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AGRICULTURE 4.0

Agricultural robotics and automated equipment for sustainable crop production

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Agricultural robotics and automated equipment for sustainable crop production

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ABSTRACT

Agricultural technologies are rapidly evolving towards a new paradigm – Agriculture 4.0. Within this paradigm, digitalization, automation and artificial intelligence play a major role in crop production, including weeding and pest control. This evolution presents both challenges and opportunities, such as leapfrogging from manual and animal-driven technologies to automated and mechanized equipment in developing countries and closing the digital divide. Traditional agricultural mechanization, characterized by the use of tractors and engine power, will be matched and even surpassed by automated equipment and robotics and the precision they can provide in farm operations.

Conservation agriculture (CA) is an approach that involves crop diversification, permanent soil cover and minimal soil disturbance (e.g. limited tillage). CA increases soil structure and soil organic matter, promotes rich microbial diversity, retains water and nutrients, and better manages pests and diseases, making agricultural soils more productive and resilient to changes in climate. However, it requires specialized equipment – for example, for direct drilling of crop seed into the soil at the right depth and sowing density. Agricultural robotics can support these environmentally sustainable practices, by allowing spot weeding and precision management of nutrients, pests, diseases and weeds through mechanical removal or spot application of chemicals. Agricultural robots will also be able to substitute arduous labour, especially when there is limited availability, thus increasing social sustainability. The development of Agriculture 4.0 will create new opportunities that can attract youth and entrepreneurs into the sector, tackling some of the causes for rural–urban migration and contributing to the economic component of sustainability.

This report analyses the application of robotics in the area of agricultural mechanization for crop production, and its specific applicability in the context of sustainable development. It takes into consideration the social, economic and environmental dimensions of its adoption and explores its potential. It presents some of the technical characteristics of robotics and highlights major challenges to overcome in order to achieve its successful adoption, such as adequate infrastructure, stakeholder capacity, economic viability and data ownership. This report provides an analysis of some of the major areas of intervention that are needed for the different stakeholders, including smallholder farmers in developing countries.

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FOREWORD

Mechanization is a key driver of efficient farming systems. It enables the transition from subsistence to market-oriented agriculture, provides off-farm employment attractive to women and youth, and catalyses rural development. Mechanization options include agricultural tools, equipment and machinery for land preparation, crop management, harvest and post-harvest activities, processing and all actions in the agri-food value chain.

There is a misconception that mechanization displaces farm labour and encourages rural–urban migration, but the opposite is true: mechanization improves well-being and increases decent work opportunities. For example, land preparation and weeding require less time and effort, thus reducing drudgery and freeing up time for non-farm activities. Moreover, off-farm activities, such as manufacture, maintenance and hiring of equipment, as well as information and communications technology (ICT) and digitalization, offer women and youth exciting job opportunities.

Mechanization has come a long way since the Industrial Revolution and the invention of the steam engine, but the last 15 years have seen radical improvements. Optimized design of agricultural machinery combined with digital data management enables small-scale farmers to access automized and semi-autonomous equipment.

Digital innovations in mechanization technologies can make agriculture more attractive to rural youth, especially in developing countries. With the necessary rural infrastructure, supply chains, services and training in place, new and more attractive jobs can be created in order to benefit those rural areas that were left behind when agriculture depended on rudimentary hand tools.

There is a vast divide between high-tech digitally supported machinery and low-tech simple hand tools. The Food and Agriculture Organization of the United Nations (FAO) and its partners must provide governments with the necessary technical support to transform agriculture in a sustainable way and create an enabling environment for this private-sector-led industry. Furthermore, the initiative is aligned with the Framework for Sustainable Agricultural Mechanization in Africa (SAMA) and Asia (SAM), and supports efforts to develop small-scale mechanization hire services to ensure that farmers have access to mechanization services.

This publication provides a timely overview of the next generation of agricultural machinery, focusing on robotics for agricultural production in order to accelerate rural development.

XIA, Jingyuan
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ABBREVIATIONS AND ACRONYMS

AI	artificial intelligence
FAO	Food and Agriculture Organization of the United Nations
FIRA	International Forum of Agricultural Robotics
GPS	global positioning system
ICT	information and communications technology
IFAD	International Fund for Agricultural Development
IoT	Internet of things
IT	information technology

1. BACKGROUND

Agricultural mechanization provides the power and equipment necessary for preparing the soil and establishing, maintaining, storing and processing agricultural crops in the field and on the farm. Over the years, it has evolved from basic hand tools and animal-powered implements to sophisticated engine-powered equipment. Unfortunately, hand tools and animal power are still in common use in developing countries, hampering agricultural productivity and negatively affecting the livelihoods of small-scale farmers. Mechanization developments are therefore driven by the desire to reduce drudgery and eliminate hard work during labour peaks (land preparation, weeding, harvesting, transport etc.).

The availability of adequate and efficient equipment and its timely use are key factors in the transformation from subsistence-based to market-oriented agriculture. Early planting and optimal sowing conditions (soil, temperature and moisture) are particularly important, especially given the increasingly erratic rainfall and temperature patterns. Data-driven agriculture, with the help of robotic solutions incorporating artificial intelligence (AI) techniques, is the basis of sustainable agriculture in the future (Saiz-Rubio and Rovira-Mas, 2020).

The United Nations General Assembly urged Member States, relevant United Nations organizations and other stakeholders to strengthen efforts to improve the development of sustainable agricultural technologies and their transfer and dissemination under mutually agreed terms to developing countries, especially least developed countries, in particular at the bilateral and regional levels, and to support national efforts to foster the utilization of local know-how and agricultural technologies, to promote agricultural technology research and access to knowledge and information through suitable communication for development strategies, and to enable rural women, as well as men and youth, to increase sustainable agricultural productivity, reduce post-harvest losses and enhance food and nutritional security.

To date, use of motorized farm power has been dominant in developed countries, with the tractor the single most prominent source of farm power. The trend in recent years has been to increase the size and horsepower of tractors and other equipment (e.g. harvesters) in order to improve efficiency and meet the needs of increasingly large farms in developed countries. However, the reality in most parts of the world is quite different with farm sizes decreasing in low-income countries (Figure 1).

Lack of farm power is sometimes held responsible for crop failures, low crop yields, and the drudgery of farming tasks and subsistence farming (Murray et al., 2016). However, this is not the only reasons as there are many other factors – for example, climate, seed quality, practices adopted, pests and diseases – that condition the final crop yield. In addition, the pressing need to increase production to feed a growing population within a limited area is placing even more pressure on agricultural systems and their productivity.

