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Agri-Robotics and Future of Sustainable Agriculture

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Abstract:
The development of agricultural robots in recent years vastly promotes the process of agricultural automation. Agricultural robots can accomplish various tasks to help producers manage the farmland better and improve the yield. The world population is expected to hit a whopping number of 9 billion by 2050. What is expected to follow is a dramatic rise in agricultural production, doubling to meet the coming demand. This need has caused farmers to turn to robotics as a solution for the coming future. Nevertheless, the growing population, rise of AI, and new developments in robotics have caused the world of agriculture robotics to explode with innovation.

Keywords: *Agricultural robots; Automation; Artificial Intelligence; Sustainable Agriculture.*

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I. Introduction

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 labor, 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.

What are agricultural robots?
Agricultural Robots, commonly known as Agribots or Agbots, serve as artificial intelligence sources in the agriculture industry. They assist farmers in improving productivity and reducing the dependency on manual field tasks.

Top 10 robotics applications in the agriculture industry :
1. Nursery Planting

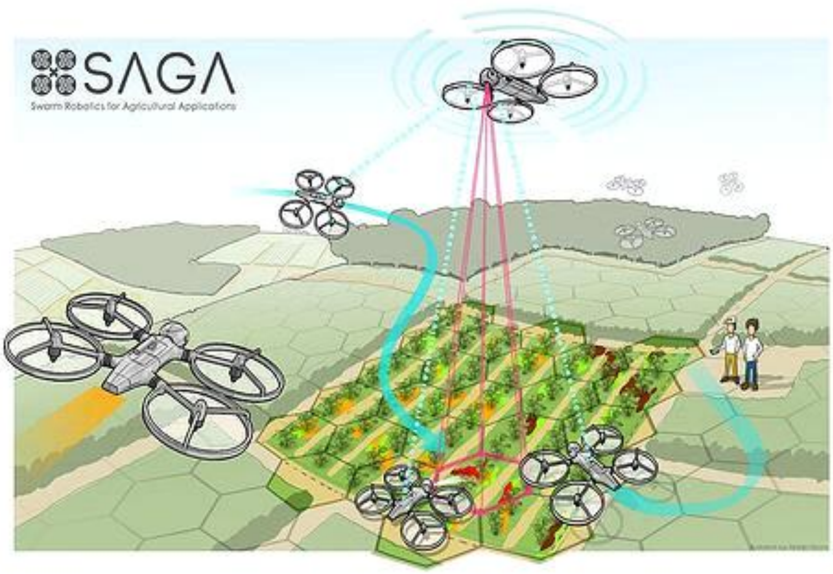
Nurseries are where seeds are grown into young plants, which are later planted outside. Nursery plants are often sold direct to consumers and landscape gardeners, but they are also the start of the food journey for some crops.

There is a rising need for nursery automation. Companies like HETO Agrotechnics and Harvest Automation (which we introduced in a previous post) provide automation solutions for seeding, potting, and warehousing living plants in greenhouses.

2. Crop Seeding

Many food plants begin life as seeds in a field. The traditional method for sowing seeds is to scatter them using a "broadcast spreader" attached to a tractor. This throws many seeds around the field while the tractor drives at a steady pace. It is not a very efficient method of planting as it can waste seeds.

Autonomous precision seeding combines robotics with geo-mapping. A map is generated which shows the soil properties (quality, density, etc) at every point in the field. The tractor, with robotic seeding attachment, then places the seeds at precise locations and depths so that each has the best chance of growing.



3. Crop Monitoring and Analysis

Monitoring huge fields of the crop is a big job. New sensor and mapping technologies are allowing farmers to get a much higher level of data about their crops than they have in the past. Ground robots and drones provide a way to collect this data autonomously.

Drone companies like Precision Hawk offer farmers combined packages which include robotic hardware and analysis software. The farmer can then move the drone to the field, initiate the software via a tablet or smartphone, and view the collected crop data in real-time.

Ground-based robots, like Boni Rob, provide even more detailed monitoring as they can get closer to the crops. Some can also be used for other tasks like weeding and fertilizing.

