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Leveraging automation and digitalization for precision agriculture: Evidence from the case studies

Background paper for
The State of Food and Agriculture 2022

FAO AGRICULTURAL DEVELOPMENT ECONOMICS TECHNICAL STUDY

24

Leveraging automation and digitalization for precision agriculture: Evidence from the case studies

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

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Preface

This study aims to raise awareness of digitalization and automation solutions as enablers of precision agriculture for large- and medium-scale producers as a contribution to *The State of Food and Agriculture 2022 – Leveraging automation in agriculture for transforming agrifood systems*. Digital and automation solutions have the potential to increase productivity and efficiency and to improve environmental sustainability and climate resilience. Nevertheless, barriers to adopting such solutions can prevent agricultural producers from realizing their benefits. Common barriers include the cost of investing in the solutions, limited digital literacy, limited information about the benefits of adoption, a lack of an enabling environment and infrastructure, among others.

The report builds on findings from 22 case studies around the world to analyse the most important barriers and drivers to adopting digital and automation solutions – including those related to the institutional, policy and regulatory environments of a given country. Solution providers as well as farmers' associations that support agricultural producers were interviewed for the report. Each case study focuses on one or more agricultural production system; these range from crops, to livestock, aquaculture and agroforestry.

Although the case studies presented here cannot provide an exhaustive representation of all available situations, by choosing examples across a broad range of agricultural production systems, the study provides a landscape analysis of digital and automation solutions for precision agriculture. Based on this analysis, the study offers guidance to providers, users and policymakers to accelerate the uptake of digitalization and automation for more inclusive, sustainable and resilient agrifood systems.

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Many thanks also to all our interviewees, whose information was essential for this study.

Abbreviations and acronyms

AI	artificial intelligence
B2B	business-to-business
B2C	business-to-customer
B2G	business-to-government
CAP	Common Agricultural Policy
CEO	Chief Executive Officer
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CSA	climate-smart agriculture
CTF	controlled traffic farming
D4Ag	digitalization for agriculture
FaST	Farm Sustainability Tool for Nutrients
FaaS	farming-as-a-service
FAO	Food and Agricultural Organization of the United Nations
FMIS	farm management information system
GNSS	global navigation satellite system
GPS	global positioning system
GRoboMac	Green Robot Machinery
HCR	Harvest CROO Robotics
ICT	information and communications technology
IoT	internet of things
IT	information technology
ML	machine learning
MV	machine vision
NGO	non-governmental organization
PA	precision agriculture
PaaS	plants-as-a-service
SaaS	software-as-a-service
SDGs	Sustainable Development Goals
UAS	unmanned aerial system
UAVs	unmanned aerial vehicles
USSD	unstructured supplementary service data
VRT	variable rate technologies
ZLTO	Zuidelijke Land en Tuinbouw Organizatie

Executive summary

Digital and automation solutions in agriculture have the potential to improve resource-use efficiency, productivity, quality, profitability and the sustainability of agricultural production. In this study, we present a number of different approaches to enabling precision agriculture, including both digital devices that are *embodied* in agricultural machinery and equipment (such as precision agriculture tools), as well as *disembodied* devices (such as smartphones or tablets) or software tools, such as advisory applications, farm management software and online platforms. Hiring machinery and sharing services through digital platforms and mobile phone services are successful examples of digital technologies that are widely employed worldwide. More recently, fully automated solutions, such as harvesting robots, have started to be used by agricultural producers; however, adoption has been mostly confined to large-scale producers in high-income countries.

A key objective of this study is to analyse the most important drivers and barriers to the adoption of digital and automation solutions, with a focus on large- and medium-scale producers, across crop, livestock, aquaculture and agroforestry production systems. Building on the findings from 22 case studies, the report relies on in-depth interviews with both solution providers (i.e. enterprises, start-ups, non-governmental organizations (NGOs) and research organizations) and farmers' associations and cooperatives to investigate the barriers and drivers to adoption – including institutional, policy and regulatory barriers. The aim is to suggest policies, investments, regulatory frameworks, research and innovation that can accelerate the uptake of digital and automation solutions for precision agriculture.

Our analysis revealed that national data policies – including data protection and privacy regulations – are key enablers of adoption, as are investing in national data infrastructures, connectivity (e.g. accurate weather forecasts, land demarcation, crop calendars and broadband internet connectivity) and electricity in rural areas. This finding applies across the entire spectrum of solutions but is especially valid for disembodied solutions integrated with machinery, sensors and drones, which are crucial to scaling adoption given its potential outreach.

Further research and information on the benefits of digital and automation solutions – economic, environmental and social – are needed to incentivize agricultural producers to invest in them. At the same time, investing in human capacity development, particularly digital literacy, will be critical. Targeting young people through government policies and investments to attract them to agriculture, build their competences and promote entrepreneurship could make a tremendous contribution to precision agriculture. Finally, to ensure that the agricultural automation process is inclusive, solutions must be adapted across agricultural production systems, regions and farm types. For example, some current milking robots could be adapted to smaller-scale indoor farms and pasture-based free cow movement installations, with potential benefits across different regions. Custom hiring centres can provide mechanization services to farmers that would otherwise not have the opportunity to make use of these solutions.

Partnerships and networks for exchanging information and promoting collaboration and matchmaking among stakeholders will be key to promoting the adoption of precision agriculture solutions. Awareness raising and communication are also important as consumers can be sceptical about precision agriculture and consider it less environmentally sustainable than other options.

