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THE STATE OF FOOD AND AGRICULTURE

LEVERAGING AUTOMATION IN AGRICULTURE FOR TRANSFORMING AGRIFOOD SYSTEMS

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THAILAND. Aerial view of a farmer using a tablet in a green rice field.

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2022 THE STATE OF FOOD AND AGRICULTURE

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FOREWORD

This report dives deep into a reality of agriculture: the sector is undergoing profound technological change at an accelerating pace. New technologies, unimaginable just a few years ago, are rapidly emerging. In livestock production, for example, technologies based on electronic tagging of animals – including milking robots and poultry feeding systems – are increasingly adopted in some countries. Global navigation satellite system (GNSS) guidance allows automated crop production, involving use of autosteer for tractors, fertilizer spreaders and pesticide sprayers. Even more advanced technologies are now coming onto the market in all sectors. In crop production, autonomous machines such as weeding robots are starting to be commercialized, while uncrewed aerial vehicles (commonly called drones) gather information for both crop management and input application. In aquaculture, automated feeding and monitoring technologies are increasingly adopted. In forestry, machinery for log cutting and transportation is currently a major aim of automation efforts. Many of the most recent technologies facilitate precision agriculture, a management strategy that uses information to optimize input and resource use.

Recent technological developments may astound and amaze, inspiring the desire to learn more. However, it is important to remember that technological change is not a new phenomenon and, crucially, not all agrifood systems actors have access to it. FAO has been studying this subject for decades. What we see today is no more than a consolidation point – for now – of a lengthy process of technological change in agriculture that has been accelerating over the last two centuries.

This process has increased productivity, reduced drudgery in farm work, freed up labour for other activities, and ultimately improved livelihoods and human well-being. Machinery and equipment have improved and sometimes taken over the three key steps involved in any agricultural operation: diagnosis, decision-making and performing. The historical evolution exhibits five technology categories: the introduction of manual tools; the use of animal traction; motorized mechanization since the 1910s; the adoption of digital equipment since the 1980s; and, more recently, the introduction of robotics. What is referred to as automation in this report really begins with motorized mechanization, which has greatly automated the performing component of agricultural operations. The more recent digital technologies and robotics allow for the gradual automation also of diagnosis and decision-making. As this report notes, this evolution is ongoing, but not all agricultural producers in all countries are at the same stage.

It is true that there are widespread concerns about the possible negative socioeconomic impacts of labour-saving technological change, in particular job displacement and consequent unemployment. Such fears date back to at least the early nineteenth century. However, when looking back, fears that automation which increases labour productivity will necessarily leave people without jobs on a vast scale are simply not borne out by historical realities. This is because automation in agriculture is part of the process of structural transformation of societies whereby increased agricultural labour productivity gradually releases agricultural workers, allowing them to enter into profitable activities in other sectors such as industry and services. During this transformation, the share of the population employed in agriculture naturally declines, while jobs are created in other sectors. This is generally accompanied by changes within agrifood systems, whereby upstream and downstream sectors evolve, creating new jobs and new entrepreneurial opportunities. For this reason, it is essential to recognize that agriculture is a key part of broader agrifood systems.

The report highlights the potential benefits of agricultural automation that are manifold and able to contribute to the transformation of agrifood systems, making them more efficient, productive, resilient, sustainable and inclusive. Automation can increase labour productivity and profitability in agriculture. It can improve working conditions for agricultural workers. It can generate new entrepreneurship opportunities in rural areas, which may be particularly attractive for rural youth. It can help reduce food losses and improve product quality and safety. It can also bring about benefits in terms of environmental sustainability and climate change adaptation. Recent solutions involving precision agriculture and the adoption of small-scale equipment – often more suited to local conditions than motorized mechanization using heavy machinery – can improve both environmental sustainability and resilience to climate and other shocks. Thanks to these numerous benefits, agricultural automation can also contribute to achieving several of the Sustainable Development Goals (SDGs).

However, the risks and problems associated with agricultural automation are also acknowledged in this report. As with any technological change, automation in agriculture implies disruption to agrifood systems. If automation is rapid and not aligned with local socioeconomic and labour market conditions, there can indeed be displacement of labour – the common outcome that must be avoided. In addition, automation may increase demand for highly skilled labourers, while reducing demand for non-skilled workers. If large prosperous agricultural producers have easier access to automation than smaller, poorer producers, automation risks exacerbating inequalities, and this must be avoided at all costs. If not well managed and suited to local conditions, automation, especially mechanization relying on heavy machinery, can jeopardize agricultural sustainability. These risks are real and are recognized and analysed in this report.

Yet, as the report also suggests, saying no to automation is not the way forward. FAO truly believes that without technological progress and increased productivity, there is no possibility of lifting hundreds of millions of people out of poverty, hunger, food insecurity and malnutrition. Refusing automation may mean condemning agricultural labourers to a future of perennially low productivity and poor returns for their labour. What matters is how the process of automation is carried out in practice, not whether or not it happens. We must ensure that automation takes place in a way that is inclusive and promotes sustainability.

Throughout this report, FAO shares the concept of responsible technological change to make agricultural automation a success. What does this entail?

First, agricultural automation needs to be part of a process of agricultural transformation that runs in parallel with, facilitates, and is facilitated by broader changes in society and agrifood systems. For this, it is essential that adoption of automation responds to real incentives. Thus, labour-saving technologies can further the process of agricultural transformation if they respond to growing labour scarcity and rising rural wages. On the other hand, if incentives for adoption of automation or specific automation technologies are artificially created, for example, through government subsidies – particularly in contexts where labour is abundant – automation take-up can be highly disruptive with negative labour market and socioeconomic impacts. However, it is also important that government policies do not inhibit automation, as this could lead to condemning agricultural producers and workers to a future of perennially low productivity and competitiveness. This report argues that the appropriate role of government is to create an enabling environment to facilitate adoption of suitable automation solutions, rather than directly incentivize specific solutions in contexts where they may not be appropriate, or inhibit adoption of automation in any way.

For coherence with the SDGs, automation needs to be inclusive. It must offer opportunities for all, from small-scale producers to large commercial farms, as well as marginalized groups such as women, youth and persons with disabilities. Barriers to adoption need to be overcome, not least for women. Making suitable technical solutions available for all categories of producers involves making technologies scale-neutral, that is, making them suitable for producers of all scales, or accessible to all through institutional mechanisms such as shared services. Building digital skills through education and training is also essential for facilitating adoption and avoiding digital divides based on unequal knowledge and skills.

FOREWORD

To enhance sustainability and be truly inclusive and transformative, automation solutions need to be adapted to the local context, in terms not only of the characteristics of the producers, but also of local biophysical, topographic, climatic and socioeconomic conditions. This report is realistic and offers no one-size-fits-all solutions. The most advanced technological solution is not necessarily the most appropriate everywhere and for everybody. As the evidence presented shows, in some situations, simple technologies such as small machinery and even hand-held equipment can lead to substantial benefits for small-scale producers and enable production on hilly terrain. There are even situations where producers may be able to leapfrog directly to more advanced technological solutions. What is essential is that agricultural producers themselves choose the technologies most suited to their needs, while governments create the enabling environment that allows them to do so.

Finally, this report also argues that agricultural automation must contribute to more sustainable and resilient agriculture. In the past, the use of large-scale heavy machinery has often had a negative impact on environmental sustainability. Addressing this requires tailoring mechanization to smaller and lighter machinery. At the same time, digital agriculture and robotics that facilitate precision agriculture offer solutions that are more resource-efficient and more environmentally sustainable. Applied technical and agronomic research can help find solutions that can lead to further progress towards environmental sustainability.

This report looks in detail at these issues, presenting an objective and in-depth examination of agricultural automation, demystifying the ill-founded myths surrounding it, and suggesting ways forward to adopt agricultural automation in different country and local settings. It identifies key areas for policy interventions and investments to ensure that agricultural automation contributes to inclusive and sustainable development.

FAO firmly and strategically believes in technology, innovation and data, supported by adequate governance, human capital, and institutions, as key cross-cutting and cross-sectional accelerators in all its programmatic interventions to accelerate impact while minimizing trade-offs. No doubt, these accelerators will be catalytic for agricultural transformation in all contexts. It is my hope that this FAO report can contribute in a constructive way to the policy debate in this area of major importance for achieving the SDGs.

Qu Dongyu
FAO Director-General

METHODOLOGY

The preparation of *The State of Food and Agriculture 2022* began with the formation of an advisory group representing all relevant FAO technical units, which, together with a panel of external experts, assisted the research and writing team. The preparation of the report was further informed by six background papers and original empirical analysis prepared by FAO and external experts. The advisory group met virtually to discuss the outline of the report on 24 January 2022 and commented on the first drafts of Chapter 1 and Chapter 2 in March 2022. Drafts of all chapters were presented to the advisory group and panel of external experts in advance of a workshop held virtually on 31 March – 6 April 2022 and chaired by the Deputy Director of FAO's Agrifood Economics Division. With guidance from the workshop and a follow-on advisory group meeting, the report was revised and presented to the management team of FAO's Economic and Social Development stream. The revised draft was sent for comments to other FAO streams and to the FAO regional offices for Africa, Asia and the Pacific, Europe and Central Asia, Latin America and the Caribbean, and the Near East and North Africa. Comments were incorporated in the final draft, which was reviewed by the Deputy Director of the Agrifood Economics Division, the FAO Chief Economist and the Office of the Director-General.

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ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
AMS	automatic milking system
APNI	African Plant Nutrition Institute
AUC	African Union Commission
CAAS	Chinese Academy of Agricultural Sciences
CEA	controlled environment agriculture
CIMMYT	International Maize and Wheat Improvement Center
COVID-19	coronavirus disease 2019
CSAM	Centre for Sustainable Agricultural Mechanization
CTA	Technical Center for Agricultural and Rural Cooperation
DPGA	Digital Public Goods Alliance
EDRI	Ethiopian Development Research Institute
EID	electronic identification
ESCAP	Economic and Social Commission for Asia and the Pacific
FAO	Food and Agriculture Organization of the United Nations
GHG	greenhouse gas
GIS	geographic information system
GIZ	German Agency for International Cooperation
GNSS	global navigation satellite system
GPS	global positioning system
GSMA	Global System for Mobile Communications
GSS	general services support
ha	hectare
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation
IFPRI	International Food Policy Research Institute
ILO	International Labour Organization
IoT	internet of things
ISPA	International Society of Precision Agriculture
IT	information technology
ITU	International Telecommunication Union
IVR	interactive voice response
LSMS	Living Standards Measurement Study
LSMS-ISA	Living Standards Measurement Study - Integrated Surveys on Agriculture
R&D	research and development
RuLIS	Rural Livelihoods Information System
SDGs	Sustainable Development Goals
SMS	short message service
UAS	uncrewed aerial system (historically referred to as unmanned aerial system)
UAV	uncrewed aerial vehicle (historically referred to as unmanned aerial vehicle)
UNICEF	United Nations Children's Fund
USDA	United States Department of Agriculture
USSD	unstructured supplementary service data
VRT	variable rate technology
WFP	World Food Programme
WHO	World Health Organization

GLOSSARY

Agricultural automation. The use of machinery and equipment in agricultural operations to improve their diagnosis, decision-making or performing, reducing the drudgery of agricultural work and/or improving the timeliness, and potentially the precision, of agricultural operations. Agricultural automation includes technologies for precision agriculture. Examples of machinery and equipment used in agricultural automation include:

- tractors that pull, push or put into action a range of implements, equipment and tools that perform farm operations (i.e. automating the performing function);
- sensors, machines, drones and satellites, as well as devices such as smartphones, tablets or software tools (e.g. advisory apps and online farm management) and platforms, to monitor animals, soil, water and plants to support humans making decisions on agricultural tasks[1] (i.e. automating the diagnosis function);
- more advanced options, such as weeding robots which spray herbicides with precision only where needed and with exactly what is needed, or drones to monitor conditions remotely and apply fertilizers, pesticides and other treatments from above[2, 3] (i.e. automating the three functions: diagnosis, decision-making and performing).

Automated equipment. Systems where some (partly automated) or all (fully automated) functions, a defined activity or behaviour of a machine or a machine system, have been automated to work without human intervention.[4]

Agricultural mechanization. The use of all levels of technologies, from simple, basic hand tools to more sophisticated, motorized equipment and machinery, to perform agricultural operations.[6] Power sources in agricultural mechanization are of three types: hand tool technology (tools and implements that use human muscles as the main power source); draught animal technology (machines, implements and equipment powered by animals); and motorized technology (mechanization powered by engines or motors).[7]

Agricultural motorized mechanization. The application of all types of mechanical motors or engines, regardless of energy source, to activities associated with agriculture.[7]

Agricultural producers. Households running agricultural businesses engaged in crop production, livestock production, fisheries, aquaculture, pastoralism or forestry.

Small-scale (agricultural) producers are those running any of the agricultural businesses defined above but operating under greater constraints due to limited access to markets and resources such as land and water, information, technology, capital, assets and institutions.[8]

Artificial intelligence (AI). Computer systems that use algorithms to analyse their environment and take actions – with some degree of autonomy – to achieve specific goals. AI can be purely software-based, acting in the virtual world (e.g. voice assistants, image analysis software, search engines, speech and face recognition systems), or it can be embedded in hardware devices (e.g. advanced robots, autonomous cars, drones or IoT applications).[5]

Machine learning. A type of AI and a method of data analysis that uses computer algorithms to automate analytical model building. It is based on identifying patterns in data to improve machine performance by more accurately predicting outcomes without explicit human instructions.

Big data. Large, diverse, complex data sets generated from instruments, sensors, financial transactions, social media, and other digital means, typically beyond the storage capacity and processing power of personal computers and basic analytical software.

Business-to-business model. Relations and sales between companies, rather than between a company and individual clients.[9]

Business-to-client model. Direct relations and sales of products and services between a company and customers who are the end users of its products or services.[9]

Conservation agriculture (also referred to as conservation tillage). A farming system that promotes minimum soil disturbance (i.e. little or no tillage), maintenance of permanent soil cover and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, contributing to increased water- and nutrient-use efficiency and improved and sustained crop production.[10]

Digital automation in agriculture. The strengthening of automated processes in agricultural machinery and equipment (e.g. tractors and their implements, feeding systems, milking machines) by adding digital tools that increase their efficiency and precision as a result of access to data and digital services through intelligent interoperable networks, platforms and farm management systems.

Disembodied vs embodied digital solutions. Disembodied digital solutions are primarily software-based solutions that do not rely on the use of agricultural machinery but instead require limited hardware resources, generally in the form of a smartphone or a tablet, or software tools such as advisory apps, farm management software, and online platforms. They may include remote sensing and/or UAS but limited to data for decision support and scouting. When digital tools are installed on agricultural machinery and equipment, they are called embodied and they enable the machinery to interact with the environment through direct action (performing), rather than just observations and decision support.[9]

Electronic identification (EID). The use of a microchip or electronic transponder embedded in a tag, bolus or implant to identify an individual farm animal.[5]

Farm. Any management-integrated agricultural production unit that produces crops, livestock, agroforestry or aquaculture products.

Fee-for-service. In the context of farm machines, a business arrangement whereby the farmer pays a provider for machine services on a per unit basis (e.g. per ha, hour, animal or tonne harvested), rather than owning the machine.[5]

Global navigation satellite system (GNSS). Any system that uses satellite signals to provide location information. Examples include the global positioning system (GPS) of the United States of America, the European Galileo system, GLONASS of the Russian Federation, and the Chinese BeiDou system.[5]

Autosteer. A GNSS-enabled technology that provides automated steering and positioning in the landscape for self-propelled agricultural machines (e.g. tractors, combine harvesters, forage harvesters, sprayers). With the most advanced autosteer, the computer does almost all the steering in the field, including turning at the end of a row. Autosteer technology typically requires a human operator present on the seat of the machine to take over in case there is a malfunction or other problem. It is a good example of a precision farming technology.[5]

Global positioning system (GPS). The United States of America's GNSS. Because it was the first GNSS available for civilian use, GPS is sometimes used as a generic term for GNSS.[5]

Internet of things (IoT). A system in which devices – including mobile phones, sensors, drones, machines and satellites – are connected to the internet.[9]

Interoperability. The ability of machines and equipment to create, exchange and consume data due to clear and shared expectations regarding the contents, contexts and meaning of those data.[9]

On the go. In the context of farm machines, a situation in which machine operation is adjusted while moving through a field based on an algorithm using sensor data without direct human intervention.[5]

Operator assistance system. A system that helps human operators of farm machines. Typically, it uses sensor data from several sources on the machine to assist the operator in making decisions; it can automatically adjust machine settings to optimize the operator's priorities (e.g. fuel efficiency, speed of work accomplished, product quality) and was first introduced on combine harvesters.[5]

Precision agriculture. A management strategy that gathers, processes and analyses temporal, spatial and individual data and combines them with other information, to manage variations in the field accurately and to support management decisions and precise machine action for improved resource-use efficiency, productivity, quality, profitability and sustainability of agricultural production.[11]

Precision livestock farming. A data-based livestock management strategy that monitors and controls individual animal or group productivity, environment, health and welfare in a continuous, real-time and automated manner. It focuses on improving resource-use efficiency, productivity, quality, profitability and sustainability of livestock production.[5]

Protected agriculture. The production of high-value vegetables and other horticultural crops in greenhouses and vertical farms. It allows farmers to grow cash crops on small plots in marginal, water-deficient areas where traditional cropping may not be viable. It is also called protected cultivation or protected crop production.[9]

Remote sensing. The process of gathering information about objects on earth from a distance, using aircraft, satellites or other platforms carrying sensors.[9]

Robot. A machine capable of autonomous operation without direct human intervention.[12] It can be stationary (e.g. a milking robot) or mobile (e.g. autodriving). The word tends to be used mainly in the media and by the general public, and robots are often anthropomorphized. More technical discussions prefer to use terms like autonomous machine or autonomous equipment.[13]

Leg robot. A mobile autonomous machine with articulated limbs instead of wheels for movement.[5]

Milking robot. Any milking machine that automates the milking of dairy animals, especially dairy cattle, without human labour. They are also called automatic milking systems (AMS).

Swarm robots. Multiple, relatively small mobile autonomous machines that accomplish work done by one large machine in conventional mechanization.

Robotics. An interdisciplinary branch of computer science and engineering, which involves design, construction, operation and use of robots. It integrates many fields, including mechanical engineering, electrical engineering, information engineering, mechatronics, electronics, bioengineering, computer engineering, control engineering, software engineering, and mathematics.

Uncrewed aerial system (UAS). A large system including aircraft (drones) with mounted sensor(s), a ground control station operated by the pilot and the software used to analyse the data gathered by the sensor(s).[9]

Uncrewed aerial vehicle (UAV) or **Drone.** A flying autonomous machine. It can be guided by remote control or using a device that is software-controlled. In agriculture, it is often used to collect aerial images or to apply fertilizer, seed, pesticides or other crop inputs.[5, 9]

Unstructured supplementary service data (USSD). A message service that is more interactive than SMS. Characterized by the use of codes that start with * and end with # (e.g. *845#). A USSD message has a maximum of 182 characters and is used to access information on agriculture, health, news, weather etc.[14]

Variable rate technology (VRT). A technology based on a combination of equipment and software to vary the application of fertilizer, pesticides, seed and other crop inputs within fields to optimize yield based on the needs of crops so that the highest possible yields are obtained with the least possible inputs.[5]

Map-based VRT. A VRT based on a map that documents spatial information on site-specific conditions within the field. A human analyst prepares this spatial information map beforehand in a separate activity to be used in guiding the VRT.

Planter row shut-offs. A GNSS-enabled VRT approach that controls individual row seeder units, based on a prescription map or sensor data. Often used to avoid seeding in non-crop areas or double seeding in end rows.

Sensor-based VRT. A VRT that is based on sensor reading collected on the go in the field, so the information guiding the VRT is automatically collected (different from a map-based VRT). Typically, the sensor is in the front of the applicator, a computer using an algorithm to vary rates is on the machine, and the application equipment is in the back of the machine.

Sprayer boom section controllers. A GNSS-enabled VRT approach that controls parts of a farm sprayer boom based on a prescription map or sensor data. Section width may vary from several metres to a single nozzle. Current technology allows nozzles to be turned on, off and pulsated at various rates.

Vertical farming. Indoor farming with a completely controlled environment, used for growing crops vertically year-round.[9]

Virtual fencing. A technology based on equipping animals with GNSS transponders to determine their location that uses audio alerts, electric shocks or other prompts to keep animals within geolocated boundaries. It potentially eliminates the need for physical fencing, and the GNSS helps growers locate animals grazing in large open pastures.[5]

CORE MESSAGES

1 Agricultural automation can play an important role towards achieving the Sustainable Development Goals (SDGs), not least SDG 1 (No Poverty) and SDG 2 (Zero Hunger) and those relating to environmental sustainability and climate change, by building resilience, raising productivity and resource-use efficiency, and improving food quality and safety.

2 Agricultural automation can deepen inequalities if it remains inaccessible to small-scale producers and other marginalized groups such as youth and women; certain technologies – large motorized machinery – can also have negative environmental impacts as they contribute to, for example, monoculture and soil erosion.

3 Before the digital revolution, motorized mechanization (e.g. tractors) was key to agricultural transformation worldwide; however, there have been wide disparities in adoption between and within countries, with adoption being particularly limited in most of sub-Saharan Africa.

4 If tailored to local needs and supported by digital tools, motorized mechanization still has the potential to improve agricultural productivity, leading to poverty reduction and enhanced food security, with positive spillover effects on the wider economy.

5 The use of digital automation technologies is growing, but mostly in high-income countries. Often their business case is not yet mature: some technologies are still in the prototype stages, while for others a limited enabling rural infrastructure – such as connectivity and electricity – hinders their dissemination, especially in low- and middle-income countries.

6 Investing in enabling infrastructure and improving access to rural services (e.g. finance, insurance, education) is key to ensure access to these technologies, especially for marginalized groups such as small-scale agricultural producers and women.

7 Digital automation technologies have great potential to achieve higher efficiency, productivity, sustainability and resilience. Yet, inclusive investments are needed – involving producers, manufacturers and service providers, with special attention to women and youth – in order to further develop technologies and tailor them to the needs of end users.

8 The impacts of agricultural automation on employment vary depending on the context. In situations of rising wages and labour scarcity, automation can benefit both employers and workers in agriculture and in the wider agrifood systems, creating opportunities for skilled young workers.

9 Where rural labour is abundant and wages are low, agricultural automation can lead to unemployment. This can happen if subsidies make automation artificially cheap or sudden technological breakthroughs bring automation costs down very rapidly.

10 In labour-abundant contexts, policymakers should avoid subsidizing automation, but rather focus on creating an enabling environment for its adoption – especially by small-scale agricultural producers, women and youth – while providing social protection to least skilled workers, who are more likely to lose their jobs during the transition.

11 Creating an enabling environment calls for multiple, coherent actions, including legislation and regulation, infrastructure, institutional arrangements, education and training, research and development, and support to private innovation processes.

12 Investments and other policy actions to promote responsible agricultural automation should be based on context-specific conditions, such as status of connectivity, challenges related to knowledge and skills, adequacy of infrastructure, and inequality in access.

EXECUTIVE SUMMARY

Throughout the ages, technological change – in agrifood systems and elsewhere – has brought gains in productivity, incomes and human well-being. Today, technological solutions are indispensable to feed a continuously growing population in the face of limited agricultural land, unsustainable natural resource use, and increasing shocks and stresses, including climate change. These solutions are needed to make agriculture more productive and sustainable across all its sectors – crop and livestock production, aquaculture, fisheries and forestry – and boost productivity levels within agrifood systems.

Technological change has reduced the need for manual labour in agriculture. This process of increased agricultural productivity and reallocation of labour away from farming is often referred to as agricultural transformation. It is accompanied by investments in agrifood systems and other physical and market infrastructures. Agricultural automation can be a driver of transformation and create new opportunities. In this respect, motorized mechanization has allowed to automate the performing of agricultural operations, while more recently, digital technologies have been creating new opportunities to automate decisions that precede the performing of physical operations.

Common fears that automation leads to growing unemployment, although understandable, are questionable and generally not supported by historical realities. Overall, automation alleviates labour shortages and can make agricultural production more resilient and productive, improve product quality, increase resource-use efficiency, promote decent employment, and enhance environmental sustainability. Negative socioeconomic impacts of agricultural automation – such as increased unemployment – usually occur when automation is not suited to specific local needs. Risks of negative impacts can be countered by facilitating the transition of farm labourers to other job opportunities, by addressing the barriers that prevent poor, small-scale producers from participating in the benefits, and avoiding policies that subsidize automation in contexts of labour abundance and low rural wages.

AGRICULTURAL AUTOMATION: OPPORTUNITIES ABOUND BUT NOT WITHOUT CHALLENGES

Any agriculture-related operation consists of three phases: diagnosis, decision-making and performing. Motorized mechanization automates the performing of agricultural operations such as ploughing, seeding, fertilizing, milking, feeding and irrigating. With digital automation technologies, it becomes possible to automate also diagnosis and decision-making. These technologies increase the precision of agricultural operations and allow more efficient use of resources and inputs, with potential gains in environmental sustainability and improved resilience to shocks and stresses. The technological evolution in agriculture can be summarized as a progressive move from manual tools to animal traction, to motorized mechanization, to digital equipment and finally, to robotics with artificial intelligence (AI).

Against this background, the report defines agricultural automation as:

> the use of machinery and equipment in agricultural operations to improve their diagnosis, decision-making or performing, reducing the drudgery of agricultural work and/or improving the timeliness, and potentially the precision, of agricultural operations.

Agricultural automation presents many opportunities: it can raise productivity and allow for more careful crop, livestock, aquaculture and forestry management; it can provide better working conditions and improved incomes, and reduce the workload of farming; and it can generate new rural entrepreneurial opportunities. Technologies beyond the farm can further reduce food loss and waste, enhance food safety, and enable value addition.

In many countries, declining rural labour availability – reflected in rising agricultural wages – is a main driver of agricultural automation. Rising consumer concerns about food quality, safety, taste and freshness, together with environmental concerns, are also driving investment in digital technologies. The same applies to challenges in livestock management and animal welfare that derive from growing herd sizes in livestock production.

On the other hand, agricultural automation can carry the risk of exacerbating social inequalities, as larger and more educated producers have greater capacities (e.g. finance, rural infrastructure, skills) to invest in new technologies or to retrain and learn new skills. Women and youth may face particularly significant obstacles, for example, obtaining quality education and training, as well as having access to land, credit and markets. Furthermore, automation is expected to reduce jobs that involve routine tasks, such as planting and harvesting, but increase skilled jobs requiring, for example, secondary education. In countries with a large rural workforce, this shift in employment can risk deepening inequalities. Overcoming these challenges requires reducing barriers to adoption – faced in particular by small-scale producers, women and youth – to ensure that automated solutions become scale-neutral, that is, accessible to all scales of agricultural producers from small to large. This can be achieved through technological innovations that tailor automation to the conditions of small-scale producers. In addition, innovative institutional arrangements, such as shared assets or machinery hire services, can contribute to scale neutrality by connecting equipment owners to small-scale producers who pay a fee for an automation service instead of bearing the cost of buying the machinery.

Reliance of agricultural automation on heavy machinery may also jeopardize environmental sustainability and contribute to deforestation, farmland monoculture, biodiversity loss, land degradation and soil erosion. However, some new advances in automation, especially in small equipment relying on AI, can actually reverse some of these negative impacts.

UNDERSTANDING THE PAST AND LOOKING TOWARDS THE FUTURE OF AGRICULTURAL AUTOMATION

Motorized mechanization has increased significantly across the world, although reliable global data with broad country coverage exist only for tractors and only up to 2009. The use of tractors as farm power was one of the most influential innovations of the twentieth century; it started in the United States of America between 1910 and 1960 and spread to Japan and Europe after 1955. Later, many Asian and Latin American countries saw considerable progress in terms of adoption of motorized machinery, in addition to the emergence of agricultural machinery manufacturing sectors in some countries. With the rise of rental machinery markets, adoption has become more widespread, allowing access for small-scale producers. However, adoption of tractors has stalled in sub-Saharan Africa in past decades, and light hand-held tools remain the main type of equipment used. Efforts during the 1960s and 1970s to promote mechanization, by providing subsidized machinery to farmers and setting up state farms and public hire companies, proved costly and mostly failed due to governance challenges. This is changing with the re-emergence of agriculture on Africa's development agenda, which has led to a renewed interest in automation.

Since the 1970s, digital technologies have found their way to agriculture through various applications. Initially they were mostly simple precision livestock technologies that facilitated management of individual animals based on electronic identification (EID) – also known as electronic tagging – which then paved the way for milking robots in the 1990s. At the same time, digital tools embodied in mechanization, such as machinery with global navigation satellite systems (GNSS), started to appear and enabled autosteer for tractors, fertilizer spreaders and pesticide sprayers. More recently, disembodied devices such as smartphones are being adopted to inform producers through sensors, high-resolution cameras and various apps embedded in them. These technologies can reduce costs and raise productivity; however, adoption seems to be driven also by non-monetary considerations such as increased flexibility in work schedules and better life quality, as in the case of milking robots.

More advanced still are internet of things (IoT) solutions, used, for example, to monitor and sometimes – at least in part – automate decisions about the care of crops, livestock or fish. Digital services also include shared asset services, which connect owners of equipment (e.g. tractors or drones), and sometimes also operators, with farmers in need of such equipment.

Digital technologies hold potential also for non-mechanized precision agriculture. Methodologies for manual, site-specific fertilizer application were developed a long time ago – variable rate technology (VRT) fertilizer for rice is one example, while a hand-held soil scanner is available in several low-income countries in Africa and Asia. Uncrewed aerial vehicle (UAV) services, commonly known as drones, are also being used by non-mechanized farmers in Asia and Africa; GNSS measures field areas (Asia) and maps field boundaries to establish land tenure (Africa).

THE CURRENT STATE OF DIGITAL AUTOMATION TECHNOLOGIES AND ROBOTICS IN AGRICULTURE

Digital automation and robotics applications in agriculture are extremely diverse. Smartphones, with a range of sensors and high-resolution cameras built into them, are the most accessible hardware for producers (especially small-scale producers) in low- and middle-income countries. However, low digital literacy in rural areas, lack of available technologies suited to small-scale producers, and the relatively high cost of these technologies remain the biggest barriers to adoption.

More recently, advanced technologies such as autonomous crop robots (e.g. for harvesting, seeding and weeding) have started to be commercialized. Drones are used to gather information and to automate input application, but their use is often strictly regulated.

In the aquaculture sector, automation is on the rise in response to labour scarcity and high wages. In forests, much of the wood harvesting work is already highly mechanized, and mobile robots, combined with new virtual reality and remote sensing techniques, are paving the way for advanced automatic machines. In addition, remote sensing is being used to monitor deforestation. There is also potential for digitalization and automation in controlled environment agriculture (CEA), which includes indoor agriculture and vertical farming. Greenhouses are the most common form of CEA and by their very nature are amenable to environmental monitoring, control and optimization.

Many technological solutions are already available for adoption in high-, middle- and low-income countries. The direction they take and their rate of adoption are greatly influenced by policy choices. Governments need to facilitate access to these technologies by all – in particular, small-scale producers, women, youth and other vulnerable and marginalized groups – and ensure that they are tailored to the specific context and needs of producers. Ideally, governments should create a level playing field for innovative technologies to enable the private sector to meet demand for automation.

ONE STEP AT A TIME: SIMPLE MOTORIZED MECHANIZATION STILL HAS A ROLE TO PLAY

While digital technologies and robotics promise great things, motorized mechanization can still bring many benefits in terms of enhanced incomes, reduced costs, labour savings and less drudgery. It can free up household labour and enable agricultural households to allocate time away from agriculture to pursue off-farm work. There can also be spillover effects on the wider economy. These may occur through increased demand for non-farm goods and services from agricultural households as their labour productivity improves, as well as the expansion of the non-farm economy as labour moves out of agriculture and into sectors with higher labour productivity. Automation can also improve food safety, thanks to preservation and storage technologies, and make agricultural production more resilient, in particular to climate shocks, by allowing farmers to complete farming activities more rapidly and be more flexible in adapting activities to changing weather.

Consequently, there is still scope for increased use of motorized mechanization in some contexts. In low- and middle-income countries, small-scale producers may benefit more from small machines, such as two-wheel tractors, which represent a less costly option and are more environmentally sustainable than traditional heavy machinery. Recent innovations to tailor motorized machinery to local needs can help countries improve resource-use efficiency and save scarce resources (e.g. water) through innovative synergies between mechanization and other field practices. Agricultural mechanization is therefore high on the policy agenda of many low- and middle-income countries. This is especially the case in sub-Saharan Africa, where agricultural mechanization was neglected for some time, following the earlier failures of state-led mechanization programmes.

Manual technologies and animal traction can also still play a major role in many contexts. Animal traction can be an important source of power for very small, fragmented farm holdings, and advanced manual tools can reduce the need for human power. While less powerful than tractors, both draught animals and advanced manual tools can still help remedy labour shortages and enable higher crop yields and land expansion in many areas. In many cases, they are probably the most viable option to increase power supply.

THINKING AHEAD: THE BUSINESS CASE FOR INVESTING IN DIGITAL AUTOMATION

The business case for investing in agricultural technology rests on the potential private gains. The relevant actors – including producers, dealers and service providers – are assumed to make rational decisions that maximize their profits and well-being. Investing in automation technologies entails costs, which tend to increase if technologies are not widely available locally. Suppliers and producers will only make the necessary commitment if the benefits outweigh the costs. For some technologies and in certain conditions, the investment costs may exceed the private benefits; on the other hand, there may be significant benefits for the wider society. In this case, public intervention is needed to align private benefits with the interests of society as a whole.

Given the scarcity of data, 27 case studies, based on interviews with digital automation service providers, were used to shed light on the business case for digital automation in agriculture. The case studies cover all world regions and agricultural production systems (crops, livestock, aquaculture and agroforestry). They represent digital automation solutions at different stages of readiness, with many still in the early stages of development and commercialization. The results reveal only 10 out of the 27 service providers to be profitable and financially sustainable. These ten providers – mostly based in high-income countries – use solutions that are in the mature phase (i.e. widely adopted) and mostly serve large-scale producers. More than one-third of the case studies suggest that farmers are benefiting from these solutions through gains in productivity, efficiency and new market opportunities. Overall, the results indicate that the business case for digital automation technologies is not yet mature, partly because many of these technologies are still in the prototype phase, but also because there are serious barriers to adoption, especially in low- and middle-income countries.

Although the development of many technologies is still in the preliminary stage, several important lessons may be drawn from the case studies. Key factors for adoption are first, awareness of a solution's ability to perform agricultural operations successfully and second, the ability of farmers to handle the solution. Frequent obstacles to adoption of these technologies are lack of digital literacy, and limited connectivity and availability of other enabling infrastructures, including electricity. These are often compounded by a reluctance to change, generally associated with ageing farming populations. Generational change is indicated as a driver of adoption, with young farmers seen as instrumental in a transformation towards digitalization and advanced automation. Another driver of or barrier to adoption is market conditions – where strong competition among producers drives them to take more risks and adopt new technologies that promise higher productivity and efficiency. Limiting factors can be government regulation of technology imports, absence of policies on data sharing, and insufficient public policies and incentives. On the other hand, if well designed, regulations or public support can be a strong driver of adoption.

BEYOND THE BUSINESS CASE: AGRICULTURAL AUTOMATION PROMISES ENVIRONMENTAL BENEFITS, BUT MORE RESEARCH IS NEEDED

In high-income countries, but also in many commercial farms in low- and middle-income countries, agriculture is already highly mechanized, mainly through the use of large machinery. However, this type of mechanization has triggered soil erosion, deforestation and biodiversity loss – all contributing to reduced resilience. Innovations in automation technologies and applied agronomic research can help to explore solutions to address these challenges. For example, motorized mechanization can be tailored to smaller and lighter machinery. Solutions with potential for small-scale producers include small four-wheel and two-wheel tractors. They can minimize biodiversity loss since they do not require substantial field clearing and reshaping. Other small motorized machines, such as power weeders and mobile threshers, may also have benefits in terms of gender equality, because women can operate them easily.

Digital automation technologies that support precision agriculture also present an opportunity for great environmental benefits. They have potential to facilitate the adoption of sustainability practices such as conservation agriculture. There are success stories on the use of computers and IoT to automate greenhouses, leading to savings in water and other inputs. Small swarm robots can lead to environmental benefits by reducing the use of pesticides and herbicides, optimizing the use of other inputs and reducing soil compaction. They are already economically feasible in certain circumstances but more research is needed, especially on their potential for small-scale agriculture, where they should have a comparative advantage over large machinery on farms with irregularly shaped fields.

These environmental benefits are currently location-specific; what is more, many solutions are still in the early stages of development and commercialization. Therefore, more research, including testing, is needed. If both policymakers and producers are fully aware of the benefits of these technologies, investment in their development should expand. Transitioning to renewable energy is also important and can offer fresh opportunities to power automation, especially in remote rural areas, but – once again – research is needed to explore which off-grid renewable energy solutions can most efficiently power each type of machinery.

AGRICULTURAL AUTOMATION HAS COMPLEX IMPACTS ON LABOURERS AND CAN ALSO BENEFIT CONSUMERS

Measuring the overall employment impacts of agricultural automation is very difficult because it requires large amounts of data tracking all the transformations and the associated reallocation of workers, not only in farm activities, but also upstream and downstream. As agricultural transformation unfolds, people exit agriculture to seek higher-paying jobs, and the share of people employed in agriculture continues to decline. The process reshapes labour supply and demand within entire agrifood systems. When all nodes in agrifood systems are changing simultaneously, it is almost impossible to ascribe labour market and socioeconomic impacts to specific occurrences of agricultural automation.

The possible effects of agricultural automation on farm employment are likely to be diverse. Demand for low-skill labour is likely to decrease as many tasks become automated. Meanwhile, automation boosts the demand for relatively skilled workers. Looking at agrifood systems in their entirety, automation could decrease low-paying seasonal employment on farms but increase higher-paying and less seasonal employment upstream and downstream.

Implications of automation may also differ for different types of farms. For small-scale and subsistence farmers, automation can free up family labour for non-farm employment, but may also allow production to expand. On family commercial farms, it can both free up family labour and reduce demand for hired labour, but if commercial agricultural activities expand as a result of automation, there may be more need for hired workers. Corporate commercial farms are the most automated with a corresponding drop in labour requirements on farms. Nevertheless, even in this case, if automation adoption is spurred by rising wages and scarce labour, it will tend to increase labour productivity and wages without causing unemployment.

If automation occurs where there is an abundance of labour, and is incentivized by subsidies that make automation artificially cheap, there is a serious risk of displacing labour and generating unemployment, with major socioeconomic implications, especially for the poorest and least skilled, who may not easily find employment elsewhere.

Agricultural automation has significant socioeconomic impacts on consumers, because it results in reduced costs of food production. Developments in digital automation may also create new entrepreneurial opportunities beneficial to consumers – for example, by allowing the revival of nutrient-dense heirloom crops that were difficult to automate – and substantially reduce production costs for organic foods, which are currently very labour-intensive.

THE AGRICULTURAL AUTOMATION PROCESS MUST BE INCLUSIVE AND NOT LEAVE ANYBODY BEHIND

Agricultural automation must involve those who experience vulnerability, exclusion and marginalization, in particular small-scale producers, pastoralists, small-scale fisherfolk, small-scale foresters and forest communities, agricultural wage-workers, informal microenterprises and workers, landless people, and migrant labourers. Involving women, youth and persons with disabilities is particularly important.

The gender implications of on-farm automation are complex. However, women lag behind men in agricultural technology adoption due to barriers in access to capital, inputs and services (e.g. information, extension, credit, fertilizer), and in some contexts also as a result of cultural norms. Policymakers and local implementation partners need to promote gender-sensitive technology development, dissemination and service provision.

Young farmers appear to be the first to eagerly embrace the process. Agricultural automation promises new types of jobs that require a strong skill set. A solid human capital development and capacity-building agenda, with a focus on youth, must be a priority.

As labour-saving automation expands on farms, not only does the farm workforce become smaller, it becomes more skilled. An important challenge is to facilitate a transition of the agricultural workforce from low-skill manual activities to working with more complex technologies. However, fears that automation will displace millions of farm workers without other job prospects are misplaced. The automation of agricultural jobs, with the consequent evolution of the farm workforce, is a gradual process that differs across localities, crops and farm tasks. The incentives to adopt labour-saving automation are greatest for specific labour-intensive farm tasks that are easily automated at low cost. As some tasks become automated, others will remain labour-intensive.

If the available automation technologies are not scale-neutral, there is a risk that small-scale producers and processors may be pushed out of business because they lack the economies of scale necessary to remain competitive. However, this is not an inevitable outcome of automation in agriculture; the key is for scale-neutral, low-cost automation to become ubiquitous.

In any case, the assumption that limiting automation can preserve agricultural employment and incomes is ill-founded. Indeed, policies to restrict automation will only make farms less competitive and unable to expand their production. To improve wages and working conditions for their workers, farms must become more productive through new technologies. Without labour productivity-enhancing technologies, the prospects of moving poor farm workers out of poverty and food insecurity are dim.

INTRODUCING A ROADMAP FOR EFFICIENT, SUSTAINABLE AND INCLUSIVE AGRICULTURAL AUTOMATION: POLICIES, INVESTMENTS AND INSTITUTIONS

Agricultural automation has strong potential for contributing to sustainable and inclusive rural development based on intensive, but sustainable, agriculture. However, achieving this potential is not automatic and depends on the socioeconomic context, as well as the policy and institutional environment in which the process of agricultural automation plays out. Whether countries gain or lose from the process depends on how they manage the transition. Countries that build the necessary physical, economic, legal and social infrastructures for digital automation stand to benefit. Countries that ignore the challenge may lose.

Like any technological change, agricultural automation inevitably entails some disruption, bringing benefits but also giving rise to trade-offs. The report proposes a range of possible options regarding policies, institutions, legislation and investments. Together they form a roadmap to ensure that agricultural automation contributes to efficient, productive, sustainable, resilient and inclusive agrifood systems. Some options focus on creating a conducive environment for business in agriculture, in particular regarding investments in automation technologies, and these need to be complemented by regulations and other actions to guarantee they lead to environmental sustainability and climate resilience. Lastly, policies and programmes must be in place to ensure the process works for all, especially marginalized groups, such as women, small-scale producers and youth.

Governments will also need to balance trade-offs between different, and sometimes conflicting, economic, environmental and social objectives. The proposed policies, investments and other public actions – discussed in the next section as part of a roadmap for agricultural automation – do not carry the same weight in all contexts. Governments must prioritize actions based on the challenges faced and their national capacities. One important cross-cutting area for government intervention is that of general services support (GSS), which represents government actions that, without distorting incentives or favouring certain actors over others (or certain sectors within agriculture), create an enabling environment for doing business in agriculture and agrifood systems.

AGRICULTURE-TARGETED POLICIES AND INTERVENTIONS ALSO AFFECT AUTOMATION UPTAKE

A number of agriculture-specific policies can support automation more directly and help overcome barriers to adoption, especially for small-scale producers. Governments can influence the adoption process through credit policies that directly target agricultural automation. Investment loans are the most common solution for financing automation and they come in various forms, such as contract-based securities, loan guarantee schemes, joint liability groups, leasing, and matching grants. In addition, "smart" targeted subsidies that do not distort markets can play a role. Improved land tenure security is essential, as insecure land tenure restricts producers' access to credit because they cannot use land titles as collateral. Reducing import duties for machinery, digital equipment and spare parts, and improving customs procedures can also help to lower the transaction costs of automation technologies and spur uptake.

Human capital development is needed to overcome digital illiteracy, for example, through vocational training centres. Knowledge and skills of manufacturers, owners, operators, technicians and farmers must all be strengthened, with youth as a strategic target as they are often the key drivers of automation. Improving agricultural extension and rural advisory services can facilitate adoption. Public extension services have always played an important role in ensuring inclusive agricultural automation. However, the shortage of well-trained extension personnel is a major constraint in most low- and middle-income countries.

While human capital is key for users (i.e. farmers and service providers), it is equally important for those involved in innovations (e.g. researchers and scientists). Governments can fund or conduct applied research and development on automation technologies, in particular aiming at solutions adapted to local needs and those of small-scale producers. An important area of research is impact assessment of precision agriculture solutions in terms of profitability, environmental sustainability and inclusiveness. There needs to be a focus on both small machinery and low-tech digital solutions, such as interactive voice response (IVR), unstructured supplementary service data (USSD) and short message service (SMS). Small machinery may be more suited to local conditions and small farms, while low-tech solutions may more easily reach all farmers at a low cost.

Finally, governments need to develop quality assurance and safety standards, which may be managed by public, market and third-sector organizations. Automation safety laws and regulations need to be based on inclusive consultation with all stakeholders, and must be transparent and supported by measures to ensure compliance by users.

POLICIES, INSTITUTIONS AND INVESTMENTS BEYOND AGRIFOOD SYSTEMS AFFECT AGRICULTURAL AUTOMATION UPTAKE

General policies and investments not specifically aimed at agrifood systems can shape the enabling environment, including infrastructure. Road infrastructure is particularly poor in low-income countries and in most of sub-Saharan Africa. Improving this infrastructure can reduce the transaction costs of access to machinery, spare parts, repairs and fuel, and facilitate the emergence of service markets. Investing in energy infrastructure, for example, through development of off-grid electricity from renewable resources, is equally important as no automation technology works without energy. The availability of renewable energy based on local investments can buffer both shocks in the energy sector and fluctuations in fuel prices.

Improving communication infrastructure and internet connectivity is critical for the proper functioning of agricultural automation. Poor connectivity is widespread even in some rural areas in high-income countries. Policies can grant tax concessions or provide low interest loans for rural internet providers. Legislation can play an important role – promoting public–private–community partnerships to improve connectivity and related infrastructure in rural areas and provide data services and support. Investments should also target associated enabling infrastructures, such as public datasets on weather forecasts and calendars for crop and livestock production.

While physical infrastructure is a primary concern, institutions, macroeconomic conditions and broader institutional capacity are also key to agricultural automation uptake. Improving general credit markets is important; indeed, small-scale producers' access to credit at affordable interest rates is usually limited, making it impossible to finance automation technologies. It is vital to strengthen institutional and political capacity to guide the development of automation technologies; if, on the other hand, powerful private technology companies get there first, the consequences are potentially negative with spillover effects on wider society. What is more, if transparent national data policies are put in place – including data protection, data sharing and privacy regulations – they themselves can facilitate digital automation. Other enablers are the development of national data infrastructures and the promotion of interoperability, that is, accurate and reliable communication among machines. Finally, exchange rate policies and trade policies can affect automation patterns through the import costs for machinery, digital equipment and spare parts.

IF DONE RIGHT, AGRICULTURAL AUTOMATION WILL CONTRIBUTE TO INCLUSIVE AND SUSTAINABLE AGRIFOOD SYSTEMS

Even assuming countries are able to create a level playing field for the provision by the private sector of innovative technologies, challenges linked to automation will remain. Agricultural automation faces three specific challenges: to not leave marginalized groups behind; to avoid increased unemployment and job displacement; and to prevent environmental damage. Policies can play a role in addressing these challenges and ensuring that automation contributes to an inclusive and sustainable agricultural transformation. Therefore, action by policymakers will most likely be required.