4. Fertilizing and Irrigation

Irrigating and fertilizing crops that have traditionally used a lot of water is quite inefficient. Robot-Assisted Precision Irrigation can reduce wasted water by targeting specific plants. Ground robots autonomously navigate between rows of crops and pour water directly at the base of each plant.

Robots also have an advantage as they can access areas where other machines cannot. For example, corn growers face the problem that the plants grow too quickly to reliably fertilize them. Robot aims to solve this problem as it easily drives between the rows of corn and targets nitrogen fertilizer directly at the base of each plant.

5. Crop Weeding and Spraying

Spraying pesticides and weed killers onto fields is not only wasteful, but it can also severely harm the environment. Robots provide a much more efficient method.

The concept of micro-spraying could significantly reduce the amount of herbicide used in crop growing. Micro-spraying robots use computer vision technology to detect weeds and then spray a targeted drop of herbicide onto them. AG BOT II is a solar-powered robot that uses this technique.

Some weeding robots don't even need to use chemicals. Robo Crop, for example, uses computer vision to detect plants as it is pushed by a tractor. It then automatically hoes the spaces between plants to uproot the weeds. Other weeding robots use lasers to kill the weeds.

6. Thinning and Pruning

Thinning involves reducing the density of plants so that each has a better chance of growing. Pruning involves cutting back parts of plants to improve their growth.

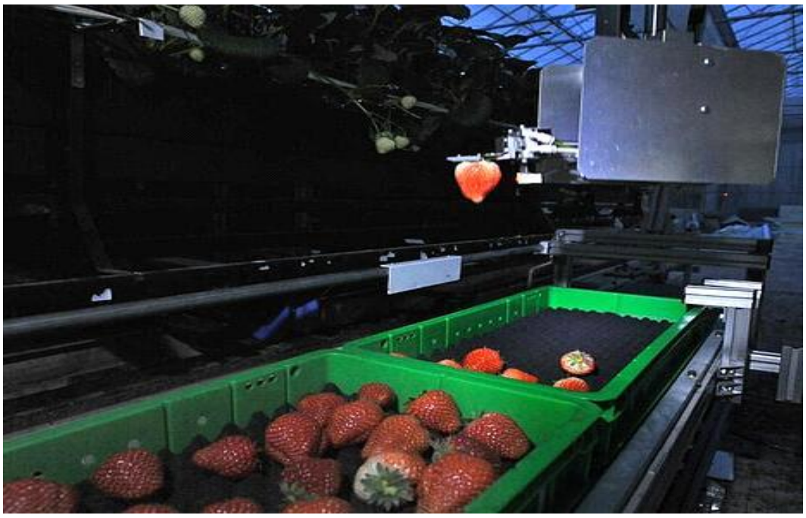
The Lettuce Bot thinning robot received an award this year for "outstanding product innovation in agriculture." It uses computer vision to detect lettuce plants as it drives over them and decides at that moment which plants to keep and which to remove.

Pruning is a complex job and the most notable attempts to automate it has come in the wine industry. Wall-Ye is an autonomous vineyard robot able to prune grapevines. The company has also developed a blueberry pruning robot.

7. Autonomous Tractors

Several of the robots I've mentioned are attachments to a tractor. As humans usually drive the tractors, the robots are designed to adapt to the speed that the human is driving. However, fully autonomous tractors are also becoming popular.

The IDTechEx Agricultural Robots report found that more than 300 thousand tractors with autonomous functionality were sold in 2016. There is also a rising trend for follow-the-leader autonomy, where tractors autonomously follow human-driven combine harvesters to collect the grain.



8. Picking and Harvesting

Harvesting crops such as corn, barley, and wheat is quite simple. It can be done with a combined harvester, which can be automated just like a tractor. However, other crops, like soft fruits, are more difficult to harvest as they require manual dexterity.

The EU-funded "Clever Robots for Crops" project is making progress on a few harvesting applications, including apple harvesting, grape picking, and sweet pepper picking.

9. Shepherding and Herding

Although most agricultural robots are currently applied in crop growing, there have been a few emerging applications within sheep and cattle farming. Farmers in both New Zealand and Ireland have been seen using drones to round up their sheep over long, difficult terrain.

Various examples of remote-controlled, cattle-herding drones can also be found on YouTube. This could be a lower-cost alternative to the expensive helicopters which Australian ranchers use currently.

