' household incomes by more than 40 percent and reduced poverty along numerous dimensions including income. Furthermore, supermarket contracts caused the largest reductions in multidimensional measures of poverty for the poorest households (Ogutu, Ochieng and Qaim, 2020). Farm households participating in supplying

goods to supermarket channels have also been shown to exhibit significantly higher calorie, vitamin A, iron and zinc consumption (Chege, Andersson and Qaim, 2015).

Although access to commercial input and output markets will make agricultural households at least as well off as prior to market access, participating in commercial markets opens agricultural producers to risk associated with price volatility. Production risk can stunt economic growth by impeding productive investments. Markets in developing countries have often used contracts to help protect smallholder farms from price risk by shifting the burden of risk to other agents in the supply chain who might be better equipped to handle risk. Contract farming in developing countries has been shown to increase yields, acreage in contracted crops, and per capita farm income (Arouna, Michler and Lokossou, 2021; Bellemare, 2012). Contract farming has also led to a significant reduction in reported days of hunger among farmers in rural Madagascar (Bellemare and Novak, 2017). Nevertheless, the opportunity to participate in contract farming could prevent farmers and their families from participating in other productive activities. For example, participation in contract farming in rural Madagascar was associated with a 79 percent decrease in the income per capita that households would otherwise receive from labour markets. It was also associated with a 47 percent decrease in income per capita from non-farm businesses, but a 51 percent increase in income per capita from agricultural activities aside from livestock or contract farming (Bellemare, 2018). The increase in other agricultural income might derive from associated technological spillovers. Overall, these findings underscore the importance of risk management in improving agricultural production.

4.2 Social impacts in commercial family farm settings

In commercial farm settings, where farms already tend to access higher value markets, the welfare impacts of mechanization often depend crucially on the market dynamics that lead to adoption. For example, exogenous introduction of a labour-saving agricultural technology might displace numerous workers. Depending on whether technology adoption generates jobs in downstream markets and ease of labour mobility, this could be very costly for farm workers. In contrast, agricultural technology adoption often originates from rising wages and increasing competition for the employment of scarce labour. In this case, we might expect agricultural technologies to increase labour productivity, allowing farms to remain in production while paying higher wages. In this case, mechanization might be seen as welfare enhancing for both producers and hired workers.

In the case of the tomato harvester, farmers in the United States of America sought technologies that would reduce their dependence on seasonal farm labour after the termination of the Bracero Program, which many believed would lead to widespread labour shortages. Major labour shortages were never realized. Farms adjusted to the reduced labour supply by adopting labour-saving technologies and shifting acreage towards crops that were easier to mechanize (Clemens, Lewis and Postel, 2018). Furthermore, vast migration networks formed during the years of the Bracero Program facilitated continued migration of Mexicans to the United States of America for growing crops that were not so easy to mechanize, though this migration was often illegal (Taylor and Charlton, 2018). Adoption of the tomato harvester after the Bracero Program decreased employment on tomato fields by about 91 hours in manual labour per acre (Schmitz and Seckler, 1970). However, the advent of the tomato harvester also expanded production in tomato processing, creating new job opportunities downstream of the farm. Presumably, workers incurred some cost of changing employment, so it is impossible to estimate the full welfare impacts of the technology. Nevertheless, Schmitz and Seckler (1970)

estimate gross social returns in the vicinity of 1 000 percent, and even if workers were compensated for lost wages, net social returns to the harvester would be positive. The key policy challenge is to address some of the distributional challenges associated with shocks that generate overall positive welfare impacts but with negative impacts for some.