In summary, although our study does not exhaust the range of technologies available for precision agriculture, by choosing a variety of solutions for a broad range of agricultural production systems, we have been able to provide a landscape analysis of digital and automation solutions and to offer to solution providers, users and policymakers that might accelerate their uptake for more inclusive, sustainable and resilient agrifood systems.

1 Introduction

1.1 Objectives

This paper aims to inform the Food and Agriculture Organization (FAO)'s *The State of Food and Agriculture 2022* report concerning state-of-the-art of digitalization and automation solutions for large- and mid-scale producers as enablers of precision agriculture. Recognizing that the most important actors in adopting precision agriculture solutions are farmers, a key aim of the paper is to analyse drivers and barriers to the adoption and use of these solutions. We also investigate their foreseeable trends in the context of the three dimensions of economic, environmental and social sustainability.

The document complements the work of Mariette McCampbell, whose paper focuses on automation and digitalization in low- and middle-income countries, considering small-scale producers and, mostly, low- to medium-advanced technologies (McCampbell, 2022). When precision agriculture solutions have obvious implications for small-scale producers, we will take them into account in this paper as well.

From a geographic point of view, the paper covers all world regions, including high-income countries, middle-income countries, as well as low-income countries, to the extent that the identified solutions are developed there and offered to farmers in those countries or elsewhere. The paper covers crops, livestock, aquaculture and agroforestry.

The two papers share a common conceptual framework as well as a few case studies based on interviews with key informants (McCampbell, 2022).

1.2 Problem statement

The paper aims to analyse drivers and barriers to the adoption of precision agriculture solutions globally. We regard automation and digitalization as enablers of precision agriculture, which promises productivity and efficiency gains, environmental sustainability and climate resilience. We also consider social sustainability to encompass considerations of its implications and trades-off in terms of labour and inclusion.

Below, we define the three concepts of automation, digitalization and precision agriculture to arrive at a common terminology and understanding:

Automation

Automation is the substitution of physical activities and human decision-making with machinery and equipment in the performance of agricultural operations, reducing or eliminating direct human intervention and improving precision in agricultural production systems. Automated technologies are technological systems or machines in which increased levels of artificial intelligence are added to an existing machine, or a new intelligent machine is developed to replace an existing application, and in which some (i.e. partly automated, such as drones, tractors with built in sensors, smartphone applications) or all (i.e. fully automated, such as automatic crop sorting and packaging and geo-intelligence services using artificial intelligence [AI]) elements are able to work without human intervention. More progressive forms of automation involve the entire production process and require re-evaluation of existing processes and often more significant changes than would simple mechanization (McCampbell, 2022).

Digitalization

Digitization in agriculture refers to the use of different sorts of data generated, among others, by sensors, machines, drones and satellites to monitor animals, soil, water, plants and humans to support agricultural tasks. It encompasses digital devices or tools that are *embodied* in agricultural machinery and equipment (such as precision agriculture tools) as well as *disembodied* devices (such as smartphones or tablets) or software tools, such as advisory applications, farm management software and online platforms.

Digitalization for agriculture (D4Ag) is the use of digital technologies, digital solutions and data to transform business models and practices across the agricultural value chain and address bottlenecks in, *inter alia*, productivity, postharvest handling, market access, finance and supply chain management (Tsan *et al.*, 2019). In this study, we will tend to use the term digitalization, which embeds digitization, to indicate the underlying transformation processes.

Precision agriculture

As defined by the International Society of Precision Agriculture (2022):

> Precision agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production (ISPA, 2022).

Precision agriculture (PA) encompasses the same principles for farming, livestock raising, aquaculture and agroforestry.

As climate change, unsustainable resource use and growing food demand in an increasingly urbanized world intensify, it becomes more urgent to put new technological solutions in place to enhance productivity across all agricultural sectors. PA has long been expected to deliver this promise by contributing to more efficient use of inputs through a good analysis of spatial and temporal variation, coordination of soil and crop needs and interventions that lead to less damage to the environment. Farmer's benefits arise mainly from increased yields, input savings and/or increased profitability of production, but also include improved working conditions, better animal welfare and the potential to improve environmental management. PA therefore contributes to the general objective of sustainable agricultural production.

Automation and digitalization, supported by technologies like data and information management and analytics, AI, machine learning, deep learning, sensors and data fusion, are key enablers of precision agriculture. Therefore, we refer to precision agriculture as an overarching concept, which encompasses elements of both automation and digitalization.

Being PA a management strategy, it is difficult to measure its adoption and impact. PA is essentially a suite of methods and approaches, a toolkit from which farmers can pick and choose (Lowenberg-DeBoer, 2022). As stated in another background paper of *The State of Food and Agriculture 2022*, the challenge of determining what counts as a precision agriculture technology has hampered efforts to collect data on adoption, let alone on scaling (Rose, 2022).

Therefore, in this paper we will use solutions and underlying technologies as proxies for precision agriculture.

1.3 Structure of the paper

After this general introduction to the topic, in Section 2 we present the conceptual framework used for this study, including an explanation of key elements used in the paper: categories of solutions and technologies, farm types, and case studies with an analysis of their drivers and barriers to adoption, adoption trends and expected impacts. Section 3 explains the research materials and methods in more detail, including the case study design. Section 4 presents the research findings, which are discussed in Section 5. Section 6 discusses the future of agricultural automation based on these findings. Finally, in Section 7 we provide some conclusions and recommendations for policy and practice.