First, governments need to ensure that women, youth and other disadvantaged groups benefit from automation. Policies addressing disadvantages faced by women (e.g. improving women's land rights or facilitating their access to credit and extension) also help increase women's access to automation. Public research and development can focus on gender-friendly mechanization technologies tailored to the needs of women. Furthermore, a specific agenda on agricultural automation is needed, targeting rural youth and other disadvantaged groups, ensuring that they acquire the necessary skills to perform the new high-skill jobs associated with automation.

Second, governments need to safeguard against negative effects on employment. Where automation emerges as a response to market forces (e.g. rising rural wages) and replaces unpaid family labour, it is unlikely to generate unemployment. On the other hand, if artificially pushed by public efforts (e.g. through subsidized imports of machinery), it could lead to unemployment, job displacement and lower rural wages. Policymakers should therefore not promote automation before it is actually needed. At the same time, they should not inhibit its adoption based on the claim that it will displace labour and create unemployment. Policy support that provides public or collective goods through GSS is the most likely to allow for a smooth transition towards greater automation without creating unemployment. This includes supporting agricultural research and development and knowledge transfer services.

Third, policies need to ensure that agricultural automation contributes to sustainable and resilient agrifood systems. While motorized mechanization has generated many benefits, it has also produced negative environmental impacts, including biodiversity loss, soil compaction and erosion, and degraded water quality. More advanced digital automation technologies, such as precision agriculture, can minimize or avoid these impacts. Applied technical and agronomic research should explore automation solutions that best fit local agroecological conditions, and governments should facilitate adoption of environmentally friendly automation technologies. Farmers can best choose which automated solutions fit their local agroecological conditions, but governments must create an enabling environment, including information on available technologies.

In conclusion, if care is taken to address the above challenges, agricultural automation can function as a catalyst to support the attainment of the Sustainable Development Goals (SDGs), particularly SDGs 1, 2, 3, 9 and 10. The right mix of technologies – as well as appropriate policies, interventions and investments – will depend on the level of economic development, the institutions in place, local agronomic characteristics, and policymakers' objectives. It is important that policymakers recognize the context specificity of adoption and assess the particular problems facing an area (e.g. connectivity, inequality, poverty, food insecurity, malnutrition) before combining policy instruments for action. It is up to agricultural producers to choose which technologies to adopt. It is up to governments to provide an enabling environment where innovation can thrive, as well as the necessary incentives to make the adoption process as inclusive as possible. ■

CHINA
Farmer monitoring chili crops with a tablet.
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CHAPTER 1
AGRICULTURAL AUTOMATION: WHAT IT IS AND WHY IT IS IMPORTANT

KEY MESSAGES

➔ Automation presents many opportunities for agricultural producers and agrifood systems generally, but uneven access and adoption across and within countries prevent realization of its full potential.

➔ In particular, agricultural automation can raise productivity, build resilience, improve product quality and resource-use efficiency, reduce human drudgery and labour shortages, enhance environmental sustainability, and facilitate climate change adaptation and mitigation.

➔ Automation in agriculture can contribute to achieving the Sustainable Development Goals (SDGs) by 2030, not least SDG 1 (No Poverty) and SDG 2 (Zero Hunger) and those relating to environmental sustainability and climate change, and drive broader changes in agrifood systems by creating new entrepreneurial opportunities.

➔ Automation can also create inequalities if it remains out of reach for some, especially small-scale and female agricultural producers. If it is not well managed, it can also have negative environmental consequences by contributing to, for example, monoculture.

➔ To unleash the full potential of agricultural automation, technologies must be available, inclusive, accessible to all, and tailored to local conditions (i.e. they need to be scale-neutral), and they must improve environmental sustainability.

➔ A key challenge is ensuring that technologies are adapted to local contexts and local innovation processes that are promoted, as well as building the capacity of producers to adopt and use such new technologies.

Technological change, driven and facilitated by processes of innovation, has been a key driver of socioeconomic transformation throughout the ages, bringing productivity and income gains, as well as improvements in human well-being. This applies to agrifood systems as it does to other sectors of the economy. Today, to nourish a constantly growing world population, we need to increase nutritious food production while addressing limited agricultural land availability, unsustainable natural resource use, increasing shocks and stresses, and the consequences of accelerating climate change. Hence, agrifood systems must meet the challenge of increasing productivity in a sustainable manner. There is an ever more urgent need to put in place new technological solutions that can make agricultural production more productive and sustainable across all its sectors – crops and livestock, fisheries and aquaculture, and forestry – and boost productivity levels in agrifood systems beyond primary production.

As technological change continues to transform our economies, recent advances in digital technologies, such as faster computers and mobile phones, sensors, machine learning, and artificial intelligence (AI), have led to ground-breaking equipment, transforming the use of machinery in agricultural tasks. As with other technologies – and innovations in general – these new technologies may complement or replace old ones. Sometimes older technologies and practices may be revived or repurposed for new uses. They have the potential to decouple not only much of the physical work from agricultural production, but also the mental work required to collect and analyse information and data and make decisions. They can therefore help implement precision agriculture[1] by improving the timeliness of operations and allowing a more accurate and efficient application of inputs.

Not for the first time in human history, there are fears about the negative consequences of technological progress for labourers. In practice, the accepted wisdom that automation leads to loss of jobs and increased unemployment is not borne out by historical realities. This report argues that, on the contrary, automation, including digital technologies, can make agricultural production more resilient to shocks and stresses, such as drought and accelerating climate change. Agricultural automation can raise productivity, improve product quality, increase resource-use efficiency, alleviate labour shortages and promote decent employment by reducing human drudgery – in addition to enhancing environmental sustainability. While it must be recognized that introducing automation technologies, particularly if unsuited to a specific local context, can lead to socioeconomic challenges for some groups, including negative impacts on the labour market, such challenges can be addressed through appropriate policies and legislation, and these are discussed in the report. Equally challenging are barriers that can prevent the application of automation, in particular among poor small-scale producers, thus creating access inequalities.

Agricultural automation is of major relevance to several Sustainable Development Goals (SDGs), not least SDG 1 (No Poverty) and SDG 2 (Zero Hunger). To the extent that agriculture around the world is receptive to automation, it can also drive progress towards SDG 9 (Industry, Innovation and Infrastructure), which calls for supporting and upgrading technological capabilities, research and innovation, especially in low-income countries. Likewise, if barriers to adoption are overcome, automation can play a role in closing the technological divide and promoting progress towards SDG 5 (Gender Equality), SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities). Through its potential to provide safer working conditions and safer, higher quality food, it can contribute to progress towards SDG 3 (Good Health and Well-being). Finally, the successful adoption of automation solutions that enhance environmental sustainability can contribute to progress towards SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life below Water) and SDG 15 (Life on Land).

This report investigates how automation in agriculture, as well as in the early stages of the food supply chain, can contribute to achieving the SDGs and ensure positive impacts. It reviews the state of agricultural automation adoption, including trends in implementation, the drivers of these trends, and their potential socioeconomic impacts. It discusses a range of policy and legislative options and interventions that could maximize the benefits and minimize the risks of automation technologies. Chapter 1 defines agricultural automation, explains its relevance for sustainable development, and outlines the opportunities, challenges and trade-offs that new automation technologies can create or shape. A fundamental premise for the analysis in this report is that advances in agricultural automation can help humanity overcome numerous challenges associated with the need to increase nutritious food production sustainably, but that these are likely to create new challenges that need to be managed if we are to make the most of the potential that automation offers. ■

HOW DID WE GET HERE?

The process of technological change in agricultural production is not new. History shows how humankind has constantly striven to reduce the toil of farming by developing ingenious tools and harnessing the power of fire, wind, water and animals. By 4000 BCE, Mesopotamian farmers were using ox-drawn ploughs,[2] and water-powered mills emerged in China around 1000 BCE.[3] Technological change has accelerated during the past two centuries, triggered by the discovery of steam power (with the emergence of steam threshers and ploughs by the mid-nineteenth century), and later reinforced by the rise of fossil-energy-powered tractors, harvesters and processing machines, as well as new food-preserving technologies, among others.[4, 5] Such changes have allowed societies across the world to gradually reduce the drudgery of agricultural production and free agricultural producers from the heavy physical toil of farming. As a consequence, there is now less need for labour in primary agricultural production; workers are released for employment in other sectors, such as industry and services, children are free to go to school, and women can pursue non-agricultural employment opportunities or household activities. This has been accompanied by tremendous advances in other agricultural operations or inputs, such as seeds, fertilizers and irrigation – advances that led to the green revolution and allowed food production to expand, even with reduced labour input and limited expansion of farmland.[6]

This process of increased agricultural productivity and reallocation of labour away from farming is often referred to as agricultural transformation. As economies develop, labour-saving technologies push agricultural workers off farms while profitable activities in the non-farm sector simultaneously pull them towards the industry and services sectors.[7, 8, 9] The share of the population working in agriculture thus declines as agricultural transformation advances. Prior to the Industrial Revolution, most people throughout the world lived in rural areas and depended on primary agricultural production for their livelihood. This is no longer the case for countries that have undergone deep agricultural transformation. In the United States of America, for example, only 1.4 percent of the workforce were employed in farming in 2020.[10] Other high-income countries also have very small shares of their population directly employed on farms.

This agricultural transformation process does not occur in isolation but involves transformation of the whole economy. Indeed, the provision of sufficient, safe and nutritious food for expanding and increasingly urbanized populations, requires investments not only in agricultural production, but also in transport, storage and food processing, as well as other physical and market infrastructures. Access to roads and transport is necessary to enable agricultural producers to source adequate agricultural inputs, including physical and human capital, and have access to lucrative markets for their produce.

The process of automation in agriculture today is occurring within the context of evolving agrifood systems. Indeed, automation in agriculture has implications for agrifood systems beyond primary agriculture and is itself affected by developments beyond primary production. Automation in primary production can be a driver of transformation in agrifood systems, not least by creating new entrepreneurial opportunities both upstream and downstream. Similarly, automation in upstream and downstream sectors has implications for automation in primary production. The effects will depend on the dynamics of agrifood systems, their components, and the bidirectional linkages between them.

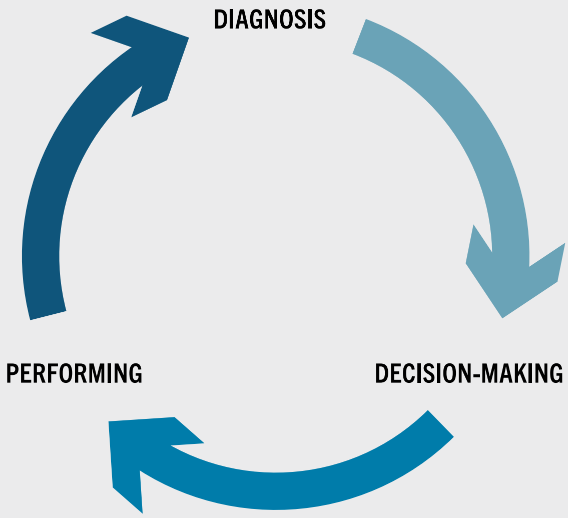
Technology uptake is also a gradual process,[11] requiring practice, testing and adaptation in various contextual realities, and its impacts take time to manifest themselves. For example, while the rise of mechanized tractors undoubtedly brought many benefits, it also had negative environmental impacts – in terms of deforestation, loss of biodiversity and excessive use of fossil fuels – which took decades to become apparent.[12, 13] A similar reasoning may be applied to the technologies adopted in the green revolution; they undoubtedly brought substantial yield improvements, but the long-term environmental costs have been very high in some places.[13] ■

WHAT IS AGRICULTURAL AUTOMATION?

Today's agricultural automation lies at the end of a long evolution of mechanization throughout the history of agriculture. The Food and Agriculture Organization of the United Nations (FAO) defines mechanization as the use of all means of machinery and equipment, from simple and basic hand tools to more sophisticated and motorized machinery, in agricultural operations.[14] With mechanization, therefore, only the performing part of agricultural work is automated, and the degree of automation increases as we move from basic hand tools towards motorized machinery.

Two phases always precede the performing of any agricultural operation: diagnosis and decision-making. Figure 1 (p. 4) represents the three

FIGURE 1 THREE-PHASE CYCLE OF AN AUTOMATION SYSTEM



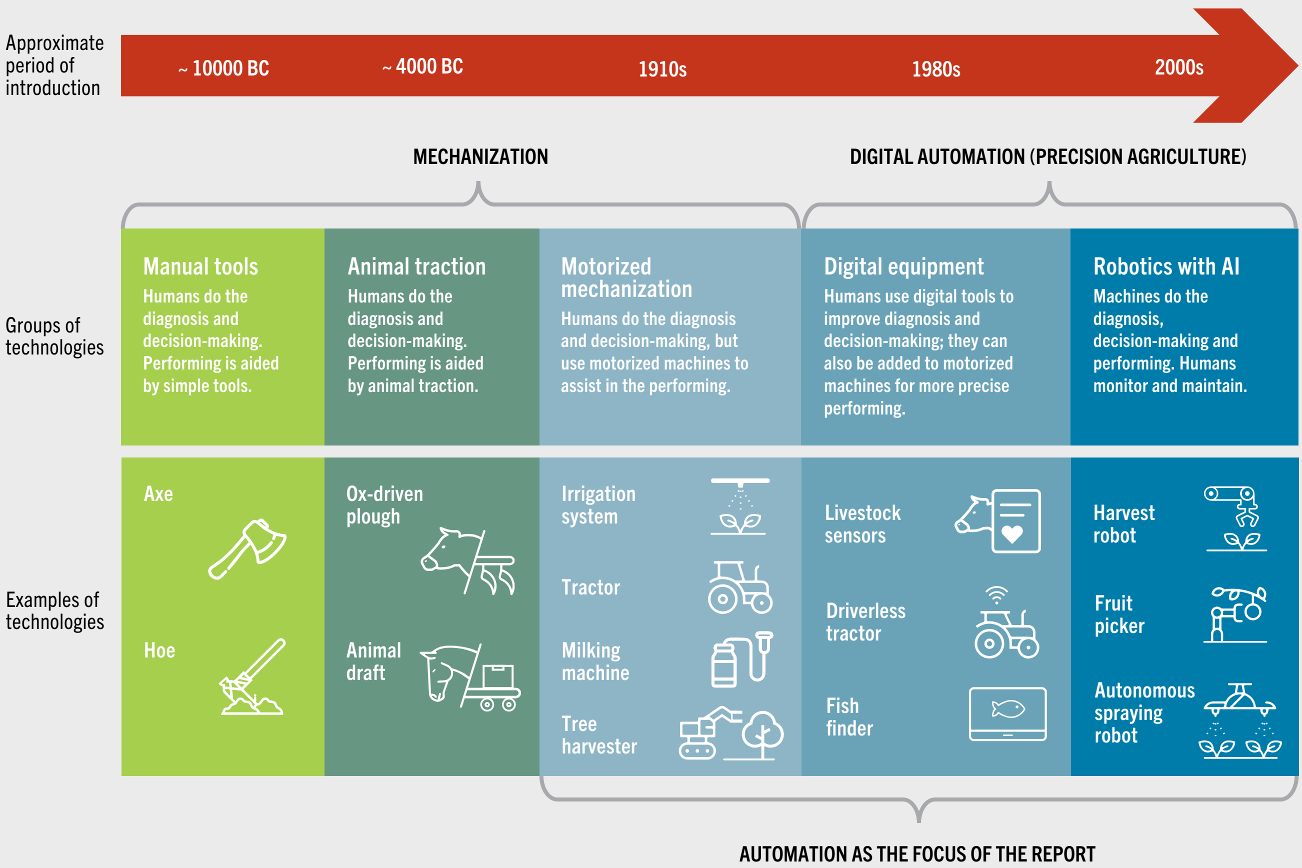
SOURCE: FAO elaboration for this report.

phases as a cyclical process with continuous feedback between them. The implementation of any agricultural operation – from harvesting, to disease control, to irrigation – generally starts by diagnosing the issue at hand to determine what, if any, action is needed. By way of illustration, before irrigating, producers need to know whether plants require water. Similarly, livestock producers need to know the health status of animals before prescribing antibiotics. A diagnosis can be made using producers' experience, but it can also be automated through sensors monitored by the producers. Once a diagnosis is made, producers decide what needs to be done (e.g. the amount of irrigation or antibiotics needed) and when. Decisions can then be made by agricultural producers based on their experience and knowledge, or they can be automated by controllers sending signals based on information received from sensors in the diagnosis phase. In the third and final phase (performing), farmers can either conduct agricultural operations directly, using hand tools or animals, or operate various machines.

The most advanced automation technologies allow the three phases to be entirely automated. Fruit-harvesting robots are a case in point. These robots carry out all three phases sequentially and automatically, while agricultural producers simply monitor the sensors and maintain the equipment.

Any technology that automates at least one of the three phases may be classified as an automation technology. Motorized mechanization using engine power[15] focuses essentially on the last of the three phases: performing. It automates agricultural operations such as ploughing, seeding, fertilizing, milking, feeding, harvesting and irrigating, among many others. For the purpose of this report, any technology that assists agricultural producers in one or more of the three phases in Figure 1 is considered an automation technology. This includes situations where, for example, agricultural producers use sensors to monitor plants and animals, thus automating the diagnosis phase, but make decisions based on their own experience without

FIGURE 2 EVOLUTION OF AGRICULTURAL AUTOMATION



SOURCE: FAO elaboration for this report.

the assistance of automated equipment. In some cases, the performing phase can also involve sensing (e.g. the creation of yield maps during harvesting), which then feeds into the diagnosis phase, hence the cyclical representation of Figure 1.

With the rise of digital technologies and automated equipment such as sensors and robots that rely on machine learning and AI, the automation of diagnosis and decision-making becomes possible. Motorized machines are increasingly complemented, or even superseded, by new digital equipment that automates diagnosis and decision-making. For example, a conventional tractor can be converted into an automated vehicle capable of sowing a field autonomously.[15] Therefore, while mechanization eases and reduces hard and repetitive work and relieves labour shortages, digital automation technologies further improve productivity by allowing more precise implementation of agricultural operations and more efficient use of resources and inputs. As a consequence, digital automation can lead to gains in environmental sustainability and greater resilience to climate shocks and stresses. However, the possible effects on labour require careful consideration, as explained later in the report.

Figure 2 represents this technological evolution, illustrating the progression of agricultural technologies – with examples of each – from those that assist solely the physical performing of operations to those that assist diagnosis and decision-making. The technological evolution may be summarized through the following technology categories:

- **Manual tools**, where humans make the diagnosis and the decisions, while the performing is assisted by simple tools, such as axes and hoes.
- **Animal traction**, where humans still make the diagnosis and the decisions, but physical agricultural operations are performed, or eased, by animals operating agricultural machinery such as ploughs.
- **Motorized mechanization**, where humans continue to make the diagnosis and the decisions, but motorized machinery and equipment perform the operations. This category marks a shift in the source of energy used on the farm from internal (e.g. human muscle and animals) to external (e.g. fossil fuels and electricity). This shift, however, calls for specific infrastructures to ensure the continuous availability of these energy sources.
- **Digital equipment**, where a wide range of digital tools assist humans to improve the diagnosis and/or decision-making by automating mental work or by increasing the precision of motorized machinery.
- **Robotics with AI**, where humans rely on agricultural robots that use AI for all functions of diagnosis, decision-making and performing. These can be static (e.g. milking robots) or mobile (e.g. fruit-harvesting robots). Humans monitor the sensors and maintain the robots. This category includes the most advanced automation technologies, some of which have not yet been scaled up or are still under development.

Unfortunately, this variety of tools and technologies has contributed to inconsistent definitions of agricultural automation in the literature, hampering efforts to collect automation data.[11] For example, some define agricultural automation as autonomous navigation by robots without human intervention, providing precise information to help develop agricultural operations.[16] Others define it as accomplishment of production tasks through mobile, autonomous, decision-making, mechatronic devices.[17] However, these definitions are very restrictive and do not capture all the aspects and forms of automation – static equipment, such as robotic milking machines, is a case in point. Moreover, the definitions exclude not only most motorized machinery that automates the performing of agricultural operations, but also digital tools (e.g. sensors) that automate only diagnosis.

Figure 2 (p. 5) is a simplification of the historical reality of the evolution of automation technologies; there can be overlaps and grey areas between the categories. Nevertheless, it helps to outline the focus of this report and define agricultural automation. The concept of agricultural automation is applied to the three blue-shaded boxes, which constitute the focus of the report. On this basis, the report proposes a definition of agricultural automation as:

> the use of machinery and equipment in agricultural operations to improve their diagnosis, decision-making or performing, reducing the drudgery of agricultural work and/or improving the timeliness, and potentially the precision, of agricultural operations.

By this definition, agricultural automation includes precision agriculture, which is a management strategy that gathers, processes and analyses data to improve management decisions (see Glossary).

Starting from the first blue-shaded box in Figure 2, motorized mechanization includes machines operated by humans to perform tasks such as ploughing, irrigating and milking. However, humans make the diagnosis based on their own observation or by measuring simple parameters; they then make decisions based on (internal or external) experience, knowledge and available resources. The last two categories of Figure 2 cover digital automation. They include a wide range of tools, equipment and software that are, or can be, multifunctional and interdisciplinary, allowing the management of resources throughout the system to be highly optimized, individualized, intelligent and anticipatory.[18] As digital automation technologies (robotics with AI) develop, all three phases – diagnosis, decision-making and performing – can be automated, with the human role largely confined to monitoring and maintenance of automation equipment. This is the case with the fruit picker, for example: when the picking arm receives a message from the controller, based on information from the sensors, it proceeds to pick the fruit.

Automation can involve any one or a combination of the three connected phases. For example, diagnosis may be carried out by sensors while decision-making and performing depend totally on humans. Alternatively, both diagnosis and decision-making may be executed by digital technologies while performing is done by humans. An example of a fully automated system where all three phases are automated is the autonomous spraying robot: the system first obtains data on soil fertility, then decides on the operation area and application rate, and finally applies fertilizer based on that variable rate. ■

WHY DO WE NEED TO LEVERAGE AGRICULTURAL AUTOMATION? UNDERSTANDING KEY DRIVERS

Agricultural automation is part of a broader agrifood systems transformation. It helps agricultural producers maintain or expand production as workers leave agriculture and move to higher-paying sectors of the economy. Besides relieving labour needs in agriculture, automation can further spur the transformation of agrifood systems by generating employment opportunities in other stages of agrifood systems. Historically, as countries develop, more attractive jobs draw workers away from agriculture, and labour-saving innovations increase agricultural productivity by reducing labour requirements per unit of output.[7, 8, 9] As a result of this combination of labour supply and labour demand trends, the share of population employed in agriculture has declined over time, including in low- and lower-middle-income countries (see Figure 3 on p. 8).

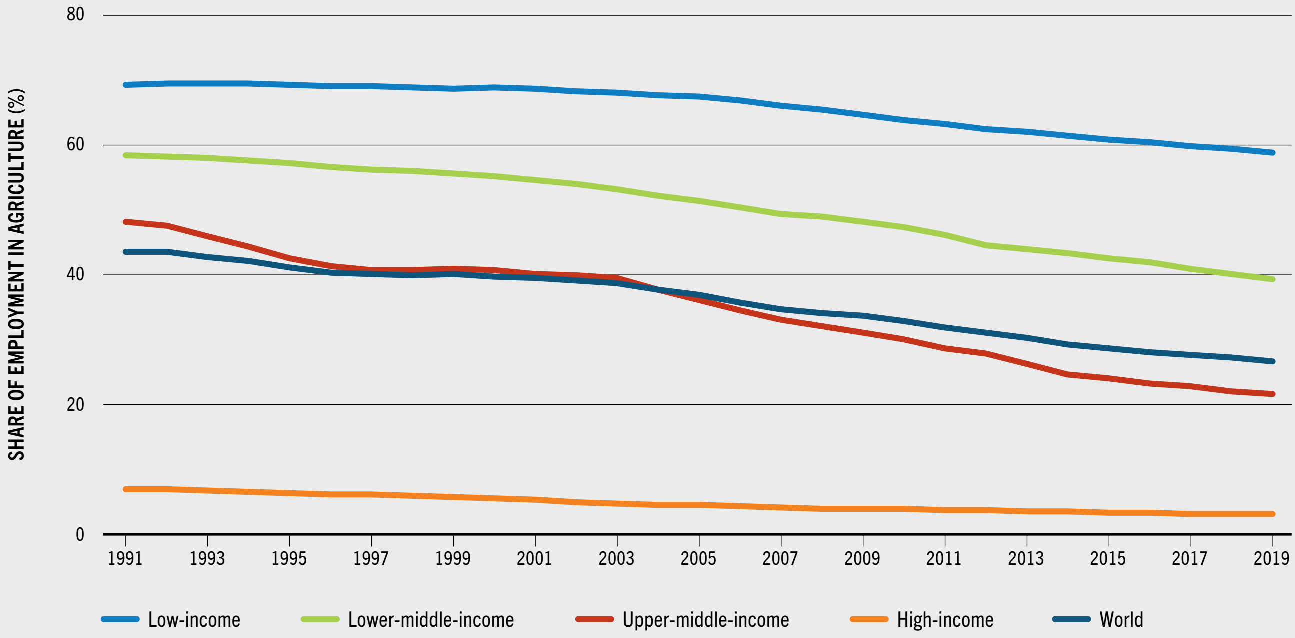
This transformation is accompanied by increased innovations, technological changes and investments, all of which are critical components of socioeconomic development, and which affect agrifood systems beyond the primary stage. For example, to provide sufficient, safe and nutritious food to an increasingly urban and affluent population requires investments, not only in agriculture but also in transport, storage, food processing and other infrastructures. Backward and forward linkages therefore connect the agriculture sector to the non-farm sector.[20] As part of this transformation of agrifood systems, agricultural automation can bring multiple benefits, discussed below.

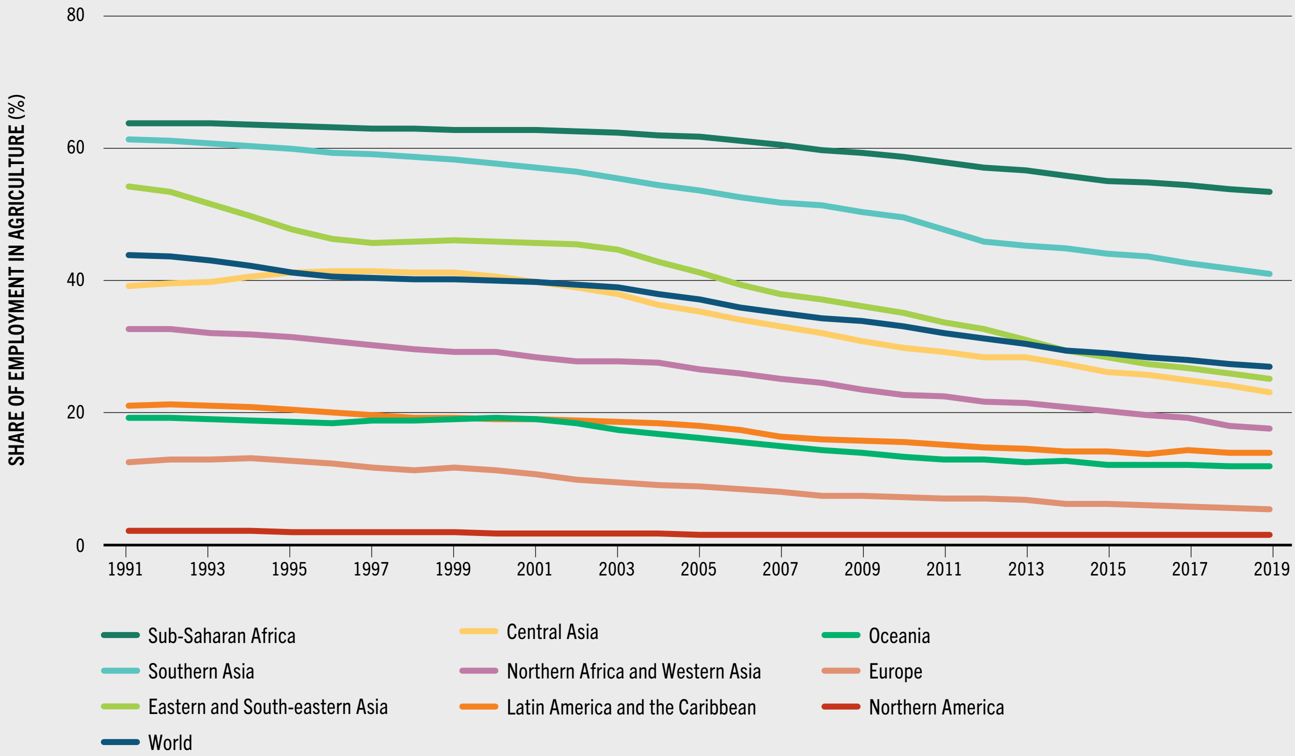
Opportunities for agricultural producers

Agricultural automation presents many opportunities for primary production and, more broadly, for agrifood systems. It can help raise land and labour productivity and profitability through, for example, more timely and careful crop and livestock management.[21, 22, 23] This, in turn, contributes to higher incomes,[24] reduced risks, improved resilience and enhanced environmental sustainability. With the progress in digital technologies, agricultural automation has the potential to become scale-neutral, in other words, include automation solutions for all scales (large-, medium- and small-scale agricultural producers), and thus be accessible also to small-scale producers. This can happen either through the development of small machines and equipment adapted to the conditions of small farms and production units, or through asset-sharing arrangements that rely on digital platforms (see Chapter 3).

Agricultural automation can also advance decent employment by providing better and safer working conditions and an adequate living income, and by reducing the workload of farming, much of which is shouldered by unpaid family members, including women and children.[25, 26] This can free up time for adults to pursue additional value-adding activities or off-farm work and carry out care activities

FIGURE 3 **SHARE OF EMPLOYMENT IN AGRICULTURE OUT OF TOTAL EMPLOYMENT BY INCOME GROUP (TOP) AND REGION (BOTTOM), 1991–2019**





SOURCE: FAO, 2022.[19]

or food preparation,[27] and for children to play and go to school.[26, 28, 29] Evidence suggests the lifestyle benefits of machine milking – freeing up time for producers to do other jobs, spend time with their family or enjoy a more flexible working day – are those most valued by adopters.[30, 31] Positive impacts related to the alleviation of drudgery can particularly empower rural women who gain time to undertake new productive initiatives and/or to expand existing activities in agrifood systems. It also helps attract youth to the sector.

Another important dimension of agricultural automation is its potential for generating rural entrepreneurship opportunities. For example, one of the main constraints to organic production is the cost and availability of labour. Although there is strong demand in many countries for organic products, consumers are reluctant to pay substantially more for them. Robots for weeding, selective harvesting, and other field operations could significantly reduce the cost of organic production, thereby creating opportunities for more producers.

In the past, for the successful automated performing of certain operations using motorized machinery, it was necessary to adapt agricultural production. For example, as tomato harvesters were adopted in the United States of America, a tomato variety was developed that ripened uniformly on the vine and had a tough skin which would not easily break when handled roughly by a machine.[32] The new advances in digital automation technologies may offer solutions for much more refined agricultural operations. For example, engineers are currently seeking robotics solutions that would permit mechanical harvesting of strawberries, one of the most delicate and labour-intensive crops.

Beyond the farm, processing, preserving, storage and transport technologies can help reduce food loss and waste, enhance food safety and enable value addition,[33] all of which are necessary for efficient agrifood systems capable of delivering healthy diets for all in a sustainable manner. Automation can also provide safer working conditions for labourers, for example, by reducing occupational hazards related to pesticide use.

Plugging the labour gap

In terms of employment, agricultural automation has been hailed as a solution to urgent rural labour shortages, occurring particularly in high-income countries (see Figure 3). Statistics show that 2.5 million workers left agriculture in the European Union in the last ten years, with a predicted further 2 percent yearly decline up to 2030.[34] The main driver of this is the unattractiveness of agriculture as a career (harsh working conditions, low pay, lack of prospects, etc.). The COVID-19 lockdowns and social distancing exacerbated labour shortages, and political events leading to immigration regulations and policies have restricted access to seasonal, migrant labour.

Many agricultural enterprises, especially fruit and vegetable production, rely on human labour to perform tasks such as picking, packing and disease treatment. Other sectors, such as livestock production, can also require a large workforce. Automation solutions could plug serious shortfalls in labour and enable agricultural producers to adapt to sudden shocks that disrupt labour markets, leading to improved resilience. At the same time, these solutions can contribute to decent employment by creating a large number of skilled jobs that provide a living income and reasonable working conditions, attracting skilled younger workers.[35] Training and capacity building are needed to ensure the transition is smooth and inclusive (see Chapters 4 and 5).

Given the declining availability of rural labour worldwide as economies continue to transform (see Figure 3), the maintenance and improvement of agricultural productivity will probably require automation – at least to perform labour-intensive tasks. In many parts of the world, the decrease in rural labour supply has led to an increase in agricultural wages, promoting further adoption of labour-saving technologies.[3, 36]

Changes in consumption patterns

Globalization has contributed to changing dietary patterns, food preferences and consumer demand, and has also led to more stringent food safety standards.[37] Consumers, especially in high-income countries, increasingly care about what they eat and how their food is produced, processed and transported.[38] There is also more concern about various health hazards resulting from plant and animal diseases or from excessive use of pesticides and other chemicals. Advanced digital automation technologies can facilitate the timely identification of outbreak points and allow early and precise treatment, thus safeguarding consumer safety and limiting financial losses for producers. This is particularly important in livestock production – since about 60 percent of emerging infectious diseases originate from animals – where automated systems can play an effective role in the prevention and control of zoonosis.[39] Digital automation technologies can also lead to reduced pesticide and chemical use on crops, as pests and diseases are targeted with more precision, ensuring effective plant protection with minimum health hazards. Owing to their outstanding precision and ability to follow food safety procedures in a standardized manner, these technologies can prevent and control pests and diseases better than humans can, resulting in major improvements in food safety. Not only do they kill pathogens and block transmission routes more effectively, they also minimize chemical use.[40]

Rising consumer concerns about food quality, taste and freshness further incentivize investment in digital automation technologies (e.g. sensors and mapping systems) that help monitor temperature and humidity conditions. Fast-changing consumer preferences and needs are therefore a key driver to implement automation in agriculture.[41]

Environmental sustainability and animal welfare

Agricultural automation is critical for the future of agrifood systems, given the rising environmental and ethical concerns surrounding food production and consumption. Digital automation technologies, in particular, can bring many benefits. Swarms of small, autonomous robots (see Glossary) could reduce soil compaction and river pollution, enabling conservation agriculture, which, in turn, enhances land and soil conservation, as well as biodiversity for food and agriculture, and improves ecosystem services within farming systems.[42] Digital automation technologies can also optimize the use of natural resources such as water, for example, through automated irrigation. Autonomous robots in the soft fruit sector could reduce fungicide and energy use, in addition to lowering carbon emissions if powered by solar energy. However, the energy-intensive process of building robots and other technologies used in precision agriculture must also be taken into account when measuring carbon footprints.[43]

Agricultural automation can help address some of the challenges associated with climate change and thus facilitate adaptation efforts. This is the case not least for digital automation technologies, which through their application (e.g. in precision agriculture) can improve resource-use efficiency in conditions which are increasingly constrained for agricultural producers. Moreover, when applied to sensing and early warning, they can help address the uncertainty and unpredictability of weather conditions associated with accelerating climate change.

As animal herds increase in size with rising numbers resulting in reduced animal welfare, livestock management is becoming more challenging.[44] In this context, new automation technologies, such as precision livestock farming, can support farmers by monitoring and controlling animal productivity, environmental impacts, and health and welfare parameters in a continuous, real-time and automated manner.[45] A variety of systems using technologies such as sensors, cameras or microphones can detect anomalies and alert farmers directly, allowing them to intervene at an early stage. While the potential of these technologies is promising, their use raises ethical concerns, due to their potential impact on the human–animal relationship – critical as it can influence both animal welfare and productivity – in particular, the objectification of animals, and the notion of care and farmers' identity as animal keepers.[46, 47] Both the benefits and the ethical challenges must be taken into consideration when evaluating different technologies.

The extent to which digital automation can contribute to more efficient, productive, inclusive, resilient and sustainable agriculture greatly depends on the progress in overcoming barriers to adoption. This requires an enabling environment and suitable solutions geared to local needs and conditions. ■

CHALLENGES POSED BY THE PROGRESS OF AGRICULTURAL AUTOMATION

As with any technology development, agricultural automation can have negative social and environmental consequences. Therefore, while the above-mentioned benefits are promised, they may not happen automatically and they depend on good management. Agricultural and economy-wide structural factors can hinder the inclusive, sustainable adoption of agricultural automation. Land fragmentation, for example, is a serious constraint in many regions and can make agricultural automation economically unviable. Lack of enabling infrastructures, such as roads, connectivity and electricity, can also shape adoption and exclude producers operating in more disadvantaged and remote areas. Under certain conditions, agricultural automation can displace rural labour and lead to negative environmental consequences such as land degradation and biodiversity loss. These challenges are introduced in the following sections and are discussed in more detail in Chapters 2 and 4.

Unequal capacity

The promised benefits of agricultural automation may not be evenly distributed among producers and other stakeholders, exacerbating social inequalities and creating new ones by favouring already powerful actors in food production.[48, 49] This may be the case in particular if technology companies – already large and with substantial market power – retain and own data, which they may use in a manner not in conformity with data protection policies, leading to the creation of data monopolies.[50] Inequalities can also be exacerbated if larger, richer and more educated producers have greater capacities (e.g. finances, rural infrastructure, skills) to invest in new technologies or to retrain and learn new skills. Indeed, many farmers may lack the basic capacity to operate digital automation technologies or understand how they work. A good agricultural practitioner is not necessarily an expert in digital technologies, and the same applies to extension officers and service providers. Capacity building and farming adaptation are essential for the uptake of automated equipment and its correct use; only with capacity can farmers exploit the full potential of automation.[15]

In this regard, women are often more marginalized than men from education opportunities[18] and have less access to finance.[51] Men tend to take over the buying and selling of crops, and to own and operate the new equipment, reducing women's control of income produced and relegating them to the more labour-intensive tasks of weeding and transplanting.[52] Similarly, rural youth, especially women, face significant obstacles to obtaining quality education and training, as well as access to land, credit or markets.[53]

Labour disruption

Emerging evidence from other industries suggests that automation may increase demand for higher-paying jobs requiring secondary education, where humans have a comparative advantage over machines (e.g. data management and analysis), but reduce demand for jobs that involve routine tasks (e.g. planting and harvesting).[54, 55] As countries develop, the numbers for total employment in agriculture decline; nevertheless, there are still approximately 300–500 million waged workers who depend on farm jobs.[56] In many countries, the percentage of the workforce in agriculture remains high – for example, in Burundi (86 percent), Somalia (80 percent), Malawi (76 percent), Chad (75 percent), the Niger (73 percent) and Uganda (72 percent) – often accompanied by high rates of illiteracy, poverty and gender inequality.

In such countries, a reduction in the direct labour requirements per unit of output may create inequalities or deepen existing ones. For this reason, in some contexts, agricultural automation may be politically unattractive and unfeasible. Ultimately, the impact on labour and wages will be determined by a series of factors, including the capacity to generate new and more attractive jobs or alternative decent employment options outside the agriculture sector. It will also depend on whether scale effects – where farmers expand the scale of their production and increase their income – outweigh substitution effects when labour is pushed out of the sector.[57] Yet, with the right policies and legislative and regulatory environment, agricultural automation can create economic opportunities, encourage decent employment that provides a living income and reasonable working conditions, and draw youth back into the agriculture sector.

Environmental concerns

There are concerns that, if not well managed, some types of agricultural automation, especially those relying on heavy, large machinery, may jeopardize environmental sustainability and resilience by contributing to deforestation, farmland monoculture, biodiversity loss, land degradation, soil compaction and erosion, salinity buildup, and drainage system malfunctioning.[58] While these concerns must be taken seriously, many can be avoided or minimized with appropriate policies and legislation. Moreover, certain new advances in automation machinery and equipment – especially small equipment that relies on AI – can actually reverse some of the negative environmental impacts of old automation machinery (see Chapter 3).

The potential opportunities, challenges and consequences of agricultural automation depend on the specific technology used, its design, and how well it suits local conditions and is adapted to local realities. In addition, the level of socioeconomic development, as well as institutional and political constraints, determine the mix of suitable technologies likely to be adopted. As a consequence, the effects – positive and negative – of agricultural automation are highly context-specific. It is important to assess whether the environmental, social and political conditions are right in each country or region before proposing specific automation solutions. Not all automation technologies are suited to all contexts, and adapted versions may have to be considered. ■

TURNING CHALLENGES INTO OPPORTUNITIES

To realize their full potential, agricultural automation technologies must be accessible to all, not least to small-scale agricultural producers in low-income countries where hand tools and animal power are still in common use, hampering agricultural productivity and negatively affecting livelihoods. In other words, the automation process must become scale-neutral. In favourable circumstances, it may even be possible to leapfrog the technological evolution, passing directly from low-tech agriculture based on manual labour or draught animal power to agricultural automation. This can be achieved through technologies that are scale-neutral by design, through innovative institutional arrangements (e.g. cooperatives and associations), or through market mechanisms that enable small-scale agricultural producers to overcome scale constraints. For example, expensive and complex agriculture equipment can be made available to local farmers through hire service providers, often producers themselves who have invested in draught animals and/or tractors and similar equipment.

Digital tools also hold great promise for hire services. They can create new business models for the adoption of automation technologies by small-scale agricultural producers. One such scheme is Uber for tractors; similar to the Uber taxi application, it allows producers to access tractor hire services. Robotics and AI are based on digital technologies; therefore, countries need to push for wider access to digital technologies, promoting the essential infrastructures, appropriate legal frameworks, and necessary knowledge and skills.

To achieve this, both agricultural producers and governments must first recognize the economic, social and environmental benefits of the dissemination and adoption of digital technologies. Thereafter, it is vital to ensure availability, inclusivity, accessibility and adaptability to local conditions, reaching out to the wide range of potential beneficiaries in order to avoid widening the technological divides that disadvantage vulnerable groups (e.g. women) and remote territories. In 2018, FAO and the African Union Commission launched the framework for Sustainable Agricultural Mechanization in Africa, which provides a menu of priority elements for countries to consider when developing their strategies for sustainable agricultural mechanization.[59] According to this framework, mechanization must be built along the entire agriculture value chain, private sector-driven, environmentally compatible and climate smart, in addition to being economically viable and affordable – especially for small-scale farmers, who constitute the bulk of African farmers. It is also vital that it targets women and youth, specifically to make agriculture a more attractive choice for decent employment and entrepreneurship.

Therefore, when encouraging the adoption of automation, it is important to focus on technologies tailored to local conditions and the specific needs of producers; a technology simply lifted from one context may not solve tangible problems in a new context. In this respect, studies show that farmers themselves can lead innovation. For instance, in Myanmar, the embracing of 3D printing techniques is improving farming efficiency and giving power to workers in poorer, rural areas by allowing them to be individually and creatively involved in the production of farm materials, agricultural machinery parts, and tools.[60] As agricultural producers are increasingly recognized as leaders of innovation in technology development, the relevant terminology and approaches have evolved to incorporate innovation systems thinking, with an emphasis on the involvement of stakeholders at different levels, including farmers and farm advisers. There needs to be a focus on knowledge sharing and exchange, collaboration and participation, and co-production of ideas and solutions between public and private actors.[61]

Automation solutions must consider both nation- and region-specific agricultural innovation systems; a one-size-fits-all approach to adoption across the world will not work. Caution must be applied when seeking to implement a tried and tested solution in a new environment or different situation. The context of implementation is vitally important. ■

WHAT IS THE FOCUS OF THE REPORT?

This report discusses the role of automation in primary agricultural production (crops, livestock, forestry, fisheries and aquaculture). With respect to broader agrifood systems, it also touches on automation downstream in the value chain, in proximity to primary production, such as on-farm post-harvest handling and processing; however, the focus is on the primary stage. The scope is limited to primary production and the initial stages of the value chain based on two considerations. First, automation of primary production and other on-farm activities is crucial to achieving various SDGs related to improved food security and nutrition, (rural) poverty alleviation and enhanced environmental sustainability. In the face of increasing shocks and stresses, agricultural automation can also contribute to building resilient rural livelihoods. Furthermore, it can help ensure safer working conditions for agricultural producers and workers. Second, although the report acknowledges that agricultural automation does not happen in isolation from similar transformative processes in other components of agrifood systems, an in-depth analysis of the drivers and impacts of automation beyond primary production would be too complex and challenging for a single edition of this report.

The report thus focuses on investigating how automation in agriculture and the early stages of the food supply chain can support sustainable and inclusive productivity increases in agriculture and agrifood systems at large and contribute to achieving the SDGs. In particular, the report examines how to tackle barriers to adoption and make the changes brought about by automation more inclusive and aligned with the objectives of poverty reduction, improved food security and nutrition, and environmental sustainability.

The report addresses the following questions:

- What are the drivers of and barriers to adoption of agricultural automation, especially in low- and lower-middle-income countries?
- What are the efficiency gains that help build a business case for automation?
- How can automation be adapted to the needs of diverse small-scale producers, in particular women and youth?
- What are the likely impacts of automation on labour, decent employment and inclusiveness?
- How can automation facilitate environmental sustainability and resilience to shocks and stresses?

The report draws on evidence from 27 case studies covering technologies along the spectrum of automation presented in Figure 2 (p. 5), at different production scales (small, medium, large), and for different sectors (crops, livestock, aquaculture, agroforestry). The case studies target service providers of different types including private companies, non-profit organizations and producer associations from all regions of the world. Table 1 summarizes the coverage of the case studies in terms of the types of technologies used, the scale of targeted producers, and their production system. Annex 1 includes a summary description of each case study, and a more detailed description is available in the two commissioned technical studies.[62, 63] The report also relies on four other background papers that summarize the evidence from literature and available data.[20, 64, 65, 66] For areas not covered by the commissioned papers and case studies, such as forestry or small-scale mechanization, the report relies on cases in the literature, as well as data from surveys, namely the FAO Rural Livelihoods Information System (RuLIS) database and the World Bank's Living Standards Measurement Study (LSMS).

The breakdown of the case studies reflects the main challenges, opportunities and potential consequences of the adoption of automation in different contexts. These relate to, *inter alia*: (i) the costs (purchase price or operation cost) of implementation, potentially making it unprofitable for some; (ii) the knowledge, capability and capacity of, for example, producers (who may lack digital literacy or not know how to operate some automated devices) or youth and other stakeholders; (iii) the availability of data management and information technology (IT) infrastructure required to acquire, process and share data; (iv) the accessibility to technical maintenance and servicing to repair equipment and provide maintenance support; (v) health and safety (as automation can significantly reduce drudgery but also heighten threats to cybersecurity and increase the risk of work accidents); (vi) the potential improvements and challenges to sustainability and the environment, including those related to energy use; and (vii) the role of culture and tradition in enabling or hindering uptake.