To the extent that agricultural employers adopt labour-saving technologies in response to rising wages and limited labour supply, economic theory generally predicts positive welfare benefits from technology adoption. Microeconomic theory predicts that, as one factor of production becomes more costly, firms will substitute other factors of production until the marginal value added from each factor is equal to its marginal cost (see for example, Charlton *et al.* [2019]). In agriculture, as real farm wages rise, farms might invest in more capital equipment that reduces total labour demanded on farm. With the capital investment, the marginal value product of labour is much higher than the less mechanized farm as the workers operate equipment that increases the volume of production per worker. Availability of productive technologies allows farms to remain in business and workers who remain in agriculture to earn higher wages. For example, stricter enforcement of immigration policies in the United States of America from 2005 to 2012, which caused numerous immigrants to migrate out of the county, reduced dairy production and operations within counties. Average labour efficiency on dairies increased within counties that implemented stricter policies and the probability that dairies still in operation used more automated technologies also rose (Charlton and Kostandini, 2021). This is consistent with capital–labour substitution in firms as labour becomes scarcer. Presumably, dairy production and number of dairies in operation might have decreased by even more if technologies had not been available.

New automated technologies are often associated with economies of scale, which can have major implications for agricultural consolidation within the rural economy. When scale and ownership of the technology have no effect on the returns to technology adoption, large farmers or independent entrepreneurs might buy the automated equipment and rent it out to other farmers (Lu, Reardon and Zilberman, 2016). In the United States of America, farmland shifted towards increasingly large operations from 1987 to 2017, and the introduction of new technologies appears to have played an important role in this market consolidation. Automated equipment often entails a high up-front cost, and farmers may not see a net profit from their investment for many years. Automation also enables farm operators to manage more cropland or livestock, so farms may consolidate even if rental markets for automated equipment or custom service provision might have been theoretically possible (MacDonald, 2020). However, there are exceptions. For example, agricultural mechanization in Viet Nam during the agricultural transformation from 1992 to 2016 did not lead to farm consolidation (Liu *et al.*, 2020), revealing that agricultural consolidation is case-specific with respect to technologies and context of adoption.

4.3 Corporate farms

The presence of capital-intensive technologies with large economies of scale can often lead to farm consolidation, eventually replacing smaller commercial farms with large corporate farms. Economies of scale play a major role in farm consolidation, though consolidation can be slowed when there are well-functioning markets for custom services that contract mechanical work to farms and thus divide economies of scale (MacDonald, 2020), or when the technology does not exhibit significant scale economies.

Corporate farms often have the economies of scale and capital to invest in robotic technologies that can reduce labour demands on farms considerably. However, robotics are not typically economically viable for most farms unless labour is scarce. For example, although robotic milking technologies have been available for commercial use for many decades, dairies in the United States of America have been slow to adopt them because farm labour was relatively inexpensive and milk prices low for many years (Barkema *et al.*, 2015). In contrast, robotic milking systems have been in commercial use in western Europe since the 1990s.

Precision agriculture and other digital technologies are often imperative to the adoption of robotics. With fewer workers to directly monitor agricultural inputs and yields, precise data gathering becomes essential. Digital technologies vary – from simple marketing SMS in small-scale family farms in developing countries to precise GPS data collection on yields and soil moisture across the field in larger farms. Small-scale farmers may need to adopt digital technologies to remain competitive with other farms and to improve knowledge of variable market characteristics. On large farms, digital technologies can reduce labour demands, along with application of other costly inputs. In many cases, the use of digital technologies can lead to improved environmental outcomes by limiting application of herbicides, pesticides, fertilizers, and other chemicals that might leach into water systems or otherwise harm the environment (Khanna, 2021).

As capital intensity of production increases, one of the primary concerns of farm consolidation is lack of market competition. Industries dominated by few large corporations might allow corporations to set monopolistic prices, which are higher than the marginal cost of production. Monopolistic price setting generally harms the consumer and limits production below that which would be socially optimal if producers charged the marginal cost of production as in a perfectly competitive market. However, to the extent that corporations enjoy economies of scale and thus might produce goods at a lower cost than smaller competitors, consumers might still be better off than they would be in a perfectly competitive market made up of many small producers.

The meat processing industry in the United States of America is an example of an agrifood industry with large economies of scale. Most meat consumed in the country comes from a few large meat processors, many of which have automated numerous stages of what is referred to in the industry as disassembly. Although there are few meat processors, competition between processors might prevent them from setting prices above their marginal cost. Even so, smaller meat processors cannot typically provide standard cuts and styles of meat at prices as low as those provided by large processors since they lack economies of scale.