2 Conceptual and methodological frameworks

KEY MESSAGES

- Selected case studies cover a wide range of solutions (e.g. sensors, drones) across agricultural production systems (crops, livestock, aquaculture and agroforestry) in medium- or large-scale farms.
- The study analyses the impact of digital and automation solutions on productivity, efficiency, profitability, resilience, sustainability, inclusiveness and employment in agricultural production.
- Some solutions are still in the prototype stages while for others, a limited enabling rural infrastructure (e.g. connectivity and electricity) hinders their dissemination, especially in low- and middle-income countries.
- Common barriers to adoption include limited knowledge and digital literacy, high investment costs and inadequate information and communications technology (ICT) infrastructure.

2.1 Conceptual framework

The conceptual framework supports the analysis used for this study as well as the background paper of *The State of Food and Agriculture 2022* by McCampbell (2022).

Figure 1 presents the conceptual framework. The box on the left-hand side of the figure indicates the types of production examined in the study and the size of the producers. As we will elaborate further elaborate, farm types are identified based on a combination of production orientation and economic scale.

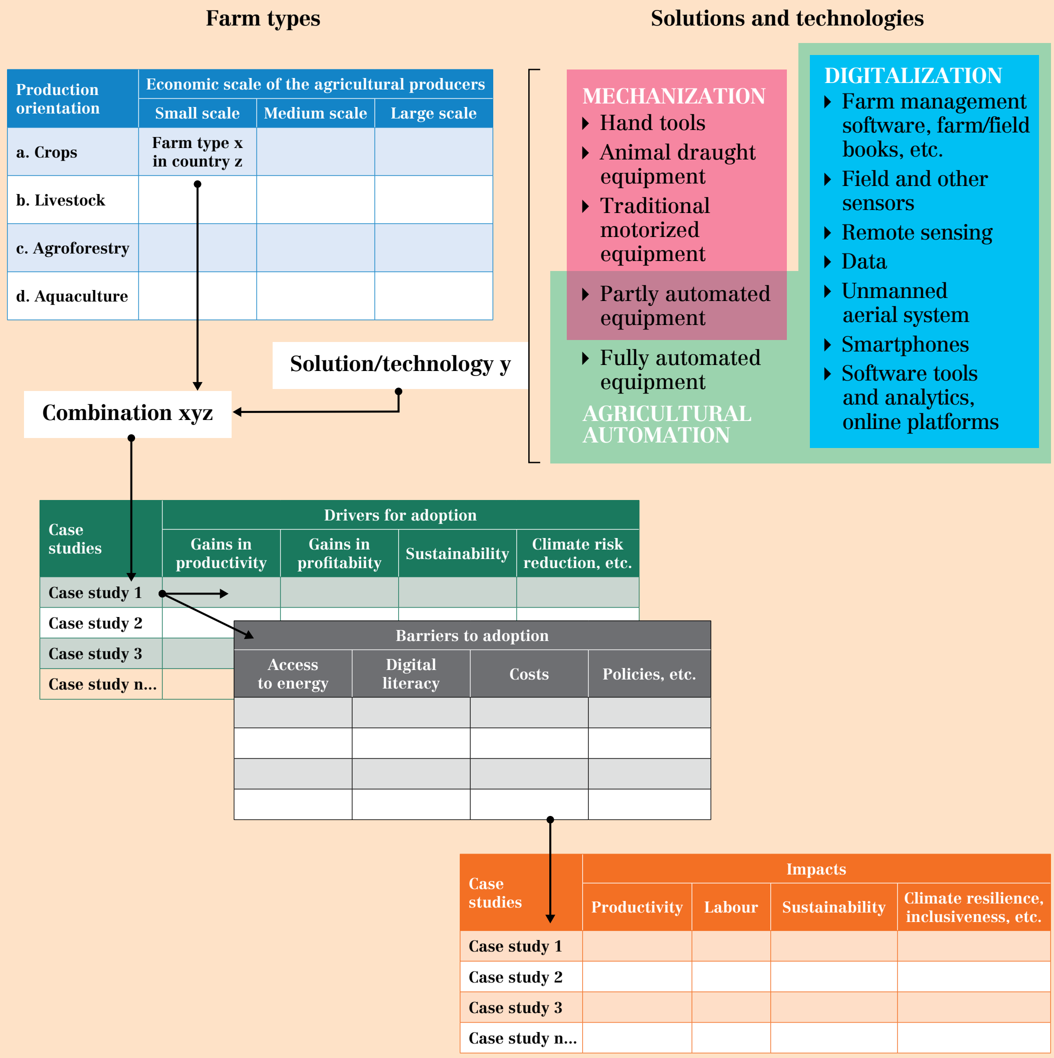
The right-hand side of the figure presents the main categories of mechanization, digitalization and automation solutions, and the underlying technologies (e.g. partially and fully automated equipment, sensors, software tools and analytics, unmanned aerial systems [UAS], etc.). Precision agriculture (PA), the focus of this paper, is a management strategy that makes use of the most appropriate solutions and technologies. The combination of both left- and right-hand side boxes makes up each individual case study, which are then analysed more in-depth to understand the barriers and drivers to adoption, as well as the impacts of the solutions provided by each case study (bottom boxes).