It is common to associate mechanization with tractors. However, the tractor is no more than a universal mobile power source with the capacity to pull, push or put into action a range of implements, equipment and tools that perform farm operations; for a tractor to realize

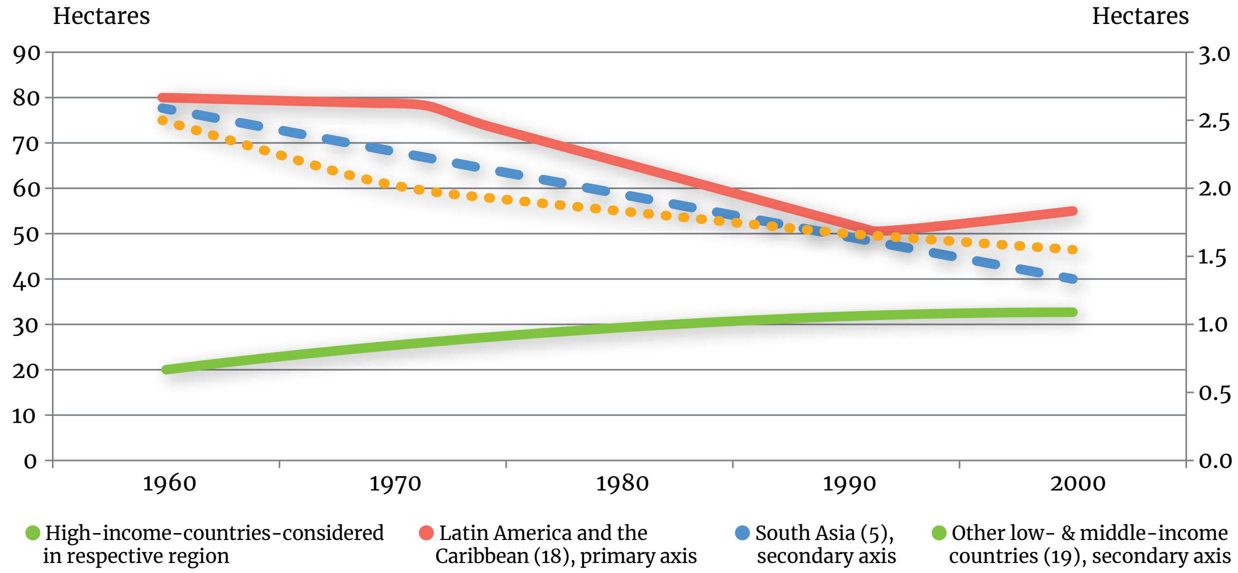

Figure 1. Average farm size, 1960–2000

Notes: Numbers in brackets indicate number of countries considered in respective region.
Source: Lowder, Skoet and Raney (2016).

its potential, it must be matched to the right equipment. Mechanization comprises numerous operations in the crop production cycle and throughout the value chain: mechanization is not synonymous with tractorization. When applied correctly, mechanization has the potential to reduce labour, improve the timing of operations, increase crop yields, apply expensive inputs more accurately and efficiently, and create added value.

This traditional association between mechanization and the farmer-operated tractor will not last into the coming decades: change is underway with the development of new and innovative technologies with the capacity to increase the efficiency of crop production to unprecedented levels thanks to the automation of machinery and equipment. The Food and Agriculture Organization of the United Nations (FAO) is currently promoting sustainable mechanization in developing countries, with the specific aim of reaching small-scale farmers who can benefit from mechanization using hire services with a focus on tractors (two-wheel, four-wheel, small to medium size), while also helping rural entrepreneurs establish hire service businesses.[1]

[1] In 2018, FAO and the International Maize and Wheat Improvement Center (CIMMYT) published the training materials, *Hire services as a business enterprise* (FAO, 2018), to help train actual and potential farm mechanization service providers. This publication focuses on the technical and managerial aspects of the business with the aim of increasing the capacity of rural entrepreneurs and fostering the implementation of services that can contribute to rural development and higher crop productivity.

1.1 Aim of report

This report presents and reflects on the opportunities that new technological developments related to automation and precision agriculture (e.g. robotics) can offer to agriculture in developing countries. These technologies are mainly targeted to support farmers that struggle with the cost of labour when harvesting crops and to tackle the declining availability of manpower for general cropping operations. The savings in terms of both cost and time (due to the precision in the use of inputs) represent an entry point for commercial farmers. However, these technologies could also be targeted at small-scale farmers, who – given the irreversible trends of urban migration – are a declining, female-headed, ageing population. These farmers could benefit from technologies and innovations in locations where agriculture is still a means of subsistence rather than an income-generating activity. The positive impact of adequate technologies can empower rural women towards equal status in society while also attracting youth to the sector.

This report explores the possible applications of agricultural technology, presents the current trends and discusses some of the principle challenges to successful adoption for sustainable agricultural mechanization in developing countries. Table 1 lists specific terms relevant to Agriculture 4.0.

TABLE 1.

Agriculture 4.0 Agriculture that integrates a series of innovations in order to produce agricultural products. These innovations englobe precision farming, IoT and big data in order to achieve greater production efficiency.
Precision farming Farming management concept based on observing, measuring and responding to inter- and intra-field variability in crops. Precision agriculture research aims to define a decision support system for whole farm management with the goal of optimizing returns on inputs while preserving resources.
Artificial intelligence (AI) The ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings (Encyclopaedia Britannica, 2020). AI can be programs that behave like humans, operate like humans, think like humans or have their own rational way of processing information and/or behaviour. Its applications are endless in the many features of technology development.
Remote sensing The science of obtaining information about objects or areas from a distance, typically from aircraft or satellites (NOAA, 2020). Images can be obtained in different wavelengths of the light spectrum by active sensors or passive sensors. Passive sensors record light as it is reflected from the Earth's surface, whereas active ones use their own stimuli to produce the image, like laser light. Remote sensing applications in natural resource management (e.g. for agricultural land use) are useful for monitoring, for example, agricultural production, yield and drought.
Blockchain technology System in which a growing list of records – known as blocks – are linked using cryptography. Each block contains a cryptographic hash of the previous block, a timestamp and transaction data. This distributed database holds records (represented by the blocks) of all transactions or digital events that have been executed and shared among participating parties (Crosby et al., 2015).
Internet of things (IoT) Global network infrastructure where physical and virtual objects with unique identities are discovered and integrated seamlessly (taking into account security and privacy issues) in the associated information network where they are able to offer and receive services which are elements of business processes defined in the environment in which they become active (Kiritsis, 2010). In the context of agriculture, any element that intervenes in the crop value chain will produce data that can later be processed for various purposes.
Information and communications technology (ICT) Different types of technologies that convey information to users through telecommunications. Technologies include wireless networks, Bluetooth, internet, mobile phones, SMS and MMS.
LIDAR Method combining different sensors of various frequencies and light types in order to measure distances that can then be used to create 3D images. Laser light is used to create the light which is reflected on the surface and then captured by a sensor. The types of light used include ultraviolet, visible and near infrared. It is a common technology in autonomous vehicles and equipment.

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2. AGRICULTURE 4.0

Drones, robots, data and information and communications technology (ICT)

Agriculture evolves with science and technology, and it is only a matter of time until the Internet of things (IoT) reaches farmscapes. Technical improvements in new agricultural technologies should:

- optimize production efficiency;
- optimize quality;
- minimize environmental impact; and
- minimize production-associated risks.