The remainder of the report is organized as follows. Chapter 2 provides an overview of agricultural automation technologies, discusses trends of adoption and their drivers and how they differ across regions. It analyses how digital automation technologies are complementing or replacing older motorized machinery, and also examines the potential of digital solutions for non-mechanized agriculture. Chapter 3 discusses the business case for agricultural automation technologies, shedding light on the challenges producers and service providers face. It discusses the role of policies, legislation and investments in shaping private incentives, and explores how to overcome barriers to adoption, tailor automation solutions to local needs and harness digital equipment to improve environmental sustainability. Chapter 4 focuses on the impacts – both positive and negative – of agricultural automation on decent employment and labour demand, with particular attention to vulnerable groups such as women and youth. Chapter 5 concludes the report with a roadmap for policies, legislation and investments that are needed to tackle barriers to adoption and ensure that agricultural automation contributes to efficient, productive, sustainable, resilient

TABLE 1 NUMBER OF CASE STUDIES BY PRODUCER SIZE, AUTOMATION LEVEL AND SECTOR

AUTOMATION CONTINUUM	SIZE OF AGRICULTURAL OPERATION		
	Small-scale	Medium-scale	Large-scale
Motorized mechanization	Crops (3) Livestock (1)	Crops (2) Livestock (1)	Crops (1) Livestock (1)
Digital equipment	Agroforestry (1) Aquaculture (2) Crops (11) Livestock (4)	Aquaculture (2) Crops (9) Livestock (3)	Crops (12) Livestock (2)
Robotics with AI	Aquaculture (1) Crops (1)	Aquaculture (1) Crops (4) Livestock (2)	Crops (5) Livestock (2)

Agroforestry | Aquaculture | Crops | Livestock

NOTES: The numbers in parentheses indicate the number of case studies that cover a given sector and production size. One case study may cover more than one dimension, which is why the sum of the numbers in parentheses surpasses 27. No cases were identified of robotics with artificial intelligence (AI) being used by small-scale farmers; however, a dedicated background paper examines the potential of the technology for small-scale farmers.[65]
SOURCE: FAO elaboration for this report.

and inclusive agrifood systems. It also examines the potential trade-offs that may arise between these different objectives and evaluates how countries should prioritize their actions based on their level of economic development, their institutions, and the objectives of their policymakers. ■

RUSSIAN FEDERATION
Robots feeding cows.
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CHAPTER 2
UNDERSTANDING THE PAST AND LOOKING TOWARDS THE FUTURE OF AGRICULTURAL AUTOMATION

KEY MESSAGES

➔ Motorized mechanization is an important form of automation in agricultural production and a fundamental component of agricultural transformation worldwide, although its adoption has been uneven and particularly limited in sub-Saharan Africa.

➔ Improving access to sustainable mechanization options for small-scale agricultural producers – including women, youth and other marginalized groups – requires technological and institutional innovations, such as mechanization service markets facilitated by digital platforms.

➔ The increasing use and variety of digital technologies has the potential to transform agriculture even in low- and middle-income countries, particularly as these technologies become more accessible.

➔ Drivers of adoption vary by technology and context. For example, adoption of milking robots is mostly driven by increased flexibility of work schedules and better quality of life; for crop automation technologies, adoption is mostly driven by higher profitability; while for forestry, safer working conditions play an important role.

➔ An array of technological solutions are already available for countries at different development stages – and more are in the pipeline. Through appropriate policies and legislation, governments can promote solutions that are suitable for the specific context and needs of different producers.

➔ In particular, small-scale agricultural producers need access to affordable and appropriate digital automation technologies to allow them to adopt these technologies and reap their benefits.

In the past, spanning several centuries, human muscle and animals were the main source of power in agriculture. Until recently, automation in agriculture was largely about replacing draught animals and human labour with motorized equipment in a multitude of agricultural operations including land preparation, weeding, harvesting, irrigation, animal milking and feeding, and on-farm handling operations, such as threshing and milling.

Recently, digital automation technologies (see Figure 2 on p. 5) have found their way into agriculture through various applications – sometimes embodied in existing agricultural machinery, sometimes separately. In both cases, these technologies have the potential to improve the diagnosis and decision-making of agricultural producers. When embodied in agricultural machines, agricultural operations can be performed with greater precision, leading to further improvements in efficiency and productivity.

Therefore, these technologies have the capacity to transform rural livelihoods and the associated agricultural landscape, including crop and livestock production, aquaculture, and forestry. In crop production, they can enhance the productivity of inputs such as seeds, fertilizers and water. In livestock and aquaculture production, they can reduce the drudgery and increase the timeliness of operations, and enhance the efficiency of inputs such as feed. In all sectors of agriculture, especially in forestry, machinery can improve working conditions and provide a safer environment for workers.

This chapter reviews the trends in automation technologies across the world, analysing how they differ across countries and regions and what has driven these differences. Due to scarcity of data, the narrative relies heavily on case studies from the literature and on two background papers prepared for this report.[1, 2] (See Annex 1 for a comprehensive description of the 27 commissioned case studies.) A historical perspective is followed, from the introduction of motorized mechanization and its dissemination among high-income countries to its subsequent transfer to some low- and middle-income countries. The chapter discusses the drivers of and barriers to adoption and how these explain the divergence in uptake across regions. It also sheds light on some of the trade-offs generated by automation, including the possible negative environmental impacts of motorized machinery. It analyses how digital technologies are transforming the use of agricultural machinery and examines the potential of digital solutions for non-mechanized agriculture. Finally, the chapter describes the state of digital automation technologies across the world and their potential to supersede traditional motorized mechanization and reverse some of its negative impacts. ■

TRENDS AND DRIVERS OF MOTORIZED MECHANIZATION AROUND THE WORLD

Adoption rates vary significantly across regions

Motorized mechanization has increased substantially worldwide. Evidence shows that wide-scale adoption started in the United States of America, where tractors rose to become the main source of farm power, replacing about 24 million draught animals between 1910 and 1960.[3] With the exception of the United Kingdom of Great Britain and Northern Ireland, where tractors were first adopted in the 1930s, the transformation of agriculture in Japan and some European countries (Denmark, France, Germany, Spain and former Yugoslavia) was delayed until about 1955, after which motorized mechanization happened very quickly, totally replacing animal traction.[4] The use of tractors as farm power became one of the most influential modernizations of the twentieth century, as it allowed, and even triggered, innovations in other agricultural machinery and equipment, such as threshers, harvesters and a wide range of associated implements.[5] This significantly eased the drudgery associated with agriculture and allowed farmers to perform tasks in a more timely manner. At a later stage, many Asian and Latin American countries witnessed considerable progress in the adoption of motorized machinery.[6] Sub-Saharan Africa, on the other hand, is the only region where progress towards motorized mechanization has stalled over the past decades,[7] despite more rapid adoption in some African countries.

When analysing trends in agricultural machinery adoption, paucity of data is a well-recognized constraint. The great diversity of machinery and associated equipment used in agricultural mechanization is an important challenge in terms of data collection (see Box 1 for how FAO is planning to overcome this challenge). The machinery can be generally classified into two groups: (i) engine-based machinery, such as tractors, water pumps and harvesters; and (ii) accessory machinery without an engine, but which combines with an engine-based machine (e.g. tractor implements such as ploughs and seeders, and irrigation schemes). Data are generally collected for engine-based machinery, although even for this category they are scarce due to the high variation in agroecological and agrarian conditions across countries. Different agroclimatic zones, soil conditions, topography and production orientation require the use of different types of machinery and equipment. For example, tractors can have different sizes and attributes (e.g. four vs two wheels). Also different livestock and aquaculture production systems may require very different types of machinery, for example, from feeding systems to milking machines in the case of livestock production.

Building on the most recent available data, and acknowledging that these are patchy and outdated, Figure 4 (p. 20) illustrates the progress

BOX 1 OVERCOMING DATA CHALLENGES IN REPORTING USE OF AGRICULTURAL MACHINERY

Until 2009, FAOSTAT reported regularly on the use and trade (volumes and values) in agricultural machinery and equipment. Statistical series, starting in 1961, were published on a relatively small number of items, including total agricultural tractors, harvesters and threshers, milking machines, soil machines and agricultural machinery.

The main source of the dataset was an annual questionnaire sent to national counterparts, covering both use and trade. Some data collected through questionnaires were sourced from national agricultural censuses – normally undertaken every ten years – and updated where possible with yearbooks and other ministerial sources and data portals in the period between censuses. Most countries reported trade data, without specifying the units of machinery in use; this raised concerns about the data and the need to improve both the quality and the detail level of the dataset.

In the early 2010s, FAO revised the questionnaire to include a request to countries for more detailed information, especially in terms of type of machinery. This was complemented with traded quantities and values obtained from the UN Comtrade database; any remaining data gaps were filled using a range of secondary sources, including country case studies.

However, the revised questionnaire did not yield the expected response rate. Only a few countries were able to provide additional details, and the reliability of the overall external information proved limited. As a consequence, administration of the revised questionnaire ceased and reported data are currently only available to 2009 (collected in 2011). The result is that very little is known about the evolution of the adoption of agricultural machinery and equipment in the last ten years. This is a major gap in our understanding of how agricultural systems are evolving.

The Statistics Division of FAO has begun the process of updating the database on machinery by combining different data sources. The methodology is still under development and, compared with the past, is more reliant on survey data, together with agricultural censuses. In the coming years, survey data are likely to be collected in the framework of a range of projects in which FAO is involved, including the Agricultural Integrated Survey Programme (AGRISurvey) and the 50x2030 Initiative to Close the Agricultural Data Gap. These projects are geared to providing technical assistance and promoting data collection in agriculture on a range of topics, touching on socioeconomic and environmental variables, following a parsimonious modular approach that covers the inter-census periods. One module among those proposed is data on machinery availability and use.

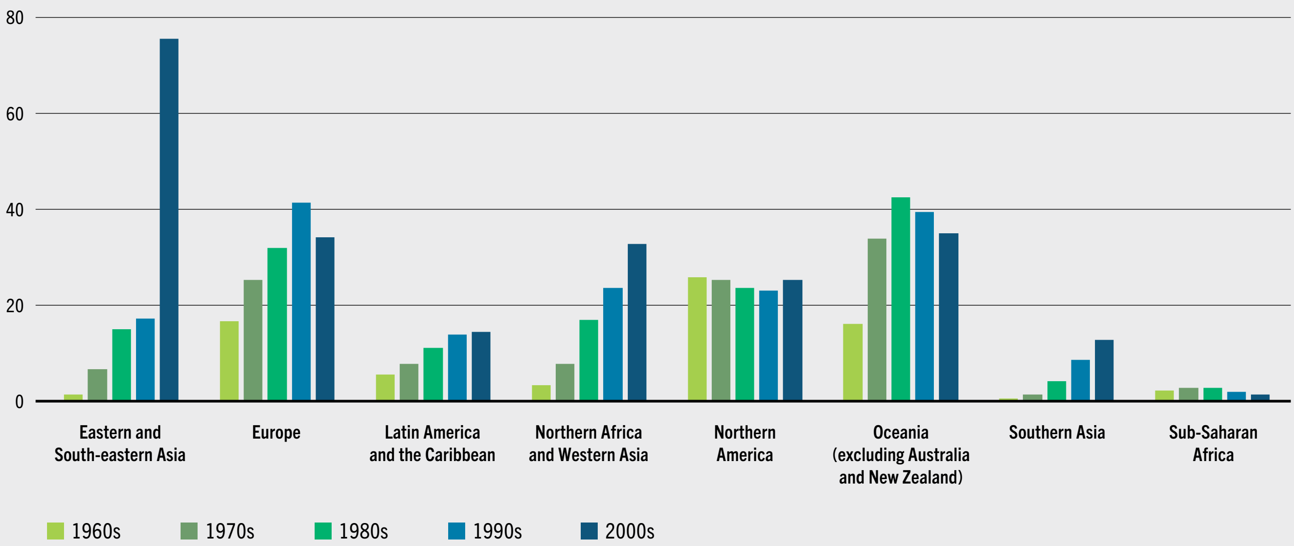
Moreover, microdata from agricultural censuses are increasingly published in a more systematic manner. For the inter-census periods, data on machinery use and stocks are available from a number of surveys, such as the household survey promoted by the World Bank – the Living Standards Measurement Study (LSMS) – and similar national surveys. A range of harmonized indicators and microdata from such surveys are gathered in the FAO Rural Livelihoods Information System (RuLIS) database, providing another source of data on machinery use.

The updated dataset will include the quantity of machinery and equipment in use and produced, and the volume of imported and exported machinery (and relative trade values).

FAO plans to evaluate all possible reliable sources by collecting, processing and developing a standardized dataset by 2023. In the longer term, the machinery data domain will be updated with data collected from the revised questionnaire for distribution to countries.

of mechanization across world regions between 1961 and 2009. It should be noted that the indicator (number of tractors in use per 1 000 ha of arable land) takes into account neither tractor size nor other types of equipment. However, the use of this indicator as a proxy for overall mechanization can be justified, in part by the unavailability of other data, and also by the fact that tractors are currently the main power source for numerous agricultural

FIGURE 4 TRACTORS IN USE PER 1 000 HECTARES OF ARABLE LAND



NOTES: Tractors refer to total wheel, crawler and track-laying type tractors used in agriculture. A fourth type of tractor (pedestrian tractor) was considered for a subset of countries as of 2000. Only countries that provided data consistently between 1961 and 2009 were considered (total of 108 countries). Central Asia was omitted due to missing data. See Annex 2 for the complete set of countries, including the 33 countries for which the fourth type (pedestrian tractor) was considered as of 2000.
SOURCE: FAO, 2021.[9]

operations such as land preparation, seeding, fertilizing and chemical spraying. In addition to transportation, tractors can also provide power for pumping water for irrigation as well as for milking machines.

The available statistics on the number of tractors per 1 000 ha of arable land (see Figure 4) highlight the unequal regional progress towards mechanization. While high-income countries (Northern America, Europe and Oceania) were already highly mechanized in the 1960s, regions dominated by low- and middle-income countries were less mechanized. Europe witnessed a decline in tractor use between the 1990s and 2000s, with the Russian Federation experiencing the greatest decrease (over 50 percent), probably due to the political and economic transition in the country during that period. However, other countries – for example, Albania, Denmark, Germany, Ireland and the Netherlands – also underwent a significant decrease, although the underlying reasons are not clear. Possibly, as tractors evolve and farms and farmland become more concentrated, the number of hectares (ha) serviced by a single machine rises.

Asia and Northern Africa witnessed rapid mechanization after the 1960s. For example, in Eastern and South-eastern Asia and Southern Asia, the number of tractors per 1 000 ha increased by 56 and 36 times, respectively – from a combined total of 2.7 million tractors in the 1960s to 20.3 million units in the 2000s. However, part of the exponential increase observed in Eastern and South-eastern Asia in the 2000s can be explained by the addition of a fourth type of tractor (pedestrian tractor) to the measurement analysis; for countries like China, Myanmar and the Philippines, this addition increased significantly the total number of tractors. In Northern Africa and Western Asia in the same period, the increase was tenfold (from 3 to 33 units per 1 000 ha). Latin America and the Caribbean also experienced significant growth, with the number of tractors per 1 000 ha of arable land almost tripling, from 5 in the 1960s to 14 in the 2000s. Sub-Saharan Africa was the only region that did not witness noticeable progress in agricultural mechanization. In this region, the number of tractors in use increased very slowly, reaching only 2.1 million in the 1980s (or 2.8 tractors per 1 000 ha of arable land), before declining to 700 000 (or 1.3 per 1 000 ha) in the 2000s. The low level of mechanization in the region is confirmed by a recent study that examined agricultural mechanization in 11 countries and found that light hand-held tools are the main type of equipment used. The study shows that only 18 percent of sampled households have access to tractor-powered machinery, while the remaining households use either simple hand-held tools (48 percent) or animal-powered equipment (33 percent).[8]

For Asia and Northern Africa, evidence indicates that the already widespread use of animal traction in the 1960s facilitated the subsequent advance towards motorized mechanization. The process was further consolidated by the agricultural intensification of the green revolution, and then by rising rural wages due to industrialization and structural transformation.[6] Similar patterns were evident in Latin America and the Caribbean, where it was largely private actors who drove agricultural mechanization. Governments, however, also played a key role, creating an enabling environment for mechanization, for example, through public programmes in Argentina, Costa Rica, Ecuador and Peru that gave access to credit at low interest rates and provided tax exemptions.[10, 11] Moreover, several countries exempted agricultural machinery from import duties (e.g. Peru).[10]

The emergence of robust agricultural machinery manufacturing sectors in some countries in Asia (China and India) and Latin America and the Caribbean (Brazil, Mexico and, to some degree, Argentina) has led to diversification with machinery exported globally.[11] This resulted in lower purchase costs of both small-scale equipment, such as two-wheel tractors (especially in Asia) and four-wheel tractors, and other machinery such as shallow tube-well pumps, threshers and grain mills.[12, 13, 14] There is also evidence that the rise of rental machinery markets has helped spread agricultural mechanization by allowing small-scale agricultural producers to access agricultural machinery at an affordable cost.[6]

In sub-Saharan Africa in the 1960s and 1970s, there were many efforts to promote mechanization by providing subsidized machinery to farmers, running state and block farms, and setting up public hire centres, often with support from donors.[15, 16] Such efforts proved costly and mostly failed due to poor infrastructure, inadequate investments in knowledge and skills development, poor maintenance capacities, lack of access to fuel and spare parts, absence of a real demand for mechanization, and governance challenges such as rent-seeking and corruption.[6, 16] In sub-Saharan Africa, and other regions where mechanization remains limited, there appears to be a lack of public sector support for creating an enabling environment through the promotion of, among others, knowledge and skills development, access to finance, and rural infrastructure.[11] Establishing commercially sustainable hire services should be a major priority in any strategy for sustainable agricultural mechanization in the region (see Box 2 on p. 22).

Data on non-tractor-powered mechanization are even more limited, but evidence indicates that even in sub-Saharan Africa some stationary activities have been mechanized for a long time, such as mechanical mills for power-intensive milling.[16] Across the world, mechanization continues to be limited for a range of operations including harvesting and weeding. Furthermore, although combine harvesters and stationary threshers are on the rise in various countries, they can only be used for harvesting cereals. With very few exceptions, fruit and vegetable production is scarcely mechanized across the globe.[6]

Regional averages mask important intraregional, and even national, differences

Although the average uptake of tractors has been higher in some regions than in others, there can also be significant variability within a region itself due to disparities in structural and agricultural transformation and technological change. »

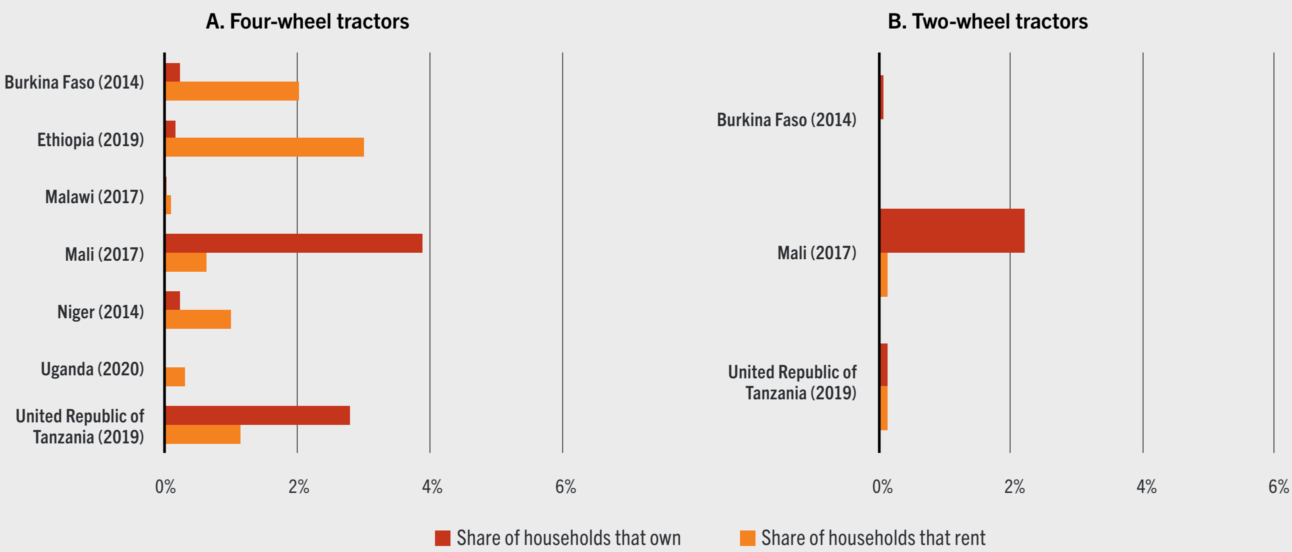
BOX 2 UNDERSTANDING MECHANIZATION IN SUB-SAHARAN AFRICA

Agriculture reliant on human and animal power continues to dominate in sub-Saharan Africa, limiting productivity. The tractor is one of the most disseminated types of agricultural machinery (with varying degrees of success) of the past seven decades.[15] However, tractors remain expensive and unaffordable for most farmers. Therefore, sustainable rental mechanisms are key for allowing farmers – in particular small-scale producers – to access mechanization. Tractor hire services operate in the region, involving both the traditional (four-wheel) tractor and – more recently and to a lesser degree – the power tiller (i.e. two-wheel tractor). In contrast to the negative image of government-operated tractor hire services, there are thousands of individuals across the region who own tractors and can provide tractor hire services to farmers. TROTRO Tractor in Ghana is a case in point (see Box 3 on p. 25).

The figure provides a snapshot of current use – through ownership or rental – of four-wheel (left) and two-wheel (right) tractors in selected sub-Saharan African countries for which data are available from the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) project.

Tractor ownership at the household level remains very low even for two-wheel tractors, which are usually less expensive. The availability of tractor rental services only slightly increases access to four-wheel tractors. The low uptake of two-wheel tractors, together with an almost non-existent rental market, highlights how suppliers are yet to establish fully operational and sustainable local franchises for the supply chains of these machines and spare parts.[15] Establishing commercially sustainable hire services (through private or cooperative ownership) is a high priority in any strategy for sustainable agricultural mechanization in the region.

FIGURE SHARE OF AGRICULTURAL HOUSEHOLDS WITH ACCESS TO TRACTORS, IN SELECTED COUNTRIES



SOURCE: World Bank, 2022.[17]

» For example, while Japan witnessed the rapid adoption of tractors in the 1960s, other countries in the region (e.g. Thailand) did not undergo a similar development until the 1990s–2000s.[9] In China, on the other hand, the spread of tractor use began in the 1970s and 1980s, while in Bangladesh, India, Myanmar and Sri Lanka, it was recently estimated that up to 90 percent of farmland (mostly used for rice production) is prepared using motorized machinery.[18, 19, 20, 21] Topographic conditions have also limited mechanization, or made its adoption uneven in some Asian countries.[6, 14] For example, in Nepal, only 23 percent of agricultural producers use tractors and power tillers in the mountainous parts of the country, while this share reaches 46 percent in the flatter Terai zone. In Latin America and the Caribbean, there is significant variability between large- and small-scale farms; large-scale farms are much more mechanized than small-scale ones due to the latter being located, at least in part, in remote and hilly areas.[10, 11, 22, 23]

Even in the least mechanized subregions of sub-Saharan Africa, adoption levels are uneven across and within countries. For example, in 2000, tractors per 1 000 ha of arable land in Botswana and South Africa numbered 8 and 5, respectively, while in countries such as Madagascar, Mali and Senegal, they did not exceed 0.4. In Ghana, it is estimated that on average one-third of farm households use tractors (mainly for tillage), but the share differs from just 2 percent in forest zones to 88 percent in the savannah.[6] In the United Republic of Tanzania, mechanization levels are highest in regions with commercial farming.[24] In Nigeria, while 7 percent of producers use tractors, another 25 percent use their own or hired animal traction for land preparation.[25] In Ethiopia, only around 1 percent of farm plots are mechanized using tractors, mainly in easy-to-mechanize wheat–barley systems, which are also dominated by large producers and have witnessed the emergence of service markets for wheat combining.

What the (limited) available data tell us about livestock and aquaculture mechanization

Data on the adoption of machinery for livestock and aquaculture production are either very scarce, very patchy or non-existent. The same applies to data for forestry. Analysis of the limited data show that livestock machinery (e.g. milking machines) is concentrated in high-income countries. On the other hand, in low- and middle-income countries, although present, such equipment is more likely to be used in large-scale production units. However, given the paucity and inconsistency of the data, it is difficult to appreciate the precise scenario in various contexts. Moreover, it is not clear what exactly constitutes a milking machine, nor how many cows are serviced by each machine. As the technology evolves, the number of cows milked by a machine goes up, and the number of machines may therefore go down. Denmark is a case in point: a major milk-producing country with a declining uptake of milking machines, there may have been a technology replacement towards more advanced methods not covered by the statistics.[9] However, anecdotal evidence from one case study (Lely) points to the consolidation of dairy farms in Northern Europe as the underlying cause of the falling numbers of milking machines resulting from technology replacement and greater economies of scale.[2] ■

THE DIGITAL REVOLUTION AND ITS POTENTIAL TO TRANSFORM THE USE OF MOTORIZED MECHANIZATION AND AGRICULTURAL PRACTICES

It is often assumed that a fourth agricultural revolution is starting, in which digital technologies will play a critical role in transforming agricultural production – comprising crops, livestock, aquaculture and forestry – in a move towards increased efficiency and sustainability. These technologies include artificial intelligence (AI), drones, robotics, sensors and global navigation satellite systems (GNSS), as well as other digital tools that help automate diagnosis, decision-making and performing in various agricultural activities, allowing increased precision and efficiency.[2] Some of these technologies are commercially available, while others are approaching readiness levels.[26]

Various scenarios for agriculture in the coming years and decades point to a likely rise in the use of different digital and automation technologies.[27, 28] In recent years, the vast proliferation of hand-held devices (e.g. mobile phones and smartphones, sensors, internet of things [IoT] devices) is clearly visible, and is largely the result of improved access to mobile networks and expanding internet coverage, even in the world's remotest regions. For example, in 2020, 69 percent of the population in Latin America and the Caribbean, 64 percent in Pacific Asia, and 45 percent in sub-Saharan Africa had acquired a smartphone, and these figures are expected to increase to 81 percent, 79 percent and 67 percent, respectively, by 2025.[29] This is the result of massive investments in infrastructure by both governments and the private sector. For example, Google is investing in Africa's first subsea internet cable through its Equiano programme.[30]

There follows a presentation and analysis of the potential of these technologies to transform the landscape of motorized mechanization and agricultural operations in general.

Digital technologies are transforming conventional agricultural machinery

Policymakers and international organizations increasingly view digitalization as a game changer in the agriculture sector. Central to most digital technologies is the possibility to collect and exchange data to support decision-making by agricultural producers or other stakeholders and, ultimately, to enhance effectiveness and efficiency.[31, 32] In recent years, these digital technologies and services have received significant attention from donors, research centres and development agencies.[29, 33, 34, 35] They are increasingly incorporated in motorized machinery, potentially transforming its use: agricultural operations are performed with more efficiency and precision, and access to agricultural machinery is extended to new regions or socioeconomic groups, such as small-scale producers.

Many of these technologies are based on applications operated by a smartphone, or via a call or messaging service. Shared asset services are a subcategory of digital services, with significant potential to expand access to motorized mechanization, connecting owners of equipment (e.g. tractors or drones), and sometimes also operators, with agricultural producers who need such equipment. Agricultural producers pay the owner per hour or per area serviced, and a percentage or fixed fee goes to the matchmaker. The best known example of a shared asset service is Hello Tractor (operating in seven African countries as well as in Bangladesh, India and Pakistan).[1] See Box 3 for two successful cases in some African countries and Myanmar.

The main benefit of these shared asset services is an improved cost–benefit ratio: farmers gain access to the equipment they need without having to buy it, while the fees paid make the equipment more cost-effective for the owner. These asset services are especially important in sub-Saharan Africa, where ownership is extremely limited (see Box 2 on p. 22).

Another group of digital services are equipment-monitoring solutions, that is, simple applications that automate the operation of equipment such as irrigation pumps,[36, 37] or GNSS devices to track movements of, for example, equipment or animals. These types of services are seen as the first smart farming solutions to emerge for low- and middle-income countries.[38] More advanced services include the IoT solutions used, for example, to monitor and sometimes (partially) automate decisions concerning the care of crops, livestock or fish in order to improve diagnosis, decision-making and performing. This in turn leads to enhanced precision, improved efficiency and increased productivity, while reducing drudgery.
A concrete example of IoT use for precision agriculture comes from China, where it supports an integrated system of automatic remote sensing, early warning and microspray irrigation for tea production; changes in environmental conditions are detected, timely warnings are provided, and irrigation is triggered

BOX 3 DIGITAL TOOLS FOR IMPROVED ACCESS TO MECHANIZATION SERVICES

Digital tools based on the Uber taxi model are on the rise and promise to reduce transaction costs for tractor services. TROTRO Tractor in Ghana, and Tun Yat in Myanmar hire out machinery and share services through a digital platform and mobile phone services. These tools demonstrate real potential for inclusive agricultural mechanization.

TROTRO Tractor matches small-scale producers with the agricultural machinery they require, primarily tractors, and with the owners of that machinery, through a digital platform accessed via smartphone apps, as well as through unstructured supplementary service data (USSD) for users who do not own a smartphone. Currently TROTRO Tractor has 75 000 farmers registered across Benin, Ghana, Nigeria, Togo, Zambia and Zimbabwe. It relies on both business-to-client and business-to-business relationships, retaining a commission percentage on the cost of the service.

In addition to tractors (offering any type of service from ploughing to harrowing, and from planting and seeding to spraying) and combine harvesters, the TROTRO Tractor platform also connects producers with drone owners who offer their services for mapping and herbicide spraying. There is growing demand for drone-based mapping as farmers appreciate the importance of land tenure and understand that accurate land data may be crucial when requesting financial services from banks or insurers.

Tun Yat provides similar tractor services through a smartphone app, specifically targeting small- and medium-scale farmers, with a focus on women (representing 30 percent of clients) and youth (with 25–30 percent of clients under the age of 30). Tun Yat owns five tractors and five combine harvesters and offers a range of mechanization and matchmaking services to more than 20 000 customers. Services include ploughing, land preparation, seeding, combine harvesting with different headers for different types of harvest (e.g. mung beans or maize), and picking (e.g. sesame or groundnut). Most customers are small-scale producers with landholdings under 2 ha, who are especially in need of reliable and affordable mechanization services.

The Tun Yat business model embraces diversification, with services including resale of inputs (e.g. fertilizer), credit brokerage, and laser levelling to assist farmers in flood-prone areas who need to level farm plots and develop drainage. It also offers direct purchase from farmer groups of raw material, which is then processed into snacks and sold at convenience stores.

In synthesis, the Uber-like business model is advantageous both for farmers who do not own tractors and for equipment owners; the latter can maximize, closely monitor and plan machinery use and fuel consumption, offering competitive rates to a broader customer base.

SOURCE: Ceccarelli *et al.*, 2022.[2]

automatically, as and when necessary, thus avoiding damage from heat, cold or drought.[39]

The transformation by digital technologies of the use of motorized machinery such as tractors and harvesting equipment is somewhat limited, especially in low- and lower-middle-income countries.[1, 2] On the other hand, the organizational models for the use of motorized machinery are undergoing significant changes. There is an increasing focus on shared rather than individual ownership of machines by producers in low- and middle-income countries. Asset sharing has existed for a long time, but with limited success due to, for example, distrust between farmers, operators and machine owners, and issues related to machine maintenance. More recently, IoT and GNSS solutions, although still very limited among small-scale producers, are being widely adopted by service providers (including those mentioned in Box 3). By facilitating monitoring of the machinery, they enhance transparency and trust between service providers and users. Perhaps the most important change is the embodiment of traditional mechanization

BOX 4 DIGITAL TOOLS NOT LINKED TO MECHANIZATION – DISEMBODIED SOLUTIONS

Disembodied digital solutions (see Glossary) are not linked to mechanization. They are primarily software-based solutions that do not rely on the use of agricultural machinery. Instead, they require limited hardware resources, generally in the form of a smartphone, tablet, software tool (e.g. advisory apps), farm management software or online platform. This sets them apart from embodied digital solutions, where digital tools are combined with machinery to interact with the environment.

Disembodied solutions may include remote sensing, but limited to data for decision support and scouting. These are increasingly used across the globe as illustrated below by examples from across the world. The South African company, Aerobotics, operates in 18 countries, offering disembodied solutions with an uncrewed aerial system (UAS) and remote sensing for decision support to growers of fruits and nuts. The technologies allow early detection of pests and diseases, enable timely monitoring of water, fertilizer and nutrient requirements, and facilitate yield management.

In Morocco, SOWIT offers disembodied solutions using remote sensing, UAS for imagery collection, and machine learning based on data from field or weather databases. The technologies can be applied to fruit trees, cereals and rapeseed and they inform farmers of irrigation and fertilization requirements, estimate yield, monitor the dry matter content of forage, and carry out plot inspections.

In Nepal, Seed Innovations offers an Android application for farmers to use satellite-based analytics, global navigation satellite systems (GNSS) and artificial intelligence to monitor crop performance – including identification of water and nutrient deficiencies or surplus, and of pest and disease threats – and access and exchange agronomic information.

Based in Fiji, TraSeable Solutions has 2 000 active customers across seven Small Island Developing States in the Pacific. The company offers two main solutions. The first is a mobile app that informs farmers about the agriculture sector, records and manages farm data, and keeps track of resources, inventory, sales and expenses. The app also helps

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equipment with IoT devices (e.g. a combination of motorized harvesting equipment from a hiring service, GNSS data and a trained operator to drive a tractor), which can result in more effective use of machines, as well as higher yields.[1]

The potential of digital technologies for non-mechanized precision agriculture

The previous section described how digital technologies can transform the landscape of agricultural machinery, making mechanization both more precise and more accessible. Nevertheless, the adoption of motorized agricultural mechanization is still limited in many low- and middle-income countries, especially in sub-Saharan Africa. There is growing research on precision agriculture for non-mechanized production and its adoption is increasing.[40, 41, 42] Methodologies for manual site-specific fertilizer application were developed a long time ago – for example, variable rate technology (VRT) for fertilizer on rice[43] – while the AgroCares hand-held soil scanner is available in several low-income countries in Africa and Asia.[44] Non-mechanized farms in Africa and Asia are adopting uncrewed aerial vehicle (UAV) services (also known as drones), while GNSS can be used on non-mechanized farms to map field boundaries and establish land tenure.[45]

However, there is a lack of information on adoption levels; it is not clear how many agricultural producers actually use digital technologies.[46] Results from two technical studies – commissioned for this report[1, 2] – indicate that at the field level, a variety of digital tools and remote sensing and mapping technologies are increasingly used by small-scale agricultural producers and pastoralists across the world (see Box 4). Smartphones, with diverse sensors and

BOX 4 (Continued)

create market linkages between agriculture value chain stakeholders. The second focuses on fisheries, specifically tuna. It involves the tagging and tracking of individual tuna along the value chain from landing through to distribution. This solution also helps to manage fleets by providing information on the crew, and on operation and maintenance costs. In addition, it supplies tuna harvest details, including trip information, catch log sheets, fishing ground analytics and reporting services.

In Peru, Coopecan offers digital services along the whole Alpaca fibre value chain. A range of technologies provide digital solutions for, among others, pasture management (satellite imagery), animal health (animal tags), and fibre processing and export sales (blockchain technology). In addition, technical assistance is available for breeders needing support in herd management (e.g. regarding animal health status) or in management of natural pastures (increasingly degraded due to excessive grazing). These services are complemented by capacity building on how to use the solutions, and a traceability system that certifies production in terms of animal wellness, fibre quality and environmental and social responsibility, leading to better working conditions, fair pay and improved animal welfare.

Finally, Agrinapsis, operating in Bolivia (Plurinational State of), Costa Rica, Ecuador, Guatemala and Mexico, is a social media platform specializing in agriculture. Managed by the Inter-American Institute for Cooperation on Agriculture, it facilitates the exchange of common knowledge among small-scale producers. The crowd-sourced information is verified and rated by all its customers and, if flagged as doubtful or of poor quality, a technical team checks and improves it. Agrinapsis enables e-commerce targeted at small-scale producers, who can sell their produce or buy inputs that respond to environmental concerns.

SOURCES: McCampbell, 2022;[1] Ceccarelli *et al.*, 2022.[2]

high-resolution cameras built in, are the most accessible hardware for everyone in low- and middle-income countries today. In combination with apps embedded in smartphones and suitable interfaces, they can already make available highly useful innovations appropriate to the context of low- and middle-income countries and small-scale agriculture and have the potential to make a real difference. One example is GoMicro: through a microscopic lens clipped onto a phone camera, combined with AI, it supports the rapid diagnostics of pests and diseases,[47] and assists efficient and accurate quality control and grading of agricultural products such as cereals and grains, fish, fruits and vegetables.[1] There are other digital solutions involving satellite or drone data (e.g. on yields, soil conditions and plant health) analysed by an algorithm; the results can be used to validate data shared by agricultural producers (based on observations and experience) or to provide advice to producers.[1]

Digital solutions deserve the attention of policymakers and international organizations. More research is needed to tailor them to the needs of small-scale producers in low- and middle-income countries, especially in least mechanized ones, such as in sub-Saharan Africa.[1] Research and experience indicate that they enable site-specific crop management, which in turn can improve yields and reduce inputs on non-mechanized farms. However, two constraints are worth mentioning. First, digital technologies may be too expensive for small-scale producers, given the current costs of the equipment. For example, hand-held nitrogen sensors are priced between USD 300 and USD 600, which is excessive for a small farmer who only wishes to use the sensor a few times a year,[48] while the more sophisticated AgroCares scanner, which provides information on a wider range of soil nutrients, sells for over USD 3 000. Second, producers need to learn how to use the technologies; without the know-how, incorrect implementation can lead to undesired results, such as increased use of inputs.

There are still places, primarily in sub-Saharan Africa, where smartphones are outside the reach of small-scale producers and rural populations.[1, 2] Data from 2020 also reveal a substantial rural–urban divide in terms of internet access in developing countries: 65 percent of the population in urban areas have access versus only 28 percent in rural areas.[49] The evidence points to high cost as a fundamental factor hindering the adoption of these technologies by small-scale producers, despite the significant potential for improving productivity. This suggests that donor-subsidized, low-cost access to digital technologies by small-scale producers may not be viable.

Therefore, more – and more diverse – efforts are needed to make these tools more accessible. Shared asset service providers, mentioned above, are one solution and they already offer a range of machinery appropriate for both small- and large-scale farms. However, the low level of digital literacy among agricultural producers may also be a significant factor in the slow adoption of digital tools. For this reason, SMS text messages, interactive voice response (IVR) and unstructured supplementary service data (USSD) services are used to communicate with small-scale producers in many African countries. For example, ICT4BXW and Justdiggit – both operating in sub-Saharan Africa – initially adopted advanced technologies such as smartphones, but then decided to use simpler means (SMS, USSD and IVR) due to low smartphone penetration and the low level of digital literacy in the region.[1]

For as long as farmers have poor digital literacy, intensive and continuous technical support and information about digital technologies must be provided. Although basic mobile phones are now accessible to almost everyone, smartphones remain limited in sub-Saharan Africa. Therefore, phones need to be used in combination with advisory services based on satellite intelligence tailored to producers' needs (e.g. on water sources and grazing grounds for pastoralist livestock keepers, and on disease outbreaks for banana farmers).[1] ■

THE STATE OF DIGITAL AUTOMATION TECHNOLOGIES AND ROBOTICS IN AGRICULTURE

The previous sections of this chapter presented the trends and drivers of motorized agricultural mechanization, and discussed the role of digital technologies in transforming agriculture in terms of their potential to enhance precision agriculture and expand inclusive access to agricultural machinery. This section looks more closely at the current state of digital automation technologies in agriculture and the main drivers of adoption, based on available evidence.

Continued use of a technology is the best indicator that it has been beneficial for at least some agricultural producers and businesses.[48] The literature on the evolution of digital automation in agriculture provides insights into its benefits, challenges and adoption trends. In summary, the adoption of digital automation technology in agriculture has been driven by two main forces: rising food demand in the face of decreasing natural resources; and developments in other sectors of the economy, which drive innovation in the agriculture sector.[48]

To understand trends in digital automation technologies in agriculture, information must be collated from a variety of sources, because data are sparse (especially in low- and middle-income countries) and, in addition, no country or organization systematically collects data on their use. An individual analysis is of limited value because of the specificity of the technology and the country involved. It is only when information is considered as a whole that patterns emerge. Table 2 presents selected milestones in digital automation in agriculture, listing the first mover of each technology. Dating the introduction of each technology at the producer level is not simple, therefore the dates, countries and technologies in the table are only indicative of general adoption patterns; indeed, no technology emerges fully developed from the laboratory or design studio before moving to the farm. On the

TABLE 2 SELECTED MILESTONES IN DIGITAL AUTOMATION IN AGRICULTURE

Year	Technology or activity	Company or organization	Country	Reference
1974	Electronic ID for livestock	Montana State University	United States of America	Hanton and Leach, 1974[50]
1983	Executive order allowing civilian use of GPS	US Government	United States of America	Brustein, 2014[51] Rip and Hasik, 2002[52]
	Drone fertilizer and pesticide application	Yamaha	Japan	Sheets, 2018[53]
1987	Computer-controlled VRT fertilizer	Soil Teq	United States of America	Mulla and Khosla, 2016[54]
1992	Milking robot	Lely	Netherlands	Lely, 2022[55] Sharipov *et al*., 2021[56]
1997	GNSS agricultural equipment guidance	Beeline	Australia	Rural Retailer, 2002[57]
	N-Sensor	Yara	Norway	Reusch, 1997[58]
2006	Automated sprayer boom section controllers	Trimble	United States of America	Trimble, 2006[59]
2009	Planter row shut-offs	Ag Leader	United States of America	Ag Leader, 2022[60]
2011	Weeding robot	Ecorobotix Naïo Technologies	Switzerland France	Ecorobotix, 2022[61] Naïo, 2022[62]
2013	Combine harvester operator assistance system	Claas	Germany	Claas, 2022[63]
2017	First fully autonomous field crop production	Harper Adams University	United Kingdom	Hands Free Hectare, 2018[64]
2018	Autonomous chaser bin	Smart Ag	United States of America	Smart Ag, 2018[65]
2022	Autonomous large-scale tractor	John Deere	United States of America	John Deere, 2022[66]

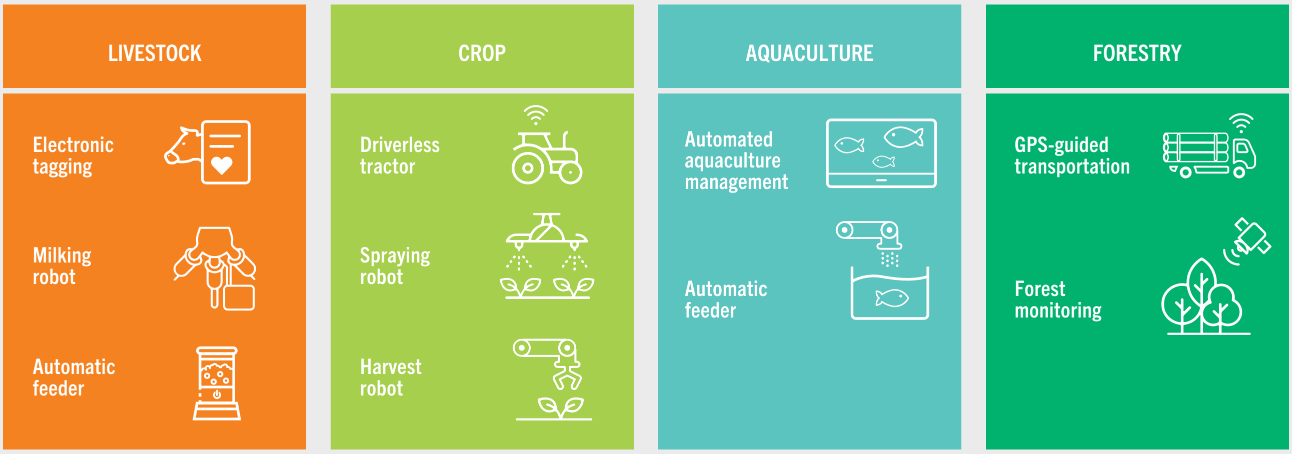
NOTES: GPS – global positioning system; VRT – variable rate technology; GNSS – global navigation satellite system.
SOURCE: Lowenberg-DeBoer, 2022.[48]

contrary, technology adoption is an iterative process; it starts with basic research to show the potential application and then converts scientific ideas into usable commercial products. Building on Figure 2 (p. 5), Figure 5 (p. 30) provides further examples of technologies covered in this chapter, organized by agricultural production system. These do not mirror, but rather complement, the technologies in Table 2.

Advances in automation for livestock production

As illustrated in Table 2, some of the first digital automation technologies emerged in the livestock sector. Precision livestock farming is made possible by attaching sensors to animals or to barn equipment to operate climate control and monitor animals' health status, movement and needs, including related to breeding.[67] Several precision livestock technologies have been developed that facilitate management of individual animals based on electronic identification (EID) tagging, the most common being milking robots, which allow cows to be milked without direct human involvement. The conventional milking machine uses a vacuum technology but still requires a human operator to place it on and remove it from the animal. On the other hand, EID automates the process by allowing a milking robot to access a database of udder coordinates for specific cows.[68] This fully automated system adapted to animal production has great

FIGURE 5 SELECTED DIGITAL TECHNOLOGIES AND ROBOTICS WITH ARTIFICIAL INTELLIGENCE BY AGRICULTURAL PRODUCTION SYSTEM



SOURCE: FAO elaboration for this report.

prospects in terms of cost savings and raising productivity.[69] However, the evidence of the monetary benefits of milking robots is mixed: some studies indicated a positive impact,[70, 71, 72] while others found no financial gains compared with conventional milking machine systems.[71] Therefore, it would seem that adoption is driven not only by monetary but also by social considerations such as increased flexibility in work schedules and better quality of life – factors particularly relevant on small and medium-sized farms. More recently, however, larger dairy farms (with over 1 000 cows) have joined medium-sized farms in adopting robotic milking systems due to labour shortages. Therefore, the decision to use robotic milking may be based on quite different considerations on larger dairy farms.[48] Box 5 presents examples of digital automation of livestock production in Africa, Europe and Latin America and the Caribbean.

Global sales of automatic milking systems (AMS) have grown from USD 1.2 billion in 2016 to USD 1.6 billion in 2019, which points to a growing demand, albeit concentrated in high-income countries, with countries such as Germany, the Netherlands and the United Kingdom being early adopters.[73, 74] Indeed, while no statistics on adoption are available across different regions and countries, the evidence indicates that adoption is confined to high-income countries, mostly in Northern Europe.[75] Demand is driven by lack of rural labour, coupled with a generational shift. Table 2 (p. 29) shows that the first commercial AMS was used in the Netherlands in 1992; it has since spread to other countries.[69] The absence of data on low- and middle-income countries suggests the technology is almost absent there.[48, 76]

In addition to milking machines, there are also technologies for the automated feeding of varying amounts of concentrates to cows based on their milk production.[77] The same applies to poultry, where feeding systems are based on bird weight and egg count, and computerized control of ventilation is based on temperature and humidity.[78] However, data and evidence regarding their adoption trends and drivers are even scarcer.