The study identified a spectrum of solutions to enable precision agriculture, ranging from disembodied solutions to embodied approaches,[1] with progressively larger levels of digitalization and automation, and consequently, control of the environmental as well as

1 The terms "disembodied" and "embodied" refer to the functional interaction of digital solutions with agricultural machinery and equipment, including UAS and robots.

animal variables that influence agricultural production. All can contribute to precision agriculture, although in different ways, from observing, to measuring and finally, responding (Blasch *et al.*, 2022; Valle and Kienzle, 2020).

FIGURE 1 Conceptual framework



Source: Authors' elaboration.

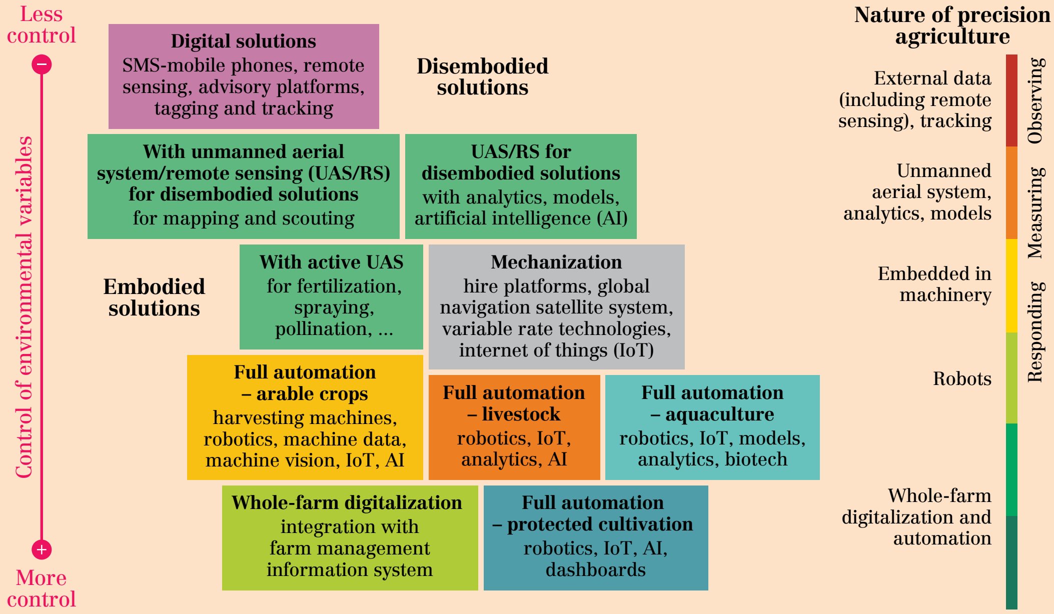
Drivers and any barriers to adoption might include gains in productivity, efficiency, profitability, contribution to climate risk reduction, human capital, digital literacy, costs (purchase price and operational costs of the technologies), availability of ICT infrastructure and energy, capacity for risk-taking, attitudes to adoption due to culture and tradition, etc.

The case studies representing each solution were then evaluated in respect to their impacts across the three dimensions of economic, environmental and social sustainability.

2.2 Spectrum of solutions and technologies

Figure 2 presents the spectrum of solutions and examples of underlying technologies that contribute to a strategy of precision agriculture. One or more specific technologies usually contribute to a given solution.

FIGURE 2 Spectrum of precision agriculture-enabling solutions



Source: Authors' elaboration.

Disembodied solutions without UAS include mostly digital services for agricultural monitoring and advisory but also offer other (bundled) services, such as weather forecasts, market prices and linkages, input procurement, credit scoring, etc. The main delivery mechanism is through SMS, mobile phones and web-based platforms. In some cases, the services may use remote sensing information, and some may include mobile tagging for production tracking. They provide a first level of precision agriculture mostly based on external and limited *in situ* data as well as expert judgement.

Disembodied solutions can also include the **use of UAS for data collection and decision support** (e.g. to map assets and monitor crop status, including pest scouting).

These disembodied solutions can be **further combined with data analytics** (e.g. from remote sensing and internet of things (IoT)-enabled devices for data collection), **machine vision (MV)**, and **dedicated models** (increasingly based on AI, particularly machine learning [ML]). Applications include yield monitoring and prediction, precision irrigation and fertilization, and detection of pests and diseases. Another possible application entails the use of geotagged images, which can be captured through a smart phone and automatically processed with AI for crop identification, status detection, quality grading, etc.

At this level, precision agriculture benefits from additional localized data from UAS as well as data models and intelligence, with applications ranging from crop and forage status monitoring to yield forecasting, pest and disease scouting (and potentially also prediction), precision irrigation and fertilization, planning and management.

When **digital tools and devices** (sensors, actuators) are **combined with machinery**, we refer to **embodied solutions**. This could involve in hiring machinery and sharing services, which is usually managed through a digital platform and mobile phone services. Such tools may include global navigation satellite systems (GNSS) and IoT-enabled devices. GNSS is used for guidance, controlled traffic farming (CTF), advanced machine control (e.g. field levelling), and precise geographic positioning of field-level data. In this context, solutions may further evolve towards the use of variable rate technologies (VRT) for precise pesticide application, weed control, fertilization, sowing, etc. VRT is combined with precision mapping services (also called application maps) and IoT-enabled sensors providing relevant field-level information (e.g. soil properties and moisture levels, yields, etc.). In perspective, there is also potential for exchanging machine data with farm management information system (FMIS) and other public information systems such as the European Union Integrated Administration and Control System (IACS) for payments in agriculture.