Examples of such improvements include: precision farming, blockchain technology adoption in value chains (e.g. transport, storage, washing, grading, packaging, labelling or processing), AI for pest and disease diagnostics and management options, remote sensing (satellite and drone imagery), and deployment of ground sensors (soil, crop or meteorological stations) or automated equipment for farm operations. Figure 2 presents a conceptual comparison between current conventional farming and Agriculture 4.0.

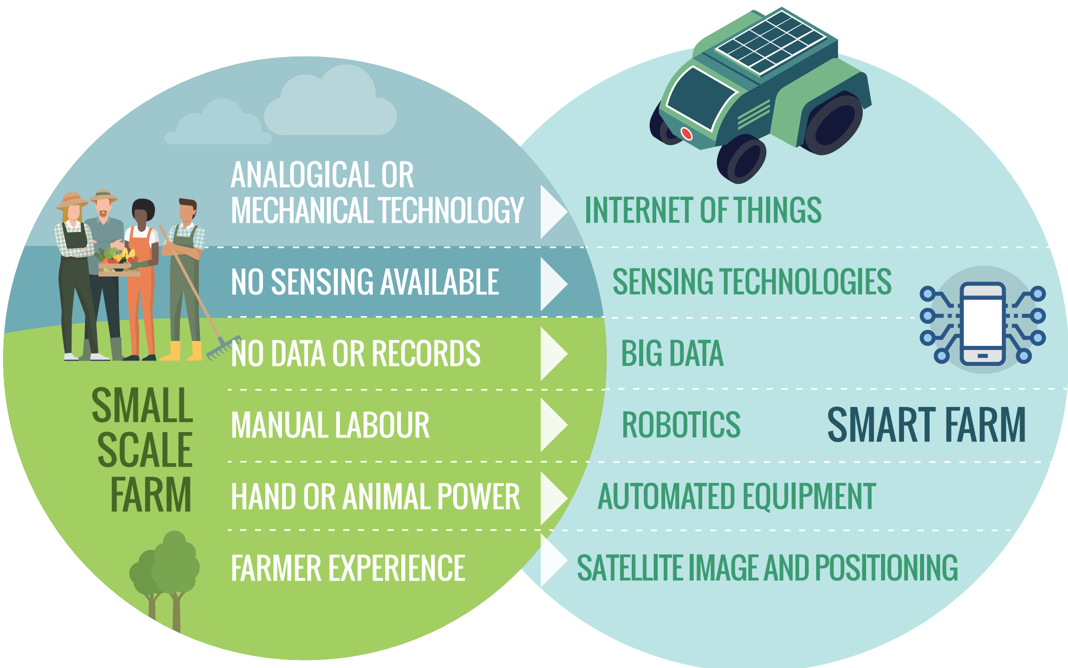

Figure 2. Comparison between a smart farm (Agriculture 4.0) and a small-scale farm (conventional agriculture)

Notes: Robotics refer to systems or machines where increased levels of intelligence are added to the machine for its autonomous work or a new intelligent machine is developed for an existing application. Automated equipment refers to existing systems, where some elements have been automated for transporting or working without human intervention.

The key players in this change are not only the industries of traditional farming equipment but also the farmers. Remote sensing, data processing, telecommunications, AI and robotics, combined with the expanding array of uses available, mean that new approaches are required to take into consideration not only agronomics, but also factors related to infrastructure, law and knowledge. Issues such as privacy, ownership of data generated in the farms, use of geolocation, insurance of non-manned vehicles and encrypted information will all be a part of digitalized agriculture. To illustrate how information management will play a key role in this new way of farming, Figure 3 shows the different stages and elements that intervene in digital agriculture: sensors monitor the crop to generate data captured by a platform; these data are processed by specific software and AI; intervention options are provided; the farmer decides how to act on the crop (directly with their own equipment or indirectly via automated equipment). Agricultural robotics can combine all the stages on one platform or specialize in some of them; it is a complex technology and it is not easy for the end user of the robot (the farmer) to have the necessary know-how and be familiar with the whole process and the elements that intervene in the cycle.

The paradigm of Agriculture 4.0 envisions farmer–machine interaction as central to the running of the farm, with the farmer making decisions and operating interconnected equipment that operates autonomously based on the above-mentioned information process. Today's commercial farmer who has a full command of existing farming skills and knowledge, will need to become a sort of information technology (IT) manager operating from an office or in front of a screen (computer, mobile phone, tablet etc.), rather than a machine operator working in the field, handling machine steering and adjusting equipment manually. For livestock management, skilled operators will still be needed, but with new sets of skills related to ICTs and automatization. This is the vision projected for countries with a highly developed agricultural sector; however, it is a long way from the reality of most countries and the majority of small-scale farmers.

Agriculture 4.0 offers many possibilities. Drones and other sensing platforms can provide information in real time, they produce imagery, capture different agronomical parameters and alert farmers of a crop's progress, the status of the soil, the surge or risk of pests and diseases,

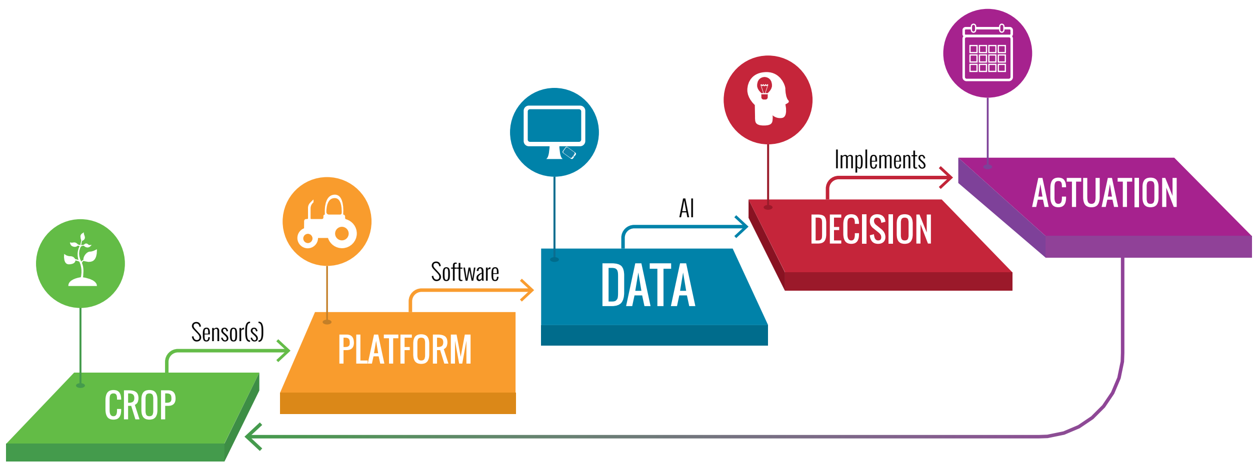

Figure 3. Information-based management cycle for advanced agriculture

Source: Sáiz-Rubio and Rovira-Más (2020).

and the development of weeds. The state of interconnectivity will be something previously unseen in agriculture, with high levels of information capture, analysis and processing between the various pieces of equipment and the systems. All this information needs to be processed by the famer who can then assess the optimal solution or action required. The farmer can use conventional technologies or autonomous equipment to intervene at field level or in controlled farming set-ups like greenhouses or vertical farms. The equipment can make use of sensed data to optimize input use according to the particular needs of the field, crop or soil. A concept image of this is shown in Figure 4.