BOX 5 DIGITAL AUTOMATION OF LIVESTOCK PRODUCTION: EXAMPLES FROM LATIN AMERICA, AFRICA AND EUROPE

The company Cattler originated in Argentina in 2019, but has since expanded its business to other countries, including Paraguay and Uruguay and, more recently, Brazil and the United States of America. It offers an automated farm management system for beef cattle farms based on satellite information and provides feedback and insights for improving management. The company targets medium-sized rather than the largest farms. According to the company, a key driver of adoption has been the need to simplify operations and make a return on investment.

In Burkina Faso and Mali, and soon the Niger, with the support of the Netherlands Development Organization, GARBAL provides highly contextualized advisory information on livestock and crop production, as well as on fodder, milk and cereal markets. With a specific focus on women and youth, the digital solutions offered help small-scale producers and pastoralists affected by climate change in the Sahel make decisions concerning grazing lands, herd migration, the weather, and various farming practices. Solutions rely on satellite imagery, mobile phone SMS, unstructured supplementary service data (USSD), and a call centre with local operators speaking local languages. The use of mobile phones makes the solution very accessible. It was driven by, *inter alia*, public–private partnerships, subsidies, engagement with local farmer and pastoralist organizations, and the bridging of traditional and scientific knowledge. Key challenges have been the need for highly context-specific solutions, the security situation in some countries, significant capacity-building requirements, connectivity and network reception problems, and data quality issues.

Lely, a family-owned company in the Netherlands, offers robotics, as well as management software solutions for dairy farming, targeting medium- to large-scale producers with more than 100 cows, but not to date the largest farms. The principal technologies adopted are stationary milking robots, followed by manure robots and feeding robots. Grass harvesting robots optimize grass production, while upcoming products focus on reducing emissions. This is complemented by management software for all farm operations, including information on animal status welfare. The technology proposed can address issues of limited labour availability, emissions regulations and animal welfare. Key drivers of adoption are energy efficiency, chemical use reduction and labour shortages.

SOURCE: Ceccarelli *et al.*, 2022.[2]

Advances in automation for crop production

Automation of crop production involves the use of many precision agriculture technologies, namely VRT, GNSS, robots, drones and AI. These may require the collection of spatial data, based on a geographic information system (GIS), using information from crop simulation models to identify the amount of inputs necessary to maximize yield and profit.[67] Underlying these applications are sensors, including proximal sensing (e.g. measurement of nitrogen in the soil) and remote sensing (e.g. satellite imaging). Depending on connectivity, operators can share these data with stakeholders via smartphones and user-friendly apps that present the data in a simple manner.[35]

Adoption varies by agricultural commodity, capital cost, wage rate and other economic factors. In any case, adoption by small-scale agricultural producers is negligible; this is because there is almost no research on its adaption to small-scale agriculture and it is not easy to transfer the technology from mechanized to non-mechanized operations.

GNSS and VRT, matched with motorized machinery, are the most widely used in crop production to enable autosteer and on-the-go application of inputs. One of the main drivers of adoption of GNSS-based technologies is their capacity during application of inputs (e.g. fertilizer) to eliminate both accidental skipping and overlapping of plants, which translates into input savings. Other drivers include reduced operator fatigue, ability of family members to work longer hours, flexibility in hiring drivers (since they do not need to be highly skilled or experienced), and environmental benefits (as there are fewer overlapping applications), in addition to other advantages difficult to quantify and more akin to side-effects of adoption. The fact that the benefits of GNSS guidance are quickly appreciated (e.g. input savings from reduction in overlap are almost immediate) and visible to both farmer and neighbours (e.g. weed strips from herbicide skips are frowned upon in the farming community) also aided adoption.[48]

VRT technologies reduce input application and optimize crop yields, which also brings environmental benefits, especially if they reduce over-application. There is mixed evidence regarding the increased profitability of VRT fertilizers,[79, 80] and this explains the modest adoption worldwide of map-based VRT fertilizer – and then mostly where profitability is consistent (e.g. nitrogen application to sugar beet).

In the most advanced automation category, autonomous crop robots entered commercial use only very recently. They appear mostly in high-income countries (e.g. France) for weeding organic vegetables and sugar beet.[81] Hands Free Hectare – a project established in the United Kingdom in 2016 to develop and showcase agricultural automation – marked the first public demonstration of autonomous crop machines taking part in producing and harvesting a commercial crop.[64] Since then, manufacturers have announced autonomous machines (see Table 2 on p. 29), and over 40 start-ups are currently developing them. Autonomous crop robots are associated with labour saving, improved timing of operations, more accurate input application and reduced soil compaction, especially with smaller swarm robots. A review of 18 cases found that autonomous crop robots used for harvesting, seeding and weeding were economically feasible in certain circumstances.[82]

In some countries, autonomous crop machines require on-site human supervision at all times, in which case the farmer may be better off using conventional equipment.[83] One study found that remote supervision (e.g. from the farm office) is optimal only if the autonomous operation is relatively trouble-free.[84] It emphasized the need for greater AI capacity to enable the autonomous machine to resolve more issues without human intervention. Similarly, speed restrictions for autonomous crop machines, as exist in the United States of America, can make them unprofitable.[85]

There are proposals to develop small, low-cost autonomous crop machines for small- and medium-scale farms as part of the solution to the lack of agricultural labour in low- and middle-income countries, with potential benefits especially for rural youth.[86, 87, 88, 89] Unfortunately, there are no feasibility analyses for low- and middle-income countries. Nevertheless, the available literature indicates that the adoption of autonomous robots in these countries has the following potential benefits: (i) reduced human labour requirement, where labour is scarce; (ii) lower costs and reduced economies of scale, ensuring accessibility of technologies to smaller farms using conventional mechanization; and, (iii) ability to use technologies in irregularly shaped fields in a cost-effective manner, avoiding the reshaping of rural landscapes into large rectangular fields (where traditional mechanization is most efficient), a process that disrupts communities.

Drones are used for information gathering and to automate input application, similarly to map-based VRT. However, their use is often subject to strict regulations due to concerns about excessive input application, pesticide drift and aviation hazards.[90, 91] For example, in the United Kingdom, drones are only allowed to apply herbicides in inaccessible locations under restricted conditions. Conversely, Switzerland allows more flexible input application by drones, which may encourage other European countries to do the same.[83, 92] About 14 percent of agricultural retailers in the United States of America provided drone input application services in 2021, expected to increase to 29 percent by 2024.[92] Drone input application

BOX 6 NEW AQUACULTURE TECHNOLOGIES: EXAMPLES FROM INDIA AND MEXICO

Aquaculture has already demonstrated its crucial role in global food security and nutrition, constituting one of the world's largest sources of animal protein, with production growing at 7.5 percent per year since 1970.[95] Given the capacity of aquaculture for further growth, but also the enormity of the environmental challenges the sector faces as it intensifies production, new sustainable aquaculture development strategies are necessary. Such strategies need to harness technical developments in, for example, feed, genetic selection, biosecurity and disease control, and digital innovation. This can, in turn, enhance precision, improve decision-making, facilitate autonomous and continuous monitoring of fish, and reduce dependencies on manual labour, thus improving staff safety, fish health and welfare, while also increasing productivity, yield and environmental sustainability.[96]

Aquaconnect in India is a case in point. Although India is one of the world's largest aquaculture producers, harvesting 7 million tonnes in 2018,[95] the industry is characterized by a lack of transparency and inefficient value chains. Aquaconnect uses artificial intelligence and satellite sensing technologies to monitor the performance of aquaculture farms and provide shrimp and fish farmers (mostly small- to medium-scale) with advice to increase productivity. This solution is combined with an omnichannel platform that sells farm inputs at affordable prices. It also bridges the gap between farmers and financial institutions and improves market linkages. These solutions are currently assisting over 60 000 fish and shrimp farmers across India to increase productivity, enhance market linkages and improve access to formal credit and insurance.[1] In parallel, the Government of India has allocated about USD 3 billion for the modernization of agriculture, including value chains of aquaculture and fisheries, and expressed interest in supporting initiatives (e.g. start-ups) that implement technologies and promote innovation.

Another ambitious project that promises to transform the aquaculture industry is Shrimpbox, the world's first robotic shrimp farm, developed in Oaxaca, Mexico (see Atarraya case study in Annex 1). The technology provides automated systems that can be monitored remotely with software capable of learning and making decisions. The systems are integrated with biocontrol based on microbial methods to reduce nitrate build-up, prevent diseases, and save water in shrimp production, leading to significant reductions in water consumption, labour requirements, risk of diseases, and losses.[2] According to the creators of the technology, a robotic farm can produce as much in 0.5 ha as a traditional 100-ha farm, while using only 5 percent of the water and remaining antibiotic-free.[97] Shrimpbox can farm shrimp in colder climates and without ocean access. This in turn means that fresh, high-quality shrimp can be delivered to regions that today depend on imports of frozen produce.

Aquaconnect and Shrimpbox are just two examples of new technologies set to make aquaculture a more sustainable, inclusive and efficient process. However, the priority should be to further develop aquaculture in Africa and in other regions where technological development is lagging and food insecurity and malnutrition are more severe.[95]

is also quite common in some middle-income countries, such as Brazil and China.[93]

Some lesser known advances in automation: aquaculture, forestry, and controlled environment crop production

Digital automation is on the rise in the aquaculture sector in response to labour scarcity and high wages. There is wide adoption of innovations that automate feeding and monitoring, despite their high investment costs, as they minimize labour and other variable production costs and reduce the labour requirements to a few highly skilled operators.[94] Box 6 showcases recent aquaculture innovations in India and Mexico.

In forestry, many wood harvesting operations are already highly automated, using motorized machinery progressively upgraded with digital »

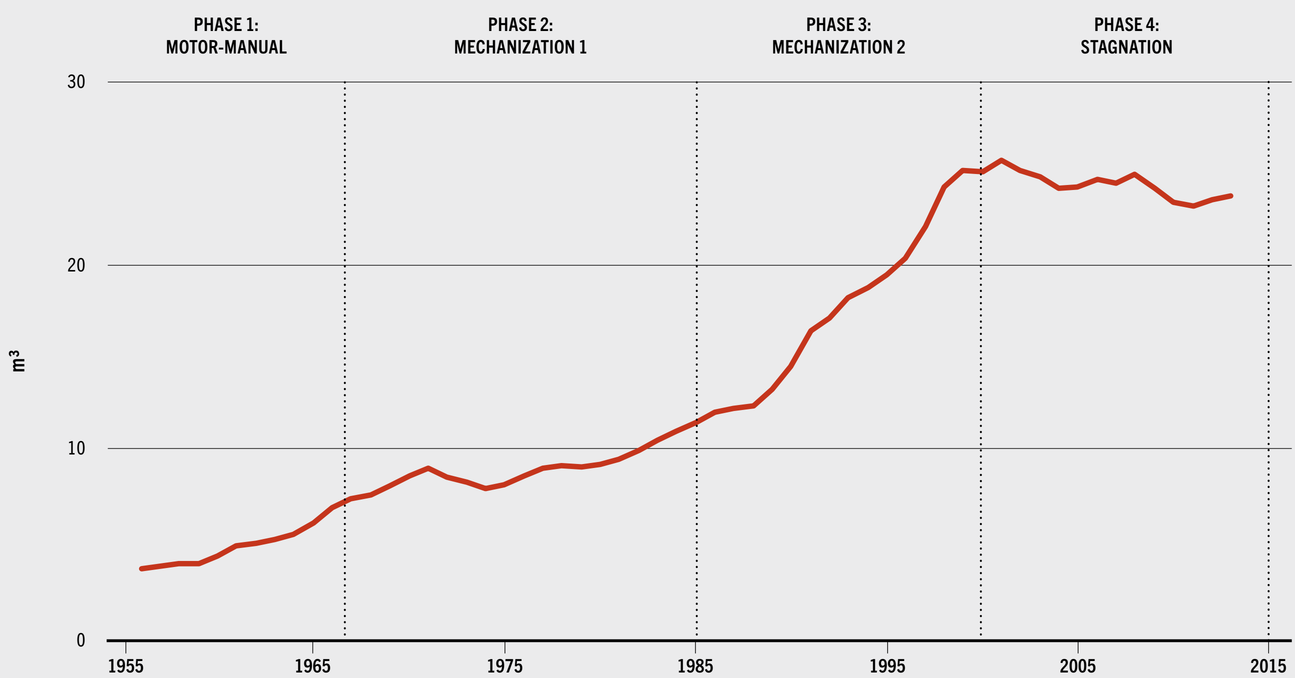
BOX 7 EVOLUTION OF THE FORESTRY SECTOR: MECHANIZATION AND DIGITAL AUTOMATION

Historically, work in the forestry sector was physically hard and potentially dangerous, especially in the wood harvesting phase. Systems with low technological input required a special logging crew consisting of a logger and a supporting logger, with an additional group of workers to trim the branches. Once trimmed, another specialized team, comprising a marker, a cross-cutter and two to three draggers, would cross-cut the trees into logs.[100] Because of the demanding labour requirements and the danger to workers, such manual logging methods are much less common now.

In the 1950s, a process began to upgrade the logging sector from reliance on mainly manual labour to mechanization and partial automation. Forestry harvesting can be divided into four distinct phases: felling of the trees, extraction from the forest, sorting and loading at a landing site, and transportation to the market. Harvester machines are now capable of multiple operations (felling, extracting, cross-cutting and sorting). Such machinery has resulted in significant increases in efficiency and improved working conditions. The advantages of mechanization and digital automation include the safety and comfort of the harvester operator. In the process, labour productivity has increased dramatically. In Sweden, productivity per worker increased sixfold from 1960 to 2010 (see figure).

Even in these more mechanized logging systems, labour typically represents about 30–40 percent of running costs in European countries.[102] The work environment is stressful since operators need to make many decisions at a fast pace, manoeuvring complex machinery and identifying differences in log quality, thus limiting the number of hours they can work. Therefore, one way to increase productivity is to raise the level of automation. The adoption of autonomous equipment is driven by productivity and operational costs. Although an autonomous machine is generally slower than operator-handled equipment, it can still

FIGURE STANDING VOLUME OF WOOD PER WORKING DAY IN THE SWEDISH FORESTRY INDUSTRY, ROLLING THREE-YEAR AVERAGE



SOURCE: SkogForsk as reported in McKinsey and Company, 2020.[101]

BOX 7 (Continued)

be more cost-effective; semi-autonomous machines may allow an operator to run multiple machines at the same time.

Most modern forestry machines can readily be converted for remote control at relatively low cost, with many working options already available. As noted, machine operation is typically slower – significantly so if the task is complex – and will not be adopted in forest operations based only on improved productivity. However, they could be considered for other reasons: to safeguard operator safety, or when a full-time on-site operator is underemployed.

There are currently no fully autonomous systems in timber harvesting. However, the extraction and subsequent transportation of stems and logs with GPS-guided systems have been identified as probable first robotic operations, soon achievable with modest research and development (R&D) investment. Plantation felling may also become economically feasible in the longer term, but this will require substantial R&D investment.[103] Finally, road transport of harvested logs is an aspect of forest operations that needs improved productivity in the wood supply chain. There are rapid developments in driverless truck technology, with the benefit that autonomous trucking reduces labour requirements and hence costs. For truck movement off public highways, autonomous vehicles are already deployed in mining operations, making an expansion to forestry a real possibility.

New, more environmentally friendly harvesting systems are also under development. A walking harvester can now meet the challenge of harvesting on steep, sensitive or uneven forest terrain. One goal is to limit the negative impact on forest soils through spot-ground contact without leaving the continuous track of wheeled or tracked harvesters.[103] While such systems are still far from the commercial stage, in New Zealand a swinging forest harvester functions while making no contact with forest soils. It operates independently of the terrain conditions (steepness, roughness, etc.) by staying above ground and moving from tree to tree using the trees themselves for support, thus reducing soil disturbance.[104]

These environmentally friendly developments can be valuable in forests where the use of motorized mechanization in harvesting can cause soil compaction and erosion, as well as biodiversity loss. Finally, if one considers that benefits provided by forests go far beyond wood production – they include carbon storage, non-wood forest products, erosion prevention, water purification and recreation – it is important to assess how, using sensors, digital automation can also increase the value of these benefits. One important example is the monitoring of deforestation, specifically illegal operations, using satellite data. The ability to monitor deforestation has greatly increased in terms of granularity of the data, which are now available globally at a 5-m resolution on a monthly basis. A concrete example in the Amazon Basin was the detection of forest loss due to oil palm plantations expanding into indigenous territory in Ecuador.[105] Having such data freely available with global coverage is a great example of how digital solutions can be used to diagnose problems.

» tools. More recently, mobile technologies, combined with virtual reality and remote sensing techniques, are paving the way for advanced automatic machines in the forest. Wood harvesters and forwarders – advanced machines used for log cutting and transport – are currently a major target of automation efforts.[98] Novel, digital-based technologies are increasingly pervasive. A recent review revealed a strong emphasis on remote sensing-based innovations for forest monitoring, planning and management, where machine-learning techniques also play an important role in data collection, processing and analysis. The continued adoption of digital tools is likely to raise new questions about forest ecosystems as dynamic, social, ecological and technological landscapes. Future research should examine more closely how forestry researchers, managers and stakeholders can anticipate and adapt to both environmental and technological uncertainty in the forest ecosystem.[99] Box 7 summarizes the evolution of the forestry sector in terms of mechanization and the potential for digital automation.

Another area where digital automation has potential is controlled environment agriculture (CEA), which includes greenhouse agriculture and vertical farming. Greenhouses are the most common form of CEA. By their very nature, they are amenable to environmental monitoring, control and optimization. Innovations in low-cost and low-power consumption sensors and instruments, communication devices, data processing and mobile applications, together with technological advances in design, simulation models and horticultural engineering, have led to a shift from conventional greenhouses to smart controlled environments.[106] Start-ups specializing in CEA, such as Food Autonomy in Hungary, ioCrops in the Republic of Korea and UrbanaGrow in Chile, point to real potential in this area.[2]

Prior to undertaking large-scale commercial development, there is need for an accurate economic analysis, given the high start-up costs involved in automation of greenhouses and vertical farming.[106] As with all the technologies presented in this chapter, the cost of increased automation relative to increased profitability is key and should be considered in future studies to justify greater levels of automation. ■

CONCLUSIONS

This chapter has presented the trends and discussed the drivers of motorized mechanization in agriculture production systems, as well as more recent digital automation technologies. It has highlighted the wide disparities in mechanization across the world: Asia and Latin America and the Caribbean have shown considerable progress regarding mechanization, driven by farming system evolution, structural transformation, and urbanization, while in sub-Saharan Africa, progress has been limited. It has also discussed how and where digital automation has been used successfully in agriculture and its potential to transform the use of agricultural machinery.

Any discussion on the benefits of both mechanization and digital automation in agriculture usually starts with labour saving, but quickly moves on to other advantages. In the case of motorized mechanization, the most recognized benefit is reduction of drudgery, in addition to timeliness of operations in the face of scarce and seasonal agricultural labour. While mechanization is associated with positive effects related to labour productivity, poverty reduction, food security, improved nutrition, and health and well-being, it also raises concerns with regard to unemployment,[107] biodiversity loss,[108, 109] land degradation,[15, 110] and growing disparities between large and small farms.[111, 112] These concerns seem to derive mainly from the dominance of large-scale motorized machinery powered by large four-wheel tractors.[7, 113, 114]

The literature on digital automation claims that it can reverse some of the above-mentioned social and environmental challenges of motorized mechanization.[48] Examples of benefits include: scale-neutral field operations (as a result of smaller equipment); accuracy of input application; reduced soil compaction (on account of small swarm robots); ability to conduct field operations where manual or mechanical technologies are hindered (e.g. wet soils and steep hillsides); profitable farming in small and irregularly shaped fields; and automated collection of crop and livestock data.[54, 82, 115]

This chapter has shown that an array of technological solutions are already available for potential adoption in countries at different stages of development. The challenge for governments is to achieve inclusive adoption by facilitating access for all, including small-scale producers, women, youth and vulnerable groups, and to ensure that available technology solutions are tailored to the specific context and needs of different producers.

Ensuring inclusive adoption, with all the challenges it entails, will allow countries to benefit from digital automation technologies and help drive the transformation of agrifood systems in an equitable and sustainable manner. The cases presented in this chapter illustrate how it is possible for small-scale producers to benefit from mechanization services and digital automation while reducing their environmental footprint. However, there is growing evidence that government policy choices will influence the direction of these technologies and their adoption in different countries and by different producers. Policy choices determine access to credit, capacity building and information. Ideally, countries should try to create a level playing field for innovative technologies that are relevant to local agrifood systems. This will allow the private sector to match supply and demand for motorized mechanization, digital automation and robotics. The next chapter will present the business case for these technologies and their prospects for transforming agriculture. In particular, it will discuss how motorized mechanization, often combined with digital solutions, can still play an important role, especially for small-scale producers in low- and lower-middle-income countries, where adoption has been slow. ■

SERBIA
Autonomous harvester in a field.
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CHAPTER 3
THE BUSINESS CASE FOR INVESTING IN AGRICULTURAL AUTOMATION

KEY MESSAGES

➔ The business case for motorized mechanization is based on its potential to reduce production costs, expand and intensify production, and improve productivity. The main barriers to adoption include inadequate access to necessary services (e.g. finance and extension) – especially by vulnerable, excluded and marginalized groups, including small-scale producers and women – absence of a conducive business environment, lack of technologies tailored to small-scale agriculture, and poor infrastructure.

➔ Motorized mechanization can still provide benefits to many low- and middle-income countries where adoption has been slow. These countries should take advantage of the wide variety of available machinery and their possible multiple uses, tailoring machinery to local needs, especially those of small-scale producers often operating in small areas on uneven terrain.

➔ Digital technologies can enhance the precision and timeliness of agricultural operations, make agricultural advisory services more effective, and address the environmental challenges resulting from past mechanization (e.g. soil erosion), while building resilience to shocks and stresses.

➔ Digital technologies enable machinery hire services, including in low-income countries, allowing access to technologies for often excluded groups, such as small-scale and female producers. Young farmers, in particular, are key drivers of the transformation of family farming towards agricultural automation.

➔ The business case for digital automation technologies is still weak, especially in low- and lower-middle-income countries, due to poor connectivity and electricity supply, and limited access to services (e.g. finance, insurance, education). This is even more so for robotics with artificial intelligence (AI), where adoption is expected to accelerate mostly for large-scale producers in high-income countries.

➔ Harnessing the potential of digital automation technologies requires addressing the factors that hinder adoption – poor infrastructure, digital illiteracy, high costs of the technologies, and lack of an enabling environment – while investing in research and testing worldwide to develop context-appropriate technologies.

Chapter 2 discussed the trends and drivers of agricultural automation, including motorized mechanization and more recent digital automation technologies associated with precision agriculture. Motorized mechanization is widely adopted around the world, although unevenly both across and within countries. Most sub-Saharan African countries still lag behind. Other regions have seen unequal access to mechanization, with generally less for vulnerable groups such as small-scale producers and women. The world is now in the early stages of a wave of digital automation in agriculture, involving sensors, robots, AI and other digital tools to automate one or more of the components of agricultural operations –

diagnosis, decision-making and performing. While many countries have adopted motorized mechanization extensively, agricultural producers and agribusinesses are still in the process of identifying which digital automation technologies are worthwhile and suitable for them, taking into account local conditions and the technologies they are currently using. One of the main barriers to adoption is a lack of perceived benefits from such an investment, due to the high purchase or operation costs compared with the labour costs of current systems. Other factors impeding adoption are the lack of technologies suitable for small-scale production, inadequate access to maintenance and repair services, the low level of digital literacy, poor connectivity, and scepticism about innovations. This chapter discusses how these factors affect the business case for agricultural automation and how to improve that case.

The business case for investing in agricultural technology rests on the potential gains for agricultural producers, as well as for those involved in producing, delivering, and maintaining or repairing the said technology. The assumption is that the relevant actors – producers, dealers, and maintenance and service providers – make rational decisions to maximize their profits and well-being. Investing in automation technologies entails costs, which tend to increase if the technologies are not widely available locally. Producers and technology suppliers will only embrace automation if the benefits outweigh these costs.

For some technologies and in certain conditions, investment costs may exceed the potential benefits, at least in the short term; this can discourage investment, despite the advantageous prospects for wider society. Public intervention is therefore required to align private benefits with the interests of society as a whole and thus incentivize the business case. This chapter also looks at (mostly environmental) issues related to motorized mechanization and considers how these can be addressed (at least partially) by new digital automation technologies, including those still in the pipeline. This is particularly relevant to some low- and lower-middle-income countries where motorized mechanization adoption has been slow but can now be implemented in a potentially sustainable, efficient and inclusive manner.

Based on the case studies commissioned for this report and the wider literature, this chapter presents and summarizes evidence for the business case of both motorized mechanization and digital automation technologies. A discussion on how policies and investments can affect the business case and shape incentives for adoption of automation technologies follows. Finally, the chapter analyses future trajectories for a wide range of technologies, and considers their potential to transform agriculture and make it sustainable, in light of the different local challenges faced by producers. ■

THE BUSINESS CASE FOR MOTORIZED MECHANIZATION CONFIRMS ITS CONSISTENT POTENTIAL IN MANY CONTEXTS

There is a large and rich literature on the benefits that mechanization has brought and can still bring to agricultural and rural development. By allowing producers to perform agricultural operations faster and more effectively, it can lead to enhanced agricultural productivity, higher incomes, labour and cost savings, and reduced drudgery, among others. For example, switching from animal-drawn ploughs to power tillers in the intensive wetland rice production systems in Asia led to major cost savings on labour used for land preparation. Rice cropping intensities and productivity also increased due to shared mechanization of land preparation and threshing.[1] The use of small mechanical mills for extremely labour-intensive and tedious tasks, such as dehusking paddy or pounding grain into flour, also resulted in substantial gains in leisure time, especially for women.[1] Mechanization has contributed to reduced crop damage and losses, as observed in India,

BOX 8 A COMPARATIVE COST–BENEFIT ANALYSIS FOR MECHANIZED VS MANUAL AND/OR ANIMAL TRACTION IN WHEAT PRODUCTION: EVIDENCE FROM ETHIOPIA AND NEPAL

In Ethiopia, farmers using a two-wheel tractor in wheat production reduced the costs of the essential operations of seeding, harvesting and threshing by 46 percent, 65 percent and 48 percent, respectively, compared with traditional technologies using manual tools or animal traction (see figure). Transportation costs also went down. The average total revenue increased: from USD 1 964 for traditional practices to USD 2 567 for mechanized operations. The average total variable cost for mechanized and conventional farming systems was USD 526 and USD 818, respectively.

As a consequence, the gross margin for mechanized operations was 78 percent higher, reaching USD 2 041. These results indicate that mechanized production of wheat is far more productive and profitable than non-mechanized production.

Similarly, in Nepal, wheat production using motorized mechanization – including a fertilizer drill, a reaper and a tractor-powered thresher – resulted in reducing the total farm operation cost by almost half and increasing the gross margin by 81 percent, reaching USD 514 (see table on p. 42).

FIGURE COST OF AGRICULTURAL OPERATIONS IN WHEAT PRODUCTION USING MOTORIZED VS NON-MOTORIZED EQUIPMENT – THE CASE OF ETHIOPIA

SOURCE: Yahaya, forthcoming.[15]

where combine harvesters reduced rice losses and raised yields by 24 percent.[2] Based on two recent case studies, Box 8 provides evidence for the business case of investing in motorized mechanization in Ethiopia and Nepal.

Even in sub-Saharan Africa, where mechanization is not widely adopted (see Chapter 2), evidence indicates that it has brought great benefits. In Côte d'Ivoire, tractor use promoted the application of modern inputs and better crop management, increasing land and labour productivity. A study across 11 African countries found that tractor use increased maize yields by around 0.5 tonnes/ha.[3] In Ethiopia and Ghana, households using tractors were able

BOX 8 (Continued)

TABLE COST OF AGRICULTURAL OPERATIONS IN WHEAT PRODUCTION USING MOTORIZED VS NON-MOTORIZED EQUIPMENT – THE CASE OF NEPAL

Items	Manual practice cost (USD/ha)	Mechanized practice cost (USD/ha)
Manure	68	34
Seeds	71	71
Fertilizers	87	87
Total input cost	**226**	**192**
Land preparation, seeding and fertilizing	85	25
Irrigation	36	11
Harvesting	102	48
Threshing	174	116
Total farm operations cost	**396**	**200**
Transportation	13	13
Total variable cost	**635**	**405**
Grain production	868	868
Straw production	51	51
Total revenue	**919**	**919**
Gross margin	**283**	**514**
Revenue–cost ratio	***1.45***	***2.27***

NOTE: USD 1 = NPR 117.57 (Nepalese rupees), as at 6 April 2021, according to the Nepal Rastra Bank exchange rate.
SOURCE: FAO, 2022.[16]

to expand their production by cultivating more land rather than trying to raise yields.[4, 5] In Zambia, agricultural households using tractors almost doubled their income by cultivating a much larger share of their land and achieved twice the gross margin per hour of farm labour compared with other households.[6] Despite reducing by half labour requirements per hectare, the demand for hired labour actually increased for all non-mechanized activities as a result of expanded production. The shift from family labour to hired labour also reduced the burden on women and children, allowing the latter to attend school.

The benefits of agricultural mechanization thus go well beyond increased agricultural productivity. Mechanization can free up household labour and enable agricultural households to spend time away from agriculture on other activities, such as food preparation – thus improving nutrition – or off-farm work to enhance their livelihoods.[7, 8, 9] It can further support the creation of new jobs, for example, mechanics to maintain and repair equipment. There can be spillover effects for the wider economy due to increased demand for non-farm goods and services.[10, 11] Mechanization can also lead to improved food safety through preservation and storage

BOX 9 LEVERAGING AGRICULTURAL AUTOMATION TO IMPROVE FOOD SAFETY

The introduction of technologies – from refrigeration for food storage and transport to innovations in dehydration and smoking processes – has vastly improved food preservation and safety. For example, in the livestock industry, the vertical meat rail system used for carcass dressing in slaughterhouses is a simple yet effective mechanism to prevent meat contamination. The automation of harvesting, sorting and packaging of foods greatly reduces the risks of transmitting food-borne pathogens from workers to food. Mechanical sorting of peanuts to reject kernels with high fungal infection has been extremely successful in improving public health. However, it is important to follow appropriate equipment sanitation and hygiene practices to prevent the transmission of food-borne hazards from the machines themselves. For example, machinery used to collect crops can introduce allergens into a supply chain unless cleaned properly. Machines can also introduce food safety hazards through oil leakages, hydraulic fluids, exhaust fumes and others.

Advances in digital automation also offer improvements in rapid detection of contaminants in food, provide better tools to facilitate timely investigations of food-borne illness outbreaks, and enhance surveillance and monitoring systems. Remote sensing technology in precision agriculture allows for early detection of pest damage and targeted and timely applications of agrochemicals, thus preventing overuse. However, benefits are not inevitable; for example, in some cases, automation may increase inputs of agrochemicals to reach the desired goal, which can be harmful to both humans and the environment. It is also important to ensure equitable access to technologies and to address issues related to data privacy and ownership.

SOURCE: FAO, 2022.[17]

technologies (e.g. dryers and cold storage), which can reduce contamination,[12] provided appropriate implementation is in place. Box 9 highlights the role of agricultural automation in improving food safety.

Mechanization also makes agricultural production more resilient. In particular, it improves resilience to climate shocks, such as droughts, since it allows farmers to complete farming activities more quickly and to be more flexible in adapting work to changing weather patterns. For example, irrigation pumps can increase or stabilize yields where rain is unpredictable and drought is common,[1] as is mostly the case in the Near East and North Africa.[13] Mechanization also helps build resilience to health shocks affecting family or hired labour, which can in turn severely disrupt agricultural production.[14]

Tailoring motorized mechanization solutions to local needs is key to enhancing the business case

The evidence presented thus far suggests there is continuous scope for the use of motorized mechanization, especially where adoption to date has been slow or absent. It may be possible to leapfrog the mechanization stage and pass directly to digital automation and robotics with AI, but this is only really feasible in a few high-income countries (see Chapter 2); in contrast, a wide variety of motorized mechanization solutions are available to low- and lower-middle-income countries. A large part of the business case for motorized mechanization depends on context and the agricultural machinery considered for adoption. For large farms located on plain terrains, agricultural producers can benefit from large machinery such as combine harvesters and four-wheel tractors. However, small-scale producers may benefit more from small-scale

BOX 10 ENHANCING THE RESILIENCE OF SMALL-SCALE PRODUCERS THROUGH SMALL-SIZED MOTORIZED MECHANIZATION

In response to the 2015 cyclone and subsequent drought in 2016 in Rakhine, Myanmar, FAO, together with the Government of Myanmar, began a one-year project (2016/17) funded by the Government of Japan. Its goal was to improve household food security and increase resilience of small-scale producers in conflict and natural disaster-prone areas. Among the project components, FAO increased the availability of small farm machinery such as two-wheel tractors and water pumps. The mechanization activities were rolled out in 7 townships and 73 villages affected by flood and conflict in Rakhine. In total, the project distributed 55 two-wheel tractors and 94 water pumps, and provided training on the use and maintenance of small machinery. In addition, 146 village members received training as tractor operators.

The results reveal significant benefits for farmers and the community in general, with lower land preparation costs (USD 1.6/ha) and major savings in time (two-wheel tractors were seven times faster than draught animals). Timely land preparation further translated into increased resilience, as farmers improved their ability to cope with erratic weather and labour shortages, and respond to other hazards. Other benefits in terms of improved incomes and food security came from cultivation of legumes and vegetables for both household consumption and markets, thanks to irrigation from water pumps installed during the dry season.

Other small machinery such as dryers, threshers and reapers can have a positive impact on the resilience of small-scale producers while creating rural job opportunities and reducing work burdens. However, the selection of one technology over another must depend on the local context and a needs assessment. Furthermore, technical support is vital, as well as the availability of repair and maintenance shops and technicians in the villages or surrounding areas, to sustain mechanization services. Finally, the project concluded that results would have been greatly enhanced by increased attention to women and youth.

SOURCE: FAO, 2019.[24]

machines such as small four-wheel and two-wheel tractors, which are both less costly and more considerate of environmental sustainability.[18] These machinery solutions have proved key for narrowing the mechanization divide in Asia.[2, 19, 20] They are better adapted to small farms as they can manoeuvre around tree stumps and stones, in addition to being easier to operate, maintain and repair, and more suitable for microfinance. Furthermore, they can be used to pull rippers and direct seeders for mechanized conservation agriculture, thus contributing to improved climate resilience.[21, 22] Box 10 provides a concrete example of the benefits of small-scale machinery in building the resilience of small-scale producers in Myanmar.

Recent innovations tailoring motorized machinery to local needs go beyond simply adapting the size of the machinery to meet local challenges. Countries in the Near East and North Africa increasingly face water shortages that limit agricultural output growth. Box 11 describes the case of mechanized raised-bed planting in Egypt – an example of innovative synergies between mechanization implements and improved inputs and field practices, which together raise yields while saving scarce natural resources.

Agricultural mechanization is currently high on the policy agenda of many low-income countries, especially in sub-Saharan Africa, where it was neglected for some time following the earlier failures of state-led mechanization programmes.[23] There are ongoing debates about which technological pathway governments and development partners should support, especially

BOX 11 MECHANIZED RAISED BEDS IN EGYPT FOR IMPROVED PRODUCTIVITY AND SUSTAINABLE WATER USE

Mechanized raised-bed planting is an effective means of increasing productivity and crop yields, saving scarce water, and reducing waterlogging through better drainage. When applied to wheat production in Egypt, the technology was associated with a 25 percent increase in productivity due to higher yields, 50 percent lower seed costs, a 25 percent reduction in water use, and lower labour costs. As a result, a mechanical raised-bed programme is now a component of Egypt's national wheat campaign, and it is estimated that by 2023 approximately 800 000 ha of wheat will be planted with the technology. It is further estimated that over a 15-year project horizon, the benefits will exceed USD 4 billion, mostly accruing to over 1 million Egyptian wheat producers. Other benefits include reduced wheat import dependency (by more than 50 percent by 2025) and increased water productivity on more than 200 000 ha of water-scarce land.

For positive results, it is essential that this technology be adapted to local conditions and that the precise components of the technology package vary according to the specific context. In Egypt, a long-term evaluation resulted in a defined technology package comprising: an improved wheat variety, seeded at a rate of 108 kg/ha; sowing dates in the period 15–30 November; bed preparation and planting using a mechanized plough/seeder; and nitrogen fertilizer applied at a rate of 168 kg/ha. When well adapted, the technology is particularly attractive to small and medium-sized farms. It is relatively affordable, can easily be implemented by small tractors, is easy to maintain with locally available crops, and allows both monocropping (e.g. wheat or rice) and multicropping for interspaced crops (e.g. corn, sugar beet, fava beans).

SOURCES: Alwang *et al.*, 2018;[25] Swelam, 2016.[26]

where automation has not yet been introduced (e.g. most of sub-Saharan Africa and many mountainous areas). There is no one-fits-all approach; instead, there will be a best fit under certain conditions.[18] Decisions to automate agricultural operations should take into account local conditions, including opportunities and barriers, and associated market demand for mechanization technologies.

The (continued) importance of manual and animal draught power

Despite the benefits of motorized mechanization, there is evidence that manual technologies and animal traction can still play an important role. Animal traction can be an important source of power for very small and fragmented farm holdings, especially if pasture and water are available and animal diseases can be contained.[18] Animal traction makes it possible to integrate livestock and crops, and optimize resource use, for example, using manure for crop production and crop residues for animal feeding. For many producers, it is also the best immediate strategy to overcome power shortages before transitioning to motorized mechanization.[21, 27] For the majority of African small-scale producers, the transition to animal draft power would mean real progress.[18]

A similar reasoning can be applied to advanced manual tools – that is, tools that rely principally on human power but are intelligently designed such that maximum results are achieved with minimum effort. Such tools are particularly suited to farms where machinery is difficult to operate. They save labour – freeing up time for rest or for other income-generating activities – reduce costs and drudgery, and improve resilience. Box 12 (p. 46) provides a concrete example of the benefits of such machinery, reviewing the impacts of the manual drum

BOX 12 SAVING TIME, EFFORT AND MONEY WITH DRUM SEEDERS IN THE LAO PEOPLE'S DEMOCRATIC REPUBLIC

In Sayabouly, Lao People's Democratic Republic, a drum seeder was field tested to support sustainable intensification of rice production in a programme implemented by the Government and small-scale producers, with support from FAO. A drum seeder is a manual tool used for sowing pregerminated rice seeds. It is more attractive than the traditional planting methods of manual transplanting and broadcasting. Indeed, it reduces time spent on planting by 90 percent, increases labour productivity by more than 40 percent, reduces production costs by 20 percent, and saves seeds at a rate of more than 60 percent. The drum seeder is also an environmentally friendly technology, as it does not require fossil fuels and is suitable for agroecological approaches, such as rice–fish systems. The drum seeder increases farmers' resilience to climate change, enabling them to perform timely planting with more flexibility in choice of planting time. Moreover, should a natural disaster destroy recently planted rice, the farmer can repeat the drum seeding easily and speedily.

SOURCE: Flores Rojas, 2018.[28]

seeder on profitability, efficiency, environmental sustainability and resilience in the Lao People's Democratic Republic and Nepal.

In summary, the potential use of draught animals and advanced manual tools depends on the context. While less powerful than tractors, they can still help overcome labour bottlenecks, deliver higher crop yields and allow land expansion. In many cases, advanced manual tools and animal traction are probably the best options for increasing power supply. A best fit framework can help governments and development partners better understand which technological pathways to promote, together with the accompanying institutions and investments, taking into account the existing agroecological and socioeconomic conditions of their country's farming systems. As innovation processes related to farm mechanization unfold in response to these changing conditions, the pathways need to adapt and adjust. ■

INVESTIGATING THE BUSINESS CASE FOR DIGITAL AUTOMATION: LESSONS LEARNED FROM CASE STUDIES

The previous section discussed the business case for motorized mechanization, highlighting its potential to enhance resilience, productivity and resource-use efficiency, and to reduce human drudgery and labour shortages. It also emphasized that, in some circumstances, manual and draught power can still generate progress. This section examines the business case for investing in digital automation technologies. Improvements in productivity, resource-use efficiency and labour savings have been key drivers of the adoption of these technologies. However, they are not without costs, and many require large upfront investments and specific skills and knowledge to operate them effectively. Farmers may also be sceptical about investing in certain innovations if they deviate from traditions

BOX 13 THE EVOLUTION OF THE BUSINESS CASE FOR ROBOTIC MILKING SYSTEMS

The adoption of livestock automation technologies is on the rise, especially robotic milking systems in high-income countries.[32] Economic benefits can result from both labour savings (estimated at 18–30 percent)[33] and increased milk production (10–15 percent per cow).[33, 34, 35] Evidence indicates that small and medium-sized dairy farms (100–300 cows) were the first to adopt robotic milking, embraced by younger farmers attracted by better and more flexible working conditions (i.e. that do not require animals to be milked two or three times every day). The business case for milking robots is based more on flexible work schedules and better life quality for smaller farms than on purely economic benefits. There is, however, more recent evidence that larger dairy farms (with over 1 000 cows) are adopting robotic milking systems in response to labour shortages.[29] The upfront costs of robotic milking machines make them non-viable for very small farms, found mainly in low- and middle-income countries, where – on the other hand – the technology may be attractive to commercial livestock farms with relatively larger herds.

and cultural and social norms. In this case, governments and service providers may need to intervene to communicate the expected benefits of investing in these technologies. This may involve trials, experiments and cost–benefit analysis to generate the necessary confidence.

An important challenge in assessing the business case for digital automation technologies in agriculture is the scarcity of information on their profitability. With the exception of motorized mechanization, digital automation technologies are new, and data on their adoption are dispersed and inconsistent (see Chapter 2). Likewise, information about the economic benefits varies widely, depending to some extent on the level of adoption of the various technologies in agriculture.[29] For this reason, the discussion herein is based mainly on the findings of two technical studies commissioned for this report.[30, 31] These relied, in turn, on 27 case studies, built on interviews with key informants across the world. They thus provide mostly qualitative evidence, based on the experience of digital automation service providers or – albeit to a lesser extent – representatives of agricultural producers. The 27 case studies cover all world regions and agricultural production systems (crops, livestock, aquaculture and agroforestry) and represent novel – yet scalable or already scaled – agricultural solutions related to motorized mechanization and digital automation technologies, targeting small- to large-scale farms. The case studies reflect the perspective of service providers rather than of agricultural producers as the final users. (See Annex 1 for a brief description of each case study and the methodology applied.[a])

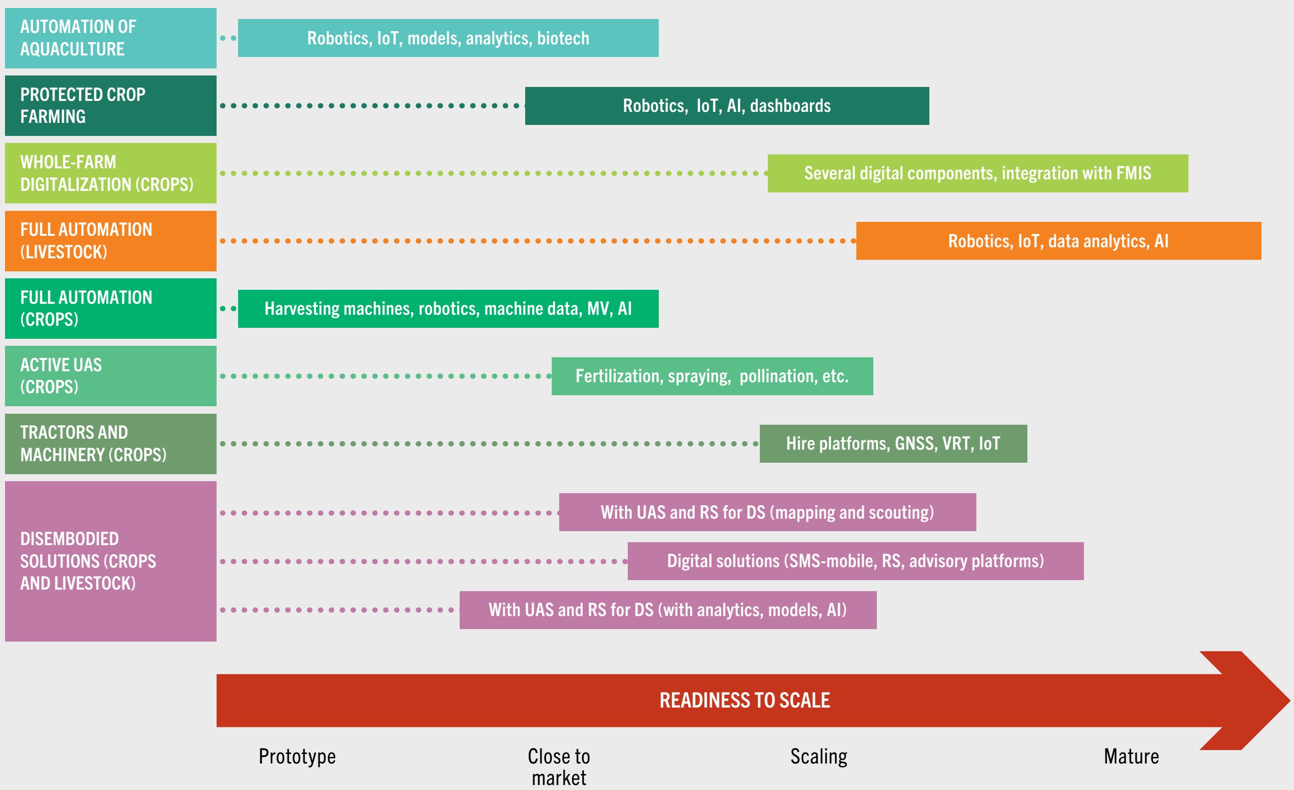
Readiness to scale of agricultural automation technologies: a framework

The technologies in the 27 case studies around the globe vary widely in their readiness for implementation. Figure 6 (p. 48) shows the four stages of readiness to scale of each type of technology. Solutions at the maturity stage mostly relate to livestock automation and whole farm digitalization. Fully automated equipment and machinery adapted to animal production have great prospects in terms of cost savings and raising productivity (see Box 13).

Among the technologies that are scaling, Figure 6 presents a variety of categories, including disembodied digital solutions (see Glossary), uncrewed aerial systems (UAS, commonly known as drones) and remote sensing, mechanization solutions with global navigation satellite systems (GNSS), variable rate technologies (VRTs), and solutions for protected cultivation. The extensive literature dating back to the 1990s and supporting the business

a For a more detailed description, see McCampbell, 2022[30] and Ceccarelli *et al.*, 2022.[31]

FIGURE 6 THE READINESS TO SCALE OF DIGITAL AUTOMATION TECHNOLOGIES ALONG A SPECTRUM



NOTES: UAS –uncrewed aerial system; IoT – internet of things; AI – artificial intelligence; FMIS – farm management information system; MV – machine vision; GNSS – global navigation satellite system; VRT – variable rate technology; RS – remote sensing; DS – decision support. Readiness to scale is divided into four stages: (i) prototype – concept has been tested and demonstrated in limited trials; (ii) close to market – solution functions under real production settings, and the service provider is investigating one or more business models to reach clients; (iii) scaling – the solution has been adopted by several end users/clients, and one or more business models are profitable; (iv) mature – the solution has a dedicated client base, one or more business models are profitable, and demand is growing.
SOURCE: Ceccarelli *et al.*, 2022.[31]

case for technologies using GNSS[36] facilitated its adoption. This was not the case for VRT, however, as evidence related to profitability is mixed (see Chapter 2).[29]

Solutions still at the close to market or prototype stages mostly include advanced automation and robotics for both field and protected agriculture, as well as aquaculture, in addition to UAS for sensing and input application. Some technologies have already proved to be profitable and are replacing manual labour in high-income countries, performing a range of tasks from irrigation, pest scouting, harvesting and weeding, to fruit selection and picking; in contrast, there is no evidence of their adoption in low- and middle-income countries.