If UAS are used in an active mode, i.e. **to perform farming operations**, such as fertilization, spraying and pollination, we also refer to them as **embodied solutions**. When UAS are used for direct input applications and are programmed to distribute agrochemicals according to previously identified patterns (for example, based on soil properties or established geolocated nitrogen needs of crop or weed infestations), they can be seen as a variant of VRT.

Fully automated (autonomous) solutions can be implemented by robots for open field crop production. Harvesting robots are often combined with machine vision technologies. We also consider precision livestock farming solutions. In the dairy sector, the starting point was milking robots and animal tagging, then sensors were used to monitor animal health, fertility and well-being. This has progressively evolved to include manure cleaning and feeding robots as well as automation solutions for barn management, including the control of gas emissions. There are also feedlot/feed yard fully automated solutions for beef production. The essence of this level of PA is, in origin, to reduce undesired variability introduced by human error and to further increase environmental control.

Whole farm digitalization solutions combine data from remote sensing, UAS and proximal sensing, integrated with other farm data (e.g. farmer's calendar and field books, administrative data) and models, and interoperable with FMIS. These solutions, usually managed through dedicated platforms and dashboards, aim to respond to several farm management needs. The solution can be closely connected to mechanization and precision irrigation through IoT enabled devices. Such whole farm solutions are currently intended mostly for open field agriculture, although they are expanding to protected cultivation.

Automated solutions for **protected cultivation** combine sensors for potentially maximizing environment and plant monitoring and control with robotics for the automation of many processes (e.g. vertical farming). These are usually combined with "whole management systems", which aim to improve agricultural management through several dedicated databases, tools, models and dashboards.

Automated solutions can also be applied to **aquaculture**. These are like the automated protected cultivation solutions, due to the high control of environmental variables. To this, biotechnologies, such as microbial methods of biocontrol, can be added.

2.3 Definition of farm types

We searched for simple yet solid definition of the types of farms used in the research, opting to combine production orientation and economic scale:

- Production orientation
  - We consider the following types of production: crops, livestock,[2] aquaculture and agroforestry.
  - Fisheries and forestry are not included in this study, although a few case studies deal with these production orientations.

[2] We were able to cover cattle raising (both dairy and beef production) but no other animal species.

- Economic scale
  - We classify farmers as small- (market-oriented), medium- and large-scale. Small-scale subsistence producers are excluded from the analysis, while small-scale, market-oriented farmers are the focus of the paper by McCampbell (2022).
  - The size of the farm enterprise (size of the holding, number of palm trees, number of livestock heads, etc.) is used as a proxy for economic scale.

The criteria for classifying farm types are, as is to be expected, difficult to generalize. As became clear from the interviews (see Annex 3), these criteria differ significantly by country and production orientation. For example, crop-based farm types with holdings below 2 hectares (ha) in Nepal are classified as small-scale, while 200 ha, according to our sources, represents the minimum threshold for small-scale citrus groves in the United States of America. A more specific definition of production orientation (e.g. arable farming, horticulture, fruit tree farming) would help, but it does not solve the problem of a contextualization at the country level and sometimes, within countries.

Automation upstream in the value chain, in proximity to primary production, and especially on-farm processing activities, is considered as much as possible. Automation within the other stages of the value chain and agrifood systems is outside the scope of this paper.

2.4 Case studies

In this paper, case studies are used to describe the application of a solution in a specific country and with reference to one (or more) farm types. The entry point for each case study is the solution and an interviewee serves as the key informant on the case. The informant can differ; it is usually the provider of the solution, whether digital or technical, such as a commercial entity, a research organization or an NGO. We have also included farmer organizations and farmer-owned companies/cooperatives. In some cases, a solution provider offers multiple self-standing or bundled solutions, although we have generally focused on the most important one. There are cases in which a solution is offered, with some variations, to different farm types (e.g. an advisory service is offered with or without the contribution of remote sensing data, which may not be a necessity for small-scale producers). Whatever the entry point, the key informant should be able to reflect the point of view of their organization as well as of other stakeholders and, most important, of the farmers.

Cases were selected based four criteria. The entities: 1) operate in one or more countries in all world regions and strike a balance between them; 2) represent a novel and scalable (or already scaled) agricultural solution involving digitalization and/or automation and mechanization, and with a general orientation towards precision agriculture; 3) target medium- and large-scale farmers as users of the solution; 4) cover one or more of the following agricultural production orientations: crop production, livestock, aquaculture and agroforestry. The case studies represent only a limited number of solutions, and we recognize that they cannot include an exhaustive representation of all the diversity the criteria provide. However, by choosing varying solutions and technologies across a broad range of agricultural production systems, the study aims to provide a landscape analysis of digitalization and automation technologies applied with the goal of precision agriculture.

2.5 Drivers and barriers to adoption

Regarding drivers of adoption, we initially considered the following:

- expected gains in productivity, efficiency and profitability;
- decreasing availability of (seasonal) manual labour force;
- desire to reduce climate risks;
- need to meet high quality standards/traceability of agricultural products;
- reduction of costs for financial service providers, for example, to assess digitally the creditworthiness of clients, which, in turn, makes easier access to credit for farmers;
- increased value addition to products and services (bypassing the middleman).