10. Milking

Finally, we have seen a great development using collaborative robots to help in the milking process on dairy farms. This case study by Universal Robots shows how a UR5 can be used to spray disinfectant on the cow's udders in preparation for milking.

It seems certain that robotics will continue to revolutionize agriculture and change the way that we think about producing food. For a list of even more agricultural robots, check out these articles at Robotics Business Review, The Robot Report, and IntoRobotics.

Robots and Farming :
Crop- Harvesting Robots :

On its face, crop harvesting seems ripe for automation. It’s physically taxing and highly repetitive — the kind of labor that's often most effectively targeted in the robot revolution. (See factories, manufacturing, mining, logistics processing.) But that’s not necessarily the case.

Picking crops also requires manual dexterity and a delicate touch. Many fruits bruise easily in the heat, and leafy vegetables are easily torn. And most robots just aren’t advanced enough to handle that level of precision. Remember, it wasn’t all that long ago that roboticists finally got a cutting-edge bot to catch a ball — simple enough for humans, far less so for robots.

But tech companies in the private sector and robotics departments in academia continue their efforts to clear that hurdle.

Crop-Harvesting Robot

Harvest Croo:
Location: Plant City, Fla.

How it’s using farming and agricultural robots: Gary Wishnatzki is vocal about the labor pinch he says growers have faced over the last few years. The owner of berry supplier Wish Farms told the New Yorker in April that he relies on workers hired through expensive temporary visa programs. Among reasons for America's labor shortage, the article identifies suppressed immigration and a diminished appetite among low-skilled domestic workers to do the backbreaking labor of strawberry harvesting. Wishnatzki's push to automate isn’t about eliminating farm jobs, he argues but meeting the demands of consumers who’ve come to expect fresh strawberries even in the dead of winter.

He’s making that push as co-founder of Harvest CROO, a startup that developed an advanced strawberry-harvesting robot called Berry 5. It uses a variety of robotic components — rather than a single arm — to grab the leaf, pick the berry and pack it. Computer vision helps Berry 5 decipher ripe berries from non-ripe ones

before plucking. And it's fast compared to human laborers, purportedly able to pick a plant in eight seconds and shift to the next in one-and-a-half.
Developed thanks to millions in investment dollars from others in the berry industry, Berry 5 is currently working in Florida fields on a trial run. The company reportedly harvest CROOopes to commercialize them before the end of 2019.

Harvest Croo

Cambridge University
Location: Cambridge, U.K.
How it's using farming and agricultural robots: Lettuce-harvesting has remained stubbornly robot-resistant thanks to the plant's fragile nature and proximity to the ground. But researchers at Cambridge University made a breakthrough with their so-called "Vegebot," another computer vision-powered prototype.
Here's how it works: One camera scans the lettuce and gives a thumbs up or down for harvesting. A second camera (positioned near a blade) then guides the pick without crushing the plant. Meanwhile, a machine-learning algorithm "teaches" the robot to avoid unripe or diseased lettuce.
Vegebot hardly works with the speed or skill of human hands, but a series of test runs have purportedly established proof-of-concept success, which also augurs well for other above-ground fruits, vegetables, and grains.
"Every field is different, every lettuce is different. But if we can make a robotic harvester work with iceberg lettuce, we could also make it work with many other crops," Simon Birrell, of Cambridge's Department of Engineering, said in a press release.
While a scalable commercial lettuce harvester remains elusive, efforts to produce one have ramped up. In 2017, for example, John Deere acquired CV agtech trailblazer Blue River Technology, which has made notable strides in lettuce-focused robotics.

Cambridge University Robot

Abundant Robotics
Location: Hayward, Calif.
How it’s using farming and agricultural robots: The apple-sucking vacuum robot from Abundant Robotics might initially appear brutish and imprecise compared to Cambridge's refined Vegebot, but the contraption’s odd appearance — it resembles a tractor-affixed suction tube — belies some advanced tech.

Employing sophisticated computer vision, the robot gulps up mature apples and bypasses its unripe brethren. It's also open to farmer assistance in that, as Wired notes, its algorithm can be updated based on feedback provided by ripeness-judging experts.