Many of the solutions are still in the early stages of development and commercialization, and their business case is yet to be determined. From the 27 case studies, some are still at the prototype stage (GRoboMac and Seed Innovations), while others propose solutions at the close to market stage (e.g. Atarraya, Food Autonomy, GRoboMac, Harvest CROO Robotics, Hortikey, UrbanaGrow).

BOX 14 THE IMPACT OF A DIGITAL ORCHARD SPRAYER IN THE EUROPEAN UNION: EVIDENCE FROM POLAND AND HUNGARY

The European Union has invested EUR 20 million in SmartAgriHubs, which aims to digitize European agriculture. Part of this project is the Smart Orchard Spray Application, designed to leverage smart spraying technologies embedded with internet of things (IoT) devices for the optimization of efficiency and treatment quality in orchards. IoT-enabled sprayers can significantly reduce use of plant protection products by adapting automatically to specific field zones as well as individual plant conditions. The integration of the Smart Orchard Spray Application cloud into farmers' existing processes and software solutions further increases efficiency, profitability and sustainability of food production. Being traceable, it can also improve food safety and quality levels. Each year, producers are able to save EUR 517/ha on fuel and reduce pesticide costs by 25 percent as well as increase revenue thanks to better decision-making.

SOURCE: IoF, 2019.[37]

There are several cases where solutions are scaling (e.g. Aerobotics, Cattler, Cropin, ioCrops, SeeTree, SOWIT, TROTRO Tractor, Tun Yat) or mature (Lely, ZLTO, ABACO, Egistic and Igara Tea). See Annex 1 for more details on the readiness to scale stage of each technology.

A closer look at the case study results

From a service provider perspective, one of the most important findings emerging from the case studies is that only 10 of the 27 businesses appear to be profitable and financially sustainable. These are in the mature phase (see Figure 6), mostly based in high- or upper-middle-income countries and serving large-scale producers, although exceptions exist (e.g. a tea business in Uganda that targets small-scale tea producers). The fact that most businesses operate in high-income countries – despite sometimes originating in upper-middle-income countries, as is the case of Aerobotics in South Africa, Atarraya in Mexico and Cattler in Argentina – suggests that the business case for investing in these technologies is stronger in high-income countries.

From a user perspective, more than one-third of the case studies suggested that farmers are benefiting from these solutions through gains in productivity and efficiency, as well as new market opportunities. For example, in Uganda a digital solution aimed at improving the productivity and efficiency of tea (Igara Tea) has enabled 7 000 farmers to increase production by 57 percent over five years. A hire service company in Myanmar (Tun Yat) testifies that each farmer using their services generates approximately an additional USD 240 per year; this is primarily due to higher threshing quality and improved handling with fewer post-harvest crop losses.[31] In three other cases – one focusing on livestock (GARBAL), another on mechanization hire services for crop production (TROTRO Tractor), and a third on fruit trees (SeeTree) – although evidence of their financial sustainability is still weak, the fact that farmers are already paying for the solutions suggests there is a business case for investing in them. Where information on the business case is lacking, the number of users or investments attracted by a solution can be an indication of its financial sustainability. For example, in five cases, service providers report the number of producers using their services (Aerobotics, Cattler, Egistic, Lely, SOWIT), and in two cases they report the investments the company has attracted (Atarraya and Harvest CROO Robotics).

The development of many of these technologies is still in the preliminary stages, with the business case yet to be determined. More evidence from cost–benefit analysis is needed to better understand how to tailor technologies to given conditions (see Box 14 for a European example).

The information gathered to date allows to understand some of the drivers of and barriers to adoption of digital automation. First, a rise in the rate of adoption of a solution suggests not only that the technology can perform the agricultural operations successfully, but also that farmers can handle them. One case study on crop and livestock digitalization (ZLTO) illustrates how agricultural producers often have little time to familiarize themselves with new solutions, especially when not in-built in the machinery; in contrast, when new agricultural machinery is already equipped with GNSS devices, the adoption of this technology – for more precise positioning of the machine during operations – is facilitated.[31]

One of the main reasons why agricultural producers struggle to employ digital automation technologies is widespread digital illiteracy and lack of awareness of the potential of these solutions. In addition, there is a reluctance to change, generally associated with an ageing farm population. These factors emerge in case studies across the world (Abaco in Europe; ioCrops in the Republic of Korea; Seed Innovations in Nepal; SeeTree in the Americas, Europe and South Africa; TraSeable Solutions in Fiji and other countries in the Pacific; and Tun Yat in Myanmar) and are not confined to low- or middle-income countries. For this reason, generational change is indicated as a driver of adoption, with young farmers perceived as essential to move a family farm towards digitalization and advanced automation. Evidence from three case studies in the Republic of Korea (ioCrops) and the United States of America (Atarraya and Cattler) suggests that young farmers are more attracted by innovations. Capacity building is, therefore, essential to drive adoption.

Another driver of or barrier to adoption is attitude to risk. Two case studies (Aerobotics and Cattler) indicate that large-scale South African and Argentinian producers, respectively, are generally more dynamic and open to digital automation solutions than their counterparts in the United States of America. This is primarily because the latter feel less exposed to market risks, while the former need to be more competitive on the international market. Indeed, the dynamism and risk-taking attitude of the Argentinian and South African producers are probably driven by exposure to international competition, leading to higher adoption of technologies.

Other driving factors – also mentioned in Chapter 2 – include labour shortages (including seasonal, as indicated by GRoboMac, Igara Tea, SOWIT and TROTRO Tractor), safer working conditions and reduced drudgery (see the cases of Lely and SOWIT). An interesting observation by TROTRO Tractor is that labour shortages are a strong adoption driver for female farmers, who have more difficulty finding workers than do male producers. Furthermore, women usually perform operations later as they access machinery only after their male counterparts have finished using it. Solutions like TROTRO Tractor allow women to access equipment independently of its use by men.[30] Another interesting finding was that the COVID-19 pandemic was considered to be a driving factor in two cases, because the need to avoid or reduce physical contact increased the value of digital solutions (see Box 15). ■

BEYOND THE BUSINESS CASE: THE ROLE OF INVESTMENTS, POLICIES AND LEGISLATION

The previous sections reviewed evidence for the business case for agricultural automation technologies. It showed that motorized mechanization has generally brought considerable benefits to agricultural producers and, when tailored to local needs, it can also generate sustainability benefits through increased resource-use efficiency and saving of scarce resources. It also highlighted – notwithstanding the limited evidence – important lessons that promote a better understanding of the business case for digital automation technologies.
The overriding message is that the business case is still weak or immature for a number of reasons, ranging from farmers' reluctance to take risks, as the technologies are still new, to lack of the digital literacy necessary to operate them.

BOX 15 COVID-19 SPURRED INTEREST IN DIGITAL TECHNOLOGIES: EVIDENCE FROM TWO CASE STUDIES

Of the 27 case studies prepared for this report, two highlighted the role of the COVID-19 pandemic as a particular driver of adoption. TROTRO Tractor, operating in several sub-Saharan African countries, mentioned the pandemic as an important driver of uptake of their services. Their platform enabled crop production in spite of movement restrictions and a system of e-vouchers facilitated adoption.

TraSeable – which offers a mobile app with simple digital tools allowing farmers in the Pacific to keep up to date on current affairs in the agriculture industry – also cited the COVID-19 pandemic as an enabling factor of adoption. The app was released in 2020 and, according to the interviewee, the remarkable increase in downloads has been in part due to the limitations on face-to-face contacts to control the COVID-19 pandemic.

SOURCE: Ceccarelli *et al.*, 2022.[31]

This section takes the analysis one step further and goes beyond the business case, looking at structural factors (i.e. policies, legislation, public investments) that shape incentives for agricultural producers and providers of automation technologies and encourage them to assume the risk of adoption. In Africa, for example, where adoption has been lower than in other regions, the demand for motorized mechanization in agriculture is already high and continues to grow. However, lack of knowledge and of machinery operation and maintenance skills, combined with trade regulations, customs policies and poor infrastructure, hold back adoption.[19] The poor infrastructure in many African countries also hampers access to urban markets and raises prices of mechanization services,[38] especially for small-scale producers who have small, fragmented plots,[9] decreasing the incentive to invest in technologies.[19, 39] Improving transport infrastructure and road networks reduces costs for producers in accessing technologies, spare parts, repairs and fuel, and facilitates the emergence of service markets.[40] By improving electricity and renewable energy supply, governments can also support the uptake of motorized mechanization technologies such as solar-powered pumps for irrigation and machinery for processing and preservation.[19, 41, 42]

Likewise, poor infrastructure hinders adoption of digital automation technologies, especially in low-income countries.[30, 31] Limited or absent connectivity and other enabling infrastructures, including electricity and data infrastructure, are consistently reported as barriers in most low- and middle-income countries, including in some of the case studies reported above (e.g. Atarraya in Mexico, and GARBAL in Western Africa). Rural populations are generally disadvantaged in terms of internet and smartphone access, and thus have limited access to valuable services. In contrast, when such investments are in place, they lead to increased adoption – as demonstrated by two case studies (TraSeable in Fiji, and Tun Yat in Myanmar), which show how rapid mobile penetration has created a favourable environment for adoption of digital automation solutions.[31]

Land tenure is important to technology adoption as it can both affect access to finance and shape producers' attitudes towards taking risks. Agricultural mechanization tends to be first adopted by large farms characterized by better tenure security, easier access to credit, extension and markets, and the ability to take risks.[43] There is evidence from across the globe that large farms often mechanize earlier than small farms.[4, 44, 45, 46] Nevertheless, small farm size does not have to be a barrier to adoption if there is the possibility for the evolution of technological and institutional solutions designed for mechanization on small farms.

For example, migratory mechanization services – that is, hire services that travel long distances, sometimes across different ecological zones and national borders, to meet demand in different places – are popular in many Asian and some African countries, although, again, undermined by poor infrastructure and by border issues in many African countries.[4, 19, 47, 48]

In the available literature and the 27 case studies commissioned for this report,[30, 31] legislation is often reported as a limiting factor, generating restrictions and involving heavy bureaucracy. This affects the dissemination and adoption of various solutions, such as UAVs, sensors and weather stations, in low- and middle-income countries. This is also true for some upper-middle- and high-income countries, illustrated by restrictions on flying permits in the European Union and South Africa (mentioned by Aerobotics), autonomous machine speed restrictions in the United States of America,[31, 49] and import restrictions for drones and IoT devices (mentioned by Igara Tea in Uganda, and SOWIT in Northern Africa and Western Asia). Legislation also affects uptake of digital automation technologies in specific sectors, such as protected crop production and aquaculture. There is a general perception that protected cultivation and fish farming are not natural, and they are therefore not favoured by sectoral public policies. For example, European Union legislation does not classify as organic chemical-free food production under protected agriculture.[31]

Other important factors limiting adoption of digital technologies are the lack of policies and legislation on data sharing and related infrastructure (mentioned by GARBAL in Western Africa), and insufficient public policies, legislation and incentives in support of innovations (mentioned by SOWIT in Northern Africa) and public–private partnerships (mentioned by Egistic in Kazakhstan). On the other hand, in one case (Atarraya in Mexico), lack of regulations was described as positive; according to the interviewees, regulations would lead to ineffective bureaucracy.

In other contexts, legislation is mentioned as a driver of adoption. In the Republic of Korea, for example, evidence from the ioCrops case study shows how public investment in high-tech farming systems, in the form of trials, demonstrations and capacity building, facilitates dissemination of agricultural digital automation. In Nepal, public insurance policies favour scaling of digital and automation solutions (see the Seed Innovations case study).

Governments, through investments, policies and legislation, can play a major role in creating and facilitating an enabling environment for innovations, and in ensuring that technologies are available and accessible to all and that they meet socially desirable objectives, such as inclusiveness and environmental sustainability. In many contexts, policies, legislation and public investments are necessary to address constraints beyond the control of private actors. This is discussed in more detail in Chapter 5. ■

FUTURE TRAJECTORIES OF AGRICULTURAL AUTOMATION: CONSIDERATIONS FOR INCLUSIVE ADOPTION AND ENVIRONMENTAL SUSTAINABILITY

This section discusses potential future trajectories of agricultural automation technologies for different types of countries and farms, in the light of structural factors that can shape the dissemination and adoption of these technologies. It looks at prospects for making mechanized agriculture more sustainable. The benefits of motorized mechanization have brought some negative environmental impacts, *inter alia*, crop land expansion taking place at the expense of forests or pastures of savannah land.[50] Furthermore, it discusses the potential for automation of small-scale agricultural production and some of the economic and social implications of future automation trajectories.

Prospects for highly mechanized agriculture to become more sustainable

In high-income countries, but also on many commercial farms in low- and middle-income countries, agriculture is already highly mechanized, partly in response to scarcity or seasonality of agricultural labour. For economies of scale, large machinery is mostly used. However, evidence shows how this has caused soil erosion, deforestation, increased greenhouse gas (GHG) emissions and biodiversity loss.[51] In many countries, service providers often use large machinery and mostly serve those farmers who have cleared trees and tree stumps from their plots;[40, 52] but the removal of farm trees and altered cropping patterns triggered by mechanization can contribute to soil erosion.[7] Moreover, the soil erosion and degradation caused by heavy large machinery also leads to declining yields.[38, 53] Using large tractors has fundamentally changed the face of rural landscapes as producers often enlarge and reshape plots, leading to a loss of farmland diversity and biodiversity for food and agriculture.[50, 52] Motorized mechanization is associated with reduced crop diversity as it encourages production shifts towards easier-to-mechanize crops, such as wheat, maize and rice.[4] Regrettably, farmers often do not adopt biodiversity-enhancing practices, such as conservation agriculture, intercropping and rotations, because they are very labour-intensive.[54] Mechanization often leads to more specialization and less commodity diversification, and this can reduce resilience.[55]

To address these challenges, innovations in motorized mechanization can be tailored to smaller, lighter machinery which can reduce soil compaction and mitigate negative environmental impacts. Scale-appropriate automation adapted to local conditions can play an important role in reducing those effects. Autonomous robots can help reduce chemical and energy use, as well as GHG emissions if powered by renewable energy.[56] Applied technical and agronomic research can help explore mechanization solutions that best fit local agroecological conditions. Governments can also use policies to promote access to machinery and equipment proven to be more environmentally friendly.[38, 40]

Conservation agriculture can reduce soil erosion, using rippers or direct planters to replace ploughs. Coupled with crop rotation and permanent soil covers, these minimum soil disturbance practices can reduce soil erosion by up to 99 percent.[57] Conservation agriculture appears to be a way forward for agriculture, but locally adapted solutions are needed to avoid some of the challenges.[58] In this context, in May 2019, regional training on appropriate mechanization for conservation agriculture was co-organized by the Centre for Sustainable Agricultural Mechanization – a regional institution of the United Nations Economic and Social Commission for Asia and the Pacific – and partners in Cambodia.[59]

Transitioning to renewable energy is important from not only an environmental perspective but also a financial one. The case studies of TROTRO Tractor in Ghana and Tun Yat in Myanmar identify increasing and unstable fuel prices as important barriers to adoption (see Annex 1). Moreover, renewable energy offers new potential to power automation along the value chain and may be particularly attractive for remote rural areas.[60] However, not all operations are efficiently run using currently available renewable energy sources. For example, electricity is not suitable for power-intensive land preparation. Research is needed to explore which off-grid renewable energy solutions can most efficiently power each type of machinery along the value chain.[51]

Chapter 2 showed that labour shortages, as well as the need for increased efficiency and resilience to climate shocks and stresses, are driving adoption of digital automation technologies and robotics with AI on highly mechanized farms. The evidence points to environmental benefits from these technologies and can be useful for guiding future innovations; however, given the limited data and the fact that many solutions are still in the early stages of development and commercialization (see Figure 6 on p. 48), it is not possible to generalize about the potential benefits. As these technologies are further developed and more widely adopted worldwide, including through shared use or hiring services, adoption may expand to smaller-scale farmers.[31]

BOX 16 SOLVING LABOUR SHORTAGES IN STRAWBERRY FIELDS USING HARVESTING ROBOTS

Automated harvesters can autonomously pick, inspect, clean and pack crops. Harvest CROO Robotics was developed in the United States of America to solve the problem of labour shortages in the strawberry production industry through a robotic harvester. Each harvester has 16 independently working robots, which navigate through the farm, inspect the quality and ripeness of the strawberries, and then proceed to pick, clean and pack them. This technology thus completely replaces manual labour in the diagnosis, decision-making and performing of this task.

Harvest CROO Robotics is one of the few known strawberry harvesting solutions currently available in the United States of America. It has attracted investment funds from about 70 percent of national strawberry growers – typically large-scale – in response to concerns related to both lack and cost of labour. A pay-as-you-go system is adopted, with producers' payments related to the volume harvested.

Once the technology scales, the aim is to have a fleet of harvesters that can be controlled remotely from an operations centre; in addition to picking, inspecting, cleaning and packing, it will also be possible to collect data to be shared with the growers.

SOURCE: Ceccarelli *et al.*, 2022.[31]

In high-income countries, robots are replacing manual labour in tasks ranging from irrigation, pest scouting, harvesting and weeding, to fruit selection and picking. For example, in one case study (Harvest CROO Robotics), the service provider noted that 70 percent of strawberry producers in the United States of America have already invested in their project to develop strawberry harvesting robots (see Box 16). Robotics technologies can lead to environmental benefits if they reduce or eliminate the use of pesticides and herbicides. Autonomous crop robots save labour, improve the timing of operations, optimize quantities of applied inputs, and reduce soil compaction, especially when using smaller swarm robots. Based on a review of 18 studies, autonomous crop robots for harvesting, seeding and weeding are economically feasible in certain circumstances.[61, 62, 63] Swarm robots, in particular, offer a cost advantage on farms with small, irregularly shaped fields.[64] Policymakers and producers need to gain a clearer perception of these benefits in order to achieve increased investments in development of the relevant technologies.

The potential of automation for unmechanized or scarcely mechanized small-scale agriculture

Small-scale agricultural producers comprise a highly diverse range of agricultural production units. Some may be highly commercialized and use modern technologies, including motorized mechanization, while others practise subsistence farming with simple tools. In general, they rely heavily on family labour and mechanize only part of their farm operations – if at all. In many contexts, however, they could benefit from the expansion of rental machinery markets. The rental market tends to be dominated by large machinery that migrates across various agroecological zones within and across national borders. In order to take advantage of these services, producers have had to adapt their farms and production systems to conform to this focus on large-scale agricultural production. There is an urgent need, therefore, to find tailored solutions to first, address past negative impacts of mechanization and second, facilitate its expansion, thus increasing productivity in a sustainable manner.

BOX 17 THE BUSINESS CASE FOR WOMEN ADOPTING MOTORIZED MECHANIZATION: EVIDENCE FROM NEPAL

There are three ways in which motorized mechanization can empower women and respond to their needs. Women may be: (i) customers of mechanization service providers – reducing the drudgery of farm work and freeing up time for resting or other social or economic activities; (ii) operators of machinery and equipment or staff in a mechanization hiring business – using their technical skills to earn an income; and (iii) entrepreneurs managing their own mechanization hiring services agribusiness – providing mechanization services to other farmers and generating revenue.

A report recently produced by FAO provides information on market-tested machinery and equipment for crop production and post-harvest operations in Nepal. The goal is to promote and support women's access to motorized agricultural mechanization as operators and/or managers. Examples of motorized equipment adopted by women include the following:

- The **power weeder** comes in several types and sizes. It performs weeding and interrow cultivation of wide-spaced crops such as vegetables, maize and sugar cane. According to the report, compared with manual labour, a single machine can weed a very large area. Women maize farmers in Dang district reported they could save NPR 10 000 (USD 84) per bigha (an area corresponding to 0.66 ha) by using the large power weeder rather than paying for manual weeding.
- The **mobile thresher** is an engine-powered thresher used for bundled rice or wheat. It eliminates the drudgery of threshing by hand, saves time and greatly increases the amount of grain threshed (8–10 times more than manual threshing). Due to its high threshing rate, it is suitable for individual service providers or custom hiring centres.
- The **maize sheller** is used to separate the grain from the cob. It eliminates the drudgery and pain of shelling by hand, saves time and greatly increases the amount of grain that can be shelled in a given time (30–40 times faster than manual shelling). Shelled maize grain also occupies less space than maize on cobs, making its storage easier.

SOURCE: Justice, Flores Rojas and Basnyat, 2022.[66]

Small machinery is a better fit for small-scale agriculture

Technological solutions such as small two-wheel and four-wheel tractors were key for increasing mechanization in Asia.[2, 19, 20] Two-wheel tractors are likely to be more profitable and better adapted to small farm sizes. They can manoeuvre around tree stumps and stones and minimize biodiversity loss since they do not require substantial field clearing. They are also easier to operate, maintain and repair, and are more suitable for microfinance.[22, 65] The same reasoning can be applied to a wider range of small agricultural motorized machines, which are more biodiversity-friendly as they do not require substantial reshaping or clearing of agricultural fields. There may also be benefits in terms of gender equality (see Box 17, which presents successful examples of small motorized machines used by women in Nepal), with potential savings in labour and resources, and an increase in women's empowerment.

Digital automation technologies can provide multiple benefits, but there are many challenges for small-scale agriculture

The increasing research on precision agriculture in low- and lower-middle-income countries highlights the need to harness the potential of digital automation technologies for small-scale agriculture.[67, 68, 69] To spur adoption, some service providers consider offering free advisory services to small-scale producers, basing their business model on the potential income generated by selling the data collected from farmers.[31] This option may be an encouraging starting point, provided it meets data sharing and privacy standards. Furthermore, there is willingness among farmers to grow the same crop on adjacent areas, to share the payment for UAS-based advisory services (e.g. in Burkina Faso,[70] Ghana[71] and Rwanda[72]).

Digital technologies have also provided a boost to agricultural advisory services for small-scale producers.[30] In low-income countries, the most frequently deployed digital solutions are disembodied digital tools, due to their low cost, but impacts on productivity and environmental sustainability are still largely unknown. Moreover, the available data are insufficient to generate the tailored advice needed by small-scale producers. Further, the low level of digital skills leads to difficulties related to scaling, and there is also a strong digital divide with women and other vulnerable groups having poorer access to solutions. Another emerging issue in many countries is the absence of data privacy and protection legislation, which may lead to misuse of data by third parties.[73]

There is also research on using drones to apply inputs such as fertilizers and chemicals on small farms (including in Africa);[74, 75] commercialization has begun, but the applied solutions are mostly map-based with very little autonomous decision-making capacity. Benefits of drone-based input application include improved precision, reduced pesticide exposure, the possibility of application in fields unreachable by equipment (because the field is too wet or difficult to access), and avoidance of damage to standing crops due to moving equipment. Profitability depends on the cost of equipment, effectiveness of application, savings in inputs due to spot application, and improved yields through reduced damage compared with use of ground-based machines. The availability and affordability of drones are key for small-scale agricultural producers, who do not usually own their own equipment. These technologies entail many challenges, such as refilling the spray tanks, fertilizer bins or seed hoppers, recharging batteries, employing pesticide labels for spot application, training users, and managing drift to non-target areas. Overcoming these issues requires technical and institutional capacities, and this in itself can be an additional challenge in many low- and middle-income countries.[76]

Given that one of the barriers to adoption of digital automation by small-scale producers is cost, improved technologies, scale and innovative business models are especially important to enhance affordability. This issue is clearly illustrated by computers and smartphones: once manufactured in large volumes, they became much less expensive, paving the way for their increased use in precision agriculture.[31] In some contexts, water scarcity is a challenge to agricultural production; in Mali, a case of successful adoption of automated greenhouses (where a computer controlled water and pesticide applications) shows that such technologies can lead to greater efficiency in water and input use.[77]

Precision livestock farming

Precision livestock farming is mainly applied in intensive systems in high-income countries where sensors monitor the health, reproductive status and behaviour of animals. Electronic tagging and blockchain are increasingly used to improve product quality by facilitating traceability of livestock marketed from extensive systems.[29] However, these advanced technologies are still too costly for most livestock producers in low-income countries, where precision livestock technologies focus more on virtual fencing systems with audio alerts, electric shocks or other prompts to keep animals within boundaries. These technologies reduce drudgery and labour requirements, facilitate reproductive management, collection of information and intensive management, and potentially eliminate the need for physical fencing. In addition, GNSS help livestock producers locate animals grazing in large open pastures; they can be linked to sensors to monitor temperature, movement and other indicators of health and reproductive status. Yet, individual GNSS for each animal are currently too costly for extensive grazing systems. As with crops, both re-engineering (to achieve lower costs and mass production) and innovative business models are needed to make these technologies available for extensive livestock production systems in low-income countries.[29] Apps for accessing useful information related to livestock management offer great potential for precision livestock farming.[78] There is anecdotal evidence from Kenya that pastoralists are increasingly using such apps to indicate the state of grasslands and help find sufficient feed when moving around with their herds.[79] Satellite data-based apps can help determine and report animal diseases, allowing livestock producers and raisers to make rapid, targeted interventions.[78]

Asset-sharing arrangements for mechanization

Digital tools also hold great promise for improving asset-sharing of agricultural mechanization for small-scale producers. For example, GNSS tracking devices and fleet management software – such as those following the Uber-type solutions for ride-hailing – promise to significantly reduce the transaction costs of small-scale producers and machinery service providers and can facilitate the supervision of machinery operators by service providers.[29] Examples include TROTRO Tractor in Africa, and Tun Yat in Asia. These initiatives face various challenges, such as poor roads and connectivity, and the fact that demand is seasonal, peaking in specific periods. Service providers are considering the use of institutional innovations to overcome some of the challenges. For example, by using booking agents to pool small-scale farmers, they reduce the transaction costs of reaching out to farmers and ensuring business continuity.[80] Potentially this can allow progressive adoption of GNSS for accurate positioning and advanced machine control, with the additional prospect of further developing precision agriculture through VRT also in low- and middle-income countries. The main challenge to the use of GNSS with large machinery is the need for fields to be rectangular, which may not be the case for many small-scale producers.

Robots with artificial intelligence

Robots designed for farms in high-income countries are often not suitable for low- and middle-income countries, where farming is still dominated by small-scale producers relying mostly on family labour and performing many operations manually. For example, automated cotton harvesting machines in high-income countries are highly efficient but only suited to cotton that matures all together at the same time. This is because the machine can damage the plants while harvesting. Such a solution does not fit traditional farms in India or Western Africa where cotton is a high-quality, multi-bloom crop with a season lasting about 150–160 days, during which cotton is picked three to four times.[31]

Costs are an additional barrier to adoption, especially for small-scale producers in low- and middle-income countries, where very few examples of robotics solutions are found. These target crops and cropping systems are traditionally designed for manual work, and are tailored to local contexts and challenges, requiring minimal to no change in the current farm structures. The drivers of adoption of these solutions are also socioeconomic, with lack of seasonal labour being a prominent one. Other factors leading to the diminishing interest in manual, poorly paid labour include better access to education, migration to cities, social stigma and government policies to support the jobless.[73, 81, 82, 83]

The literature suggests that autonomous robots designed specifically for conditions in low- and middle-income countries bring the following potential benefits: (i) reduced human labour requirements; (ii) lower costs and reduced economies of scale, ensuring technologies are also accessible to smaller farms using conventional mechanization; and (iii) ability to use technologies in irregularly shaped fields in a cost-effective manner, thus avoiding the need to reshape rural landscapes into large rectangular fields on which traditional mechanization is most efficient. Unfortunately, there are no feasibility analyses for these countries to support the business case for investing in these technologies.[29] This is in part due to the fact that the organizations developing these solutions lack the capacity to attract or retain talented personnel who

BOX 18 A VISION FOR LOW-COST AUTONOMOUS CROP ROBOTS

An example of a potentially feasible robot for small-scale producers would be a small-wheeled autonomous crop robot that can seed, weed and harvest, and costs the same as a motorbike (USD 500–1 000) – something that many agricultural households in low-income countries own and therefore serves as a useful price point. A leg robot could also be useful in fields, since it can step over obstacles, but it is much more expensive. Given the autonomous crop robot's ability to learn using artificial intelligence (AI), there is great potential for a substantial increase in food production, far beyond currently feasible levels. However, producing specialized robots for each crop and for specific agroecological conditions is a high-cost, low-volume business. Therefore, a plausible business model is that a manufacturer delivers a generic autonomous machine, with a range of tools adapted to different tasks, some of which locally manufactured. The autonomous machine would be fitted with a global navigation satellite system (GNSS) device to allow it to create maps (e.g. soil colour, soil strength based on force required for hoeing, yield). It could be powered using various energy sources (e.g. fuel, solar, methane). To make such autonomous machines more affordable, especially in the early stages, they could be hired out or fees for service farm work could be charged.

With a generic autonomous crop machine, many other types of digital automation become possible. For example, with the incorporation of a crop sensor, the autonomous machine might determine fertilizer needs,[84] make use of use previously recorded soil, plant and yield maps, and identify pests, diseases and weeds, applying insecticides, fungicides or herbicides as needed.

While it will be challenging for small-scale producers to access digital automation, at the same time millions of them represent a business opportunity and an enticing, new market. A similar process of research, technology development and entrepreneurship occurred with hermetic grain storage throughout Africa and Southern Asia.[85] Prior to the Purdue improved Crop Storage (PICS) bag, manufacturers were reluctant to invest in grain storage innovations for small-scale producers because of their perceived lack of buying power. However, once PICS had sold millions of bags in more than 30 countries, many imitators and competitors emerged.

SOURCE: Lowenberg-DeBoer, 2022.[29]

can conduct such an analysis; they are generally small enterprises competing against large companies.[31] Box 18 presents potential opportunities and challenges when developing robots for small-scale producers.

Broader implications of digital automation technologies for agriculture

Agricultural technologies often have economic, social and environmental implications that extend far beyond their farm-level benefits and costs. For example, motorized mechanization of agriculture has often been associated with increased farm sizes, reshaping of fields and declining rural populations.

Digital automation technologies have great potential to address the environmental challenges in highly mechanized agriculture as discussed above. If well-tailored, they also have great potential in small-scale farming, especially if combined with adapted motorized machinery. Looking further into the future, if the digital automation technologies discussed in this chapter, including robots and AI, are well developed and widely adopted, they could lead to broader positive implications including the following:

- **Farm structure:** Small swarm robots allow a reduction in economies of scale and eliminate incentives to expand farm size, thus avoiding social and environmental disruption. By reducing drudgery, increasing profitability and enhancing the reputation of agriculture as a high-tech industry, swarm robots can help rural communities retain the young and also attract workers from other sectors (see more on youth in Chapter 4). Motorized mechanization agriculture has led to the abandonment of small irregularly shaped fields; swarm robots could allow commercial agriculture to reclaim some of these abandoned fields, which are often characterized by good soil quality, reliable rainfall and proximity to markets. In turn, as swarm robots help improve the profitability of such fields, subsidy programmes directed at small-scale farms may become less costly. Furthermore, both small-scale farms and larger farms still relying on animal traction may be able to leapfrog motorized mechanization and adopt directly digital automation, avoiding the need to reshape rural landscapes, and thus contributing to greater biodiversity.

- **Agricultural equipment market structure:** Ensuring access for small and medium-sized agriculture – including crops, livestock and aquaculture – to various digital automation technologies may lead to changes in the structure of the associated equipment market. This can create opportunities for entrepreneurs who have the technical capacity to develop affordable, reliable, autonomous machines and equipment, and link that technology with innovative business models.

- **Crop protection as a service business:** Crop protection currently focuses mostly on selling large quantities of pesticides. Targeted spraying may reduce the quantity used by as much as 90 percent, with significant environmental benefits, while mechanical or laser weed control could eliminate herbicides entirely.[29] This could strengthen the role of local entrepreneurs who provide standardized autonomous machines to identify weeds and pests. These machines might be provided under a fee-for-service model or sold directly to farmers.

- **Safer and more efficient and resilient livestock and aquaculture:** Digital automation can significantly facilitate remote work and help minimize the work burden, while improving also management.[86] There is increasing research on the potential uses of digital technologies in aquaculture and on how the sector can make significant shifts in associated business models and farm structure.[87] For example, IoT technologies can automatically monitor water conditions and allow fish farmers to take immediate action.[88] In livestock production, the growing use of biometric sensors, which monitor an individual animal's health and behaviour in real time, allows producers to obtain real-time information and thus perform targeted actions that can deliver many benefits, including reduced use of antibiotics. Sensors also enable blockchain technology, which can guarantee traceability of animal products from farm to table and provide key advantages in monitoring disease outbreaks and preventing associated economic losses and food-related health pandemics.[89]

Other implications will emerge as the technologies evolve and become more accessible. The exact implications will, however, depend on many factors, including technology characteristics, connectivity, legal and regulatory frameworks, business decisions by corporations and start-up companies, social media reactions, and cultural attitudes to agricultural digital automation. Governments can promote adoption and enable positive outcomes through digital infrastructure, appropriate legal and regulatory approaches, research, and education (see Chapter 5). ■

CONCLUSIONS

This chapter has presented available evidence for the business case for various automation technologies. The business case for agricultural motorized mechanization is well established, given the benefits in terms of, *inter alia*, substantial cost savings due to reductions in labour use, timely performing of agricultural operations, reduced drudgery, expansion and intensification of agricultural production, and increased resilience to climate and health shocks. In addition, mechanization has contributed to freeing up family labour of agricultural households, enabling household members to allocate time away from agriculture to pursue off-farm work that can enhance their livelihoods.

Over the coming decade, mechanization is still likely to play an important role in the agricultural transformation of countries where adoption has been slow – particularly in sub-Saharan Africa – but it must be tailored to local needs through strategies based on careful assessment of the demand. Various types and sizes of machinery are available for different topographic and agroclimatic zones, capable of meeting the needs of small-scale producers. Technological solutions such as small four-wheel tractors and two-wheel tractors – as well as the wider range of small agricultural machines, which are more agrobiodiversity friendly for food and agriculture – can be part of the picture where adoption is still low.

In spite of the potential, mechanization is still lagging in many parts of the world due to structural factors, such as poor infrastructure, and lack of technical skills and a conducive business environment. Many areas and socioeconomic groups are still without access to mechanization, due to either financial constraints or limiting structural factors, such as restrictive policies or inadequate infrastructure. More policy support is needed for public or collective goods through general services support (GSS). This includes fostering agricultural research and development, together with knowledge transfer services (e.g. training and technical assistance), and supporting infrastructure development and maintenance (e.g. improving rural roads, irrigation systems, storage infrastructure). Both these GSS entry points can support an enabling environment for automation without distorting market incentives, and they are often necessary to make a viable business case for automation, especially in low- and middle-income countries.[90]

In contrast, digital automation technologies – in particular crop robots and digital automation of aquaculture – are still in the early stages of development and commercialization, and the economic impacts on agricultural producers are still speculative. Livestock precision agriculture, on the other hand, is in a more mature phase, although still concentrated in high-income countries. Other technologies, such as disembodied digital solutions, active UAS and remote sensing, mechanization solutions with GNSS and VRT, and solutions for protected cultivation, are scaling. However, based on the 27 worldwide case studies discussed in this chapter, these technologies have so far proven they are profitable only in high-income countries and for large-scale producers. Clearly, more evidence related to the benefits and costs is needed to better understand which technologies can be tailored to different conditions.

As in the case of mechanization, structural factors – including lack of connectivity, electricity, digital literacy and awareness of potential – affect the business case for digital automation technologies. Evidence from both the literature and the case studies suggests that young farmers are instrumental in transformation of the family farming business towards digitalization and advanced automation. Other important factors shaping adoption are increased competition from international markets, lack of sufficient labour, and the potential to reduce drudgery and improve working conditions. In a few instances, the digital platforms that enable access to mechanization services also help women overcome social bias against them and improve their access to services (see Chapter 4).

Digital tools are also changing the landscape of mechanization by expanding rental machinery markets, thanks to substantial reductions in transaction costs. Furthermore, certain digital automation technologies have the potential to reverse some of the negative environmental trends resulting from past mechanization. To address these challenges, it is necessary to tailor innovations in motorized mechanization to smaller and lighter machinery that can reduce soil compaction and mitigate negative environmental impacts. Applied technical and agronomic research can help to explore mechanization solutions that best fit local agroecological conditions.

This chapter has also introduced the role of public policies, legislation, investments and innovations in addressing structural barriers to adoption, and tailoring interventions to small-scale producers and environmental concerns. A more in-depth discussion on the social impacts of automation and the role of public policies follows in Chapters 4 and 5, respectively. ■

KENYA
A farmer engaged in conservation agriculture drives a tractor in Kathonzweni, Makueni County.
©FAO/Luis Tato

CHAPTER 4
SOCIOECONOMIC IMPACTS AND OPPORTUNITIES OF AGRICULTURAL AUTOMATION

KEY MESSAGES

➔ The process of agricultural automation can improve productivity and generate new jobs, both in agriculture and in wider agrifood systems, creating opportunities for young workers, women and marginalized groups, such as people with disabilities.

➔ To understand all the social implications of agricultural automation, we must go beyond primary production and look at the impacts on the agrifood systems in their entirety.

➔ In situations of rising wages and labour scarcity, automation can benefit both producers and hired workers. In particular, it can help small-scale agricultural producers overcome labour shortages and allocate time away from agriculture to other activities, thus improving welfare.

➔ On the other hand, when labour is plentiful and subsidies lower the cost of automation adoption, there is a risk of job displacement and unemployment, especially for poorer, less skilled workers.

➔ Inclusive automation requires a bottom-up approach that prioritizes skill and capacity development, engaging women and youth and all relevant stakeholders in the design of technology development to take into account their concerns, needs and knowledge.

➔ Governments should neither implement distortive subsidies that risk increasing unemployment, nor restrict automation on the assumption that this will preserve jobs and incomes, thus making agriculture less competitive and productive. Instead, the focus should be on creating an enabling environment that ensures the full involvement of women, youth, small-scale producers, and other vulnerable and marginalized groups in order that they all benefit from automation.

➔ In parallel, the root causes of poverty, vulnerability, and marginalization must be addressed to ensure that automation does not aggravate the exclusion of the most vulnerable and marginalized groups.

Chapters 2 and 3 examined the trends and drivers of motorized mechanization and digital automated technologies, as well as the (potential) impacts on productivity, efficiency, resilience and environmental sustainability. This chapter looks into the implications of agricultural automation for inclusiveness – specifically, identifying the winners and losers in the process. It begins with an overview of the characteristics of agrifood systems and how automation can affect labour within them. It then discusses the impacts of agricultural automation on decent employment and on different socioeconomic and demographic groups – large- vs small-scale producers, landless vs self-employed agricultural workers, women and youth – who are involved in the process. The chapter further recognizes that countries with different levels of agricultural and structural transformation will experience these impacts differently and thus face different policy challenges with regard to automation. ■

AN AGRIFOOD SYSTEMS APPROACH FOR ANALYSING SOCIAL IMPLICATIONS

Agricultural production is changing rapidly. The adoption of labour-saving technologies, from tractors, threshers and harvesters in low- and middle-income countries, to high-tech artificial intelligence (AI) solutions found mostly in high-income countries, is occurring in the context of a continuous process of agricultural transformation and evolution of agrifood systems.

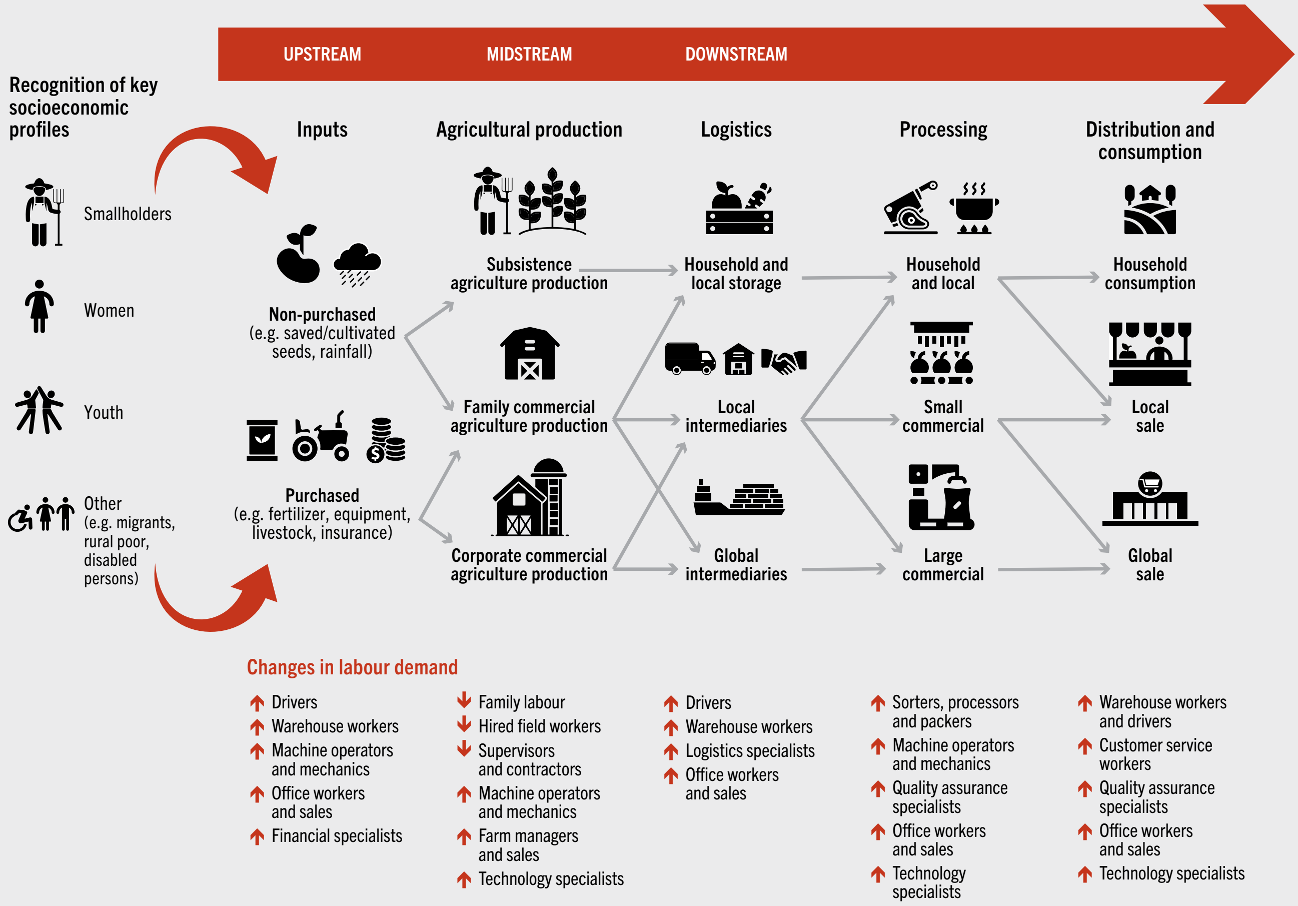
Understanding the dynamics of agrifood systems is pivotal for analysing and predicting the effects of automation at any node in the systems, taking into account possible trade-offs or unintended consequences. Responses upstream and downstream are equally important for understanding the implications for agricultural production, prices, trade flows and decent employment. These also depend on the type of agrifood value chain, as described in the 2021 edition[1] of this publication: (i) traditional, mostly linked with small-scale subsistence agricultural production; (ii) transitional, often associated with small- and medium-scale family commercial agricultural production; or (iii) modern, where large-scale corporate commercial agricultural production plays a major role. These value chains differ in many aspects, including labour requirements. Grasping bidirectional linkages along agrifood value chains is crucial for understanding the impact of automation technologies, including how labour requirements change within different components of agrifood systems and the potential for workers to transition between them. Effects will also depend on, *inter alia*, gender roles, worker categories (e.g. migrant/local or seasonal/non-seasonal) and the skill sets of workers.

Unravelling agrifood systems

Figure 7 provides a conceptual framework for analysing the impact of automation on employment across the different components of agrifood systems. It illustrates some of the main characteristics of the three typical types of agrifood value chains mentioned above, separating upstream, midstream and downstream markets, and listing key activities undertaken in each market. It also shows linkages across markets and highlights differences in common market activities for three distinct categories of agricultural producers – subsistence, family commercial and corporate commercial. Different socioeconomic and demographic groups (on the left side of the figure) are recognized as key actors in agrifood systems, and they include small-scale producers, women, youth and other marginalized groups (e.g. persons with disabilities and migrants), despite the latter often being the most excluded, marginalized and vulnerable. The process of agricultural automation offers the possibility of pursuing an inclusive approach, ensuring that all people, especially the vulnerable, excluded and marginalized, participate in and benefit from development processes, through enhanced opportunities, access to productive and natural resources, empowerment, agency and respect for rights. Inclusivity is both a means to deliver better and more fairly, and an end in itself to ensure no one is left behind.[2]

At the bottom of Figure 7, there is a list of the major types of labour in each market, indicating (with upward and downward arrows) how automation technology could affect demand for each labour type, although the concrete impacts will be context-dependent and must be verified empirically. While automation technologies reduce labour demand for the tasks they automate, they simultaneously create new tasks with associated labour requirements, such as equipment maintenance and operation. Figure 7 provides a reference point for the ensuing discussion on the implications of agricultural

FIGURE 7 AN AGRIFOOD SYSTEMS APPROACH TO AUTOMATION IMPACTS ON EMPLOYMENT



SOURCE: FAO elaboration based on Charlton, Hill and Taylor, 2022.[3]

automation for inclusiveness. This section provides background on the market linkages within agrifood systems that are critical to transmit employment impacts of automation across the components of agrifood systems.

Agricultural production types

Agricultural production (midstream) is central and comprises the three above-mentioned types (see Figure 7). In subsistence agricultural production, production is part of a household livelihood strategy; there are few input purchases and the household consumes most of its own agricultural products.[4] Subsistence production is common in low-income countries, but can also aptly describe small homesteads in rural areas in high-income countries.[5] While subsistence agricultural production is characterized as the production of food for own consumption, this does not mean that households necessarily produce all their own food; in fact, subsistence production households are often heavily reliant on purchased foods.[6, 7, 8]

In family commercial agricultural production, agricultural production activities are an important part of a household income strategy; most inputs are purchased, and agricultural products are sold in local, national and global markets. Family commercial agriculture includes small-scale production in high- and low-income countries, as well as medium- and relatively large-scale operations in high-income countries, owned and operated by a household.

Finally, corporate commercial agricultural production consists of large-scale producing businesses. It is more common in high-income countries but can also be found in low-income countries in the form of plantations and large-scale estates.[9]

Activities at this node of agrifood systems are all directly associated with crop, livestock, fisheries and aquaculture production, as well as forestry and agroforestry. Relative operations include soil maintenance and preparation, planting, weeding and plant care, pruning and harvesting, as well as breeding, raising, daily care and health monitoring. At this level, automation of selected agricultural tasks can lead to increased output, with repercussions for downstream activities, including transport, packing, storage, processing and distribution. These downstream activities will create increased demand for most types of workers in order to handle the higher volume of output.