The interconnectivity of rapidly changing mechanical devices is a major component of Agriculture 4.0, but this should not obscure the importance of the transparent algorithms driving these devices. The analysis of data coming from the devices will be understood via machine learning, leading in some cases to AI. An example of this is PlantVillage (PlantVillage, 2013): it has access to a vast image collection and through machine learning is able to provide more precise diagnostics than via other means (e.g. consulting an IPM guide or using phone cameras to diagnose crop diseases) and it links to satellite systems through portals such as the Water Productivity Open-access Portal (WaPOR) at FAO (FAO, 2019). The algorithms are transparent, having been built together with agronomists at public institutions such as FAO and the CGIAR System Organization. However, transparency cannot be assumed in the private sector, where issues of intellectual property demand a close-guarding code. Machines in an Agriculture 4.0 setting may make mistakes that are not easily discerned by farmers and others.

Farmers and agriculture professionals will need to acquire new skills to manage all these new systems and assess how to best perform agricultural operations based on all the possible parameters. The challenges for the farmer are not to be underestimated! Likewise, the public and private sectors will face new challenges in terms of capacity building around these new technologies.

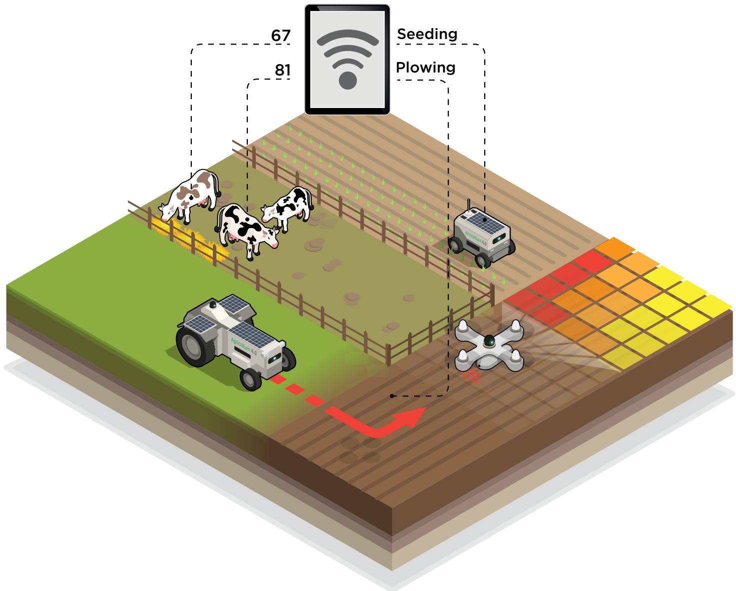

Figure 4. Graphic concept of Agriculture 4.0 at farm operation level

Source: Art&Design srl

2.1 Agricultural robotics

There is no formal definition for the term "agricultural robot" or "agrobot" and no official recognition of the function of robots that perform agricultural operations. Lowenberg-DeBoer *et al.* (2019) propose the following working definition for field working robot: a mobile, autonomous, decision-making, mechatronic device that accomplishes crop production tasks (e.g. soil preparation, seeding, transplanting, weeding, pest control and harvesting) under human supervision, but without direct human labour. Bechar and Vigneault (2017) define agricultural robots as: perceptive programmable machines that perform a variety of agricultural tasks, such as cultivation, transplanting, spraying and selective harvesting (Figure 5). The term "agrobot" is undoubtedly an effective description for autonomous machines that are able to carry out different repetitive agricultural tasks on the farm – from land preparation to harvesting – without direct human intervention.

In dynamic and unstructured environments, agricultural robots can often produce inadequate results due to the inherent uncertainties, unknown operational settings and unpredictability of events and environmental conditions. In 2019, as explained at the

International Forum of Agricultural Robotics (FIRA), an annual event held in Toulouse, there were over 60 known projects worldwide on the development of agrobots (FIRA, 2018), and this number continues to grow. They comprise a wide range of sizes, are designed for a variety of uses and apply different technologies. Only a small number are currently at the commercial stage, but the coming years will see new projects and increasing availability. As the technology is in its early stages, it aims to meet the current demands faced by farmers with a focus on commercial farming oriented towards intensive production, a sector which can afford to invest in this technology. However, the demand for agrobots needs to be driven by farmers' requirements, which can be quite specific. According to FAO (2019b), about 90 percent of farmers worldwide operate on a small scale and the technology must become accessible to this large group.

2.2 Use of agrobots

An agrobot can perform a vast array of tasks. The first commercially available agrobots cover three main tasks: eliminating weeds, monitoring pests and diseases, and harvesting specialized crops (berries or vegetables). An agrobot offers cost-saving opportunities as it reduces labour requirements (weeding and harvesting), limits the use of inputs (pesticides) and reduces yield losses resulting from the late detection of pests and diseases. Figures 6–8 show examples of commercially available specialized robots.