As for barriers, we refer to Santos Valle and Kienzle (2020), who highlight the following:

- limited access to evidence of benefits resulting from adoption;
- purchase price and operating costs of the technology/service;
- concern about the availability and costs of technical maintenance;
- human capital level: limited knowledge, in terms of literacy and, specifically, digital literacy;
- limited access to electricity and energy on farm;
- inadequate availability of ICT infrastructure (e.g. internet connection);
- reluctance to adapt farming system;
- limited capacity to take risks;
- concerns about ownership, custodianship and management of digital (personal) data;
- resistance to adoption due to culture and tradition.

We also considered adoption drivers and barriers related to the institutional/policy and regulatory environments, which are relevant to the selected case studies (e.g. mechanization, data and ICT policies, including the development of digital literacy, as well as regulations on imports, the environment, research and innovation) affecting both micro and macro levels. Most important barriers will depend on the findings of the case-studies, which focus on precision agriculture for large- and mid-scale producers.

2.6 Impacts

We also considered the impact and trades-off of a particular solution, with reference to specific Sustainable Development Goals (SDGs).[3] For example, from a perspective of agricultural transformation, we consider the impacts below with their respective trade-offs in mind:

- productivity
- profitability
- sustainability
- labour
- employment
- inclusiveness/social equality
- climate resilience and adaptation.

[3] Namely SDGs 1 (No Poverty), 2 (Zero Hunger), 9 (Industry, Innovation and Infrastructure), and 10 (Reduced Inequalities).

As noted in McCampbell (2022), we were not able to obtain evidence of impacts in a systematic way. In fact, with some exceptions, our key informants did not have the knowledge, time or interest to invest financial and human resources in impact assessment. We have therefore limited ourselves to assessing – based on our interviews and the documentation in our possession – how various solutions can affect economic, environmental and social sustainability.

2.7 Taking stock of the status of automation solutions

Several trends can be observed from analysing the case studies. The concept of "readiness to scale" (with reference to the solutions) is portrayed in Figure 3.

FIGURE 3 The stages of readiness to scale

Source: Authors' elaboration.

The concept derives from the case studies, where the range of solutions vary from functioning prototypes to mature solutions with an existing client base. The approach differs from the commonly-used technology readiness level, which uniquely focuses on the maturity of the technological aspect, while readiness to scale aims to demonstrate technological and market readiness as well as adoption trends.[4] The four stages on the readiness scale are:

- **Prototype:** This describes a solution whose concept has been tested and demonstrated in limited trial conditions.
- **Close to market:** This describes a solution whose prototype phase is complete, and has been shown to function in real production settings. At this stage, one or more business models are being investigated by the service providers for acquisition of clients (farmers in the case of business-to-consumer [B2C] models, or others, in the case of business-to-business [B2B] or business-to-government [B2G] models).
- **Scaling:** The solution has been adopted by several end users/clients, and at least one business models has demonstrated success.
- **Mature:** The products and services resulting from the solution have a dedicated client base, one or more business models have been successful, and there is further demand for the solution (e.g. in other geographies).

We assume this scale can be used as a proxy for adoption trends by farmers.

[4] For more on technology readiness, see Herrero *et al.* (2020).

3 Materials and methods

KEY MESSAGES

- A total of 22 interviews – one for each case study – were conducted, covering all world regions. Interviewees were usually the representative of the enterprise/organization providing the solution.
- Interviews covered topics related to the solution itself, as well as the customer base, business model and prospects for scaling.
- Questions on the most important drivers and barriers to adoption, from the perspectives of both solution providers and users, were also included.

Each case study involved an interview. Interviews used a semi-structured approach, with separate interview guides for service providers (i.e. enterprises, start-ups, NGOs and research organizations) and farmers' associations and cooperatives (see Annex 3). Interviews were conducted in MS Teams and were audio and video recorded as well as being automatically transcribed by the MS Team software. Transcripts were then manually analysed and coded in MS Word. The interviews were used as an input to the case study narratives (see Annex 2). They included questions on the organization providing the solution, the customer base and business model, the value proposition and prospects for scaling. Additional questions explored the adoption drivers and barriers and the sustainability perspective according to the three cited dimensions, both from the viewpoint of the provider and of the farmer.

The informant was, in most cases, a representative of the provider of the solution. The solution is usually developed, implemented or promoted by a commercial entity, a research organization or an NGO. We also found cases where solutions came from farmers' associations or cooperatives). In total, we worked on 22 cases (five are shared with McCampbell (2022).[5]

One of the case studies comes from Northern America, three from Latin America and the Caribbean and five from Europe. Three studies are from Northern Africa and Western Asia, four from sub-Saharan Africa, one from Central Asia, three from Southern Asia, two from Eastern and South-eastern Asia and one from Oceania. See Table 1 for the locations of the various studies.[6]

5 The common cases are Garbal, TROTRO Tractor, Igara Tea, Seed Innovations and Tun Yat.

6 These are the countries where the organization was established or where they mainly operate. It is often the case that an organization will offer its services in other countries as well.