Upstream and downstream activities

Upstream activities comprise all those associated with providing inputs for agricultural production. These broadly include the production and distribution of seeds, fertilizers, machinery, animal feed and irrigation equipment, in addition to the provision of insurance, technical assistance and finance. Subsistence agriculture relies primarily on non-purchased inputs (including saved seeds), animal feed from cultivated crops and rainfall (rather than irrigation).[10] Depending on size, location and other characteristics, family commercial agriculture may use non-purchased or purchased inputs, or a combination of the two. In this representation of the agrifood systems (see Figure 7 on p. 65), agricultural technological innovations generally come from the input side, and depend on the availability of improved (or less costly) seeds, feed, fertilizers, and equipment and machinery, including automation technologies. Once adopted, these technologies change the way inputs are used in agricultural production (midstream).

Downstream activities include post-harvest/slaughter/catch operations, such as storage, transport, processing, packaging, wholesale and retail, and, finally, consumption by households and food services. In subsistence agriculture, these operations take place in the household or village.[11, 12] In family commercial agriculture, logistics activities may take place in the household or village, but using local or global intermediaries. Corporate producers, on the other hand, may source produce from different sites, and store it in large, designated warehouses. Transport includes ocean, air, rail and road freight. Distribution involves bulk deliveries of agricultural commodities to processors or wholesalers. Often, automation technologies lead to increased agricultural production midstream, which may in turn lead to expansion, growth and further technological innovation downstream. For example, introduction of the motorized tomato harvester increased the amount of tomatoes to be processed, incentivizing innovation in the processing sector.[13] Conversely, innovation downstream can also influence demand for upstream and midstream products, with a consequent effect on technology adoption by agricultural producers. For example, lower processing costs for canned tomatoes can boost demand for this product creating an incentive for tomato farmers to increase production and meet rising demand by adopting relevant technologies (e.g. improved varieties, irrigation equipment, harvesters).

Wholesalers and retailers, including informal microenterprises, together with consumption at the household and food service level, constitute the final node in agrifood systems. Automation in wholesale, retail, restaurants and food services has reduced labour needs[14] and increased productivity and sales.[15] The most substantial technological advance in the global distribution sector has been e-commerce,[16] which further drives technological innovation upstream, especially innovations focusing on sustainability, such as more sustainable packaging[17] and, in low-income countries, improvements in transport infrastructure, logistics and online services.[18, 19, 20] In India, the explosion of e-commerce platforms has allowed farmers to connect with wider markets and realize higher prices.[21] In China, a selection of case studies illustrates how rural e-commerce is creating opportunities for diversification and new markets for rural people and communities in various parts of the country, including vulnerable groups such as women and youth.[22] ■

LABOUR IMPACTS OF AGRICULTURAL AUTOMATION

Automation can affect agricultural production and decent employment opportunities in various ways. In crop production, it becomes possible to expand cultivated land or improve yield per hectare, which in turn increases production. In livestock production, automation can improve labour productivity and substantially reduce drudgery by enabling workers to milk or feed animals with minimum manual intervention. Similar reasoning applies to fisheries, aquaculture and forestry (see Chapter 2); in the case of forestry, improved worker safety is an important additional benefit driving automation. All these benefits can result in major increases in welfare. If automation involves large economies of scale, widespread adoption among larger producers can sometimes put smaller producers out of business and precipitate consolidation in the agriculture sector. As agricultural labour demand decreases and new technologies make some skill sets obsolete, automation can displace workers, especially the poorest, who may struggle to find employment elsewhere. Appropriate policies, legislation and investments must be in place to avoid, mitigate or address the negative social impacts, especially for the most vulnerable.

The following sections consider the impacts of agricultural automation on employment in agrifood systems in different contexts. This report analyses the impact of agricultural automation under the particular lens of decent rural employment, defined as work that provides a living income and reasonable working conditions. Box 19 (p. 68) describes the standards of decent employment to be used to evaluate the impact of agricultural automation technologies.

The employment impacts of agricultural automation are difficult to measure, because they typically involve changes across agricultural production activities, as well as upstream changes deriving from changing demand for inputs, and downstream changes affecting transport and logistics, processing, distribution, and retail. As agricultural transformation unfolds, people leave agriculture to seek higher-paid jobs, and the share of people employed in agriculture continues to decline, as described in Chapter 1 (see Figure 3 on p. 8). The process reshapes labour supply and demand in all agrifood systems, as it affects the production, processing and distribution of food and other agricultural outputs. When all the nodes in agrifood systems are changing more or less simultaneously, it is difficult, if not impossible, to ascribe social impacts – such as changes in decent employment and the implications for gender, youth and small-scale producers – to specific incidents of agricultural automation. Understanding the transformation of agrifood systems is a fundamental step towards grasping its social impacts, especially on employment. Note that this chapter does not include the potential *indirect* effects of automation adoption (e.g. increased demand for researchers and scientists to develop and improve technologies), nor does it consider the possible economy-wide implications, which may also have significant social repercussions. How the comprehensive set of possible final impacts plays out in reality remains an empirical question and will depend on the specific circumstances in different countries and societies.

Figure 7 (p. 65) helps to illustrate two main points. First, the possible effects of agricultural automation are multiple, and impacts on farm employment are likely to be diverse. Demand for low-skilled labour – whether family or hired labour – is likely to decline as many tasks are automated. Automation of some tasks may resolve problems of labour bottlenecks, allowing production to increase, by either horizontal expansion or intensification. Automation is likely to increase the demand for relatively skilled workers who complement the new technologies. Second, the overall

BOX 19 ANALYSING AGRICULTURAL AUTOMATION THROUGH THE LENS OF DECENT EMPLOYMENT

Decent rural employment refers to any activity, occupation, work, business or service performed for pay or profit by women and men, adults and youth in rural areas that:[23] (i) respects core labour standards as defined in International Labour Organization (ILO) conventions (i.e. against child and forced labour and discrimination and with guaranteed freedom to negotiate); (ii) provides an adequate living income; (iii) ensures adequate employment security and stability; (iv) adopts safety and health measures; (v) avoids excessive working hours; and (vi) promotes training. For an analysis of agricultural automation through the lens of decent employment, it is necessary to examine its impacts on the following:

Child labour. According to a recent empirical study covering seven developing countries, use of tractors (and of combine harvesters in India) reduces by 5–10 percent the probability of children's employment, while improving their school attendance. However, where access to education is limited, the introduction of agricultural machinery may merely result in a shift for children from farm to non-farm work activities.[24]

Adequate living income. In certain situations, automation can contribute to improved incomes, livelihoods, profitability and job opportunities.[25, 26] For example, in Uganda, mobile phones are associated with positive increases in household income and gender equality due to improved access to markets, services and information.[27]

Occupational safety and health. New technologies can reduce drudgery and health risks (e.g. through decreased use of herbicides and pesticides).[28]

Reduced working hours. Time savings from agricultural automation can allow more time for rest and recreational activities. This can also enable small-scale producers to engage in non-agricultural employment, generating more stable income and contributing to resilient livelihoods.

impacts of agricultural automation on decent employment within agrifood systems are likely to be very different from the impacts on individual agricultural business sites. Automation could easily reduce low-paying seasonal employment on farms but increase higher-paying, less seasonal employment upstream and downstream. The question is whether the positive social impacts of the increase in higher-paying, less seasonal work compensate for the negative impacts of the decrease in availability of low-paying seasonal employment for workers, allowing the latter to find alternative employment.

Employment seasonality is a concern in agriculture around the globe. Crop and livestock production activities are inherently seasonal. This means that unemployment and underemployment tend to be high in some seasons, while there may be severe labour shortages in others. For an agricultural producer, not having access to labour at critical times (e.g. during crop harvest and livestock shearing) can have serious ramifications for farm operations and may lead to losses or discourage cultivation altogether. Automation that eases excess labour demands during some seasons could, in theory, maintain employment in other seasons. This raises important questions. Which cropping tasks, in which seasons, are easiest to automate, and do they coincide with the labour shortages farms face? Conversely, what are the impacts for the poorest, unskilled workers who find themselves without a job once businesses start to automate and their skills become obsolete? Which policies can ensure a more productive, efficient, sustainable and inclusive automation process?

For the most labour-intensive crops – primarily fruits and vegetables – tasks occurring in the most labour-lean seasons are often the hardest to automate because of the potential damage to plants or fruits caused by machinery. By way of illustration, it is worth taking a look at automation in the richest agricultural areas, where farm wages are relatively high and automation solutions most available. In California, United States of America, land preparation is universally mechanized, including ploughing, tilling and land levelling. Harvesting of crops for use in processing (e.g. tomatoes or wine grapes) is automated. Harvesting of fresh fruits and vegetables for final consumption, however, still relies on manual labour and is harder to automate, even though produce-picking robotics solutions are on the horizon, incentivized by a shortage of harvest workers and rapidly increasing wages.

These new employment opportunities are appropriate for many kinds of workers. Drivers, warehouse workers, machine operators and mechanics all require little formal education, but they experience differences in terms of pay, job security and the job skills required.[29, 30] Such jobs can also be seasonal, especially in small processing firms, but they may be stable if offered by large commercial processing firms. In both cases they are less seasonal than field jobs in agriculture. The vast majority are filled by men.[31, 32] Office workers, salespeople and specialists requiring more formal education, training and experience, are the highest paid and typically include a higher proportion of women employees.[33]

Implications for small-scale and subsistence producers

Implications for labour demand depend on the type of work and production. Subsistence producers operate their production units using family labour. They are often poor, food-insecure and with limited access to markets and services.[34] In the Plurinational State of Bolivia, up to 83 percent of small-scale producers are poor, compared with a national poverty average of about 61 percent. In Ethiopia, where 30 percent of the population lives under the national poverty threshold, the poverty headcount ratio for small-scale producers is 48 percent. In Viet Nam, more than half of small-scale producers are poor, while in the country as a whole only about 20 percent of the population lives in poverty. In such conditions, the higher rate of poverty among those involved in agriculture is caused – at least in part – by low productivity rates as they survive on subsistence or quasi-subsistence farming. If these farms adopt automation, they can raise productivity and improve incomes and livelihoods by expanding production, potentially becoming a family commercial farm. For example, availability of tractors for small-scale family farms in Zambia allowed producers to more than double their incomes, primarily by cultivating more land and applying more inputs (mainly fertilizer), increasing yields by 25 percent.[35] Adopting automation can free up time, to be used for other activities such as education for children, and lead to long-term economic benefits for households. It can also allow household members to find work in non-farm activities, where available.

Agricultural automation can also give access to higher-value markets and allow agricultural households to sign contracts with supermarkets or foreign buyers, provided their produce is of consistent quality and quantity. Participation in such high-value markets can bring significant welfare gains to agricultural households. In Kenya, supermarket contracts with small-scale vegetable farmers increased farmers' household incomes by more than 40 percent and led to the largest reductions in multidimensional measures of poverty for the poorest households.[36] Farm households supplying goods to supermarkets have also exhibited significantly higher consumption of calories, vitamin A, iron and zinc.[37]

Even in other regions of Africa, where labour is relatively abundant and fertility rates high, there is evidence that lack of agricultural labour limits production. Thus, automation offers the possibility to improve production and household income. A study of farm-level data from four countries in Eastern and Southern Africa justifies the current efforts to mechanize agriculture in Africa, as labour and other sources of farm power appear to be major factors limiting agricultural productivity in the region.[38]

BOX 20 THE LABOUR IMPACTS OF MECHANIZED HARVESTING OF SUGAR CANE IN BRAZIL

In Brazil, a set of laws and regulations were created to prohibit the practice of pre-harvest burning of sugar cane from 2020 for environmental reasons. This put an end to manual harvesting – which involves the practice of burning sugar cane prior to the harvest – and saw sugar cane producers increasingly invest in motorized harvesting. While this legislation has brought environmental benefits in terms of less pollution and has increased productivity, it was estimated that it would reduce by 52–64 percent the workforce directly employed in sugar cane production. Least qualified workers (with no more than three years of education) would be the most severely affected, while the demand for skilled labour in the sector was expected to increase. Such changes in employment call for immediate public action to protect the most vulnerable from the negative effects of automation.

SOURCE: Guilhoto *et al.*, 2002.[39]

Many of the potential benefits of agricultural automation are neither immediate nor automatic. Small-scale producers and subsistence farmers lack the managerial and technical skills to benefit from the opportunities of agricultural automation. They also need to update and modernize their business models to align with prevailing market requirements and standards. This highlights the importance of building capacities and putting in place effective rural advisory systems that can ensure timely access to information on technologies and markets (see Chapter 5).

Implications for medium- to large-scale commercial production

Commercial family production units are owned and operated by family labour, but may also use hired labour (e.g. hired field workers, labour supervisors, contractors). Automation can reduce demand for all three types of labour, but can also induce producers to expand their operation. If family commercial producers choose to expand towards corporate commercial agriculture, family labour will most likely be replaced by hired professionals, including farm managers, sales personnel, machine operators and mechanics. If, as is often the case, technology adoption is spurred by rising wages and scarce labour, agricultural automation will tend to increase labour productivity and wages, in which case automation might enhance welfare for both producers and hired workers. However, automation can also displace workers, especially the poorest and least skilled, who will be forced to seek jobs elsewhere, possibly putting downward pressure on wages for unskilled labour as their skill set makes it difficult to find other jobs (see Box 20). Another possibility is that subsistence farms exit agriculture entirely due to technology adoption by commercial farms – so-called farm consolidation. In these cases, policies, legislation and investments must be in place to ensure that subsistence and small-scale producers, as well as low-skilled workers, are not left behind, but rather are able to reap the benefits of agricultural automation. It may be necessary to provide targeted social protection and training during the transition.

Corporate commercial farms employ all types of labour, except family labour. These farms are the most advanced and are generally automated to a significant level. They often have the economies of scale and capital to invest in more robotics technologies that may reduce considerably on-farm labour demand – with potentially negative consequences for workers, in particular low-skilled workers – or change the type of labour needed on the farm. For example, with digital automation, a former tractor driver may supervise a swarm of autonomous crop machines or retrain to carry out repairs. However, robots are not

BOX 21 AUTOMATION AND RURAL MIGRANT-SENDING COMMUNITIES: THE CASE OF CALIFORNIA

As crop production expands while supply of domestic farm labour contracts, countries seek new sources of farm labour through immigration. For example, in California, United States of America, over 90 percent of the farm workforce is composed of immigrants. Reliance on foreign farm workers is universal in today's high-income countries. It might seem automation would negatively affect migrant-sending communities. However, California's agricultural automation does not occur in a vacuum. In Mexico, the home of most immigrants, fertility rates are falling, school attendance levels are rising sharply and access to non-farm jobs is increasing, reducing the rural labour supply. Secondary school construction in rural Mexico is extending education to boys and girls who would otherwise seek jobs in agriculture, thus accelerating the agricultural transformation. Indeed, better educated people are more likely to work in the non-farm sector, even when they emigrate.[44] As a consequence, the agricultural labour supply has shrunk significantly in California; between 2008 and 2018, agricultural wages increased 18 percent faster than non-agricultural wages.

Before the decline in the Mexican farm labour supply in the 1990s, there was little incentive to adopt and develop new labour-saving technologies in California. Today, in both countries, there is a race between automation and a declining farm workforce. The automation process usually begins with the most labour-intensive and easiest-to-automate operations, but as more advanced solutions are developed and commercialized, the United States of America in particular is starting to automate more complex operations such as harvesting fruits and vegetables.

SOURCES: Charlton, Hill and Taylor, 2022;[3] Taylor and Charlton, 2018.[45]

typically economically viable for most farms, unless labour is scarce. By way of illustration, although robotic milking technologies have been in commercial use for many decades, few dairies in the United States of America have adopted them, as farm labour is still relatively inexpensive.[40] In contrast, they have been in commercial use in Western Europe since the 1990s.

In general, if automation technologies are adopted where there is no labour scarcity, but because they are made artificially cheap (e.g. due to government subsidies), there is a risk of displacing workers and generating unemployment. Labour displacement can be costly for farm workers; the overall impact will depend on whether they can move to new jobs generated upstream or downstream (see Figure 7 on p. 65). On the other hand, agricultural technology adoption spurred by rising wages and increasing competition for scarce labour is likely to increase both wages and overall productivity, benefiting both producers and hired workers.

Automation on farms in high-income countries or regions within countries could have negative impacts on migrant remittances to poorer countries and regions. If demand for unskilled migrant agricultural workers declines, this could increase unemployment levels in migrants' home countries and regions, as well as reduce remittance flows.[41] In Brazil, automation of coffee harvesting has significantly reduced the demand for unskilled labour – mostly internal migrants from poorer areas of the country – but increased the demand for skilled workers.[42] This calls for immediate, inclusive social policies to help unskilled workers who lose their jobs so they can find employment elsewhere.

Automation often seems to occur in the context of diminishing farm labour and rising wages in migrant-sending areas. Box 21 provides an example of how agricultural automation in the United States of America is being driven by a growing scarcity of labour in the migrant-sending communities of Mexico. Another study in the United States of America found that the automation of greenhouses increased the gross revenue of horticultural businesses, allowing them to pay higher wages and retain migrant workers longer, while hiring fewer new skilled workers.[43] ■

AGRICULTURAL AUTOMATION BRINGS NEW ENTREPRENEURIAL AND TRANSFORMATIVE OPPORTUNITIES WITH IMPLICATIONS FOR NUTRITION AND CONSUMERS

Developments in agricultural automation can create new entrepreneurial opportunities, for example, related to organic farming and botanicals with valuable aromatic, medicinal and nutritional properties. It may also contribute to the revival of nutrient-dense heirloom crops that were difficult to mechanize. This is already beginning in some high-income countries. In France in 2018, there were 150 robots used for weeding organic vegetables and sugar beet.[46] Where one of the main constraints to organic or biodynamic farming is the high cost of labour, using autonomous weeding machines to control weeds and AI to identify plant diseases allows rapid expansion of organic production, which can bring down the prices of organic products substantially. This is good news for consumers who prefer to buy organic products but are unable to afford the current high prices.[47]

Another example is maize. With the mechanization of maize production, hybrids were developed with ears at about the same height in order to facilitate mechanical harvesting. However, the plant breeding process led to the loss of some nutritional and culinary values. Nevertheless, it is now possible to restore these values, as autonomous machines with AI are able to harvest traditional, tastier and more nutritious, maize varieties with ears at different heights. Likewise, the mechanization of tomato harvesting required varieties that ripen evenly, but this process resulted in loss of nutritional value and flavour. Selective harvesting with autonomous machines could allow commercial production of flavourful heirloom varieties.[47]

In addition to the entrepreneurial opportunities mentioned above, automation can bring more good news to consumers, as it offers the potential to produce lower-cost food. The main risk from a consumer perspective is that automation spurs concentration in the food industry, leading to a small number of large corporations holding a dominant position; these then set monopolistic prices, harming consumers and reducing production to socially suboptimal levels. On the other hand, corporations enjoy economies of scale and thus can produce goods at a lower cost than smaller competitors. If excessive concentration can be avoided, consumers may still be better off than in a perfectly competitive market made up of many small producers. In the Greater Los Angeles area in the United States of America, unlike small food retailers, supermarkets do not raise food prices as a function of market concentration or increased market shares. The competition between supermarkets prevents them from setting monopolistic prices, and consumers thus reap the benefits of reduced costs associated with gains in efficiency from economies of scale.[48] Policies that favour market competition are essential to limit business consolidation and to protect consumer welfare.[3]

There is a risk that if automation technologies are not scale-neutral, small-scale producers and processors may be pushed out of business because they lack the economies of scale to remain competitive. However, this does not have to be an outcome of introducing digital automation in agriculture; to avoid such inevitability, low-cost (i.e. scale-neutral), highly effective digital automation needs to become as ubiquitous as mobile phones. With the right enabling digital infrastructure, and legal, regulatory and cultural environment, there is great potential for sustainable rural economic development based on intensive, but sustainable agriculture. Whether countries – and in particular low- and middle-income countries – gain or lose from agricultural automation depends on how they manage this transition. Those that build the necessary physical, economic, legal and social digital automation infrastructure stand to benefit. Countries that ignore the challenge may lose the low-wage manual agricultural employment they now have, without developing higher-wage agricultural opportunities based on automation. History suggests that international cooperation is essential to prepare for the transition; nevertheless, the political will to recognize these opportunities and take action accordingly is no less essential.[3, 47, 49] ■

AN INCLUSIVE PROCESS OF AGRICULTURAL AUTOMATION

This report sees in agricultural automation both an opportunity and a responsibility to include those who experience higher levels of vulnerability, exclusion and marginalization through their livelihoods in agrifood systems. Among these are small-scale producers, pastoralists, small-scale fishers and foresters and forest communities, agricultural wage workers, informal microenterprises and workers, landless people, and migrants.[2]

These individuals are responsible for a large share of food production and are custodians of natural resources and biodiversity. Yet they remain marginalized, lack equitable access to resources, are without tenure rights, do not participate in policy- and decision-making processes, and are disproportionately affected by climate change and extreme climatic events. They are the most likely to lack safe, nutritious food, resources, markets, basic public and social services, infrastructure, tools and technologies, social protection and income-generating opportunities.[2] Addressing the multiple barriers and constraints these actors face is essential for achieving an inclusive agricultural automation process, which will lead to sustainable, resilient, productive and efficient small-scale agriculture.

Poverty and extreme poverty should be a key focus of this process, as it cuts across all the above-mentioned population groups. Four out of every five individuals living below the international poverty line reside in rural areas and depend at least partly on agrifood systems for their livelihoods.[50] Most are deprived of multiple dimensions of well-being and fundamental individual and collective human rights. Legal frameworks have an important role in ensuring that the human rights of all are recognized, protected and promoted. Governments should include measures to: represent marginalized and vulnerable groups (e.g. Indigenous Peoples and people with disabilities) in decision-making; identify the potentially adverse impacts of automation on human rights, especially of these groups; and implement special measures to prevent, end or mitigate the negative impacts of automation.

Gender and youth are two other critical themes for inclusivity. Within the FAO Strategic Framework 2022–2031, gender and youth are treated as separate cross-cutting themes to highlight their importance and ensure that these agendas receive special attention.[2] Policies, legislation and investments should ensure human rights-based monitoring approaches, including collecting disaggregated data to measure impacts on the livelihoods, rights and opportunities of youth and women. Gender and youth are discussed separately in the following sections. Many others also face exclusion and marginalization from agricultural automation due to race, sex, poverty and socioeconomic status, language, ethnicity, religion, age, disability, caste, or other grounds. Indigenous Peoples and persons with disabilities are a case in point (see Box 22 on p. 74).

Gender implications of agricultural automation

The gender implications of on-farm automation are complex and varied. They depend on the previous gender distribution in performing manual agricultural tasks that are newly automated and on the division of labour between genders in agrifood systems, as well as within households (e.g. distribution of assets). In many places, there are fairly rigid

BOX 22 INCLUSION OF PERSONS WITH DISABILITIES

Persons with disabilities are often excluded from development processes based on psychosocial, physical/sensory and intellectual disabilities, preventing fair and equal access to social and economic opportunities. Poverty, food insecurity and malnutrition can be the causes of disability, while people with disabilities are more at risk of poverty, hunger and malnutrition. Agriculture is one of the three most dangerous sectors to work in, with exposure to a wide variety of hazards, long hours and poor working conditions, often without appropriate occupational health and safety policies or legislation.

Automation can contribute to ensuring decent job opportunities that eliminate labour-related hazards and break the link between poverty, malnutrition and disabilities. Inclusion of people with disabilities may also entail: (i) adapting and improving existing, or developing new, agricultural automation technologies that meet their special requirements, using alternative communication media (e.g. large print, Braille, sign language) and adopting pictorial, audio (recorded tapes or discs) and electronic formats; and (ii) strengthening the technical skills of persons with disabilities in agriculture and broader agrifood systems.

It is particularly important to allow young people with disabilities to become independent and active. FAO has used its junior farmer field and life schools (JFFLS) to address the gap in access to education, as well as the stigma and lack of economic opportunities faced by people with disabilities, building on innovative technologies. This involves a simple, yet effective, methodology to educate vulnerable children and young people about agriculture while incorporating life skills.

SOURCE: FAO, 2022.[2, 51]

gender divisions on farms. For example, in Morocco, cultivation of the crocus flower, from which saffron is extracted, is a male-dominated activity, while processing of the flowers – involving tedious, labour-intensive work – is performed almost exclusively by women.[52] Therefore automation in flower cultivation would release mostly male labour. Moreover, if it led to an expansion of flower production, there would be an increased demand for female labour. While this may be good news for hired female workers, it is bad news for family female labour.

In a case study in Zambia, men and women shared labour-intensive tasks (e.g. weeding). When tractor services were adopted for land preparation, cultivation increased, but this did not place a disproportionate additional burden on women or children. On the contrary, all household members were able to enjoy more leisure.[35] Further evidence from Eastern and Southern Africa shows that, in many instances, the mechanization of land preparation replaces the labour of both men and women – but especially women, who are mostly responsible for weeding, which involves considerable drudgery.[38] In Western Kenya, the adoption of motorized mechanization also freed up time for both men and women, and the household was able to increase investment in children's education.[53] These examples underline how assessing the impact of automation on women must include understanding specific gender roles; it is important to not make poorly founded generalizations about automation benefiting only men simply because it mainly automates the operations they perform.
For other successful examples of agricultural automation technologies being used by women and youth, see Box 23.

Despite the potential of on-farm automation to ease women's time and work burdens, while enhancing productivity, income and welfare, research suggests that women lag behind men in agricultural technology adoption due to barriers in access to capital, inputs and services, (information, extension, credit, fertilizer), limited physical accessibility, and cultural

BOX 23 INCLUSION OF WOMEN AND YOUTH: EVIDENCE FROM CASE STUDIES

Several of the case studies in Chapter 3 have a strong focus on women and youth empowerment through technology development. Successful examples include the following service providers:

Igara Tea. About 18 percent of users are women, of whom 4 percent are household heads. At the farm level, 65 percent of the labour force comprises youth. In processing tea leaves, women and young people comprise more than half the total workforce.

TraSeable Solutions. Women and youth represent approximately 40 percent and 15 percent of registered users, respectively.

Tun Yat. Approximately 30 percent of users are women, and 25–30 percent are young people aged up to 30 years. This is also a consequence of internal male migration, where men move to urban areas for work, leaving women to perform agricultural tasks. By focusing on employment of (local) women and youth, Tun Yat incentivizes women's empowerment in rural areas. The company employs women and youth in food processing and food safety, and as tractor operators and mechanics.

SOURCE: Ceccarelli *et al.*, 2022.[54]

norms.[55] By way of illustration, according to the Ghana Institute of Management and Public Administration, 78.6 percent of female farmers in the coastal zone cannot access tractor services.[56] Women are often unable to embrace automation technologies and cannot take jobs that require skills in farm operation and management due to lower literacy levels, lack of suitable tools/equipment, absence of infrastructure, and insufficient funds for women's extension programmes.[56]

It is usually men who conduct commercial transactions of agricultural automation services at the farm level. Consequently, it is men who make the decisions and control the resources required to invest in automation (especially capital).[56] Agricultural equipment and tools are usually designed to meet men's ergonomic characteristics, with little attention paid to those of women.[57] In Bangladesh, women do not use irrigation pumps because of their technological complexity, the physical requirements to operate them, and the difficulty of hiring and supervising labourers.[58] There is a clear need to design and provide access to gender-friendly automation technologies. Indeed, a recent literature review highlights the need to incorporate – in future research and policy – gender differences related to design, promotion and adoption of automation technologies to reduce women's work burdens and enhance welfare outcomes.[55]

These gender constraints must be overcome to increase productivity, safety and comfort, and reduce drudgery as part of an all-round sustainable development of society.[57] To favour women's adoption of technologies, policymakers and local implementation partners also need to assess the enabling environment and promote gender-sensitive technology development, dissemination and service provision. Gender-sensitive technologies are those suited to both male and female physical characteristics.[59] Policies, legislation and investments should also promote women's capacity and autonomy, as well as gender equality in ownership and/or control over key productive assets.[60] Targeted strategies and actions which simultaneously address the technology adoption constraints that women face at the household, service and policy level can lead to positive outcomes. Evidence from Ghana, for example, shows that provision of training for women in typically male-dominated value chain nodes can have a positive impact on not only women but also the wider community (see Box 24 on p. 76).[56]

BOX 24 WOMEN IN THE DRIVING SEAT: ADVANCING WOMEN'S EMPOWERMENT THROUGH TRACTORS

The Women in the Driving Seat tractor training programme aims to break down barriers for women in agricultural automation, traditionally a male-dominated area. The training programme's objective is to sustainably drive women's participation and leadership in operating agricultural machinery in Ghana.

As a result of the programme, 182 women tractor operators have received certificates since 2018. The successful completion rate has shown that women can excel in tractor operation and maintenance. Graduates established the Women in Tractor Operation Association to organize and support each other.

Women's involvement in automation has helped shift the mindset, not only of women, but of practitioners, employers and the wider society. These newly employed women now contribute to the security of a stable home environment and make critical household decisions about resources and income. The operation has thus promoted gender equality in the workplace and at home.

SOURCE: GIZ, 2020.[56]

A review of the differences in women's and men's involvement in emerging markets for reaper harvester machinery services in Bangladesh also highlights the potential of hiring services.[58] In particular, women benefited from managing and sometimes owning machinery services, as well as from the direct and indirect consequences of hiring such services to harvest their crops. Initiatives promoting hire services should focus on engaging women, both as business owners and as machinery users.

Involving rural youth – opportunities and challenges

Young farmers appear to be the first to embrace agricultural innovation. They are therefore perceived as instrumental in generational change and agricultural transformation.[54] Agricultural automation promises new types of jobs that differ from traditional jobs in the agriculture sector, which are often associated with inferior, more hazardous and underpaid working conditions. These new jobs involve innovative technologies that require distinct skills to make productive use of them, leading to decent wages and safer working conditions.

A recent paper on stakeholder perceptions on mega-topics for African agricultural transformation finds that, overall, there is great optimism that farming can attract youth, with 78–98 percent of stakeholders agreeing with this statement. Nevertheless, a large share of respondents feel youth are not sufficiently involved in policy processes (72–97 percent), and a significant share said youth lack role models in agriculture (48–79 percent). There is also the perception that education systems do not prepare youth adequately for the job market, in particular in Benin (70 percent) and Kenya (63 percent).[61] Highly skilled jobs are out of reach for most rural youth,[62] and it is therefore essential that youth acquire the necessary skills. A strong human capital development and capacity-building agenda, with a focus on youth, should be prioritized in government policies and investments.[54] ■

THE FUTURE OF THE AGRIFOOD WORKFORCE

As labour-saving automation expands on farms, the workforce evolves. It not only becomes smaller, but also more skilled, capable of complementing new and increasingly complex technologies. A major issue faced by high-, middle- and low-income countries is where the farm workforce of tomorrow will come from and how to facilitate its transition from primarily low-skilled manual activities to work involving more complex and sophisticated technologies, including new digital technologies that are likely to increase the demand for skilled workers on farms and lead to higher farm wages.[63]

The fear that crop-picking robots will displace millions of farm workers without other job prospects is not well founded. In general, the automation of agricultural jobs and evolution of the farm workforce are gradual processes, and are not uniform across localities, crops and farm tasks. The incentives to adopt labour-saving methods are greatest for specific tasks that are labour-intensive and easy to automate at a low cost. Over time – but not at the same time – the supply of agricultural workers diminishes in different localities, closely linked to rising incomes, declining fertility, increasing education, and the rise in off-farm employment opportunities. Therefore, although the decline in the farm workforce is undeniable, it is happening unevenly across the globe.

Rather than rapidly dislodging large numbers of workers, automation is likely to continue incrementally. As the farm labour supply decreases, some tasks will be automated while others will 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 less skilled workers from newly automated tasks to other activities that are more difficult to automate. With some activities – for example, soil preparation and ploughing – automation will open up new tracts of land, thus increasing the demand for workers in other tasks (planting, weeding, thinning, harvesting) as food production expands.

That is not to say the process will be without friction; the adoption (or non-adoption) of labour-saving technologies will create unemployment (or labour shortages) at some times and in some places. Excessive automation may occur if there is a sudden breakthrough that gives farmers easy access to labour-saving technologies, providing an incentive to adopt them even while wages are low. This scenario is unlikely to play out in high-income countries, where rural labour shortages and rising wages are already the norm. In low- and middle-income countries, especially where rural labour is abundant and wages are low, excessive and too rapid automation could have a negative impact on commercial farm workers, particularly those with skill sets made obsolete by new technologies.[3] Box 20 (p. 70) provides an example of the latter case from Brazil. In any case, automation can still improve the livelihoods of small-scale producers, as it enables family members to allocate more time to education and off-farm employment opportunities and enhances efficiency, productivity and resilience.

Another scenario is too little automation, especially if government policies create obstacles to automation on farms on the assumption this will preserve jobs in the agriculture sector. In the context of shrinking farm labour supply and rising wages, the assumption that limiting automation will preserve agricultural employment and incomes is likely to be flawed, for two reasons. First, restrictive automation policies make farms less competitive and unable to expand their production to satisfy growing domestic markets or exports. Second, key to improving wages and working conditions for farm workers is increasing their productivity, by coupling their labour to new technologies. Most of the world's farm workers have family incomes below the poverty line, and the prospects of moving out of poverty remain dim without worker productivity-enhancing technologies. Limiting the adoption of labour-saving (and thus worker productivity-enhancing) technologies leads to persistently low farm worker wages.[3]

In light of this, expanding food production in an era of declining farm labour supply, while continuing to build educational systems to prepare the workforce of tomorrow, is a major policy challenge around the world. This challenge is not limited to primary production – it also applies to the other parts of agrifood systems, including processing and distribution. If workers are not available with the necessary skills to complement new technologies, it will be difficult to meet a growing global demand for food, especially in places where the farm workforce is growing slowly or even declining. ■

CONCLUSIONS

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

It is easy to imagine automation creating unemployment and depressing farm wages. Such an outcome is indeed possible in some scenarios. However, past experience suggests that innovation and adoption of labour-saving technologies tends to be a long process. It is not easy to create machines that emulate the dexterity and skill of humans in performing agricultural tasks. 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, harvesting). In this way, automation can stimulate agricultural employment by enabling farms to expand their production in response to growing domestic and global food demands.

There is evidence that growth in agricultural production, facilitated by automation, stimulates job creation at other nodes of agrifood systems – in input-supply activities upstream and in logistics, storage, processing and marketing activities downstream from farms. In addition, it creates new entrepreneurial opportunities to develop new businesses.

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 to adopt labour-saving methods on farms. On the supply side, massive advancements in research and development will continue to place new farm automation solutions for new tasks within reach of farmers, and at a gradually decreasing cost. In the end, the overall impact remains an empirical question, hinging also on the importance of agriculture in the economy and the possible economy-wide impacts that agricultural automation may trigger.

This is good 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 and labour availability. This could result in automation concurrent with rising unemployment and falling or stagnant wages on farms in some places and at some times. The obvious policy response should be to avoid creating market distortions that encourage premature automation, and instead immediately begin to prepare workers with the skills necessary to access new, higher-skilled jobs. This is especially important for young people and women, for whom a number of technical, economic and cultural barriers hinder full participation in these benefits. Given the risk that small-scale producers are forced out of agriculture as a result of technology adoption by commercial farms, it is important to protect their livelihoods and ensure that they are not left behind.

This chapter has provided suggestions for initiatives to promote inclusive agricultural automation that more fully engages women, youth and small-scale producers. Government policies on agricultural automation have a role to play in this regard, in addition to ensuring that agricultural automation is a driver of the transformation of agrifood systems. The role of government policy and legislation is discussed in more depth in Chapter 5. ■

THAILAND
Robots analysing crop leaves, foliar fertilization and pollination.
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CHAPTER 5
POLICY OPTIONS TOWARDS EFFICIENT, SUSTAINABLE AND INCLUSIVE AGRICULTURAL AUTOMATION

KEY MESSAGES

➔ Creating an enabling environment for responsible uptake of automation technologies is key and calls for a range of policy instruments to work together in a coherent way. These relate to, *inter alia*, appropriate legal and institutional frameworks, incentives, and general services support (GSS) for infrastructure, education, training, research and private innovation processes.

➔ Investments to promote responsible automation should be based on context-specific conditions, such as status of connectivity and infrastructure, knowledge and skills challenges, and inequality in access to automation technologies.

➔ Policies to address environmental sustainability issues and enhance resilience should recognize the potential synergies between automation and other sustainability approaches, such as landscape planning and conservation agriculture.

➔ Policymakers should focus on setting up transparent legislation and regulatory frameworks, providing non-distortive GSS – including research on technologies (pilots, testing, etc.) that are farmer-centred and demand-driven – as well as training to help workers transition to new tasks, both inside and outside agriculture.

➔ While agricultural producers must choose which technologies to adopt from the wide range available, the role of public interventions is to ensure inclusive access to agricultural automation. Multistakeholder initiatives that, for example, share knowledge on automation can further enable adoption.

As discussed in earlier chapters, agricultural automation brings many opportunities for the sustainable and inclusive transformation of agrifood systems, but it also carries risks. It requires parallel efforts by private, public and third-sector actors, with coherent and complementary objectives, to create an enabling environment for agricultural automation, in order to harness opportunities and mitigate risks and ensure sustainable and inclusive agricultural transformation. Drawing further on lessons learned from the case studies prepared for this report (see Annex 1) and the available literature, this chapter identifies policy and legal instruments to encourage adoption of agricultural automation in a sustainable and inclusive manner, leaving no one behind. The overarching principle for agricultural automation is *responsible technological change*, leading to efficient, productive, inclusive, resilient and sustainable agrifood systems. Responsible technological change is a process that entails anticipating the impacts of the technologies on productivity, resilience and sustainability, while focusing on marginalized and vulnerable groups, including women, youth and small-scale producers. The process must include the wide range of stakeholders, responding to their concerns, and drawing on their ideas and knowledge.[1] To be responsible, agricultural automation must be flexible, farmer-centred, demand-driven, respectful of data privacy and cultural diversity, participatory and inclusive in design, and transparent. It must recognize the importance of context and tailor technologies to local needs by involving local actors and building on their adaptive innovation capacity. ■

TOWARDS RESPONSIBLE AGRICULTURAL AUTOMATION

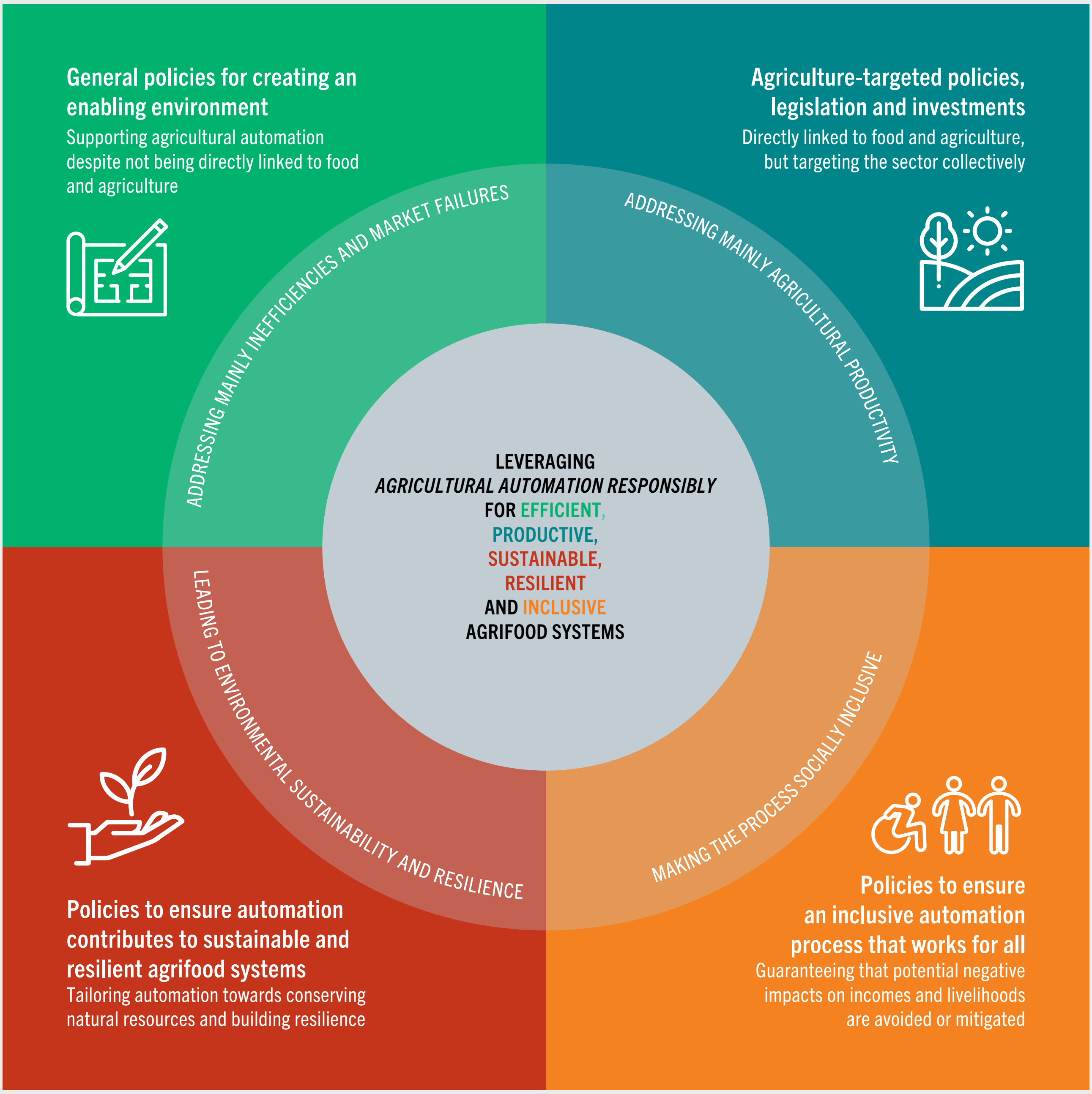
Like any technological change, agricultural automation inevitably entails disruption to agrifood systems, bringing benefits but also giving rise to trade-offs, and ultimately leading to winners and losers. Efforts to accelerate adoption need to consider the socioeconomic and political processes that either impede or catalyse technology development and adoption. Agricultural automation affects agrifood systems in various ways. It affects the livelihoods of vulnerable groups through its possible impacts on food security and nutrition, resilience, poverty reduction, and employment in rural areas – hence potentially affecting inequality. It indirectly affects the overall well-being of communities with possible implications for environmental sustainability, including natural resource conservation and biodiversity. Considering these impacts, responsible technological change should be central in policy debates, with inclusiveness and sustainability at their core.

Action towards more sustainable, inclusive and resilient agrifood systems must include all relevant stakeholders – especially small-scale producers and other marginalized and vulnerable groups, for whom agricultural automation technologies are usually out of reach.[1,2] This chapter presents a range of possible options regarding policies, institutions, legislation and investments – for putting into practice the notion of responsible technological change – organized in four key areas. Together they form a roadmap to ensure that agricultural automation contributes to efficient, productive, sustainable, resilient and inclusive agrifood systems. Every one of these options builds on key findings from case studies and available literature presented in this report. They address the main barriers to adoption discussed and analysed in Chapters 2–4. The policies, which complement and reinforce each other, are represented in Figure 8 and summarized below.

- **General policies for creating an enabling environment.** These include policies not directly linked to food and agriculture but that nevertheless support agricultural automation uptake. They address existing or potential inadequacies in infrastructures – such as roads, energy and connectivity – in addition to national policies on finance and data management.
- **Agriculture-targeted policies, legislation and investments.** These are directly linked to food and agriculture and target the sector collectively. They include, among others, agricultural research, knowledge transfer services, and finance targeting agricultural automation.
- **Policies to ensure agricultural automation contributes to sustainable and resilient agrifood systems.** These policies focus on encouraging agricultural producers to adopt automation technologies that, *inter alia*, conserve natural resources, support environmental sustainability and build resilience.
- **Policies to ensure an inclusive agricultural automation process that works for all.** These policies complement those in the three other groups and aim to ensure everyone – especially marginalized groups such as women, small-scale producers and youth – can benefit from agricultural automation, and that potentially negative impacts on incomes and livelihoods are addressed.

One very important policy area is general services support (GSS). This represents government support not directly linked to agricultural output and the use of inputs (see Box 25 on p. 84). GSS is key for creating an enabling environment to do business in agriculture and in agrifood systems more generally. It does not distort incentives but enables agricultural producers, their input and service providers, and other involved stakeholders, to set up thriving businesses, make informed decisions about automation, and stimulate innovations. Unfortunately only one-sixth of total global support to food and agriculture (about USD 111 billion) falls under GSS.[3] It is lowest where it is most needed, that is, in countries where agriculture is still a key sector for the economy, jobs and livelihoods (i.e. low- and some lower-middle-income

FIGURE 8 A ROADMAP OF POLICY OPTIONS TO LEVERAGE AGRICULTURAL AUTOMATION RESPONSIBLY



SOURCE: FAO elaboration for this report.

BOX 25 HOW DIFFERENT TYPES OF GOVERNMENT SUPPORT CAN POTENTIALLY LEVERAGE AGRICULTURAL AUTOMATION

Worldwide, support provided to food and agriculture amounted to almost USD 630 billion per year on average over 2013–2018.[3] The lion's share of this support targets agricultural producers individually, through trade and market policies, or via fiscal subsidies largely tied to production (e.g. price support for specific commodities) or specific variable inputs (e.g. fertilizer in some countries). This support can affect the business case for automation through multiple pathways. For example, it can affect the mix of commodities produced, since agricultural support is largely for starchy staples (in low- and lower-middle-income countries) and dairy and other protein-rich foods (in high- and upper-middle-income countries). The mix of products will in turn determine options for adopting automation technologies, which may be suitable for some products but not for others. Globally, approximately one-third of all support is through price incentives connected to a specific product or group of products.

Likewise, adoption of automation can be affected by support to production factors, specifically incentives favouring capital accumulation. For example, credit subsidies for agricultural producers will favour more capital-intensive automation technologies. Who receives this support – large producers or small-scale producers – will be key in terms of automation inclusiveness. Globally, approximately one-tenth of the support provided to farmers individually is based on production factors.

Support linked to production – whether through prices or factors of production – distorts incentives in ways that may be counterproductive, unintentionally favouring some producers over others. While inclusiveness may be favoured by specific support measures, this is not usually the guiding rationale.

General services support targets food and agriculture collectively and is not directly linked to production, individual producers or specific production factors. It includes support for agricultural research and development and knowledge transfer services (e.g. training and technical assistance), as well as infrastructure development and maintenance (e.g. improving rural roads, irrigation systems, storage infrastructure, connectivity). Such support is important for adoption of automation, without distorting incentives or favouring certain groups of producers over others.

countries).[4] In these countries, creating a level playing field for agricultural automation will most likely require an increase in GSS, which would, however, entail significant development financing.

When designing policies and planning investments, governments will also need to balance trade-offs between different, and sometimes conflicting, economic, environmental and social objectives. The relevance of the policies, investments and other public actions proposed below varies depending on the context. Governments should prioritize actions based not only on local challenges but also on national capacities and resources – including financial ones – that they can mobilize to design policies and transform them into action.