Automated apple picking faces challenges similar to those of lettuce and strawberry picking. According to Abundant CEO Dan Steere, it "requires solving several complex technical problems in parallel, from visually identifying harvestable fruit and physically manipulating it to pick without bruising, to safely navigating the orchard itself."

This past March the apple picker made its maiden commercial voyage, in the New Zealand field of fruit grower T&G Global.

Abundant Robotics

Harvest Automation
Location: Groton, Mass.
How it’s using farming and agricultural robots: All those charming decorative grasses, flowers, and shrubbery accents at your local gardening center are big business. The commercial greenhouse market is poised to become a $38 billion industry within the next four years, and growers are increasingly using robots to help fill the high labor demand.

Founded by former employees of Roomba inventors iRobot, Harvest Automation made its first product with this fast-growing market in mind. The behavior-based HV-100 robot handles the important, but highly repetitive and strenuous, work of spacing container crops and plants. (Greenhouse plants need space between them so they grow thick and bushy and resilient, but too much space means square footage isn't being optimized.) The HV-100 is built to keep running even in the scorching temperatures and less-than-pristine environments of nurseries that grow ornamental plants and specialty fruits and veggies.

Harvest Automation

Weeding Robots

If you've ever tended a personal garden, you're well aware that weed control is both important and difficult. Commercial agriculturists know it, too, but on a massive scale. Even when crop rotation is possible, many large outfits rely at least somewhat on the use of herbicides. But given the fact that plants can become resistant to weed killers and consumers are increasingly averse to chemically treated food, it's hardly a perfect solution. That's why weed-management robots — including ones that incorporate advanced AI to help distinguish between crops and weeds — are an attractive option.

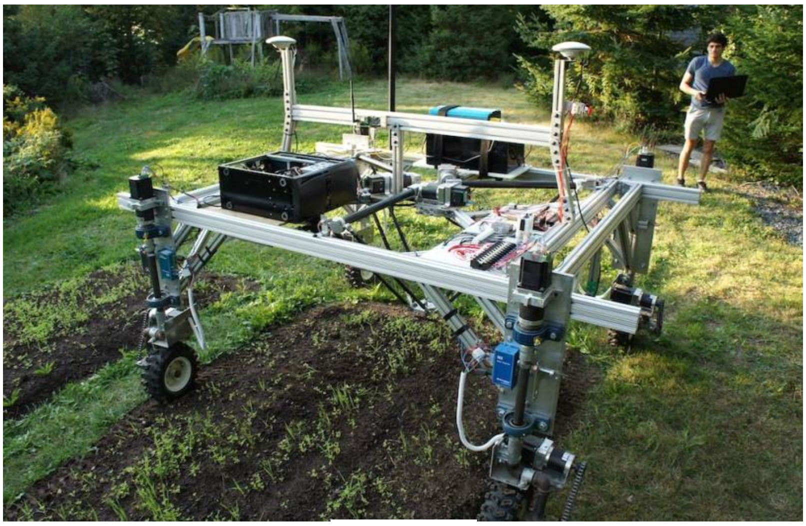
Weeding Robot

Naio Technologies
Location: Ramonville-Saint-Agne, France
How it's using farming and agricultural robots: One of the Old World's preeminent wine producers, Château Mouton-Rothschild is very New World when it comes to vineyard maintenance. The famed estate is among several vintners that have partnered with Naio Technologies to enlist Ted, the company's vine-tailored robotic weed killer.

Electric and shaped like an inverted U, the long-running Ted simultaneously rolls over and around a vine row, using RTK satellite navigation to stay on course. (A drone maps out the initial plot of land that Ted surveys.) Industry-standard blades and finger weeders run along the base, pulling unwanted weeds from the vines and consequently decreasing the need for herbicides. Ted's robotic cousins include weeding robot Oz and vegetable robot Dino.

Naio Technology Robot

Nexus Robotics
Location: Dartmouth, N.S.
How it's using agricultural robots: This scrappy Nova Scotia startup played David to some of North America's most prestigious robotics-program Goliaths at last year's Weed and Feed ag-bot competition. The company's top prize-winning entry, a weed-yanking autonomous robot dubbed R2Weed2 (yep, you read that correctly), employs artificial intelligence to differentiate between weeds and crops so the former is stripped and the latter left to grow. As it runs, R2 also gathers data that help farmers with soil analysis and environmental monitoring. A commercial version will reportedly be available later this year.