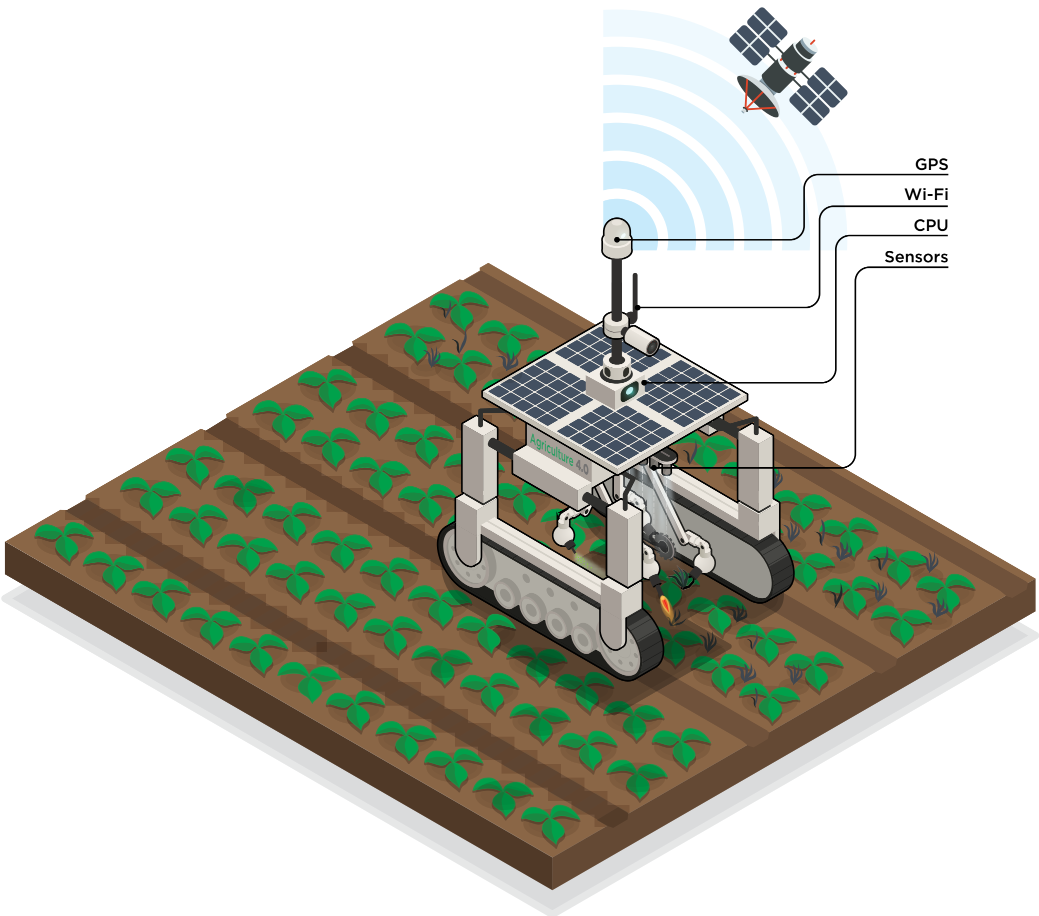

Figure 5. Concept of an agrobot weeding mechanically with a beam of light

Source: Art&Design srl

Figure 6. Solar-powered robot (Agerris Farmhand, Australia)

Notes: Able to control weeds with individually targeted mechanical weeding.
Source: Agerris (2020).

Figure 7. Self-powered platform (Agrointelli, Denmark)

Notes: Able to prepare, sow or weed conventional crops using traditional implements from tractors.
Source: Agrointelli (2018).

Figure 8. Small robot for weeding (OZ, France)

Notes: Able to weed in row crops and orchards.
Source: Naio Technologies (2016).

There are as many potential uses of agrobots as there are agricultural tasks. Prototypes already exist that can prepare the soil, sow, control pests and harvest cereal crops (e.g. barley or maize). The automation of agricultural equipment can adopt various approaches, from making existing machinery autonomous (i.e. driver free) to developing new autonomous platforms capable of carrying out tasks. These new platforms tend to be very sophisticated and new types of equipment are continuously being developed; however, simple agrobots designed for basic, straightforward tasks can already help farmers with a wide range of operations.

The level of complexity is closely related to cost and maintenance requirements – as with any technological equipment. The uptake of these technologies at field level requires farmers to adapt their farming practices and capacity accordingly.

Annex 1 presents examples of commercially available and advanced projects of agrobots

BOX 1.

Dino, the robot that weeds crops

Dino is just one of a handful of robots that Naïo Technologies (France) has developed for agriculture. This robot is specialized in mechanical weeding of vegetable crops; it recognizes the weeds in the crop rows and can discriminate between the commercial plant and the weed with artificial intelligence (AI) applied to image recognition. It is already under production and has sold over 100 units to farmers of high-value horticultural crops. Mechanical weeding eliminates the costs and risks associated with herbicide use. It also saves labour costs, since one person can simultaneously control up to three of them.

Given that the technology is still in its early stages, costs are high and its potential is not fully reached; the next challenge is to equip it with AI that can identify plants so that it can weed between plants in the crop row.

Source: **Bloch, S**. 2019. Robotic weeders are racing to replace glyphosate and dicamba. In: *The Counter* [online]. New York. [Cited 4 August 2020]. https://newfoodeconomy.org/robot-weeders-glyphosate-dicamba-herbicide-replacement/

3. DRIVERS OF ADOPTION

At present, the main drivers for farmers to invest in agrobots regard the **economic** and **environmental** aspects.

The adoption of agrobots in commercial farms offers major cost-saving opportunities. Many commercial farmers struggle to find sufficient manpower to cover labour needs during the harvest season, especially in fruit and vegetable plantations. Agricultural robots can eliminate this gap and reduce the cost of specialized manpower. Moreover, they can operate over long periods as they are not subject to the limitations – physical and legal – of humans. At harvest, some models are even able to pick fruits or vegetables individually, depending on the stage of ripening (Figure 9).

Agricultural robots enable the farmer to reduce inputs – pesticides, herbicides and fertilizers – with positive implications for the environment. Mechanical weed control is already a reality; other functions under development include micro-application of inputs and early detection of pests, which will considerably decrease, even eliminate, the need for inputs. Agrobots are also lighter than conventional machinery (i.e. tractors with implements or specific equipment for spraying or harvesting) and can thus alleviate problems associated with soil compaction and are able to access fields not suitable for heavy machinery (e.g. vineyards on slopes or land affected by wet conditions).

Figure 9. Specialized agrobot for strawberry harvesting

Notes: Different arms between the wheels pick the berries individually. *Source*: Agrobot (2020).

3.1 Challenges

The implementation of any technology entails challenges. The main challenges for the adoption of agricultural robotics are described below:

Ownership and management of digital data

Digital technologies involve the collection of individual data. As in other sectors, the data produced by the sensors of agricultural equipment are used by companies for their business model; indeed, data analysis and processing are crucial for the correct functioning and operation of agrobots. Clear **laws and regulations** need to be in place and should always be on the side of the farmer/individual to avoid misuse by third parties. However, the continuous need for data to perfect, design or run the AI behind the software that operates autonomous equipment can also present an opportunity for farmers to **monetize the data** generated. Furthermore, data generation is a way to **monitor ecosystem services or environmental indicators** (e.g. carbon sequestration).

Capacity

With the breakthrough of any new technology, the adoption rate depends on key factors: **knowledge, capability and capacity**. Many farmers may not have the capacity to operate agrobots or understand how they work. A good agricultural practitioner is not necessarily expert in digital technologies and automation, and the same applies to extension officers and service providers. Therefore, **capacity building** is essential for the uptake of automated equipment and its correct use; only with capacity can farmers unleash the full potential of agrobots.

A report published by the International Fund for Agricultural Development (IFAD) and GrowAsia (Grow Asia Partnership, 2019) highlighted that the adoption of digital technologies among small-scale farmers entailed five stages:

- Face to face
- Phone call
- Peer group dialogue
- Active discovery
- Digital service engagement

The process is not straightforward; support must be provided throughout by various actors adopting a range of methodologies. In the absence of external incentives (e.g. policies or market prices), the main driver for change is **willingness to adapt and adopt**.