4.4 Gender implications of farm automation

The gender implications of on-farm automation are complex. They depend on the previous gender distribution in newly automated farm tasks, as well as the division of labour between genders in the linked upstream and downstream activities. Surveys of agricultural households in eastern and southern Africa revealed that, except on plots controlled by women, men supplied most of the labour in crop production, including soil preparation, planting, weeding and harvesting, though it is common for women to assist in the fields at key points in the crop cycle (Baudron *et al.*, 2019). It is not obvious whether increased use of tractors for soil preparation and planting disproportionately frees up male or female labour on subsistence or commercial farms, even though men more frequently perform tasks that are directly substitutable with the use of

tractors. However, in India, increased tractor use disproportionately reduced female labour hours on farm by reducing weed growth and thereby decreasing the demand for weeding labour, which is traditionally performed by women. To the extent that men operate and maintain machinery, men's labour might be complementary to automated technologies (Afridi, Bishnu and Mahajan, 2022). On the other hand, increased use of tractors in Ghana showed no differential impacts on demand for men's and women's labour, likely because men and women cultivate separate plots of land rather than dividing specific tasks (Cossar, 2019).

Differential impacts of agricultural automation on men and women are of great importance in understanding welfare impacts of technology adoption given the significant role that women play in agricultural production worldwide. The United States Census of Agriculture found that 36 percent of farmers in the country are women and 56 percent of all farms have at least one female decision maker (Shearing, 2019). World Bank studies that gather time-use data find that the female share of labour in crop production averages 40 percent in Ethiopia, Malawi, Niger, Nigeria, Uganda and the United Republic of Tanzania (Christiaensen and Demery, 2018). Often, there are rigid gender divisions on farms. For example, a study of saffron production in Morocco found that while cultivation of the crocus flower (from which saffron is extracted) is a male-dominated activity, processing of the flowers – tedious and labour-intensive activities – is performed almost exclusively by women (Filipski *et al.*, 2017). This means that automation in flower cultivation would release mostly male labour, and if this automation enabled an expansion of flower production, it would certainly increase the demand for female labour for processing. This example serves to illustrate that, even on individual farms, automation of one task may have different effects on employment for men and women.

Uneven access to resources can often prevent women from adopting agricultural technologies. In Senegal, many women reported pooling resources through local women's organizations and enterprise groups to afford larger investments (Voss *et al.*, 2021). Female-headed households have also frequently been found to have less access to agricultural extension services, knowledge of field experiments and exposure to information from other farmers within the community (Lambrecht, Vanlauwe and Maertens, 2016). Research suggests that the gender gap in agricultural technology adoption may increase over time if women have fewer opportunities to adopt them and only learn how to use them via their own experimentation (Mishra *et al.*, 2020). Reduced initial investments in automated technologies can potentially have long-term impacts. In Uganda, recent adoption of agricultural technologies was a primary predictor of technology adoption in the following period, whereby lower previous adoption resulted in lower future adoption for female-headed households (Mishra *et al.*, 2020). This shows that disparities in adoption rates across gender or other racial or social distinctions could foreseeably grow over time if not addressed through policy interventions that provide equitable access to technological information and resources.

4.5 Automation and seasonality of employment

Seasonality of employment is a concern in agriculture around the globe. Crop production activities are inherently seasonal. This means that unemployment and underemployment tend to be high in some seasons, while there may be severe labour bottlenecks in others. For a farmer, not having access to labour at critical times (most notably but not exclusively, at harvest) can have serious ramifications for crop production, and it may discourage cultivation. Automation that relieves excess labour demands in some seasons could maintain employment in other seasons. This raises important questions: which cropping tasks, at which seasons,