The next sections present in more detail recommended policies and investments according to the four policy categories. ■

GENERAL POLICIES FOR CREATING AN ENABLING ENVIRONMENT

Globally, demand for technologies to replace human labour and improve precision of agricultural operations has been a major driver of past mechanization and is currently the main driving force behind digital automation and robotics. Through general policies, legislation and investments affecting agricultural development, governments can shape the enabling environment for relevant stakeholders, from agricultural producers, to service providers, logistics operators and manufacturers.[4] In particular, promoting and investing in agricultural development, for example, by improving infrastructures, can help promote the business case for digital automation technologies. Such policies and investments play a critical role in correcting market failures and reducing transaction costs caused by poor connectivity, electricity supply, data protection and access to services (e.g. finance, insurance, education), thus improving overall economic efficiency. The following sections highlight important areas of focus.

Improving transport infrastructure

Poor infrastructure can lead to high transaction costs in accessing production items and inputs, and reaching output markets, thus reducing incentives to invest in technology, including agricultural automation. Better transport infrastructure improves farmers' access to high-value markets, reduces transaction costs for machinery, spare parts, repairs and fuel, and facilitates the emergence of (migratory) service markets.[5] Improving transport is of particular importance in sub-Saharan Africa, where it is generally poor (see Chapters 2 and 3). However, it is also relevant in other low- and middle-income countries where there appears to be limited adoption of agricultural automation.

Investing in energy infrastructure

No automation technology works without energy. Most machinery relies on fossil fuels (although some are electric) and digital automation requires electricity. Even in countries where the electric grid extends to rural areas, electricity is usually only available in towns. Access in fields is rare, even in high-income countries. For this reason, many low- and middle-income countries depend on off-grid electricity to supply energy to rural areas – if they have access to electricity at all. Policies that improve electricity supply (e.g. through off-grid electricity from renewable resources) can help support the local manufacturing sector, and facilitate uptake of agricultural digital automation and mechanization (e.g. pumps for irrigation, and machinery for processing and preservation).[6, 7] Governments may want to focus on the potential of renewable energy for power mechanization down the value chain.[8] Renewable energy based on local investments can also buffer, at least to some extent, shocks in the energy sector and fluctuations in fuel prices that affect the profitability of agriculture.

Improving communications infrastructure

Improving communications infrastructure is particularly important for the uptake of digital and automation technologies. Poor connectivity is widespread in many low- and middle-income countries, but it can also affect some high-income countries. What is more, access to the internet is also essential for digital automation: it allows software updates, improves computer capacity (through cloud computing) and enables access to remote sensing data and other databases. Internet access in rural areas worldwide is often sparse and expensive, especially in low- and middle-income countries. Policies to encourage the development of rural digital infrastructure could include low interest loans for rural internet providers and support for communication cooperatives that offer data services. In Europe, connectivity has improved in rural areas through the implementation of a variety of solutions, including private, public and community-led initiatives, most involving collaboration between several different parties (see Box 26 on p. 86 for a case in Slovenia). These examples show the importance of public–private–community partnerships for improving rural connectivity and infrastructure.[9] Legislation can also play a role; in some jurisdictions, internet access is a protected legal right (e.g. Finland).[10]

Investments should also target associated enabling infrastructures, such as public datasets on weather forecasts and calendars for crop and livestock production. An example of a cooperative effort in this field is provided by the Digital Public Goods Alliance (DPGA), a multistakeholder initiative of which FAO is a member. DPGA facilitates the discovery, development and use of, as well as investment in, digital public goods in multiple sectors, including agriculture.

BOX 26 BROADBAND OPEN ACCESS NETWORK IN KOMEN, SLOVENIA

In Slovenia, approximately 50 percent of the population – close to 1 million people – live in rural areas, on average 30 people per km^2. The municipality of Komen, an area with a low and declining population in the Western Slovenian region of Carst, received funds from the European Union to build open broadband networks. A public–private partnership seized the opportunity, bridging the local digital divide through rapid deployment of infrastructures, and achieved high penetration rates. A strong focus on the project's long-term sustainability and operational costs was key to its overall success.

The 103 km^2 area of Komen comprises close to 1 340 households in 35 villages. A challenging, rocky terrain and low population made it unviable for commercial providers, given the high costs and minimal returns. The local municipality developed the project, with support from a private partner.

Work proceeded swiftly with very tight completion deadlines. The local authorities collaborated actively with the private partner; their help in overcoming permit issues led the municipality to issue the necessary paperwork promptly – key for respecting the work schedule. Communication and awareness-raising, aimed at all citizens of the Carst region, was very effective and smoothed relationships with the local population. This close cooperation between the partners during the buildout phase rapidly led to high penetration rates.

SOURCE: European Commission, 2020.[11]

Improving general credit markets and exchange rate policies

Credit is critical for investing in agricultural automation and for financing agricultural technologies generally. Small-scale producers' access to credit is usually limited, especially for women, due to a lack of collateral (e.g. land titles) and high transaction costs, among other challenges.[12] Prohibitive interest rates often make it impossible to source credit to finance machinery[5, 12] and other automation technologies. Unlike seeds, fertilizers and pesticides, automation technologies are expensive with the costs spread over several years. Interest rate policies can heavily influence automation patterns, as seen in various Asian countries.[6, 13] Exchange rate policies can also affect automation due to their impact on the import costs of machinery, spare parts and fuel.[5, 13] Guaranteeing affordable interest rates for credit and ensuring stable exchange rates are essential for long-term investments in most automation technologies.

Establishing transparent national data policies and legislation

Digital automation technology often collects massive amounts of data regarding crops, livestock, aquaculture and forestry. This may include proprietary information and thus raises privacy issues for agricultural producers. Data that are unprotected by privacy legislation can be a valuable commodity, and legal frameworks may be needed to clarify who benefits from use of the data. Transparent legislation on data protection, sharing and privacy is a key enabler of digital automation as it allows to build trust among farmers. In particular, there is a need for clear rules concerning ownership and control of data. It is recommended to consider the notion of "privacy by design", integrating data protection into technology design.

There is also a need to support responsible and progressive digitalization of the agriculture sector, including development and support of national data infrastructure. Interoperability (accurate and reliable communication among machines) is vital for data sharing and needs to be technically defined and legally enforced. Legal interoperability defines the regulatory framework for data exchange, while protecting aspects such as privacy.

Another related area is the institutional and political capacity for digitalization and automation. Experience from low- and middle-income countries shows that powerful private technology companies often anticipate such a governance system, with potentially negative consequences. This is referred to as digital colonialism,[14, 15] where power and influence are concentrated in large corporations through, for example, proprietary software, to extract data and profits from users. Most low- and middle-income countries cannot develop a competitive digital industry using their own resources. However, it is important to develop the capacity of national and regional governance to at least guide automation technologies, rather than the other way around. Cooperative efforts to address data challenges are also important, as exemplified by the diverse set of partners in the DPGA, which disseminates digital public goods. These efforts also emphasize the potential of digital communication to share information on automation technologies and raise awareness of their potential. ■

AGRICULTURE-TARGETED POLICIES, LEGISLATION AND INVESTMENTS

Beyond general policies, legislation and investments, policymakers need to target the agriculture sector to support automation more directly. Governments can use a range of policies, legislation, investments and other interventions to target the sector, especially small-scale producers, to support adoption of automation technologies. These include land tenure policies, investments in capacity building, legislation on quality assurance, applied research, and targeted finance. The specific priority ranking of such actions largely depends on context, including the overall development level of a country or region and the agroclimatic and topographic characteristics of agriculture. National strategies for agricultural automation are needed to guide more specific actions, policies and investments. This is essential in areas where automation is either lacking or in the early stages. Such national strategies should be based on surveys and field studies that take account of the experiences of researchers, agricultural producers, service providers and manufacturers. The basis for producers adopting specific machinery and digital equipment must be their conditions and needs, which vary within and between countries. In Africa, where agricultural automation is still limited, governments have come together to accelerate adoption, recognizing the advantages of the digital revolution (see Box 27 on p. 88).

The following sections present possible policies, investments and legislation that governments can focus on, based on the conditions and needs of producers, to harness the potential of automation technologies and establish a business case for the widest possible range of producers.

Improving access to automation technologies, especially for small-scale producers

As previously stated, the functioning of credit markets has important implications for access to finance to adopt costly technologies such as automation. Farmers can use their savings to purchase machinery, but when savings are limited, they resort to credit. Governments can influence this process through credit policies that directly target agricultural automation. Investment loans are the most common solution for financing automation, but they can be undermined by lack of security or have high costs. Contract-based securities, loan guarantee schemes, joint liability groups, and leasing are all potential options. With leasing, various incentives may be applied, for example, matching grants or providing "smart" subsidies (i.e. subsidies that do not distort markets).[26] Such tools are used in some Asian countries to enhance farmers' access to credit.[13] Other options for moving forwards include value chain finance, cooperative credit (as seen in India[27]), and savings and insurance products, especially for larger equipment.[26] In addition to producers and service providers, local manufacturers and maintenance and repair shops may also need loans.[5, 22]

BOX 27 NATIONAL STRATEGIES FOR A STRONGER ADOPTION OF DIGITAL TOOLS IN AFRICAN AGRICULTURE

The African Union (AU) and several African governments are accelerating efforts towards an enabling environment for the effective use of digital tools to transform agrifood systems. A key recent step is the AU Digital Agriculture Strategy, under the leadership of the African Union Commission Department of Rural Economy and Agriculture. This is a follow-up to the Digital Transformation Strategy for Africa (2020-2030), which includes agriculture.[16] The Digital Agriculture Strategy, yet to be officially adopted, encourages governments to better leverage the power of digital innovations to boost the performance, inclusiveness and sustainability of agriculture and other rural sectors, calling for digital agriculture strategies and the use of digitalization to strengthen mechanization services.

In addition, Smart Africa, an intergovernmental agency created by African heads of state and governments, has developed the AgriTech Blueprint for Africa,[17] while some years earlier, FAO and the International Telecommunication Union proposed to governments a guide for their digital agriculture strategies.[18] Building on these various efforts, many agriculture ministries in Africa are designing new policies to better seize the opportunities offered by digitalization.

Evidence from the 27 case studies discussed in Chapter 3 shows that when agricultural producers – especially small-scale farmers – lack financial capacity, service providers can seek alternative business models to make their solutions profitable. In some cases, services are tied to credit, insurance or farming contracts, such as contract farming agreements that guarantee offtake and a fixed price for raw materials. This helps reduce production risks, improves investment capacity, and leads to higher yields and better quality outputs. In the absence of contract farming or supply chain legislation that improves small-scale producers' contractual capacity, such business models may create technological lock-ins (i.e. requiring farmers to use specific services), or unwanted dependencies and power asymmetries, with unintended socioeconomic consequences. These solutions may also coerce farmers, buyers and service providers to follow certain behaviour patterns and agronomic practices desired by more powerful market actors. At the same time, these solutions embed farmers in a closed, proprietary system.[25] More organized, formal services help reduce production risks, but can also restrict a farmer's options. Legislation is needed to protect small-scale producers from falling into coercive contracts.

Another policy area where governments can facilitate access to finance is land tenure. Insecure tenure creates disincentives for agricultural producers to invest in agricultural technologies – and in their farms generally – because it causes great uncertainty about whether farmers can ever reap the benefits of their investments. It restricts access to credit, as they cannot use land titles as collateral. This is particularly a problem when the investment is costly and takes several years to repay, as in the case of motorized machinery. Better land tenure security facilitates credit access, especially for small-scale producers, and incentivizes machinery investment. In Myanmar, for example, land tenure reforms have significantly increased the likelihood of being granted a bank loan to purchase agricultural machines.[23] Farmers can use this credit to purchase inputs such as fertilizers and improved seeds; the synergies between these inputs and use of machinery and digital equipment contribute to raising productivity and resource-use efficiency. Credit for automation should be led by market actors and guided by commercial viability. Public efforts to directly finance agricultural automation have often come up against considerable governance challenges.[26, 28]

Trade policies can play a role in accessing agricultural automation technologies. The supply of agricultural automation can be affected by high import duties, lengthy customs procedures and non-tariff barriers to trade, such as sanitary measures. In Asia, the removal of import restrictions greatly contributed to mechanization,[13] while in Africa, machinery is now exempt from import duties in many countries, although some remain in place.[12, 13] In other countries where machinery is mostly exempt, spare parts often attract high duties, undermining the sustainability of mechanization. Reduction of duties on machinery, digital equipment and spare parts, together with improvement of customs procedures, can help lower transaction costs of automation technologies and spur uptake. Governments should give priority to duty and tax exemptions for machinery and equipment that best fit local conditions and address the main challenges relative to national objectives for improved productivity, enhanced sustainability and stronger resilience.

Building knowledge and skills

Manufacturers, owners, operators and machinery technicians, as well as agricultural producers, all need to acquire knowledge and skills on how to create, manage, operate, maintain and repair agricultural automation equipment. Lack of this specific expertise can undermine the profitability and sustainability of automation technologies; despite this, they are often poorly promoted.[5] A case in point is Ghana, where 86 percent of tractors have frequent and long-lasting breakdowns due to poor maintenance and a shortage of skilled operators and mechanics.[19] Public efforts to build knowledge and skills have played a key role throughout the history of mechanization across the world.[20] Vocational training centres, combining applied and theoretical training, may be particularly adapted to provide the necessary knowledge and skills. Training is also essential for human supervisors of digital automation. In Australia, the code of practice specifically prepared for users of machines with autonomous functions places great emphasis on how to alert supervisors and how they should report incidents.[21]

Digital illiteracy, as well as lack of skills to supervise, maintain and repair automation technologies, is another major barrier to adoption of digital automation worldwide, especially for small-scale producers (see Chapter 3). Human capital development is essential and a capacity-building agenda is required, including investments to scale digital skills. This agenda should not only target agricultural producers, but also other actors in the agricultural value chains, covering all stages, from input and service provision to further downstream (e.g. processing and trading). Such an agenda is essential to support the transition of workers from low- to high-skilled jobs, and it is particularly important for youth – often perceived as key drivers of the transformation of family farming towards agricultural automation, as they tend to embrace it more than their parents. Government policies and investments should therefore target young rural workers.

Investing in applied research and development

Private research and development largely drive automation technologies. Governments can provide general support through relevant institutions and can conduct or fund research on technical, agronomic and economic solutions for locally adapted and sustainable automation. The research agenda should also cover studies on the impact of specific precision agriculture solutions for profitability, environmental sustainability (including carbon, water and energy footprints), labour safety, and inclusion of women, youth and other vulnerable groups. Another relevant area concerns different types of farming in protected and controlled environments (e.g. vertical agriculture or greenhouses), not always perceived positively by consumers and policymakers. It is also essential to develop and validate specific agronomic models for a better understanding of crop responses to specific precision agriculture technologies, such as variable rate technology (VRT). Governments can support national research and innovation systems – private or public – to adapt and upgrade existing machinery and digital equipment, tailoring them to the needs of producers as farming systems evolve.

Research is needed on the use of big agricultural data and analytics as a public good capable of offering free advisory services

BOX 28 ADAPTING DIGITAL AUTOMATION TO VARIOUS CONTEXTS: EVIDENCE FROM 27 CASE STUDIES

The 27 case studies in this report illustrate how to adapt digital automation to local needs across production systems, countries and farm types. For example, in crop production there is evidence of low-income countries developing small automated machinery – for example, tea leaf pickers in Uganda, and automated cotton harvesting machines (a difficult operation to automate, as mentioned in Chapter 3) in India and Western Africa. These technologies are currently available to medium- and large-scale producers, and their use is expected to become more widespread, managed by producer organizations through hiring centres.

In precision livestock farming, the business and service models for milking robots provide valuable lessons in terms of application of technologies to different farm types. While milking robots are mainly adopted by medium- to large-scale farms in high-income countries, there are other technologies adapted to small-scale indoor farms, as well as pasture-based free cow movement installations in middle-income countries.

Finally, with regard to agriculture in controlled environments, greenhouses are increasingly common in high- and middle-income countries where there is a certain level of automation (e.g. for climate control). These solutions are appearing in countries across the globe, for example, Chile, Mexico and Saudi Arabia. Controlled agriculture, and in particular greenhouses, represent an important opportunity for robotics with artificial intelligence (AI).

SOURCE: Ceccarelli *et al.*, 2022.[25]

to small-scale producers. Applied research is also recommended to explore the adaption of automated solutions to different regions, countries, agroecological conditions, production orientations and farm types (see Box 28). Ideas that have worked in one place may not be suitable elsewhere. To encourage the development of relevant autonomous agriculture, research and development frameworks need to bring innovators together with farmers to design and scale solutions. One example from the United Kingdom is a scheme by Innovate UK called Science and Technology into Practice. The programme is publicly funded and requires innovators to work with end users throughout the project, hold demonstration events, and gather and act on feedback from farmers.

A final research area is that of the emerging power dynamics in low- and middle-income countries as a result of increasing reliance on digitalization and automation technologies. It is necessary to understand the commercial interests of big players in technology development and service provision, and the potential impacts on small-scale producers, particularly in terms of concentration of power, redistribution of land and wealth, and loss or creation of knowledge and skills, as well as the implications for labour and employment.

Quality assurance and developing safety standards

A lack of quality assurance in the form of testing and certification of machinery, equipment and spare parts can undermine the uptake of various agricultural automation technologies as it increases the uncertainty and risks associated with their purchase.[13] For example, in Ghana a locally produced maize sheller that can be attached to a tractor costs less than an imported one, but the quality is difficult to assess prior to purchase due to a lack of standards or certification schemes. Many farmers thus opt for foreign brands.[5] Testing may not actually be feasible for small- and medium-scale manufacturers without assembly lines; what is more, they lack incentive if local markets do not require formal certification. However, public, market and third sector organizations can organize testing to effectively mitigate information asymmetries without substantially raising machinery costs.

The presence of a public validation service that appraises the cost-efficiency, effectiveness and user-friendliness of technologies could have a positive impact on uptake. Likewise, strengthening the institutions that set standards can support the manufacturing and trade of automation technologies.[22]

Policymakers need to ensure safe agricultural automation through a balanced package of laws and regulations. Such rules should cover all aspects, whether positive or negative, and be based on an inclusive consultation, interacting with all stakeholders both before and after application of the regulations. In the United Kingdom, for example, the Government has severely restricted the use of drones in input application on safety grounds, despite the significant benefits for the environment and human safety. The legislation also requires 100 percent on-site human supervision of autonomous machines to ensure they do not cause accidents. Analysis found that such legislation wipes out the economic benefits of autonomous equipment for small- and medium-scale producers and increases economies of scale, making them profitable only for larger farms.[24] When policymaking is transparent and inclusive, such findings may lead to a revision of policy.

To guarantee safety, governments should adopt transparent frameworks. Essential elements are inspections to verify user compliance, standards to provide guidance, and mechanisms to enable self-regulation through, for example, assurance schemes (voluntary schemes that establish production standards covering food safety, animal welfare and environmental protection). Standards could be legally binding or not. In Australia, a code of practice has been adopted to guide the use of autonomous machines in agriculture.[21] It gives growers the confidence to adopt autonomous solutions, while giving manufacturers the confidence to scale them. It aims to standardize the approach to machinery automation. The code of practice covers several areas, including general hazard controls and emergency preparedness, vehicle transport between fields, maintenance and repair requirements, emergency management, and legislative provisions and standards.

Similar work is being undertaken in the United Kingdom for robots including those used in agriculture.[9]

Harnessing the potential of low-cost agricultural automation technologies

When the business case for investing in larger machinery is lacking due to financial constraints, or because the machinery is not suited to local topographic conditions (e.g. hilly terrain) or farm sizes (e.g. very small, fragmented plots), small machinery can provide great benefits to crop producers, especially those operating small plots in relatively marginal areas. Such machinery and equipment include two-wheel tractors or power tillers, drum seeders, rotary dibbers and power weeders.[29] There is evidence of the business case for adopting small machinery (see Box 17 on p. 55). Indeed, these simple technologies can lead to a significant reduction in drudgery, as well as savings in time and inputs, leading to improved productivity and enhanced resilience through timely performance of operations. They are also more environmentally friendly as they require little or no fossil fuel to operate, and many of them are suitable for agroecological approaches, such as rice–fish systems and alternate wetting and drying (where farmers apply water-saving technologies to reduce water consumption in rice fields without affecting yield). In some contexts, they allow for greater inclusion of women, who may be excluded from mechanization due to cultural norms and traditions.[29, 30]

Technologies such as IVR, USSD and SMS, in addition to call centres, are available in most low- and middle-income countries and are therefore the most common – if not the only – solutions for small-scale producers, especially in sub-Saharan Africa. They give access to bundled services, since they can reach farmers (regardless of the devices they use and their digital skills), are low cost and require little maintenance. Bundled services often combine various subservices (e.g. provision of information on markets, climate and weather, and real-time farm monitoring data), and also link actors. These technologies have the potential to limit digital divides thanks to their high accessibility. They are less sensitive to infrastructural failures as they require less energy and simpler data infrastructure compared with advanced data-driven technologies, and generate the highest return on investment. It is important, however, that the solutions offered not only meet local needs but also provide reliable advice.[25] ■

POLICIES TO ENSURE AGRICULTURAL AUTOMATION CONTRIBUTES TO SUSTAINABLE AND RESILIENT AGRIFOOD SYSTEMS

So far, this chapter has discussed the role of a range of measures to overcome barriers to adoption of agricultural automation, focusing on the needs of small-scale producers. This section reviews what needs to be done to ensure that agricultural automation adoption contributes to sustainable and resilient agrifood systems and avoids further environmental degradation. As mentioned, motorized mechanization has generated many benefits, including productivity gains, resulting in enhanced food security, reduced poverty, and better health and well-being, among many others. However, this has often been at the cost of environmental sustainability, with effects such as biodiversity loss, soil compaction and erosion, and water degradation. These impacts can be greatly minimized or avoided if accompanied by appropriate policies, legislation and investments, and the use of more advanced technologies such as digital automation solutions. The sections below examine important areas of focus.

Safeguarding against biodiversity loss, land degradation and carbon emissions

Motorized mechanization can lead to farmland expansion at the cost of forests and savannah, contributing to climate change and biodiversity loss (see Chapter 3). Such negative effects can be – at least partially – addressed or avoided by land-use planning and monitoring, enabled by digital automation technologies that target the land most valuable for mitigating climate change and conserving biodiversity. Investments should also follow the principles of responsible investment in agriculture and agrifood systems, endorsed by the Committee on World Food Security.[31]

Sustainable cultivation strategies such as crop–livestock–forestry systems, which come with fewer climatic effects and allow for more biodiversity, can also play a role in mitigating negative environmental effects.[32] One of the 27 case studies examined in Chapter 3, Justdiggit (see Annex 1), promotes large-scale landscape restoration in Africa, for example, by turning degraded rangelands into green, fertile land. This process of landscape restoration is implemented through rainwater harvesting, grazing management and tree pruning. It is assisted by remote sensors that monitor tree growth and calculate volumes of associated carbon sequestration.[33] In some countries, governments have successfully minimized farmland expansion with land-use planning and monitoring. Such initiatives and practices should be encouraged and possibly replicated elsewhere. In other countries, public interventions have contributed to negative effects, for example, when supporting large-scale block farming schemes or land investments. Any such interventions still in place should be halted and avoided elsewhere.

A combination of technologies can reduce greenhouse gas (GHG) emissions and enhance soil carbon storage, allowing agriculture to achieve negative net emissions while maintaining high productivity. Through synergies between digital automation, crop and microbial genetics, and electrification, an estimated 71 percent reduction in GHG emissions from row-crop agriculture is possible within the next 15 years. It is estimated that current row-crop agricultural practices generate about 5 percent of total GHG emissions in the European Union and the United States of America. Emerging voluntary and regulatory ecosystem service markets can incentivize progress along this transition pathway and guide public and private investments towards technology development.[34]

Lighter machinery can reduce soil compaction and erosion, often caused by large motorized machinery. Moreover, conservation agriculture with crop rotation can reduce soil erosion by up to 99 percent, using rippers or direct planters to replace ploughs, and thus promoting minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil cover, and plant species diversification.[35] It appears to be the way forward for agriculture across the globe, including in low- and middle-income countries.[22] There is evidence that combining motorized mechanization with reduced tillage can lead to synergies between productivity and soil health.[36] However, in order to overcome some of the challenges associated with this practice, locally adapted solutions must be developed.[37] Applied technical and agronomic research can explore mechanization solutions that best fit local agroecological conditions. For example, there is increasing research on drone input application for small farms – a technology with numerous potential benefits: exposure to pesticides is reduced, and application is possible in fields that are too wet or problematic for machines to access, as well as in standing crops (avoiding crop damage from machinery movements).

Nudging automation technologies known to be environmentally friendly

The notion of scale-appropriate mechanization, where machines are adapted to farm size (not farm size adapted to machines),[38] can help reduce negative environmental effects. For example, small four-wheel or two-wheel tractors are better able than large tractors to manoeuvre around landscape features and on-farm trees. Small swarm robots, now in the experimental phase, can generate environmental benefits, such as reducing soil compaction while delivering higher yields. While most agricultural robots currently in the pipeline have very little decision-making capacity, in the long term, AI has the capacity to make them useful for environmental sustainability. For example, swarm robots embedded with AI can avoid field obstacles and precisely target pests and weeds, thus reducing chemical use and protecting biodiversity.

The scaling of these technologies is a major challenge; without scaling, it is not possible to optimize their potential to reduce negative environmental effects and increase productivity in a sustainable manner (see Chapter 3). High purchasing and operation costs represent an important obstacle to scaling, especially for small-scale producers; to increase affordability, there needs to be a focus on technology improvement and innovative business models. Mobile phones are a case in point: scalability made them much more affordable, paving the way for smartphones, which are increasingly used for precision agriculture.

Farmers themselves are in the best position to choose which mechanization solutions fit their local agroecological conditions. Governments must create an enabling environment, disseminating information on available technologies and how to use them to achieve multiple objectives, including environmental sustainability. An example of such information support is the mechanization catalogue prepared by FAO in collaboration with the Centre for Agricultural Infrastructure Development and Mechanization Promotion and the Agriculture Machinery Entrepreneurs Association in Nepal. The catalogue contains straightforward information about the various machines available on the Nepalese market, with a focus on those that are gender-sensitive and adapted to small-scale agricultural production.[29]

Several governments have introduced legislation to mitigate the adverse environmental and social impacts of agricultural supply chains by requiring companies to establish mandatory risk-based due diligence systems.[39] For example, the European Commission has adopted a proposal for a directive on corporate sustainability due diligence. It aims to foster sustainable and responsible corporate behaviour throughout global value chains. Companies must identify, prevent, end or mitigate the adverse impacts of their activities on human rights (e.g. child labour and worker exploitation) and on the environment (e.g. pollution and biodiversity loss). For businesses, these new rules will bring legal certainty and create a level playing field; for consumers and investors, they will provide greater transparency.[40]

Awareness raising and improved communication

One of the lessons learned from the 27 case studies is that consumers have yet to appreciate precision agriculture and its potential in terms of efficiency, environmental sustainability and animal welfare. Indeed, while the term "low-input farming" (and its association with environmental sustainability) is immediately understood by consumers, "precision agriculture" still fails to resonate. Communication is key. The fact that vertical farming, for example, cannot be labelled organic in some countries hinders communication of its benefits to consumers. Policies can help prioritize legislation and certification for precision agriculture in order to clearly communicate its advantages to consumers and thus strengthen the business case for investment (see Chapter 3). In order for precision agriculture to realize its potential environmental benefits, it is fundamental to establish a dialogue across agrifood systems in their entirety.[25] Digital communication itself can play a key role in raising awareness, disseminating information and performing advocacy for precision agriculture. ■

POLICIES TO ENSURE AN INCLUSIVE AGRICULTURAL AUTOMATION PROCESS THAT WORKS FOR ALL

One of the main challenges faced by agricultural automation is the risk of leaving behind marginalized groups – such as women, small-scale producers and youth – given the scale bias of automation towards larger farms. The high costs of many existing automation technologies and their associated skill requirements can lead to widening inequalities and deepening of digital divides. Automation may be linked with increased unemployment and job displacement for unskilled labourers; not only can this have negative implications for inclusiveness, but it can distort perceptions about its benefits. Policies can play a central role in mitigating or avoiding any of the above negative impacts and ensuring that automation contributes to inclusive agricultural transformation.

Addressing the technological divide through technical and institutional innovations

More recent technologies, including those associated with the digital revolution, can make automation come close to scale neutrality and thus be more accessible to all. The deployment of small machinery has enabled small-scale producers to automate many agricultural operations (see Chapter 3). Institutional mechanisms, such as shared service provision and cooperative ownership facilitated by digital technologies, have supported the adoption of automation technologies.[41] It is farmers who should choose which automation solutions best fit their local agroecological conditions, while governments should create a level playing field. The latter can support the emergence of service markets by improving rural infrastructure, providing good legal conditions, facilitating border crossings, and developing service providers' knowledge and skills, including business training. Third-sector organizations, such as producer associations and cooperatives, can help reduce the transaction costs of working with small-scale producers, for example, by organizing farmers in groups.[42] Digital tools can address some of the challenges associated with service markets and reduce transaction costs. Governments can facilitate the use of such tools by building digital connectivity, literacy and trust.[43]

Ensuring that women benefit from automation

The impacts of automation on women can be both positive and negative; taking account of their needs is key for avoiding negative effects.[26] Women often have less access to automation technologies – partly because their plots are smaller and more fragmented and they have less access to markets, credit and extension (see Chapter 4). Policies, legislation and investments that address these disadvantages (e.g. through improving women's land rights and access to credit and extension) can help increase their access to automation. It is important to adopt human rights-based monitoring approaches, collecting disaggregated data to measure impacts on women's livelihoods, rights and opportunities.

National legal frameworks should also provide for gender-sensitive regulatory impact assessments, and develop and budget for measures aimed at avoiding and mitigating any diverse impact on women. Legal frameworks must recognize the gender-specific challenges that women face and take measures to address them. These may include allocation of financial resources to expand access to entrepreneurship through credit, provision of training (including in digital literacy), and measures designed to improve their access to input and output markets.

Women's poor access to mechanization also depends on social norms. Potential entry points to change this include gender awareness campaigns (e.g. showcasing women who are successful service providers or operators) and support to female-based mechanization cooperatives or associations, in which women collectively manage machinery, and can gain access to knowledge and skills development and finance. More research is needed to better understand how to improve women's access to mechanization. Automation usually involves heavy upfront costs; as female-owned businesses tend to be smaller with less capacity to invest, this has important implications for women's competitiveness.

Women may also be less able to express their needs due to lack of empowerment.[44] Policies, legislation and investments that use human rights-based monitoring approaches and enhance women's power can help them to better express their needs. Public research and development can focus on gender-friendly mechanization technologies, tailoring their design to the needs of women.

Focusing on rural youth to ensure a smooth and inclusive transition in the digital era

One of the main challenges for agricultural development is the outmigration from rural areas of youth – especially those with higher education levels – leaving behind an increasingly ageing population and serious challenges in terms of the sustainability of agriculture and agrifood systems. Agricultural automation can play a key role in reversing this trend. It can fill labour gaps; digital technologies can spur the interest of rural youth to find jobs in the agrifood sector, including at the farm level, creating new employment opportunities with better working conditions and incomes.[45]

As mentioned in previous chapters, young farmers are often the first to adopt and operate automation technologies – in part due to their better access to information and digital technologies, such as smartphones – and are thus instrumental in digital automation in agriculture.[25] They combine insights and expertise in agricultural practices with the digital skills necessary for new technologies.[46] A specific agricultural automation agenda that targets rural youth and ensures they acquire the necessary skills to perform new highly skilled jobs should become a policy priority. Such an agenda should aim to build their competences not only for agricultural production but also for performing high-tech operations along agrifood value chains. This should be complemented by financial and policy support, as well as research, development and technical assistance to ensure a holistic approach to the transformation of agrifood systems.
Public education can play a vital role in a smooth transition and equitable access to new employment opportunities.[47] This is particularly important as young rural people are likely to continue exiting agriculture, especially in low- and middle-income countries, but can then transition to higher-skilled jobs at other stages of agrifood systems.

Community-led rural development initiatives should include youth in consultation, planning and decision-making. Legal frameworks can support these initiatives by creating an enabling environment for local development, establishing mandatory quotas for youth participation and creating youth organizations.

Improving agricultural extension and rural advisory services

Publicly funded extension services have always played an important role in ensuring inclusive agricultural automation. Apart from the various challenges which small-scale producers face, limited access to reliable and timely advisory services is a major constraint to increasing their productivity. Across the world, publicly funded extension services are a fundamental part of transforming agriculture, as they represent a major source of information. In many countries, extension continues to use different approaches. Given the lack of well-trained extension personnel – a major constraint in most low- and middle-income countries – e-extension is a valid complement to traditional extension, using digital models for knowledge generation and dissemination. When scaled, this can lead to a new generation of extension services that also support tailored automation solutions.[48, 49]

There is an urgent need to collect and transform neglected knowledge and make it available to producers through novel delivery systems; such systems can adapt scientific results, tailoring advice to suit producers with different contexts and profiles. Lessons from two technical studies developed for this report point to the potential of digital tools to revolutionize extension and advisory services; innovative delivery methods can substantially increase access to services and build skills for sustainable automation use.[25, 33] In a number of cases (e.g. Igara Tea in Uganda; SOWIT in Ethiopia, Morocco, Senegal and Tunisia; and Tun Yat in Myanmar), service providers also offer extension service provision. Some assist agricultural producers to use the service and operate machinery as part of the solution. Digital technologies – for example, IoT, audio- and video-recordings and calls on cell phones, GIS, simulation modelling, and remote sensing – can open up whole new landscapes for effective knowledge delivery. These technologies must be harnessed and exploited to fill existing information gaps and provide the effective guidance that farmers need. This also suggests that, in addition to publicly funded extension services, public–private partnerships have an important role to play in improving farmers' access to field support. Finally, digital tools can also facilitate agricultural advisory services channelled through contract farming operations or supply chain contracts.

Safeguarding against negative effects on employment

Automation can have a wide range of effects on rural employment, both positive and negative (see Chapter 4). Where it emerges as a response to market forces (e.g. rising rural wages due to structural transformation) or replaces unpaid family labour, it most likely will not cause unemployment but will help fill labour gaps. On the other hand, if automation is artificially promoted by large-scale public efforts (e.g. subsidies on machinery imports) – before the emergence of a demand for automation – the result could be unemployment, job displacement and falling or stagnant rural wages. Policymakers should be careful not to promote automation before it is needed; however, nor must they inhibit adoption under the assumption that it will displace labour and create unemployment.

Policy support that provides public or collective goods through GSS – contributing to an enabling environment for the agrifood sector and beyond – is the most likely to deliver a smooth transition to greater automation without creating unemployment. This includes supporting agricultural research and development and knowledge transfer services (e.g. training and technical assistance), as well as infrastructure development and maintenance (e.g. improving rural roads, irrigation systems, storage infrastructure and internet connectivity). Massive advances in research and development, mostly in the private sector, continue to place new farm automation solutions within the reach of farmers at a decreasing cost. This is good news for the need to raise food production as farm workforces around the world contract.

Building digital skills for inclusiveness

Farmers and agriculture professionals must acquire skills to manage the new systems with agricultural automation and also to access new, higher-skilled jobs in agrifood systems; this needs to be the focus of governments. Skill acquisition is especially relevant to young people who are a transformative power.[25] In some contexts, targeting children at school can be helpful as they can function as a technological bridge for their parents,[41] and schools that already equip farmers with agronomic and zootechnical knowledge can expand to include digital literacy. Access to information is crucial to producers' ability to keep pace in an increasingly competitive world. Moreover, information should always be a public good; its provision is the responsibility of government. With the right skills and access to information, those who lose their jobs to automation will be equipped to either accompany the new technology on-farm or find alternative work downstream or upstream in the agrifood supply chain. At the same time, part-time agricultural producers can also acquire better skills to find off-farm employment and improve and diversify their incomes. ■

CONCLUSIONS

Agricultural automation is key to attaining the Sustainable Development Goals (SDGs). The 2022 edition of *The State of Food and Agriculture* focuses on the potential of mechanization and digital automation to transform agriculture in a way that contributes to more efficient, productive, sustainable, inclusive and resilient agrifood systems. It analyses the different constraints that producers face regarding the uptake of automation technologies and provides guidance on policies, legislation, interventions and investments, keeping in mind the heterogeneity of agricultural producers (large vs small, women vs men, old vs young) across production sectors, including crops, livestock, aquaculture and agroforestry.

The report also indicates how agricultural automation can lead to trade-offs between economic, environmental and social objectives, and that a proper balance of these trade-offs depends on context. The mix of technologies – as well as appropriate policies, legislation, interventions and investments – to be promoted will depend on the level of economic development, the institutions in place, local agronomic conditions, the characteristics of producers and the objectives of policymakers. The series of policy and legal instruments presented in this chapter are not mutually exclusive. On the contrary, they need to work together to create the right conditions for responsible adoption of agricultural automation. Policymakers should note the context-specificity of adoption and understand the pressing problems facing an area (e.g. connectivity, inequality, poverty), before combining policy or legal instruments for targeted action.

Farmers, service providers and manufacturers may all have a financial incentive to invest in automation technologies, but they do not have the same market power. A key message is that while farmers should choose which technologies to adopt – from the hugely diverse toolkit of automation technologies – the main role of public interventions is to create an enabling environment, where innovation can thrive, and incentives make the adoption process as inclusive as possible. Multistakeholder initiatives, at national or international level, that share knowledge on automation can be an effective way to overcome barriers to adoption.

The report stresses that public investments and interventions aimed at broad economic development are essential for creating an enabling environment. However, priorities will differ, depending on the ultimate objectives of policymakers. While concerns about labour scarcity are driving adoption in high-income countries, low- and middle-income countries may be more concerned about improving rural livelihoods, overall food security and nutrition. Governments in these countries may choose to focus on harnessing the digital revolution towards creating decent employment opportunities that are accessible to vulnerable groups, including small-scale producers, women and youth, thus leaving no one behind while progressing towards the SDGs. This requires particular attention to the specific needs that these groups face to make the transition an inclusive one.

In summary, it is the hope that this edition of *The State of Food and Agriculture* can contribute to the dialogue and debate about how to harness agricultural automation and shape action towards the transformation of agrifood systems to make them more sustainable, productive, inclusive, efficient and resilient. ■

UKRAINE
Aerial view of green field with circular crop irrigation.
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ANNEXES

ANNEX 1
DESCRIPTION OF THE CASE STUDIES

METHODOLOGY UNDERLYING THE 27 CASE STUDIES

The case studies were collected by a team of researchers from Wageningen University and Research and by Mariette McCampbell, to take stock of agricultural automation technologies around the world and analyse the barriers and drivers to their adoption. Each case represents one company or organization which has developed and/or implements one or more solutions that fit the definition of agricultural automation presented in Chapter 1. Case studies were purposely selected based on the following criteria: (i) covering all SOFA regions (Ceccarelli *et al.*, 2022) or representative of the Global South (i.e. Eastern and South-eastern Asia, Southern Asia, sub-Saharan Africa, Latin America and the Caribbean) (McCampbell, 2022); (ii) covering the following agricultural production systems – crops, livestock, aquaculture and agroforestry; (iii) representative of a novel yet scalable, or already scaled, agricultural automation solution; and (iv) targeting small- to large-scale agricultural producers. Information was collected through interviews with key informants, and complemented with information on agriculture, literacy, automation, and policy and legislation from secondary national data sources and available literature. Interviews were conducted virtually in English or Spanish and were audio- and video-recorded for transcription and analysis. For each solution, the interviews focused on the economic, environmental and social sustainability, and the barriers to and drivers of adoption of that solution. Thematic analysis was performed on interview data, using a code frame.

While the 27 selected case studies may not fully represent the wide variety of technologies available, they provide a comprehensive view of the global trends and developments in agricultural automation. Case study data were used as input for two background papers, with Ceccarelli *et al.* (2022) using data from 22 cases and McCampbell (2022) using data from 10 cases; 5 cases were covered by both papers.

SOURCES: McCampbell, 2022;[1] Ceccarelli *et al.*, 2022.[2]

SUMMARY OF CASE STUDIES

ABACO

Year of establishment
2013

Current number of users
Not disclosed

Operating in
Europe (based in Italy), Central Asia, South America

Targeted sectors
Crops, forestry, livestock

Services provided
A digital platform in the field of precision agriculture that gathers and shares land, agriculture and weather data. Other applications are in the organic farming sector and for territorial management for use by national and local governments.

Targeted customers and users
Farmer organizations, individual farmers (both small- and large-scale) and national and local governments. Other targeted groups include insurance companies, soil laboratories and uncrewed aerial vehicle (UAV) operators.

Business model and financial sustainability
Revenues generated from multitier subscriptions (farmers) and service contracts (governments). The offer is tailored to the needs of the customer and ranges from a freemium model with limited functionalities to a paid subscription based on the size of the holding and other parameters.

Drivers
Demand for precision agriculture technologies and the need to comply with environmental standards and regulations. For small producers, there is the possibility of free use for a limited period.

Barriers
Time required to learn how to operate the platform and the need to translate the platform into different languages for scaling in other countries. In some countries (e.g. in Africa), local languages, in addition to low penetration of smartphones and limited IT infrastructure, are seen as barriers to customizing the solutions.

Policy as a barrier or enabler
No policy-related adoption barriers are noted. Policy-related adoption drivers are the European Union's Common Agricultural Policy (CAP) and its Green Deal policy goals with corresponding subsidizing mechanisms, as well as specific regulations on pesticide use.

Interviewees
Giovanna Roversi and Fabio Slaviero

AEROBOTICS

Year of establishment
2014

Current number of users
300

Operating in
18 countries, including Australia, Chile, Peru, Portugal, South Africa, Spain, United States of America

Targeted sector
Fruit and nut trees

Services provided

Use of sensors and drone and satellite imagery for early detection of pests and diseases. Aerobotics also offers location-specific datasets necessary to use variable rate technology (VRT) for irrigation and fertilizer requirements, and measures tree growth and performance, estimating yields and planning for harvest.

Targeted customers and users

Large-scale fruit and nut farmers in 18 (mostly high-income) countries; companies providing insurance to farmers and fruit juice processors and retailers.

Business model and financial sustainability

Based on an annual subscription for multitier services. Growers pay per hectare (or per acre), at yearly or monthly intervals. Different services are bundled according to the needs of the customer, with the cost depending on the attributes required. A different business model applies to crop insurance companies, who pay a fee per hectare/acre to collect data for inspection or auditing purposes. About 95 percent of the company's revenue is generated in the United States of America, where 40 percent comes from the crop insurance market. Investment in the company has so far been in the form of private equity.

Drivers

Demand for variable rate application of agrochemicals, thus economizing on usage and mitigating their negative environmental impacts. In the United States of America, farmers embrace technological innovations and digital solutions, and thus Aerobotics.

Barriers

Lack of awareness among farmers.

Policy as a barrier or enabler

In the United States of America, regulations on drones are clear and their use is permitted, while in South Africa complying with regulations proves very expensive.

Interviewee
Benjamin Meltzer

AGRINAPSIS

Year of establishment
2020

Current number of users
Unknown

Operating in
Bolivia (Plurinational State of), Costa Rica, Ecuador, Guatemala, Mexico

Targeted sectors
All

Services provided

A social media platform specializing in agriculture that enables farmers to access knowledge and information by interacting with experts and practitioners. Users verify and rate the information so that Agrinapsis can ensure it can be trusted and is of high quality. Agrinapsis also enables e-commerce among farmers to sell their agricultural output and buy inputs as required (e.g. seeds, fertilizers).

Targeted customers and users

Mainly small-scale farmers, with a particular focus on women and youth. However, everyone involved in agriculture – from academia and students, to agronomists – can benefit from the solution. Use of the e-commerce platform is enabled only for farmers; large corporate farms are not allowed to use it.

Business model and financial sustainability

Funded by the Inter-American Institute for Cooperation on Agriculture. As a non-profit organization, it has no revenue from services provided. Since the project is in its infancy, it is difficult to assess its sustainability.

Drivers

A wealth of unshared knowledge derived from the experiences of small-scale producers. Thus, Agrinapsis aims to make this knowledge accessible across countries after verifying its validity. It is seen as a tool to democratize knowledge and drive social and environmental change. Increased digital literacy, particularly among young people, bringing women together (especially older women) and the rise of influencers promoting Agrinapsis, have all played an important role in disseminating the platform, especially since it is the first agriculture-specialized social media platform in Latin America.

Barriers

Lack of internet access in remote and rural areas, despite national and international efforts to increase connectivity. Digital illiteracy is still high in rural areas, particularly among the elderly; integration of languages needs to be inclusive (e.g. in the Plurinational State of Bolivia alone there are eight official languages).

Policy as a barrier or enabler

Political uncertainty can affect the sustainability of the platform since it is funded by the Inter-American Institute for Cooperation on Agriculture, which depends on support from its 34 member states.

Interviewee
Santiago Velez

AQUACONNECT

Year of establishment
2018

Current number of users
60 000

Operating in
India

Targeted sector
Aquaculture (shrimp)

Services provided

Digital aquaculture solutions to monitor and document performance on aquaculture farms, link farmers with input providers and produce buyers, and support access to finance, insurance and markets. Aquaconnect also maintains physical centres (AquaHUBs) in communities, enhancing its last-mile connectivity, where producers can buy inputs, sell produce and obtain advisory services.

Targeted customers and users

Small- and medium-scale shrimp farmers.

Business model and financial sustainability

Free use for farmers of solutions such as the Aquaconnect App, the e-bazaar and web store. Revenue is generated from the stakeholders with whom the farmers are connected (e.g. banks, insurers, processors, input providers). Revenue is generated on a per transaction basis, through the linking services and data intelligence provided. In addition, equity funding is raised and used to expand operations. So far, the business model is profitable.

Drivers

Demand created from low productivity and inefficient market linkages. The service allows for enhanced environmental sustainability, as well as efficiency, predictability and transparency in the value chain. Interest by farmers in digital technologies is slowly increasing. Having a team physically on the ground facilitates adoption and provides technical backstopping.

Barriers

Poor capacity of farmers to operate digital technologies. The high cost of advanced technology, such as internet of things (IoT) devices, limits affordability. There is a ceiling on the size of loans farmers can obtain per hectare of land and it is insufficient to invest in equipment and aquaculture production in general.
The premium rates for insurance for aquaculture are significantly higher than for crop production.

Policy as a barrier or enabler

The Government of India has allocated USD 3 billion for the modernization of agriculture, including aquaculture fishery value chains. There is interest from the Government, expressed in the form of policies, to support start-ups that implement technologies across the value chain. However, there are currently no subsidies for aquaculture and no specific subsidies for IoT tools.

Interviewee
Sudhakar Velayutham

ATARRAYA

Year of establishment
2019

Current number of users
Unknown

Operating in
Mexico, United States of America

Targeted sector
Aquaculture (shrimp)

Services provided

Shrimpbox: an automated and controlled shrimp farm, located in shipping containers – "shrimp boxes". Each shrimp box uses sensors, machine learning, big data, biotechnology and robotics to control aquaculture operations, including nutrition intake, water quality and oxygen content.

Targeted customers and users

Mostly shrimp producers, but also poultry farmers who want to switch to shrimp farming. Restaurants, universities, corporations and consumers who want to access and serve fresh, sustainable seafood are also targeted. Some restaurants are also partners of Atarraya.