Capacity building must go beyond existing farmers. It is important to prepare youth – the farmers of the future – to engage in agriculture by familiarizing them with new technologies during their schooling (programming and robotics are part of many high school curricula nowadays). By steering their interest in digital technologies towards applications in agriculture, individuals with new ideas can be attracted to the sector of agricultural robotics. The **adaptation of academia and education programmes** is essential if countries are to have the skilled labour necessary to operate, maintain and develop the technology. Moreover, the acquisition of knowledge must not be limited to the end users: capacity building must reach all stakeholders, from policymakers responsible for creating the right environment through laws, incentives or training programmes (education, industry and agriculture) to extension officers, technicians and farmers.

Farming system adaptation

Farmers who introduce agrobots into their production system do not always find it easy to make the robot work properly. It is a common misperception that robots will simply replace existing equipment and immediately carry out its function in the system. The reality is quite the opposite, and in order to achieve the best results, the **farm system must adapt to the robot**. Farmers needs to adapt, in terms of both timing and mentality. For example, with row spacing or terrain levelling, a farmer accustomed to a certain spacing between crops or a specific crop structure (e.g. the architecture of fruit trees) needs to adapt the spacing/structure to ensure that it matches exactly the operational parameters of the agrobot as it moves among the cultivated crops. There is already evidence that farmers who adapt accordingly achieve better results and profitability based on the good performance of the agrobots (FIRA, 2018). Agrobots currently are not cheap when compared to standard practices and equipment; as with any new technology, the first available models are very high in price. Agrobots are of interest to farmers operating in all kinds of situations in a wide variety of locations. However, some robots may be designed specifically to operate in a given location, based on the parameters of a particular farm; this limits the usability of the equipment and compromises business models that imply input sharing or service provision.

Purchase price

The **purchase pric**e or **operation cost** may exceed available resources and make production unprofitable. On the other hand, on large commercially oriented farms producing high-value horticulture crops where labour costs are high during harvest season (due to high manpower requirements or lack of availability of human labour), farmers find it already lucrative and increasingly profitable to use specialized agrobots that lower costs and reduce dependency on scarce human labour. While agrobots are already being used in some highly specialized horticulture farms – proving that it is possible to achieve lower opportunity costs through automation – there is a need to find profitable business models where the farmer does not necessarily own the robot, but can benefit from the technology. Two possible solutions, already in place in many farming systems, are service provision and cooperative ownership.

IT infrastructure

The concept of Agriculture 4.0 is closely linked to the use of ICTs and is heavily reliant on the availability of adequate IT infrastructure to **acquire, process and share data**. Agrobots are dependent on the availability of the correct infrastructure and to work autonomously, they rely on data provided by built-in sensors, remote sensors (i.e. satellite image), external sensors (drone imagery, soil probes), programmed actors and many agronomic parameters stored in their software. All this information needs to be acquired and shared, and access to reliable IT infrastructure is essential, with the right signal coverage, energy supply and strength to support the data transfer, not only for satellite positioning (e.g. as global positioning system [GPS]), but for telephone or radio signal. Not only does the agrobot need to be fed with data to operate, but the farm manager and the operators need to control the agrobot, process the data it produces while operating and make decisions based on the information available. This is a major challenge since the bandwidth of a phone signal does not extend to all rural areas, especially in developing countries (Figure 10). Engineering solutions may be required for challenging environments and settings to adapt agrobot ICTs to the conditions of developing countries.

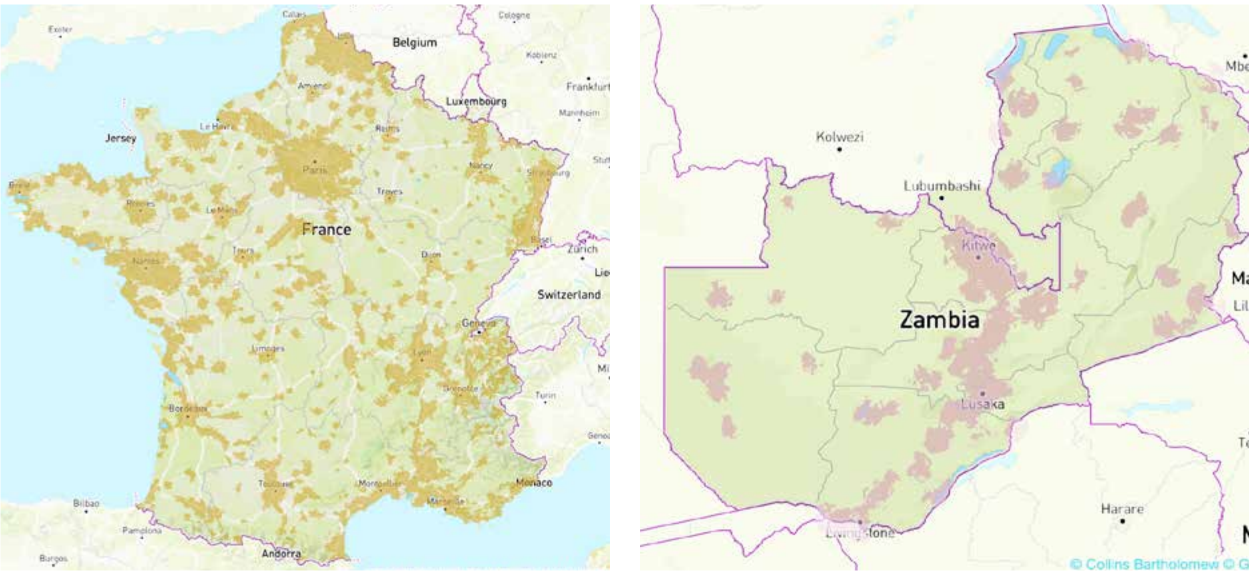

Figure 10. Signal coverage of 3G technology in France and Zambia

Notes: Coloured areas represent the signal coverage: 675 417 km² in France and 752 614 km² in Zambia. *Source*: GSMA (2020).

Technical maintenance and servicing

For the successful adoption of agricultural robots, appropriate technical servicing and after sales services must be available. As with other new technologies, it is a waste of time and resources to purchase a new technology or automated equipment, only to discover after a short time that spare parts are not available within a reasonable distance or time. The same applies for the specialized and qualified technicians needed to repair equipment and provide maintenance support; furthermore, in the case of agrobots, not only mechanics, but also ICT engineers and robotic technicians are needed.

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4. DEVELOPING COUNTRIES AND AGRICULTURAL ROBOTICS PERSPECTIVES

4.1 Agricultural applications

Considering the wide range of features of agrobots and despite the challenges faced, automation offers great potential in many applications in developing countries.
At present, two main trends exist in terms of automation of agricultural field operations:

- **Creation from scratch of new equipment** to perform different specialized farm operations or serve as a multipurpose platform for a range of tasks similar to those performed by a tractor when fitted with the right implement for a specific farming activity.
- **Conversion of standard agricultural equipment** into autonomous equipment, through the use of sensors and automatisms designed to replace the physical intervention of the farmer.