are easiest to automate, and do they coincide with the labour bottlenecks farms face? For the most labour-intensive crops, which are primarily fruits and vegetables, the most labour-intensive tasks occur at harvest. This can create bottlenecks and challenges around this time as many farmers compete to attract workers from the available pool. Harvest tasks are also often the most difficult to automate, even with advanced artificial intelligence (AI) and other IT solutions. It is useful to look at automation in the richest agricultural areas, where farm wages are relatively high and automation solutions are most available. In California, land preparation is automated with autonomous ploughing, tilling, and land-levelling machinery. Harvest of some crops that are processed, like tomatoes and wine grapes, are automated. Harvests of fresh fruits and vegetables for final consumption, however, continue to be labour-intensive, even though produce-picking robotic solutions are on the horizon and are likely to be implemented in the near future, incentivized by a decreasing availability of harvest workers and rapidly increasing wages (Charlton *et al.*, 2019). Adoption rates will depend in large part on how efficiently mechanized and robotic solutions can harvest these crops and how quickly farm wages rise.

Over time, as the agricultural transformation unfolds and technologies as simple as tractors become widely available to automate some farm tasks, labour productivity rises in relatively low-income countries. This is evident by dividing countries' agricultural gross domestic product (GDP) by their total agricultural employment. Doing this for Mexico, Zahniser *et al.* (2018, Figure 6) show a clear rising trend in agricultural labour productivity over time, up to around USD 9 500 per worker per year as of 2017. In 2022, the average pay for a crop worker in Mexico is considerably higher: USD 12 780 (Economic Research Institute, 2022).⁵

4.6 Automation and migrant-sending communities

As crop production expands while domestic farm labour supplies contract, countries seek new sources of farm workers through immigration. California is an extreme, but it is often seen as a predictor of future trends in other places. The share of immigrant workers in California's farm workforce is greater than 90 percent. Reliance on a foreign agricultural workforce is universal in today's high-income countries, and is also high in many middle-income countries (Taylor and Charlton, 2018). Mexico, the largest source of hired farm workers in the United States of America, which is the largest importer of farm workers in the world, is exporting fewer farm workers than before, and it now hires farm workers from Guatemala to the south of the country (Charlton, Rutledge and Taylor, 2021; Charlton and Taylor, 2016).

Countries' increasing reliance on immigrant workers over the agricultural transformation raises important and rarely asked questions about the social impacts of automation on farms. In California, farm automation reduces the demand for immigrant workers. It might seem, then, that automation of farm operations in California would negatively affect villages in rural Mexico, from which most of its immigrant farm worker force comes and to which it remits large sums each year. California's agricultural automation is not occurring in a vacuum, however. In rural Mexico, fertility rates are falling, schooling levels are rising sharply, and access to non-farm jobs is increasing. Due to these and other trends, Mexico's supply of labour to farm work is decreasing by around 1 percent or 155 360 persons per year. The wages of California's

⁵ In United States dollars, evaluated at USD 1 = MXN 20.

agricultural workers rose 18 percent between 2008 and 2018, faster than non-agricultural wages (Zahniser *et al.*, 2018).

Before the 1990s, when the decline in Mexican farm labour supply appears to have started, there was little economic incentive for Californian farmers to adopt new labour-saving technologies, and little incentive for private or public institutions to develop them. Today, however, farmers in both Mexico and the United States of America have to deal with this declining supply of Mexican agricultural workers through automation. There is a race between automation and a declining farm work force in both countries. Automation begins with the most labour-intensive and easiest-to-mechanize operations, but today, some of the most advanced IT solutions from Silicon Valley start-ups are being developed to reduce labour demands in hard-to-mechanize tasks, like harvesting fresh fruits on trees and in the fields (Charlton *et al.*, 2019; Taylor and Charlton, 2018).

In general, it might seem that automation on farms in relatively high-income countries would have negative impacts on migrant remittances to poorer countries, and this could be true. However, this automation appears to be happening in a context of a diminishing farm labour supply in migrant-sending areas, together with rising farm worker wages, both of which are positive trends for welfare in agricultural labour-exporting economies.