Business model and financial sustainability

Not yet profitable because still in the early phase. Shrimpbox previously relied on subsidies from the Government of Mexico, while there is now growing interest from private investors. The business model is still to be decided. Atarraya does not seem inclined to operate the solution directly due to difficulties in scaling. Contract farming is the preferred option, with Atarraya leasing the solution; however, to make this option attractive, the technology transfer needs to be seamless. Clients (from China) are interested in purchasing Shrimpbox, but Atarraya is not ready to pursue this.

Drivers

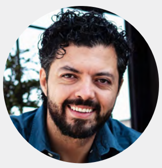
The high demand for shrimps worldwide coupled with the environmentally harmful practices of most shrimp farms. Current practices are associated with high losses triggered by rapidly spreading diseases and also cause the destruction of mangrove forests, an important carbon sequester worldwide. In contrast, Atarraya's service improves shrimp production in a sustainable and flexible manner by, for example, not needing to be close to an ocean. A very important and promising factor for increased adoption is the generational shift: young farmers are much more open to implementing new technologies.

Barriers

Scepticism of older shrimp producers, coupled with remoteness, leading to resistance to a change in business model. Also poor road infrastructure is an important barrier given the heavy logistics required.

Policy as a barrier or enabler

Public research and development grants helped in the early stages but have now come to an end.



Interviewee
Daniel Russek

CATTLER

Year of establishment
2019

Current number of users
Unknown

Operating in
Latin America and the Caribbean, United States of America

Targeted sector
Livestock (beef)

Services provided

Initially two stand-alone products: (i) an animal weight predictor; and (ii) automation of barn management. It has since developed a whole automated cattle farm management system, whereby sensors, satellite imagery, electronic tagging and feeding systems perform operations from automatic feeding and prediction of daily growth rates and nutrition, to health scans and diagnosis.

Targeted customers and users

Mainly medium- and large-scale cattle farmers with between 2 000 and 40 000 heads of cattle, who mostly operate in the beef (feedyard) sector. It is now also potentially targeting operators in the cow–calf and rangeland-based stocker segments.

Business model and financial sustainability

Revenue still generated from selling the two stand-alone products, accessible through a mobile and desktop software platform, despite increasing focus on the whole automated system. To operate this, Cattler switched to a freemium model: the entry level is free, but it includes only basic product features. If users want to add devices or features, they need to take out a subscription which depends on which functionalities are included. Although the number of users is not known, the number of animals covered is estimated at 90 million in the United States of America, 200 million in Brazil, and 50 million in Argentina.

Drivers

Reduced costs as it helps automate several operations. Farmers in the sector increasingly need to perform these operations in a more integrated way to improve efficiency.

Barriers

Slow adoption rate in the United States of America compared with Argentina. The reason given is that Argentinian farmers need to be more dynamic and competitive on the international market.

Policy as a barrier or enabler

Easy access to credit by farmers is an enabler. In Argentina, political uncertainty is a barrier, while in the United States of America, protective policies may discourage farmers from adopting new solutions.

Interviewee
Ignacio Albornoz

COOPECAN

Year of establishment
2008

Current number of users
1 500

Operating in
Peru

Targeted sector
Livestock (alpaca)

Services provided

Digital services – from advisory services, pasture monitoring and animal traceability, to blockchain (introduced in 2020) – to improve and certify animal welfare standards and the quality of the alpaca fibre, thus increasing its value.

Targeted customers and users

Mainly small-scale breeders in the Peruvian highlands with herds of 50–100 animals and annual revenues of USD 1 500–1 800. Intermediaries along the alpaca fibre value chain, including distributors, suppliers and consumers who are concerned about the origin of the product are also targeted.

Business model and financial sustainability

Operative since 2008. In the past decade, it has increased its reach and developed important projects to improve working conditions, offering fair pay and protecting animal welfare. External funds from donors sustain the service and it does not aim to generate profits.

Drivers

Increasing demand for transparency and animal welfare standards in the alpaca fibre value chain, translating into a higher-value product.

Barriers

Lack of internet access in remote areas and absence of national IT companies to support the service, in addition to the ageing of alpaca breeders. The majority are currently women and the elderly, as young people are not interested in continuing alpaca farming due to the working conditions and remoteness. They prefer to acquire an education in the cities and then find better paid jobs.

Policy as a barrier or enabler

Political uncertainty translates into frequent policy changes, and this inhibits support to the sector.

Interviewee
Dagoberto Fernandez

CROPIN

Year of establishment
2010

Current number of users
225

Operating in
Global presence (primarily India and sub-Saharan Africa)

Targeted sector
Crops

Services provided

Software platform that provides a complete farm and farmer management system. It uses technologies such as big data analytics, AI, IoT sensors and remote sensing to provide insights across different levels of the value chain and help managers make better decisions.

Targeted customers and users

Farming companies, seed production companies, agri-input companies, fruit and vegetable exporters, commodity traders, banks, financial and microlending institutions, crop insurance providers, government and development institutions and agencies.

Business model and financial sustainability

Client portfolio split between the enterprise sector and the development sector.
Most revenue is generated from the enterprise sector (60–65 percent), which includes clients working with smart farming, digital marketplace and supply chain traceability.
For the development sector, it provides hyper local farm and farmer data to government, banks and development institutions in exchange for a grant. Data ultimately help clients to assess the creditworthiness of small-scale producers and help banks to provide loans and insurance to farmers.

Drivers

Significant data and information gaps leading to information asymmetries throughout value chains, hence the call for data-driven software.

Enterprise sector clients leverage their services in automation and mechanization of individual farms to maximize value per hectare and farm-level traceability. Development sector clients leverage their aggregated data models and data science and also influence the industry with data-driven policy advice.

Barriers

Lack of digital assets, poor literacy and data connectivity, risk aversion.

Policy as a barrier or enabler

The Ministry of Agriculture and Farmers Welfare in India has developed major digital applications under the India Digital Ecosystem of Agriculture (IDEA) to boost technology adoption among farmers. The National Agriculture Market (eNAM) is a pan-India electronic trading portal to create a unified national market for agricultural commodities. Finally, the Direct Benefit Transfer (DBT) Central Agri Portal, launched in 2013, is a unified central portal for agricultural schemes across the country. The portal helps farmers adopt modern farm machinery through government subsidies.

Interviewee
Arjun Goyal

EGISTIC

Year of establishment
2018

Current number of users
Almost 1 500

Operating in
Kazakhstan

Targeted sector
Crops

Services provided

Integrated solution for monitoring and managing crop areas, using remote sensing technology, high precision satellite navigation, geoinformation systems, and machine learning technologies. Services include: analytics (yield forecast, crop rotation history); satellite images of fields; digital advisory consultations; global positioning satellite (GPS) monitoring system with tractors and combine harvesters; management of agricultural activities; and agrochemical soil analysis.

Targeted customers and users

Mostly large-scale farmers but also food distributors and agrochemical and fertilizer companies. Most registered users of the platform are in the 18–45 age group.

Business model and financial sustainability

Revenues generated through annual subscriptions for the platform. As of 2022, the platform is financially sustainable and attracting investors. In 2021, it received the last round of grants. The subscription also covers technical support such as webinars, videos and a user guide.

Drivers

Increasing demand among large-scale farmers for automated farm management solutions. They receive a high return on their farm investments due to fuel savings on farm machinery.

Barriers

Poor internet connectivity in rural areas.

Policy as a barrier or enabler

The company wishes to scale up services by integrating its data with government data, but current policy frameworks have no policies for public–private partnerships.

Interviewee
Zhandos Kerimkulov

FOOD AUTONOMY

Year of establishment
2018

Current number of users
2

Operating in
Hungary

Targeted sectors
Microgreens, leafy greens, seedlings and cosmetic plants in vertical farming settings

Services provided

Various crop production technologies, recipes and the corresponding hardware and software solutions for vertical farming, in addition to full-scale remotely controlled modular vertical farms for industry and research applications. All technologies offered are available either as separate services or fully integrated into vertical farms.

Targeted customers and users

Small-, medium- and large-scale users for germination, research and production.

Business model and financial sustainability

Current funds for the vertical farming business primarily via internal investment from Food Autonomy's indoor plant cultivation lighting business arm. A grant from the Government of Hungary supports the research farm facility. The FaaS (farming as a service) model operates the farm on the user's behalf, while the PaaS (plants as a service) model offers the client dedicated production capacity.

Drivers

Increasing demand for organic, sustainable, high-quality and affordable produce; increasing interest in vertical farming; low energy and water use; possibility to produce food locally next to cities and in arid regions.

Barriers

High initial investment cost.

Policy as a barrier or enabler

The Government of Hungary is promoting automation and data-driven operations in agriculture. However, while it supports locally produced food, it does not directly support vertical farming. Furthermore, regulations do not identify vertical farming as organic, even if production takes place in a chemical-free environment.

Interviewee
Zoltan Sejpes

GARBAL

Year of establishment
2017

Current number of users
More than 500 000

Operating in
Burkina Faso, Mali
(and soon the Niger)

Targeted sectors
Livestock (pastoralists), arable crops

Services provided

An integrated digital solution providing small-scale producers and pastoralists in the Sahel region with highly contextualized advisory information about suitable grazing lands, herd migration, weather, farming practices, and markets. The solution uses satellite and other data. It also has a digital marketplace to obtain fodder and sell milk and cereals.

Targeted customers and users

Small-scale farmers, pastoralists, traders and herd owners. Women represent 22–30 percent of users.

Business model and financial sustainability

Based on a public–private partnership, crucial to overcome donors' and funders' risk aversion to developing innovative digital solutions in fragile contexts. GARBAL relies primarily on donor funding and contributions from project partners. Revenues come from calls to the call centre (generated based on airtime) or from modest payments to use the unstructured supplementary service data (USSD). Despite this income, which is reinvested in the solution, it is not near break-even point. The business strategy is to generate new revenue streams through the digital marketplace and a digital finance solution.

Drivers

Traditional knowledge of farmers and herders challenged by climate change and insecurity, and farmers' livelihoods threatened. The solution can potentially improve access to markets and support farmers' resilience and adaptation capacities in the face of shocks. Being a public–private partnership is key for end users to accept the solution. Capacity building and penetration of mobile phones – even though most are not smartphones – also enable adoption. Finally, face-to-face engagement with local farmers, pastoralists and their organizations is fundamental to gain trust and increase outreach.

Barriers

Differing needs between countries, hence essential to adapt the solution to the context of each country. Political unrest and insecurity in some countries is a challenge, as is lack of digital infrastructure (e.g. energy, connectivity, smartphones). Additional challenges are lack of skills, poor awareness of the benefits of the technology, and lack of data quality and management.

Policy as a barrier or enabler

Support from the local ministries (e.g. sharing databases) has been instrumental in providing content for the advisory service. However, political unrest and insecurity hamper investments in some countries.

Interviewee
Catherine Le Come

GROBOMAC

Year of establishment
2014

Current number of users
Not applicable (solution still being tested)

Operating in
India

Targeted sector
Cotton

Services provided

A single person-operated, electric-powered semi-autonomous automatic precision cotton-picking machine, which can pick cotton, without damaging the crops, using a high-speed robotic arm assisted by computer vision and AI technology. It allows precision harvesting of multi-bloom cotton in multi-row cropping systems.

Targeted customers and users

Initially medium- and large-scale cotton growers, with the possibility of later including small-scale farmers. In the long term, the machine can be run by farm producer organizations, farmers' collectives and hiring centres, a service organization being promoted in India for running farm operations in a pay-per-use model. The machine is intended to be primarily operated by women, who are the main workforce in cotton picking in India.

Business model and financial sustainability

Not yet commercial. The company is primarily supported by personal investments and grants. In the future, the aim is to sell individual robots directly to customers and, in the longer term, to operators and service providers.

Drivers

Lack of manual labour during peak seasons.

Barriers

Benefits of the technology still to be fully perceived by investors. In addition, the return on investment can take a long time.

Policy as a barrier or enabler

The Government of India encourages agricultural start-ups through grants. For example, GRoboMac received a grant of about USD 30 000. The company also submitted a proposal for cotton picking following a request for proposals for robotics as a service in the southern Indian state of Telangana.

Interviewee
Manohar Sambandam

HARVEST CROO ROBOTICS

Year of establishment
2013

Current number of users
Unknown

Operating in
United States of America

Targeted sector
Strawberries

Services provided

Robotic harvesters that autonomously navigate through a farm to pick, inspect, clean and pack strawberries. Each harvester has 16 independent "arms" that perform the agricultural activities autonomously along 16 rows.

Targeted customers and users

Large-scale strawberry farmers (> 10 ha).

Business model and financial sustainability

Solution is not yet commercialized. Funds come from private investors and financial institutions, with the public sector playing a minor role. The business model it follows is a pay-as-you-go service, where the amount depends on the volume harvested. If there is high demand, it is projected that early contributors to the investment will receive priority.

Drivers

The lack and increasing cost of labour, especially during peak harvesting periods. Consequently, about 70 percent of strawberry growers in the country have invested in the company. The technology has been successfully tested on real farms.

Barriers

Scaling the manufacturing of necessary hardware and software.

Policy as a barrier or enabler

The National Science Foundation offers limited support. Policy is seen neither as a strong driver nor as an explicit barrier.

Interviewee
Gary Wishnatzki

HORTIKEY

Year of establishment
2015

Current number of users
Not disclosed

Operating in
Netherlands

Targeted sector
Tomatoes

Services provided
Integrated system comprising a self-driving robot equipped with cameras, smart software using algorithms, and AI to provide reliable data and crop estimations, including the number and ripeness of tomatoes, through daily measurements with no need for new infrastructure. The insights from the data, combined with climatic and meteorological data, are used for business-specific harvest forecasts 1–4 weeks in the future.

Targeted customers and users
Medium- to large-scale commercial tomato growers in controlled environments (e.g. greenhouses).

Business model and financial sustainability
Revenues generated from sales of the robots and monthly subscription fees for the software. Alternatively, both are available for a total monthly fee under a service contract. Developments are currently supported by investments from shareholders.

Drivers
Value for growers of crop forecasting information. Variability in tomato prices calls for accurate estimates of production capacity and there is a need for expertise in tomato growing as farm sizes increase.

Barriers
Scepticism of some tomato growers regarding the technology. Confidence can only be built over time.

Policy as a barrier or enabler
The Knowledge and Innovation programme of the Netherlands promotes investment in innovation. In some countries, there are laws that prevent data sharing with other countries, which makes it difficult to expand into certain markets.

Interviewee
Andreas Hofland

ICT4BXW

Year of establishment
2018

Current number of users
More than 7 000

Operating in
Rwanda

Targeted sector
Bananas

Services provided

A range of advisory and information services for banana production, including e-training. Services are available for both smart and basic phones, combined with non-digital information (e.g. a paper crop calendar). There is a focus on the diagnosis and monitoring of banana *Xanthomonas* wilt disease while collecting data about farmland. Banana farmers register through an Android app allowing them to access services which helps extension agents and government officials to monitor diseases. ICT4BXW uses drones to map land under banana production, collecting information about the varieties used and diseased banana crops.

Targeted customers and users

Small-scale banana farmers, local extension agents, and the Government of Rwanda (primarily researchers and technicians from the Rwanda Agriculture and Animal Resources Development Board).

Business model and financial sustainability

Currently not profitable. The service is free and relies on donations from the German Federal Ministry for Economic Cooperation and Development, and therefore does not generate revenue. In the future, it is hoped that the Rwandan Ministry of Agriculture will invest in the solution with plans to move towards a bundled service. There are two potential business models: (i) ICT4BXW becomes a public good model; or (ii) the tools become part of a larger digital ecosystem which farmers pay a small fee to use, a percentage of those revenues going to maintain ICT4BXW services. There are standing partnerships with for-profit companies, Arifu and VIAMO.

Drivers

Increasing demand for solutions that diagnose and control banana *Xanthomonas* wilt disease, which threatens production of a major food and income security crop in Rwanda. In addition, increased use of smartphones and government interest in the use of digital technologies in the agriculture sector facilitate adoption.

Barriers

Limited smartphone penetration and poor digital literacy.

Policy as a barrier or enabler

The Government of Rwanda is promoting adoption of smartphones by farmers and digitalization of the agriculture sector through targeted policies. It also sometimes provides capacity building on the development and maintenance of digital technologies.

Interviewee
Julius Adewopo

IGARA TEA

Year of establishment
1969 (investment in digital solutions from 2017)

Current number of users
More than 7 000

Operating in
Uganda

Targeted sector
Tea

Services provided

Using digital technologies: provision of information about tea farmer profiles, farm boundaries, land use and cover; tracking, tracing and monitoring of production of tea leaves; assessment of health status of tea plants; simulation of production capacity; delivering information to lenders; tailored advice and e-extension services; and enabling access to credit. In the future, small mechanization devices are envisaged to improve precision and reduce the labour of, for example, tea leaf pickers.

Targeted customers and users

Small-scale tea farmers. About 18 percent of users are women and young farmers perform 65 percent of farm labour. In processing of tea leaves, women and youth comprise more than half the workforce. Banks and credit providers are also targeted.

Business model and financial sustainability

Initially funded with grants, revenue currently generated through the sale of tea on behalf of tea farmers. Igara Tea acts as a buyer, processor and seller of tea. It adds value and sells tea on local and international markets on behalf of their shareholders (tea farmers), who sell their raw material to them. Digitalization helps to optimize procurement, saving up to 70 percent of costs associated with receipt books, pens, paper, etc. The payback time for investments in digital hardware and software was 1.5 years. Today, without grant funding, the company invests in hardware and software.

Drivers

Demand for greater certainty, transparency and timeliness for buyers, farmers and loan providers. The development of tea leaf pickers is driven by increased labour costs.

Barriers

Limited tea leaf processing capacity hindering expansion; low tea prices worldwide; lack of financial capacity of farmers to invest in machinery. Igara Tea is considering developing a mechanization sharing scheme.

Policy as a barrier or enabler

The Government of Uganda is determined to advance the use of technological solutions to solve the country's development challenges. Yet, it is still difficult to get financial support from the Government. High levels of bureaucracy translate into higher costs and there is a lack of clear regulations and policies about the use of drones.

Interviewee
Hamlus Owoyesiga

IOCROPS

Year of establishment
2018

Current number of users
More than 200

Operating in
Republic of Korea

Targeted sector
Indoor crops
(e.g. tomatoes and bell peppers in greenhouses)

Services provided

Autonomous crop management solutions, including climate monitoring in indoor farms; data analysis and decision-making platform; crop management advice and forecasts; automated cultivation; remote farm operations to manage farms across the world without the need for specialized greenhouse managers on each farm.

Targeted customers and users

Medium- to large-scale greenhouse growers. It is estimated that in the Republic of Korea less than 10 percent of greenhouses are owned by women, and less than 30 percent by young people.

Business model and financial sustainability

Revenue generated through sale of sensors and web-based solutions. ioCrops also rents out automated greenhouses and controls all greenhouse plant operations, ranging from climate and crop management to labour and post-harvest logistics management. Most of the investment is from venture capital funds, with limited contribution from subsidies.

Drivers

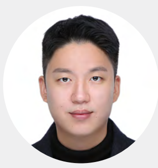
Increasing need for automation solutions as farm sizes increase. Greenhouse coverage area is increasing, as is the number of large-scale producers. The younger generation is more open to IT solutions. Wages are increasing and labour supply is decreasing.

Barriers

Scepticism among some farmers about high-tech solutions. There is also the risk that this technology will push smaller producers out of business.

Policy as a barrier or enabler

The Government of the Republic of Korea is investing in high-tech greenhouses, including educating operators and allowing companies such as ioCrops to conduct experiments. At the same time, the Government is concerned that such solutions will harm small-scale producers, so there are parallel efforts to maintain more traditional systems.



Interviewee
JinHyung Cho

JUSTDIGGIT

Year of establishment
2009

Current number of users
More than 700 000

Operating in
Kenya, United Republic of Tanzania

Targeted sectors
Trees, grasses

Services provided

Digital and communication solutions (e.g. SMS, phone apps, drones, satellite imagery, machine learning) to promote large-scale landscape restoration in Africa, such as turning rangelands degraded by Maasai pastoralists in Kenya into green, fertile land. Specifically, these solutions inform farmers about landscape restoration, monitor tree growth and landscape change over time, and can also calculate associated carbon sequestration volumes. Justddigit also helps women to sell indigenous grass seeds and crops.

Targeted customers and users

Small-scale and subsistence farmers and pastoralists. Justdiggit also works with trainers – half of whom are women – who train farmers in agroforestry and regreening land.

Business model and financial sustainability

Non-profit organization dependent on grant funding. It works with a large network of media partners who are active in the Netherlands and Africa to raise funds and create awareness. Justdiggit receives donations from individual consumers, private companies, larger institutions and funding schemes, as well as some family foundations. The organization has seen steady growth. Staff numbers increased from 4 to 40 over about seven years. It aims to become less dependent on donations in order to facilitate scaling.

Drivers

Increased awareness of accelerating climate change. The solution increases crop yields and water availability, positively affecting incomes and livelihoods, and reduces soil erosion and runoff, benefiting soil fertility and moisture. There is growing interest in nature-based and regreening solutions.

Barriers

Limited smartphone penetration, digital illiteracy and limited internet access. Digital capacity building of trainers is often required.

Policy as a barrier or enabler

In Kenya, land subdivision can cause distrust as landowners decide whether the land remains public or is privately owned and subdivided into smaller plots.

Interviewee
Sander de Haas

LELY

Year of establishment
1948

Current number of users
More than 25 000

Operating in
Australia, Europe, North America

Targeted sector
Dairy

Services provided

Robotics and (management) software solutions for dairy farming. Specifically, it provides stationary milking, manure and feeding robots, and is developing barn management solutions (to control gas emissions) as well as grass harvesting robots. In addition, the management software provides information and advisory services on all farm operations, including animal health and welfare.

Targeted customers and users

Medium- to large-scale dairy farmers, not the very largest.

Business model and financial sustainability

Revenue generated through sales of these solutions and service contracts. It offers financial and operational lease constructions, which lead to more adoption by farmers. It also receives funding through national and European Union grants. Turnover is estimated at EUR 650 million, an important part of which is reinvested in research and innovation.

Drivers

Demand for more flexible working schedules and less drudgery; labour shortages; compliance with environmental regulations (e.g. emission reductions on dairy farms); concerns about animal welfare; provision of financial services; gains in energy efficiency and use of renewable energy sources. Solutions offered are easy to integrate for conventional farms.

Barriers

Not mentioned.

Policy as a barrier or enabler

On the one hand, policy-related adoption drivers are environmental and animal welfare regulations and subsidy programmes invest in barn solutions reducing emissions. On the other hand, adoption can be slow as farmers wait for subsidies before investing. Discussions on new regulations for free animal movements and natural behaviour needs new strategies to adapt the milking solutions offered at present.

Interviewee
Martijn Bruggeman

SEED INNOVATIONS

Year of establishment
2019

Current number of users
1 500

Operating in
Nepal

Targeted sector
Crops

Services provided

An Android app – PlantSat – for farmers to use satellite-based analytics to monitor crop performance, including identification of threats such as water and nutrient deficiencies or surplus, and to access and exchange agronomic information. Integrated services include: identification of production threats, calculation of nitrogen and plant moisture, farm calendar notifications, expert assistance, weather information, and recording of farm data. A simplified bundled service solution, it reduces the need for data connectivity (offline data entry) and lowers the cost of operation (e.g. by limiting the server space required to store data points).

Targeted customers and users

Mostly medium- to large-scale farmers for satellite-based advisory services and market-oriented small-scale producers for generic advisory services.

Business model and financial sustainability

Solution currently free for farmers. In the future it will sell annual subscription plans to insurance companies, who then gain access to the information collected and can thus monitor crop and farmer performance and eligibility for insurance claims. Approximately 40 percent of funding comes from grants.

Drivers

Reduced need for connectivity and low cost of solution.

Barriers

Scepticism towards new technologies.

Policy as a barrier or enabler

The Government of Nepal supports low-income farmers to participate in insurance schemes by subsidizing 75 percent of their premium. Furthermore, there are no strict privacy protection, data security, or intellectual property policies or regulations to slow down adoption.

Interviewee
Suman Ghimire

SEETREE

Year of establishment
2017

Current number of users
More than 3 000

Operating in
Brazil, Chile, Greece, Mexico, Portugal, South Africa, Spain, United States of America (data analysis, research and development in Israel)

Targeted sector
Fruit and nut trees

Services provided

Digital solutions through a data intelligence platform to monitor tree health, fruit optimization and growth, manage inventory and production, estimate yield, track farming operations and measure their impact.

Targeted customers and users

Mainly large-scale growers, in addition to fruit cooperatives in order to reach small-scale growers.

Business model and financial sustainability

Based on an annual subscription to access the data intelligence platform via either a web-based app or a mobile app. The services help growers to use resources precisely, conduct inventory management and make better use of labour hours. The platform currently generates annual revenue of USD 30–100/ha; the larger the landholding, the lower the price per hectare.

Drivers

Huge demand among large-scale growers with large landholdings for solutions that increase productivity and resource-use efficiency, and reduce uncertainty regarding yield and market prices. There is also a growing interest in sequestering carbon to obtain carbon credits.

Barriers

Scepticism of growers towards digital technologies and limited digital literacy, hindering understanding of the value of the solution from pilot demonstrations. Furthermore, growers expect a one-stop shop to implement recommendations made by data-driven decision-making and networking with local supply chain actors. In some regions, weak market linkages among input suppliers are slowing adoption and preventing some growers from accessing and implementing recommendations.

Policy as a barrier or enabler

Not applicable.

Interviewee
Israel Talpaz

SOWIT

Year of establishment
2017

Current number of users
More than 17 490

Operating in
Ethiopia, Morocco, Senegal, Tunisia

Targeted sectors
Fruits, cereals, rapeseed

Services provided

Decision support tools and information insights, mainly regarding irrigation, fertilization and yield estimation.

Targeted customers and users

Large-scale agribusinesses and medium- and small-scale farmers. In Morocco, more than 20 percent of farmers served are women. SOWIT staff also comprise a large share of women (44 percent), and all employees are in the youth category.

Business model and financial sustainability

Based on a yearly subscription. The annual price per hectare varies (USD 10–70) depending on the number of decision support tools requested, including both mobile and web-based multilingual access interfaces. Since its establishment, SOWIT has secured finance through equity fundraising and grants from development agencies such as the United States Agency for International Development. In 2021, grant funding represented 25 percent of turnover.

Drivers

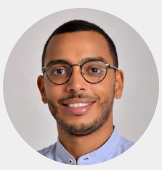
Impact of climate change and other factors on the availability of water for irrigation, with increasing need to optimize its use. Hence, the call for a system offering daily location-specific recommendations on irrigation. The solution can also optimize fertilizer use, whose cost is also rising. Increasingly, insurance companies need to offer affordable crop insurance policies. SOWIT offers an alternative to index-based insurance, as it can provide yield estimates based on the real situation. A farmer can insure a crop against the expected yield, which corresponds to the average yield in the specific agroclimatic zone.

Barriers

In Morocco, technology import barriers and limited digital payment options for clients.

Policy as a barrier or enabler

In Morocco, the Government is investing in innovating the agriculture sector, for example, promoting agricultural entrepreneurship among young people, reinforcing the role of agricultural cooperatives, and developing new subsidies for digital solutions. In particular, the Generation Green 2020-2030 strategy aims to connect 2 million farmers to digital platforms, including SOWIT. On the other hand, the absence of regulations regarding the use of drones represents a barrier to the development of the technology. For this reason, SOWIT switched to satellite remote sensing.



Interviewee
Hamza Rkha Chaham

TRASEABLE SOLUTIONS

Year of establishment
2018

Current number of users
More than 2 000

Operating in
Cook Islands, Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu

Targeted sectors
Crops, tuna, timber

Services provided
A set of digital tools that provide farmers with information about the agricultural industry, as well as about their own farm, including resources, inventory, sales and expenses. The solution also helps create market linkages. In addition, the company offers a solution focusing on tuna fisheries, involving tagging and tracking of tuna along the value chain. The solution includes fleet management, providing information on the crew, operational expenses, maintenance costs, tuna harvest details, etc.

Targeted customers and users
Mostly small-scale producers, in addition to some medium-scale, as well as farmer organizations and agribusinesses (mainly those involved in exporting commodities). Women and youth represent, respectively, approximately 40 percent and 15 percent of users. Customers include mainly development organizations interested in data on a regional scale.

Business model and financial sustainability
Farmers able to download solution at no cost, but tiered subscription payable by farmer organizations, agribusinesses, fisheries and processing plants wishing to access services. The company provides consultancy services, which represent the bulk of revenue, and it has received grants to fund its business.

Drivers
Increasing interest among producers – especially exporters – in cheap, effective collection of data; increasing interest among farmer organizations in capacity building and advisory services; need to comply with food safety regulations and traceability. The COVID-19 pandemic accelerated uptake of and interest in digital solutions. Development agencies consider the capacity of TraSeable Solutions in networking across the region and data gathering as an interesting value proposition.

Barriers
Strict data regulations rendering creation and management of digital solutions difficult. Digital literacy is low among farmers.

Policy as a barrier or enabler
Not mentioned.

Interviewee
Kenneth Katafono

TROTRO TRACTOR

Year of establishment
2016

Current number of users
75 000

Operating in
Benin, Ghana, Nigeria, Togo, Zambia, Zimbabwe

Targeted sector
Arable crops

Services provided

Digital rental platform that matches small-scale producers with a vast range of agricultural machinery and equipment and with the owners who provide hire services. Recently, drone owners have begun to offer their services (e.g. mapping and spraying). All machines are equipped with TROTRO's internet of things (IoT) tracking device.

Targeted customers and users

Small-scale farmers, although some are medium- to large-scale, and increasingly companies for contract farming. Almost 40 percent of clients are women, and the company would like to increase this percentage.

Business model and financial sustainability

Main revenue streams from the matchmaker fees (10 percent per transaction) received for each agricultural machinery service contracted out. Additional revenue is generated through sales of their IoT GNSS tracker device (purchasing this device is mandatory for owners renting out equipment through their platform). The company is profitable in all countries where it operates, except Ghana, possibly because only about 40 percent of registered users there are regular clients. The company partially relies on grants, which it primarily uses to expand the business.

Drivers

Tractors unaffordable for most small-scale farmers, who must rent if they are to mechanize. The platform enables transparency and reliable access – not possible in traditional market mechanisms. Female farmers are increasingly using the service as it protects them from discrimination arising from social norms. Young farmers also prefer the service as they tend to be more dynamic and open to innovative solutions with some young people being trained as machine operators. The COVID-19 pandemic accelerated digitalization of agriculture and spurred this solution. Use of drones is driven by growing demand from farmers for accurate land data to help them obtain finance, credit and insurance.

Barriers

Increasing fuel prices, making the service inaccessible for some farmers; lack of credit and finance for operators to buy machinery and then rent it out to farmers. Poor road infrastructure can prevent movement of the machinery to make the service available in different areas.

Policy as a barrier or enabler

Provision of subsidies and incentives to farmers to produce staple crops encouraged mechanization, in addition to investments in infrastructure and digital technologies.

Interviewee
Kamal Yakub

TUN YAT

Year of establishment
2017

Current number of users
More than 20 000

Operating in
Myanmar

Targeted sectors
Primarily rice, mung bean, sesame, groundnuts, maize

Services provided

Mechanization services in both delta and dryland regions of Myanmar. Tun Yat maintains its own fleet of tractors and acts as an intermediary between machine owners and farmers.

Targeted customers and users

Mainly small-scale producers, but also medium-scale farmers. Approximately 30 percent of clients are women and 25–30 percent are youth aged up to 30 years.

Business model and financial sustainability

Revenue generated by paying for the service, either per acre or per hour. The highest margins are generated by direct services using their own fleet. Smaller margins come from matchmaking services. Tun Yat also generates revenue by conducting research in South-eastern Asia.

Drivers

Inability of farmers to afford their own machinery; unreliable service delivery of this machinery; increased penetration of mobiles and smartphones.

Barriers

Increasing prices for inputs and fuel, with users able to bypass Tun Yat's matchmaker service once they know each other; poor digital literacy and connectivity; low levels of trust (e.g. in mobile payments); need for technological handholding and capacity building.

Policy as a barrier or enabler

The Government of Myanmar is committing to digital policies, but the current uncertain political environment hampers innovation and investment. Furthermore, existing policies related to digitalization and data use are more focused on cyber security and surveillance, which can also slow adoption.

Interviewee
Hujjat Nadarajah

URBANAGROW

Year of establishment
2019

Current number of users
Unknown

Operating in
Chile

Targeted sector
Leafy greens

Services provided

Modular units for vertical farming in a highly controlled environment. Products are mostly leafy greens such as lettuce and basil. The farms use LED lights and sensors to control temperature and humidity, in addition to a water recycling system to minimize water consumption. Production is tailored to clients' needs.

Targeted customers and users

All operators at the end of the food supply chain, including retailers, supermarkets, restaurants, consumers and occasionally governments, who want to produce fresh leafy vegetables for sale or for their own consumption.

Business model and financial sustainability

Still in the early phase but soon to become commercially available. It is also sustained by international collaborators (e.g. the Fraunhofer Institute, Germany). It plans to sell controlled-environment, modular farms, with everything needed for crops to grow according to the type and quantities of vegetables each client needs.

Drivers

Increasing demand for fresh produce, especially in more remote areas where agriculture is not feasible due to climatic conditions. The technology also responds to the increasing demand for environmentally sustainable, high-quality, safe, fresh produce. The increasing adoption of 5G will work as a facilitator since good connectivity is required.

Barriers

Scepticism among some agricultural producers and consumers about controlled agriculture. There is also a lack of awareness of climate change and other environmental issues, thus reducing the value added of the service.

Policy as a barrier or enabler

Rising environmental standards in agriculture drives adoption; however, unclear regulations on the use of agrochemicals enables competitors to produce food – although of poorer quality – at lower prices.

Interviewees
Maricruz Larrera and Eduardo Vásquez

ZLTO

Year of establishment
2013

Current number of users
13 000

Operating in
Netherlands

Targeted sectors
Horticulture, livestock (including dairy), arable crops

Services provided

Technical assistance and advisory services on digitization and data management. In cooperation with the Netherlands Enterprise Agency (RVO), the farmer organization, Southern Agriculture and Horticulture Organization (ZLTO), also connects farmers with suppliers and supports innovation processes for farmers, with precision farming and livestock production as core activities.

Targeted customers and users

Members of the organization. Main activities targeted are horticulture, pig husbandry, dairy production and arable crop production.

Business model and financial sustainability

Not directly applicable to ZLTO, as it is not a solution provider.

Drivers

Familiarity with and interest in information and communications technology (ICT) among young farmers. Labour supply is another driver: there is lack of unskilled labour that drives the adoption of robotization and automation, and an abundance of skilled labour that wants, and is able, to work with digital technologies.

Barriers

Benefits of investing in machinery and digital technologies not fully perceived by farmers. There is uncertainty about the monetary returns on investing in new equipment and the training to learn how to operate it.

Policy as a barrier or enabler

No policy-related adoption barriers are perceived. In terms of drivers, ZLTO is running dissemination projects incorporating precision agriculture, automation and robotics. The European Union is also promoting an agricultural data sharing policy and considering making it a public good.

Interviewees
Peter Paree (ZLTO) and Folkwin Polemen (RVO)

ANNEX 2
STATISTICAL TABLES

TABLE A2.1 TRACTOR USE PER 1 000 HECTARES OF ARABLE LAND, LATEST YEAR AVAILABLE

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
WORLD				
AFRICA				
Northern Africa				
Algeria	2008	104 529	7 489	14.0
Egypt*	2009	110 304	2 884	38.2
Libya	2000	39 733	1 815	21.9
Morocco	1999	43 226	8 818	4.9
Tunisia*	2008	42 783	2 835	15.1
Western Sahara	1975	11	2	5.5
Sub-Saharan Africa				
Eastern Africa				
Burundi	1992	170	930	0.2
Djibouti	2006	6	1	4.6
Eritrea	2000	463	560	0.8
Kenya	2002	12 844	5 091	2.5
Madagascar	2004	550	2 950	0.2
Malawi	1968	692	1 800	0.4
Mauritius	1968	283	100	2.8
Mayotte	2003	14	7	1.9
Mozambique	1970	4 193	2 785	1.5
Rwanda	2002	56	1 116	0.1
Réunion	2005	2 941	35	84.0
Seychelles	1974	30	1	30.0
Somalia	2006	1 371	1 140	1.2
Uganda	1977	2 076	4 023	0.5
United Republic of Tanzania	2002	21 207	8 600	2.5
Zambia	1987	5 628	2 568	2.2
Zimbabwe	1997	22 496	3 500	6.4
Middle Africa				
Angola	1971	8 108	2 900	2.8
Cameroon	1991	508	5 950	0.1
Central African Republic	1969	56	1 760	0.0
Chad	1965	27	2 897	0.0
Congo	1974	647	526	1.2
Democratic Republic of the Congo	1971	1 062	6 470	0.2
Sao Tome and Principe	1971	117	1	117.0

TABLE A2.1 (Continued)

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
Southern Africa				
Botswana	2008	3 371	279	12.1
Eswatini	2007	1 550	178	8.7
Lesotho	1995	2 000	320	6.3
South Africa	2004	63 200	13 300	4.8
Western Africa				
Ascension, Saint Helena and Tristan da Cunha	1996	12	4	3.0
Benin	1998	182	2 250	0.1
Burkina Faso	1995	1 933	3 380	0.6
Cabo Verde	2004	56	48	1.2
Côte d'Ivoire	2001	8 981	2 800	3.2
Gambia*	2009	100	428	0.2
Ghana	2005	1 807	4 076	0.4
Guinea	2000	5 388	2 149	2.5
Guinea-Bissau	1996	19	270	0.1
Mali	2007	1 300	5 808	0.2
Mauritania	2006	390	400	1.0
Niger*	2006	375	14 137	0.0
Nigeria	2007	24 800	37 000	0.7
Senegal	2004	645	2 987	0.2
Sierra Leone	1997	81	484	0.2
Togo*	2008	159	2 340	0.1
AMERICA				
Latin America and the Caribbean				
Caribbean				
Antigua and Barbuda	1976	228	3	76.0
Bahamas	1996	98	6	16.3
Barbados	1989	577	16	36.1
British Virgin Islands	1987	3	3	1.0
Cuba	2007	72 602	3 573	20.3
Dominica	1968	54	7	7.7
Dominican Republic*	2009	51	800	0.1
Grenada	1999	12	1	12.0
Guadeloupe	2005	853	19	44.9
Haiti	1998	146	900	0.2
Jamaica	1970	1 745	145	12.0
Martinique	2005	873	10	87.3
Montserrat	1987	12	2	6.0
Puerto Rico	2007	3 255	37	88.2

TABLE A2.1 (Continued)

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
Saint Kitts and Nevis*	2009	26	4	6.5
Saint Lucia	2007	14	2	5.8
Saint Vincent and the Grenadines	2003	112	2	56.0
Trinidad and Tobago	2004	5 129	26	197.3
United States Virgin Islands	2007	119	1	119.0
Central America				
Belize	1985	940	43	21.9
Costa Rica	1973	5 432	283	19.2
El Salvador	1971	2 642	488	5.4
Guatemala	1970	3 150	1 100	2.9
Honduras	2000	5 200	1 068	4.9
Mexico	2007	238 830	23 519	10.2
Nicaragua	1997	2 700	1 750	1.5
Panama	2000	8 066	548	14.7
South America				
Argentina	2002	244 320	27 862	8.8
Bolivia (Plurinational State of)	2000	6 000	3 144	1.9
Brazil	2006	788 053	48 914	16.1
Chile	2007	53 915	1 262	42.7
Colombia	1997	21 000	2 539	8.3
Ecuador	2000	14 652	1 616	9.1
French Guiana	2005	317	12	26.4
Guyana	1977	3 401	422	8.1
Paraguay	2008	25 823	3 757	6.9
Peru	1995	13 191	3 740	3.5
Suriname*	2009	1 037	58	17.9
Uruguay	2008	36 465	1 826	20.0
Venezuela (Bolivarian Republic of)	1977	33 888	2 964	11.4
Northern America				
Bermuda	1998	45	0	112.5
Canada	2006	733 182	39 283	18.7
United States of America	2007	4 389 812	161 780	27.1
ASIA				
Central Asia				
Kazakhstan	2007	40 228	28 641	1.4
Kyrgyzstan	2008	24 445	1 280	19.1
Tajikistan	2008	15 951	741	21.5
Turkmenistan	1993	52 304	1 586	33.0

TABLE A2.1 (Continued)

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
Eastern Asia				
China*	2000	13 688 736	119 666	114.4
China, Hong Kong SAR*	1996	4	6	0.7
China, mainland*	2009	21 024 788	121 385	173.2
Democratic People's Republic of Korea	1984	67 500	2 285	29.5
Japan	2005	1 910 724	4 360	438.2
Mongolia	2008	3 232	1 197	2.7
Republic of Korea	2008	253 531	1 565	162.0
Taiwan Province of China	2009	47 004	595	79.0
South-eastern Asia				
Brunei Darussalam	1983	72	3	24.0
Cambodia	2008	4 611	3 700	1.2
Indonesia	2002	4 097	20 081	0.2
Lao People's Democratic Republic	1981	664	780	0.9
Malaysia	1995	43 295	901	48.1
Myanmar*	2009	160 506	10 794	14.9
Philippines*	2002	1 528 053	4 935	309.6
Thailand	2002	697 956	15 389	45.4
Timor-Leste	1997	90	127	0.7
Viet Nam	2000	162 746	6 200	26.2
Southern Asia				
Afghanistan	2009	223	7 793	0.0
Bangladesh	2006	3 000	7 880	0.4
Bhutan	2008	136	100	1.4
India*	2003	2 812 200	159 799	17.6
Iran (Islamic Republic of)	2007	308 422	16 869	18.3
Nepal*	2008	37 872	2 220	17.1
Pakistan	2006	439 741	30 320	14.5
Sri Lanka	1982	13 976	857	16.3
Western Asia				
Armenia*	2009	14 777	449	32.9
Azerbaijan	2009	21 542	1 874	11.5
Bahrain*	2007	21	1	15.0
Cyprus	2003	11 717	112	104.6
Georgia*	2007	40 100	463	86.6
Iraq	2001	72 775	4 300	16.9
Israel*	2009	21 591	304	71.0
Jordan	2008	5 483	150	36.7

TABLE A2.1 (Continued)

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
Kuwait	2008	109	11	9.6
Lebanon	1999	8 256	129	64.0
Oman	2004	201	29	6.9
Palestine	2008	7 756	83	93.4
Qatar	2005	73	12	6.3
Saudi Arabia	1998	9 792	3 637	2.7
Syrian Arab Republic	2008	109 890	4 699	23.4
Türkiye*	2008	1 070 746	21 555	49.7
United Arab Emirates	2000	380	60	6.3
Yemen	2000	6 340	1 545	4.1
EUROPE				
Eastern Europe				
Belarus	2009	48 100	5 544	8.7
Bulgaria	2008	53 100	3 088	17.2
Czechia	2007	83 813	2 626	31.9
Hungary*	2005	128 250	4 601	27.9
Poland	2009	1 577 290	12 066	130.7
Republic of Moldova*	2009	35 984	1 817	19.8
Romania	2009	176 841	8 789	20.1
Russian Federation	2009	329 980	121 649	2.7
Slovakia	2008	21 372	1 382	15.5
Ukraine*	2009	369 131	32 478	11.4
Northern Europe				
Denmark	2005	113 402	2 332	48.6
Estonia	2006	33 744	559	60.4
Finland	2005	175 232	2 237	78.4
Iceland	2009	11 432	124	92.2
Ireland	2005	174 800	1 184	147.6
Latvia	2007	59 562	1 188	50.1
Lithuania*	2009	118 041	2 054	57.5
Norway	2005	132 673	862	153.9
Sweden	2005	159 590	2 687	59.4
United Kingdom of Great Britain and Northern Ireland	1989	509 780	6 702	76.1
Southern Europe				
Albania*	2009	7 883	609	12.9
Andorra	2009	353	1	458.4
Bosnia and Herzegovina	1996	29 000	900	32.2
Croatia	2002	4 242	858	4.9
Greece	2006	259 613	2 584	100.5

TABLE A2.1 (Continued)

COUNTRY/TERRITORY	Year	Tractors (units)	Arable land (thousand ha)	Tractors per 1 000 ha of arable land
Italy	2002	1 754 401	8 287	211.7
Malta*	2002	2 012	9	223.6
North Macedonia	2007	53 606	431	124.4
Portugal	2005	176 394	1 305	135.1
Serbia	2008	5 844	2 661	2.2
Slovenia*	2005	108 461	176	616.3
Spain*	2009	1 320 599	12 497	105.7
Western Europe				
Austria*	2005	432 177	1 381	313.0
Belgium	2005	95 010	843	112.7
France	2005	1 176 425	18 378	64.0
Germany*	2009	681 200	11 945	57.0
Liechtenstein	1990	446	4	111.5
Luxembourg*	2009	6 527	62	105.7
Netherlands	2005	144 600	1 111	130.2
Switzerland*	2009	163 600	406	403.0
OCEANIA				
Australia and New Zealand				
Australia	1974	332 560	14 778	22.5
New Zealand	1986	81 441	2 585	31.5
Melanesia				
Fiji	2008	5 983	169	35.4
New Caledonia	2002	1 941	7	285.4
Papua New Guinea	1997	1 160	197	5.9
Solomon Islands	1990	8	11	0.7
Vanuatu	1971	35	15	2.3
Micronesia				
Guam*	2007	84	1	84.0
Kiribati	1975	14	2	7.0
Northern Mariana Islands	2007	99	0	396.0
Polynesia				
American Samoa	2003	36	4	9.3
Cook Islands	1998	165	2	82.5
French Polynesia	1995	273	3	91.0
Niue	1984	10	1	10.0
Samoa	2002	94	13	7.2
Tonga	2004	243	15	16.2

NOTE: The data collected refer to three types of tractor (wheel, crawler and track-laying); for countries marked with an asterisk (*), a fourth type of tractor (pedestrian tractor) was included as of 2000.

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ANNEX 1

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THE STATE OF
THE WORLD

2022
THE STATE OF FOOD AND AGRICULTURE

LEVERAGING AUTOMATION IN AGRICULTURE FOR TRANSFORMING AGRIFOOD SYSTEMS

Automation has been shaping world agriculture since the early twentieth century. Motorized mechanization has brought significant benefits in terms of improved productivity, reduced drudgery and more efficient allocation of labour, but also some negative environmental impacts. More recently, a new generation of digital agricultural automation technologies has appeared, with the potential to further enhance productivity, as well as resilience, while also addressing the environmental sustainability challenges driven by past mechanization.

The State of Food and Agriculture 2022 looks into the drivers of agricultural automation, including the more recent digital technologies. Based on 27 case studies, the report analyses the business case for adoption of digital automation technologies in different agricultural production systems across the world. It identifies several barriers preventing inclusive adoption of these technologies, particularly by small-scale producers. Key barriers are low digital literacy and lack of an enabling infrastructure, such as connectivity and access to electricity, in addition to financial constraints. Based on the analysis, the publication suggests policies to ensure that disadvantaged groups in developing regions can benefit from agricultural automation and that automation contributes to sustainable and resilient agrifood systems.

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