Nexus Robot

Robotic Greenhouses/Robot Farming

Instead of bringing robots to the field, one of the next great advances in farming automation will bring the field to robots.

Below are two well-financed coastal startups —one West, one East — that are helping, um, plant the seed for a robotic-greenhouse future. Not everything is growable in this way, but for certain crops the improvements are striking. Both of these companies promise a dramatic decrease in the amount of water used (between 90 and 95 percent less) for an equivalent crop yield, and both boasts controlled indoor environments that eliminate the need for pesticides. Here's how they do it.

Robotic Greenhouses & Robot Farming

Iron Ox
Location: San Carlos, Calif.
How it's using agricultural robots: Inside what the company describes as "the world's first autonomous farm," an 8,000-square-foot space that more closely resembles a research lab than a farm field, two cloud-connected robots oversee the growth of leafy greens (romaine and butterhead lettuce, bok choy, kale, arugula)

and herbs (basil, cilantro, chives, sorrel, parsley), all grown inside heavy hydroponic pods. Using computer vision and sensors as its "eyes," one robot does the heavy lifting, transporting the pods across the facility; the second analyzes and picks the individual plants.

It all happens beneath high-efficiency LED lights and under the watchful eyes of some dozen on-site robot and plant scientists. The Y Combinator-backed company — founded by two Willow Garage alumni — claims the small space can yield as much as a one-acre traditional farm.

Iron Ox began production last October in its greenhouse-style facility and started selling at its first partner store, a market in its hometown San Carlos, a few months later. The long-term goal is to establish additional farms near other high-demand areas, which would cut out the long-slog transportation costs that exist when growing is isolated to just a few regions in the country.

Iron Ox

Bowery Farming
Location: NYC
How it's using agricultural robots: Unlike the large, low-profile vats in which crops are nurtured at Iron Ox, Bowery Farming stacks up layers of trays, each filled with greens, in the traditional vertical-farming format inside its Kearney, N.J., growing space.

But it's also using robotics, artificial intelligence, and LED to grow leafy greens and herbs with the same end goal in mind: addressing the problems posed by labor scarcity, population booms, and centralized farming.

Here, a proprietary operating system and complex array of sensors collect data and maintain an ultra-precise balance of water, temperature, nutrients, and humidity. At the same time, a team of vertical farmers helps to harvest and watch over the crops.

The company — which has received investment capital from the likes of celebrity chef Tom Colicchio and Uber CEO Dara Khosrowshahi — sells its greens and herbs at Whole Foods, Foragers, and Westside Market. In the New York metro area, they're also available through Peapod, Jet.com, Amazon, and in two of Colicchio's high-end restaurants.

Bowery Farming

Aerial Imagery Drones And Seed Planting Drones

Aerial imagery can save farmers a lot of time by giving them a bird's eye view of crops; that way, they can quickly get a sense of vegetation's health, insect issues, irrigation layouts, and weed growth. It even allows them to precisely determine how much pesticide the crops require.

Farmers can use a variety of subscription services to access these valuable flyover images (including thermal, infrared, and NDVI) of their fields, but fewer companies have taken the full plunge into unmanned aerial vehicles (UAVs). That's most likely because of FAA restrictions on autonomous drones, which require that pilots be immediately ready to take control of a drone. Small unmanned aircraft must also be kept within a would-be pilot's line of sight when airborne.

But they're out there, if not yet in large numbers. Here are some companies that prove there's something's in the air when it comes to agricultural imaging, seed planting, and cloud seeding.

Aerial Imagery and Seed Planting Drones

American Robotics

Location: Marlborough, Mass.

How it's using agricultural robots: One of several Boston-area companies making notable agtech breakthroughs, American Robotics is the team behind Scout, an aerial imaging drone that fits the so-called "drone in a box" model.