5 The future of the agrifood workforce

As labour-saving automation expands on farms, the farm workforce evolves as well. It not only becomes smaller but also requires new skills, capable of complementing new and increasingly complex technologies. Where the future farm workforce will come from and how to ensure the agricultural workforce acquires skills to manage more complex and sophisticated technologies is still to be determined. These new technologies are expected to increase the demand for skilled workers on farms and lead to higher farm wages (Khanna, 2021).

The fear that crop-picking robots will displace millions of farm workers without other job prospects is not likely to be well founded. In general, the automation of agricultural jobs and evolution of the farm workforce are gradual processes, uneven across localities, crops, and farm tasks. The incentives to demand and adopt labour-saving methods are greatest for specific farm tasks that are labour-intensive and relatively inexpensive and easy to automate. Over time, the supply of agricultural workers diminishes in different localities, closely linked to rising incomes, declining fertility, increasing education, and expansion of employment opportunities off the farm. Because of this, the declining farm workforce, while undeniable, is happening unevenly across the globe.

Rather than dislocating large numbers of workers, automation is likely to continue occurring incrementally. As farm labour supplies decrease, some tasks are automated while others continue to be labour-intensive. The benign view is that market signals will continue to guide the development and adoption of labour-saving techniques, and a process of incremental automation will release workers from newly automated tasks to more difficult-to-automate ones. In some cases, like soil preparation and ploughing, it will open up new tracts of land that increase the demand for workers in other tasks (planting, weeding, thinning, harvesting) as food production expands.

That is not to say that there will not be friction along the way, with the adoption (or non-adoption) of labour-saving technologies creating unemployment (or labour bottlenecks) at some times and places. Too much automation resulting from sudden breakthroughs could give farmers access to labour-saving technologies that they have an incentive to adopt even with ample workers and low wages. This scenario is unlikely to play out in high-income countries, where worker shortages and rising wages are already the norm, but is plausible in low-income countries. This might improve livelihood for smallholder producers in these countries, by enabling family members to allocate more time to education and off-farm employment opportunities and by enhancing productivity and profitability. This might negatively impact workers on commercial farms in these countries, however, by reducing employment opportunities, particularly for workers with skillsets that are made obsolete by new technologies. Too little automation could happen if government policies create obstacles to automation on farms, on the assumption that this will preserve agricultural jobs. In the context of a shrinking farm labour supply and rising wages, the assumption that limiting automation will preserve farm employment and incomes is likely to be flawed, for two reasons. First, restrictive automation policies make farms less competitive and able to expand their production of food for growing domestic markets or export. Second, a key to improving wages and working conditions for farm workers is making them more productive by coupling their labour with new technologies. Most of the world's farm workers (including in California) have family incomes below the poverty line. The prospects of moving out of poverty are dim if labour productivity-enhancing technologies are not available. In microeconomic theory, workers receive a wage

that cannot logically exceed the value that their efforts add to production (if wages are higher than a worker's marginal product the worker will not be hired). Limiting the adoption of labour-saving (and thus worker productivity-enhancing) technology assures that farm worker wages continue to be low.

In light of this, facilitating the expansion of food production in an era of declining farm labour supply, while continuing to build educational systems that can prepare the workforce of tomorrow, is a major policy challenge around the world. This challenge is not limited to crop production – it applies more generally to the entirety of agrifood systems, all of whose nodes inevitably are affected by automation, incentivized by rising non-farm as well as farm wages. If workers with the skills needed to complement new technologies upstream and downstream in agrifood systems are not available, it will be difficult for agrifood systems to expand to meet a growing global demand for food, especially in places where the growth of the farm workforce is slowing or declining.

6 Conclusion

Understanding the social implications of farm automation requires taking a step inward, to see which farm tasks are automated and how they relate to other tasks, as well as outward, to appreciate how crop production interacts with upstream and downstream nodes in agrifood systems. At a given point in time, automation affects individual tasks on some farms. It releases labour from those tasks to other, more labour-intensive tasks on the farm, as well as to other activities up and down the agrifood value chain.