The approach of automatizing the existing fleet of standard agricultural equipment is accepted by farmers and makes use of implements that are already available on farms (Figure 11) with various projects underway. For example, a conventional tractor can be converted into an automated vehicle capable of sowing a field autonomously. Nevertheless, the low level of mechanization and machinery use in many developing countries means that machinery is not widely available for transformation into autonomous equipment; therefore, the conversion of equipment is not necessarily a good entry point. On the contrary, creation of equipment may be more effective in areas where machinery is not already widely used in farming.

However, in some developing countries – mainly in Asia – the domestic industry of small machines

Figure 11. Hands Free Hectare project: a 1980s harvester and a conventional small four-wheel tractor pulling a trailer

Notes: The two machines are working together and autonomously for winter wheat harvesting.
Source: Hands Free Hectare, Harper Adams University (2020).

and engines, including machinery repair and servicing, has expanded in recent decades and has the potential to form the basis of a local autonomous equipment industry (Justice and Biggs, 2020).

To date, most agrobot applications have focused on weed control and crop monitoring. Indeed, an electric battery has limitations in terms of power and weight, complicating the use of agrobots for tillage or soil preparation. However, if the industry can design agrobots capable of seeding into non-tilled soils, there are potential advantages in terms of soil preservation with the application of direct seeding and soil cover maintenance.

Weed control options range from mechanical (robot with an arm that physically removes the weed) to chemical (low dose of herbicide applied directly to the weed plant); other options such as infrared ray and laser are also being considered. The technology considerably lessens the need for herbicide and pesticide inputs, reducing also the environmental and health risks that their misuse present.

Agrobots for no-tillage/direct seeding agriculture with combined (chemical and mechanical) spot weeding would be a huge step forward; even for smallholders, it would mean that an autonomous agrobot could apply a mechanized agronomic system in line with the overall principles of sustainable intensification also promoted as "Save and Grow"[2] with conservation agriculture[3] principles at its core. According to Sims *et al.* (2018), commercial robotic machines using real-time kinematic GPS will be soon available for spot weed control using a combination of herbicide and laser; non-soil inversion mechanical weed control systems for no-till crops are also a possibility. Robotic weeding machines are light and cheap and have the potential to practically eliminate damaging soil compaction caused by the passage of heavy spray rigs during the weed management operation.

4.2 Agribusiness options

Small robots at an affordable price for purchase or hire represent a potential alternative in areas where manpower is scarce and conventional machinery is not available or is too costly for smallholders. Although farmers traditionally own most farm equipment, in the case of robotics, leasing or a service provision model may have advantages for both farmers and equipment providers (Lowenberg-DeBoer ***et al.***, 2019). One of the most arduous labour tasks for smallholders is hand weeding; youth and able teenagers refuse to carry out this hard manual work, they lose interest in rural hand labour farming and leave their villages for alternative income sources in bigger urban centres and beyond. Therefore, the introduction and adoption of small agrobots capable of doing this type of work more efficiently, in less time and at an affordable rate may offer a very interesting business model for young entrepreneurs in rural areas. Robotics could awaken the interest of rural youth in innovative agricultural technologies with the emergence of new types of jobs through rural mechanization and partial automatization. There are numerous potential benefits for farmers: increased efficiency, reduced drudgery and likely improvements in production, resulting in increased or sustained yields. The time saved could be dedicated to other farm tasks or businesses such as poultry farming, vegetable gardens or other value chain-related income opportunities. With a stable IT structure in place, agrobots do not require the presence of a human to perform physical work: while the robot is working, the farmer can be carrying out other tasks.

After sales services and IT, infrastructure requirements may become two major obstacles to the introduction and adoption of agrobots in developing countries. It is therefore useful to perform an analysis to understand what types of agrobots are appropriate and fit the context. The technology is highly adaptive and can be greatly simplified, making the machines easy to operate and maintain. For example, a robot designed to spray herbicides in row crops can be complex with multiple sensors to identify weeds and spray each weed plant, or simplified so that it just detects crop rows and sprays alongside them (this option has much more basic maintenance requirements).

[2] Save and Grow is a paradigm promoted by FAO which promotes intensive crop production, one that is both highly productive and environmentally sustainable. For further information, see http://www.fao.org/ag/save-and-grow

[3] Conservation agriculture is a farming system that promotes maintenance of permanent soil cover, minimum soil disturbance (i.e. no tillage) 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 to improved and sustained crop production. For further information, see http://www.fao.org/conservation-agriculture/en/

Agrobots can be designed to enable spare parts to be obtained via 3D printing, enabling decentralized production and facilitating the related logistics. It also opens a door to the development of new businesses relating to 3D printing and robot design in the countries of operation, rather than relying on innovative technologies from foreign countries. The introduction of new agrobot technologies can serve as an anchor for youth in rural areas, making the farming business more attractive and creating new opportunities for entrepreneurs and innovators to assist small industries and businesses.

A key factor for the successful adoption of agrobots in developing countries is to design and offer technical solutions at a low (affordable) cost but with a high impact. The impact may be in terms of crop yield, manpower cost reduction, timeliness of farm operations or drudgery reduction. Simple weeding agrobots offer great potential in developing countries, as well as technologies to improve input use efficiency, for example, robots that distribute fertilizer according to the required rates or that broadcast seeds.

4.3 Drudgery reduction for small-scale farmers

The multiple applications and possible uses of agrobots can provide important support to rural livelihoods, especially once the IoT is further developed. For example, simple wheeled platforms that follow a person carrying a smartphone could help to carry goods, drinking water or heavy tools, significantly reducing drudgery and increasing productivity for a person who relies on their own muscle power. Development of such a technology could have a major impact since carrying drinking water in developing countries is often part of women's daily routine (taking as long as 2–3 hours per day) and the transport of goods to and from local markets is also time-consuming. Automated robots could also eliminate the need for mechanical weeding, another manual task which usually falls to women in the context of small-scale farming.

Given the cost of purchase and necessary specialization to operate and maintain this sort of equipment, the most profitable way for farmers to secure such benefits may be via hire services where a specialized operator who owns or works for the owner of the equipment performs the task (e.g. weeding) for a service fee. Farmers can thus benefit from the agrobots without needing to request big loans or make considerable expenditures for equipment requiring specialist skills for operation. The hire service model also creates an opening for entrepreneurs in rural areas who have the knowledge and/or capital and are willing to invest in the equipment.