TABLE 1 Location of case studies

Case study	Originated/operating in
Abaco	Europe (**Italy**), Central Asia, South America
Aerobotics	18 countries, including Australia, Chile, Peru, Portugal, **South Africa**, Spain, United States of America
Atarraya	**Mexico**, United States of America
Cattler	**Argentina**, United States of America
CropIn	Global presence (primarily **India** and sub-Saharan Africa)
Egistic	**Kazakhstan**
Food Autonomy	**Hungary**
Garbal	**Mali**, **Burkina Faso**
GRoboMac	**India**
Harvest CROO Robotics	**United States of America**
Hortikey	**Netherlands**
Igara Tea	**Uganda**
IoCrops	**Republic of Korea**
Lely	Australia, Europe (**Netherlands**), Northern America
Seed Innovations	**Nepal**
SeeTree	Brazil, Chile, Greece, Mexico, Portugal, South Africa, Spain, United States of America (data analysis, research and development in **Israel**)
SOWIT	Ethiopia, **Morocco**, Senegal, Tunisia
TraSeable Solutions	Cook Islands, **Fiji**, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu
TROTRO Tractor	**Ghana**, Togo, Benin, Nigeria, Zimbabwe, Zambia
Tun Yat	**Myanmar**
UrbanaGrow	**Chile**
ZLTO	**Netherlands**

Notes: Countries in bold are where the solution was initially developed; the remaining countries listed represent those where the service is currently present. Some of these cases are also covered in McCampbell (2022).

Source: Authors' elaboration.

Nineteen men and three women served as key informants: a clear unbalance in terms of gender, which is worth noting. The interviews were complemented with data from secondary sources.

The conceptual framework was applied to the case studies to develop a cross-case analysis. The analysis focused on several elements, presented in detail in Section 5: the solution and technology spectrum; production orientation; farm typologies; the business case, sustainability perspective, readiness to scale; the main adoption drivers and barriers; and the three pillars of economic, environmental and social sustainability. Details on the case studies can be found in Annex 4. The full interviews of the key informants are available upon request.

4 Exploratory analysis: mapping the case studies to the conceptual framework

KEY MESSAGES

- The case studies cover digital and automation technologies ranging from disembodied solutions, to machinery hiring services, devices (e.g. sensors) that are combined with machinery, fully automated solutions, such as automated feeding and protected cultivation (e.g. vertical farming).
- There is substantially less evidence on agroforestry technologies than for other production systems, especially livestock and crops. Most agroforestry technologies available are UAS-based.
- In some cases, farms of different sizes employ the same solution, usually with customized versions or modules. However, in most cases, the main targets are large- and medium-scale farmers.

In this section, we introduce the results of the interviews with reference to the elements presented in the conceptual framework. This information is also summarized in Table A1 (see Annex 2).

4.1 Solution and technology spectrum

Case studies involving **disembodied solutions without UAS** are drawn from TraSeable Solutions in Fiji and other countries in the Pacific and GARBAL in West Africa. TraSeable Solutions has developed digital services for agricultural advisory services and mobile tagging for production tracking, including blockchain technologies (see Glossary in Annex 1). GARBAL offers advisory services on crop production, herd movements and the status of pastures for pastoralists using remote sensing data. These are bundled with other services such as market price information. The main delivery mechanism is through SMS, mobile phones and web-based platforms.

Disembodied solutions, including the use of UAS for data collection and decision support are described in the case of Igara Tea in Uganda.

These solutions, further combined with **data analytics**, **machine vision** and **dedicated models** (also based on ML) are applied by SOWIT (Ethiopia, Morocco, Tunisia) and SeeTree (Israel, Mexico, United States of America, etc.), Aerobotics (South Africa, Spain, United States of America, etc.). SOWIT and Seed Innovations in Nepal also make use of geotagged images to identify and monitor crops.

Examples of **machinery hiring** and **sharing services** deployed through digital platforms and mobile phone services in lower-middle-income countries can be found at Tun Yat in Myanmar and TROTRO Tractor in Ghana, Togo and other African countries. **Devices** (sensors, actuators) are also increasingly **combined with machinery**, including GNSS and, to a limited extent, IoT-enabled devices. As described by Zuidelijke Land en Tuinbouw Organizatie (ZLTO) in the Netherlands, the new farm machinery employed by many large farms in high- and middle-income countries usually includes GNSS, although the application of VRT is happening at a slower pace.[7]

Although our case studies revealed only pilot applications of **UAS used in an active mode** (Seed Innovations), we are aware of successful applications of this type, including by AcquaMeyer Drone Tech in Ghana, Alley Capital Group in Zimbabwe, CLIN SARLU in Mali and Togo and Development Partners in Benin.

Fully automated (autonomous) solutions for open field crop production have been taken up by Green Robot Machinery (GroboMac) in India and Harvest Crop Robotics (United States of America). In both cases, harvesting robots were used together with machine vision technologies, mostly to harvest fruits and vegetables. In the dairy sector, Lely, which operates in Australia, the Netherlands, Western Europe and Northern America, is utilizing precision livestock farming solutions. For beef production, we have feedlot/feed yard fully automated solutions developed by Cattler (in Argentina and the United States of America).

Abaco in Europe, Central Asia and South America, Egistic in Kazakhstan and CropIn in India developed **whole-farm digitalization solutions** that integrate several types of georeferenced data with farm data and models. In the case of Egistic, the solution is linked to machinery through IoT-enabled devices.

For automation in **protected cultivation**, we have the cases of Hortikey in the Netherlands, ioCrops in the Republic of Korea, UrbanaGrow in Chile, and Food Autonomy in Hungary. UrbanaGrow and Food Autonomy develop vertical farming solutions.

The case of Atarraya (Mexico and the United States of America) is similar to vertical farming but applied to **aquaculture**. Biocontrol based on microbial methods are added, i.e. the control of microbial communities that reduce nitrate build-up, prevent diseases and save water in shrimp production.