Between flights, Scout lives inside a weatherproofed box, where it self-charges and processes (via edge computing) all the data it collects. When it takes flight to examine fields, the box top opens and the fully autonomous drone lifts off, using artificial intelligence to plot and conduct the run. During missions, which can be scheduled or launched on-demand, Scout gathers crop stress data that farmers can use throughout a crop's life cycle. It's the kind of aerial surveillance that remains a key facet in the growing field of so-called precision agriculture.

American Robotics

Taranis
Location: Tel Aviv
How it's using agricultural robots: Given the FAA's restrictions on autonomous drones, perhaps it's no surprise that some of the leading purveyors of agriculture-focused UAVs are headquartered outside the U.S. and cater to an international clientele. That includes Israel-based Taranis, which has brought its high-resolution scans to farmers in Europe, South America, and North America. Along with more traditional aircraft, the company operates drones that use computer vision and data science to monitor crop stress and self-improve identification capabilities.

Taranis

UAV System of International
Location: Las Vegas
How it's using agricultural robots: Any UAV pilot who wants to fly a drone that weighs more than 55 pounds at takeoff (including cargo) needs to petition for a special exemption through the F.A.A. That means non-exempt farmers who want to drone-scatter seeds over their acreage are limited in how many pounds of seed they can spread in a single run. Still, several manufacturers have developed drones marketed specifically for that purpose.
UAV Systems International sells two drones that spread seed and fertilizer, one with a payload capacity of about four pounds and another with a roughly 11-pound payload. Both have a two-mile flight range and a 20-minute

limit, according to the company. UAV also markets crop sprayer drones and surveillance drones that inspect crop health.

UAV Systems International

Desert Research Institute
Location: Reno, Nev.
How it's using agricultural robots: Cloud seeding is all about making it rain — literally. The concept dates back to at least 1946 when Dr. Bernard Vonnegut discovered that, under certain conditions, introducing silver iodide particles to clouds could spur the creation of ice crystals, potentially precipitating precipitation. (Fun fact: Bernard was brother to literary legend Kurt Vonnegut.) But decades later, the process still has critics who note that variables abound and that it's tough to measure how much rain or snowfall is the product of a cloud seed. (The weather-modification practice also has military applications and, it should be noted, is internationally banned for use in war). But as droughts worsen, government agencies keep trying. In July, Indonesia's disaster mitigation board used cloud seeding in an attempt to save drought-stricken crops.

Today, clouds are seeded using airplanes, ground generators, or gun- or rocket-propelled canisters, but scientists are also exploring whether drones can handle the task. In 2017, the Desert Research Institute — part of Nevada's higher education system — in conjunction with Drone America notably launched an unmanned cloud-seeding drone during an hourlong autonomous fight and beyond researchers' naked line of sight.

"Reaching this milestone," said Mike Richards, president and CEO of Drone America, "allows us to now focus on higher altitude, longer distance flights; as well as the extreme challenges of flying our advanced unmanned fixed-wing aircraft in the harsh, icy weather that comes with optimal winter cloud-seeding conditions."

Desert
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 an 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 smallscale 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 a 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 programs is essential if countries are to have the skilled labor 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 programs (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 to achieve the best results, the farm system must adapt to the robot. Farmers need to adapt, in terms of both timing and mentality. For example, with row spacing or terrain leveling, 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 robot 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 robots (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 price 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 labor costs are high during harvest season (due to high manpower requirements or lack of availability of human labor), farmers find it already lucrative and increasingly profitable to use specialized agrobots that lower costs and reduce dependency on scarce human labor. 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 providers 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. Engineering solutions may be required for challenging environments and settings to adapt agrobot ICTs to the conditions of developing countries.

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 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 to 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.

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 muscle power. The 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 that 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.

Contribution to achieving 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. Sustainable Development Goals to which agricultural robotics can contribute (1,2,8,9,12,15).

- **Improvement of livelihoods.** The 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 intak**e.**
- **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 the 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 labor 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 labor 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 labor 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 the 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.

II. Conclusion

While agricultural robots are very clear indications of their potential sustainable agriculture. The challenges ahead are not only technical but also socio-economic, in particular about capacity building and the need to fully understand the principles and the technologies involved. However, given their versatility, aerobots will be able to perform tasks under conditions that are by nature very labor-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, be time and cost-effective, and carry innovation and advanced technologies to new areas.

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