4.4 Contribution to achieve Sustainable Development Goals

Agricultural robotics have a role to play in sustainable development. Indeed, the technology can contribute to achieving several of the United Nations Sustainable Development Goals (SDGs) (Figure 12):

- **Improvement of livelihoods.** Reduction of drudgery directly improves the livelihoods of farmers, especially small-scale farmers. Improved crop yields (compared with those achieved with traditional practices) increase both income and food intake.
- **Food sovereignty and adequate nutrition.** Increased crop production and diversification of the types of crops grown due to the optimization of the cropping system can contribute to reducing the dependence on food items from distant production areas. Furthermore, diversifying food consumption can enhance the dietary intake and overall nutrition of the farmers.
- **Impact on the rural–urban migration dynamic.** The establishment of new types of rural enterprises focused on agricultural production, technical assistance, and operation and maintenance of agricultural robots creates an opportunity to revitalize educated youth and encourage them to remain in rural areas.
- Creation of employment and businesses. The need for qualified and trained labour to operate and maintain all the elements of the

technology (mechanics, telecommunications, data management) creates a new employment niche for trained youth and rural entrepreneurs to establish enterprises for more efficient crop production and service provision of mechanized agricultural labour and also to provide the related technical support for operation and maintenance. New types of business models will thus emerge.

- Closing the technological divide. The integration of different types of technologies such as machine learning, satellite positioning or automatisms contributes to closing the gap between developed and developing countries. Robotics are intrinsically adaptable, facilitating the adoption of the technology in different contexts. This implies the possibility to leapfrog the technological evolution of mechanized operations for crop production, passing directly from subsistence farming based on manual labour or draught animal power to commercial farming based on precision agriculture.
- Intensification of sustainable production. Adoption of precision agriculture procedures to optimize the use of resources and increase the timeliness of crop operations through, for example, direct seeding, mechanical weeding at individual level or ultra-low volume spraying, allows farmers to produce more with less.
- Sustainable resource management. Reducing the use of inputs, limiting soil disturbance and increasing production without compromising the existing natural resources can all improve the livelihoods of farmers and the rural population in a sustainable manner.

Figure 12. Sustainable Development Goals to which agricultural robotics can contribute

5. CONCLUSION

While agricultural robots are still in their early stages, there are very clear indications of their potential. The challenges ahead are not only technical, but also socio-economic, in particular with regard to capacity building and the need to fully understand the principles and the technologies involved. However, given their versatility, agrobots will be able to perform tasks under conditions that are by nature very labour intensive, and thus make an important contribution to improving sustainable crop production and the livelihoods of smallholder farmers in developing countries. Agricultural robots present an opportunity to increase crop production efficiency, improve agricultural sustainability, and bring innovation and advanced technologies to new areas. FAO has an important role to play in this process, pushing for the inclusive development of this technology and ensuring that new agricultural technologies in the form of automated tools and bots are helping to enhance and promote principles of sustainable intensification of agriculture. FAO aims to help the technology become accessible to small-scale farmers, ensuring that adequate policies and frameworks are developed and enforced to this end.

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ANNEX

List of typologies and examples of agrobots

This list is not exhaustive and may be outdated in a matter of years as the technology evolves rapidly. The information contained in the list of the Annex is for general information purposes only. The mention of a company or of its products and services in the publication, does not imply that these have been endorsed, accredited or recommended by FAO. Under no circumstances shall FAO be responsible or liable for any use or any failure of performance or dysfunction of the products or services of the companies listed herein, nor for any loss or damage resulting therefrom.

TABLE A1.1

Single purpose – robots specialized in one specific job or task

Product	Function	Tasks performed and other information	Website
Cerescon	Asparagus harvesting robot	Harvests asparagus, covers scarcity of specialized manpower for hand harvesting	https://www.cerescon.com/EN/home
Deserbiocut	Weeding robot	Weeds and maintains soil covers, prototype of a mechanical weeding robot powered by solar energy	https://deserbiocut.com/
Jackal	Research platform	Scouts and monitors, equipped with sensors of many different types	https://www.clearpathrobotics.com/jackal-small-unmanned-ground-vehicle/
HV-100	Material handling robot	Handles green materials and plants contained in pots	https://www.public.harvestai.com/
Swarm Farm	Crop protection robot	Sprays products for crop protection, is able to work in swarms	https://www.swarmfarm.com/
Ecorobotix	Weeding robot	Weeds and maintains soil covers, prototype of a mechanical weeding robot powered by solar energy	https://www.ecorobotix.com/en/autonomous-robot-weeder/
Dino	Weeding robot	Weeds vegetable crops	https://www.naio-technologies.com/en/agricultural-equipment/large-scale-vegetable-weeding-robot/
Ted	Weeding robot	Weeds vegetable crops	https://www.naio-technologies.com/en/agricultural-equipment/vineyard-weeding-robot/
Oz	Weeding robot	Weeds protected crops	https://www.naio-technologies.com/en/agricultural-equipment/weeding-robot-oz/
Harvest Croo	Strawberry harvesting robot	Inspects and picks ripe strawberries, covers scarcity of specialized manpower for manual harvesting	https://harvestcroo.com/
Vitirover	Mowing robot	Mows permanent covers in perennial crops	https://www.vitirover.fr/en-robot
Agrobot	Autonomous strawberry picking robot	Harvests strawberries in row crops	https://www.agrobot.com
Guss	Autonomous spraying robot	Moves through orchards without an onboard operator using sophisticated combination of GPS, LiDAR, vehicle sensors and proprietary software to	https://gussag.com
Vinerobot	Autonomous vineyard scouting robot	Scouts vineyards and monitors soil and crop parameters to advise on irrigation, treatments and crop status	https://www.youtube.com/watch?v=013z1OvwM3Y

Notes: GPS – global positioning system.

TABLE A1.2

Multipurpose platforms – can carry two or more tasks simultaneously or interchangeably

Product	Function	Tasks performed and other information	Website
Digital Farmhand Robot/Agerris	Multipurpose platform	Couples with conventional implements, designed for small-scale farming	www.agerris.com/
DOT	Multipurpose platform	Couples with conventional implements	www.seedtorun.com
Farmdroid	Seeder–weeder platform	Powered by solar energy	http://farmdroid.dk/
Husky	Development platform	Autonomous platform used to carry payload, carry sensors or serve for other types of operations	https://www.clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/
Robotti	Implement platform carrier	Diesel-powered platform that can operate tillage equipment, seeders and weeders	http://agrointelli.com/robotti-diesel.html#rob.diesel
CEOL	Implement platform carrier	Autonomus platform that can carry conventional implements for soil preparation, seeding, weeding and spraying	https://www.agreenculture.fr/

TABLE A1.3

Automated agricultural equipment – conventional equipment able to work unmanned with the installation of sets of communication and control

Product	Function	Tasks performed and other information	Website
Hands Free Hectare	Automation of existing equipment	This Harper Adams University project has operated 1 ha over 3 years cultivating cereal crops without any direct human intervention on the ground using automated existing agricultural equipment. It is currently expanding and testing the technology with farmers in the area.	http://www.handsfreehectare.com/
Bear Flag	Self-driven technology for tractors and implements	The company has developed a technology that converts conventional tractors and implements into self-driven autonomous equipment.	http://bearflagrobotics.com/
University of Hokkaido	Automation of existing equipment	The Agricultural Research Institute in collaboration with Japanese machinery manufacturers has developed a technology that allows existing tractors and equipment to work in swarms and perform farm operations autonomously.	https://youtu.be/pvzez_CWztQ

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