It is easy to imagine automation creating unemployment and depressing farm wages, and this outcome is possible under some scenarios. However, past experience suggests that innovation and adoption of labour-saving technologies usually is a long process (Charlton *et al.*, 2019). A delicate interplay of biological and mechanical design makes research and development (R&D) to automate new tasks increasingly complicated. Tractors can be used for many tasks, and they are becoming more and more available in poor countries, in part thanks to digital solutions that make tractor services available to small farms. However, it is not easy to create machines that can emulate the dexterity and skill of human hands performing agricultural tasks, or human eyes spotting weeds, crops to thin, or fruits ripe and ready to be picked. There are many examples in which the automation of one farm task (e.g. soil preparation using a tractor) increases the demand for workers in other tasks (e.g. sowing, weeding, thinning, and harvesting). In this way, automation can stimulate agricultural employment at the extensive margin by enabling farms to expand their production in response to growing domestic and global food demands.

There is also evidence that growth in agricultural production, facilitated by automation, stimulates job creation at other nodes of agrifood systems (in input-supplying activities upstream, in logistic, storage, processing, and marketing activities downstream). The agricultural revolution is characterized by increasing complexity in agrifood systems, with a reduction in the share of employment on farms and a rise in the shares in other agrifood systems' activities as well as labour-saving innovations throughout systems. A feature agrifood systems' employment, crucial for worker welfare, is that jobs off the farm tend to be higher paying and more stable and secure than farm jobs for workers at similar skill levels.

How the development and adoption of labour-saving agricultural technologies affect employment and wages depends largely on what drives farm automation. Market signals – specifically, changes in wages relative to other factor prices – create incentives or disincentives for R&D and the adoption of labour-saving methods on farms. It is important to recognize how these incentives are playing out in the context of the global agricultural transformation, which includes a diminishing farm labour supply that is universal but uneven around the world. As birth-rates and labour-force growth decline and educational levels and non-farm employment opportunities expand, there is upward pressure on wages on farms as well as across agrifood systems. This is evident in countries as disparate as China, Mexico, Myanmar and the United States of America. Automation of some tasks is essential to avoid labour bottlenecks that prevent growth in food production. As wages rise, the most labour-intensive and, above all, easiest-to-mechanize tasks are automated first. Rising labour costs naturally create a demand for automation on farms as well as at other nodes of agrifood systems. A basic take-away message from these observations is that policymakers should be careful before intervening in markets to inhibit automation, where it might otherwise occur, or promote automation, where it has not yet occurred.

On the supply side, massive advancements in R&D continue to put new farm automation solutions for new tasks within the reach of farmers at a cost that is decreasing over time. This is positive news from the perspective of raising global food production as farm workforces around the world contract. At the same time, very rapid development of farm automation, or government policies that promote automation before its time, could result in abrupt changes in labour demand and break the link between automation, on one hand, and labour availability, on the other. This could result in automation concurrent with rising unemployment and falling or stagnant wages on farms at some places and times. The policy response logically should be to avoid creating market distortions that encourage automation before its time, and begin work immediately to prepare young people in agricultural households with the skills so that they can access new, higher-skilled jobs on farms or in other parts of agrifood systems.

From this perspective, some insights emerge about the role of government policies with respect to farm automation. Do not block but facilitate the process of market signals guiding automation. Recognize that people – particularly young people – are moving away from the farm, and automation is key to maintaining and expanding food production in their wake. Access to information and the infrastructure to automate, like energy and internet access, is crucial to farmers' ability to compete in a world of growing farm labour scarcity. Information is (or should be) a public good, and providing it is a government's responsibility. Public educational systems will play a vital role in preparing the future workforce and enabling agrifood systems to compete and satisfy world food demands. This will also facilitate the transition of rural workers – especially younger, more educated workers – towards other non-farm activities. This will help ensure a smooth transition and equitable access to newer and better employment opportunities for rural populations as the agricultural transformation continues to unfold.

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Food and Agriculture Organization of the United Nations
Rome, Italy

ISBN 978-92-5-137074-2 ISSN 2664-5785



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CC2610EN/1/10.22