4.2 Production orientation

We examined the use of automation and digitalization solutions in different types of production systems. There is little evidence of the use of such solutions in the **agroforestry** domain: these are mainly confined to the use of UAS for mapping purposes, coupled with digital management tools and analytics for agronomic advice (Seed Innovations in Nepal).

For **crops**, automation and digitalization solutions are mostly dedicated to arable farming. These include technologies ranging from disembodied solutions without the use of UAS (e.g. TraSeable Solutions) to UAS-based solutions (quite a few, including Igara Tea), adding mechanization (Tun Yat, TROTRO Tractor) and autonomous operations through robotics (GroboMac). Companies employing solutions for fruit trees and nuts, such as SOWIT, SeeTree and Aerobotics, mostly used remote sensing and UAS-based approaches with sensors and image processing, supported by analytics and dedicated models often based on AI/ML. In the case of horticulture, most solutions were fully automated (Harvest CROO Robotics) and aimed at protected cultivation like Hortikey, ioCrops, UrbanaGrow and Food Autonomy.

[7] Based on a recent survey conducted by ZLTO, only 5 percent of farmers in the Netherlands apply VRT (see Annex 2). In his background paper for *The State of Food and Agriculture 2022*, Lowenberg-DeBoer indicates that less than 20 percent of agricultural producers adopt VRT fertilizer. Rose (2022) cites a series of studies on the adoption of automated crop technologies globally, concluding that GNSS guidance is the only one that is widespread (see also Maloku, 2020).

With regard to **livestock**, we have separated dairy and beef production solutions. Dairy solutions are well established; they include milking robot technologies, manure sweeping and feeding automation as well as integrating animal health sensors and robotics for barn management and emission control, as implemented by Lely. Beef production, as in the case of Cattler, is also promoting whole feed yard management solutions that integrate feedlot management, feeding and health monitoring, including machine vision as well as virtual fences and remote sensing monitoring for pasture-based cattle raising. In the context of pastoralists in lower-middle-income countries, solutions are emerging (GARBAL) for providing advisory services on rangelands and water conditions via mobile phones, mostly based on remote sensing.

For **aquaculture**, examples range from disembodied solutions (TraSeable Solutions) to fully controlled solutions including automation, IoT and data analytics, as well as biotechnologies (Atarraya).

Finally, in some cases we found that some solutions, especially those utilizing full farm digitalization in the context of high- and middle-income countries (Abaco, ZLTO, both in Europe), address both crop and livestock production. This applies also to GARBAL which has developed solutions for advisory and monitoring for both pastoralists and crop producers in West Africa.

4.3 Farm types

Several solution providers work with multiple farm types, usually offering customized versions of the same solution. In most cases (15), the main targets are **large- and medium-scale farmers**. In seven cases the (usually fully digital) solution is said to address all types of farmers (Egistic, CropIn, Abaco). Two case studies (Tun Yat and Igara Tea), address small- and medium-scale farmers only.

As mentioned previously, defining the different farm types is heavily dependent on the country and the production orientation and value chain. What qualifies as small-scale production for crop-oriented farming systems in Nepal (< 2 ha) is not applicable in Italy (< 50 ha), let alone in Kazakhstan (< 5 000 ha). Farm type classification criteria, therefore, cannot be generalized.

A digital solution that is applied to a range of farm types usually entails a different set of input data and functionalities. For example, Seed Innovations offers basic advisory services to small-scale farmers, excluding the use of remote sensing data since the spatial resolution would not be sufficient to capture the size of their holdings. Abaco offers an "off-the-shelf" version of their solution for small farms under 50 hectares with limited functionalities. Different versions of a solution also come with different subscription models (freemium). Usually, a product is initially provided to small- to medium-scale farmers for free, and then a progressively more expensive subscription fee is applied, depending on the product functionalities and the size of the enterprise. This was the business model for Abaco, Seed Innovations, SOWIT and Cattler. When dealing with full automation, we often find that the proposed solutions depended on the scale of the enterprise, as was the case for aquaculture (Atarraya) and protected cultivation (UrbanaGrow).

5 Shedding light on business models for investing in agricultural digitalization and automation

KEY MESSAGES

- Given the novelty of some technologies, only seven out of the 22 cases are considered profitable and financially sustainable to date. Most of these serve large-scale producers in high-income countries.
- Most solutions are still scaling or getting close to the market. Only five are considered mature and these relate to livestock or whole farm digitalization.
- Most reported drivers of adoption include the operational and economic viability of technologies, their ease of use, the need to fill labour gaps, and the environmental benefits some technologies bring.
- Important barriers include a lack of capacity and knowledge (e.g. digital illiteracy), of an enabling environment and of key infrastructure (e.g. electricity).
- Policies, regulations and investments were seen as both drivers and barriers to adoption, depending on the context.

This section presents business models and an assessment of the overall financial sustainability of the solutions from the perspective of the providers. A summary is provided in Table A2 (see Annex 2). We also report the main findings in terms of adoption drivers and barriers, readiness to scale and impacts, according to three pillars of sustainability (economic, environmental and social, with an additional focus on social inclusiveness). When considering economic sustainability, we will also include the perspective of the farmer as users of the solutions. This information is summarized in Table A3 (see Annex 2).

5.1 Business models, sustainability, readiness to scale of the solution

We present the **perspective of the solution provider** on the business model and overall economic sustainability independently from that of agricultural producers, which will be covered later. Given that key informants for this study were service providers, their perspective is better covered than that of agricultural producers.

Table A2 (see Annex 2) provides an overview of the various business models – including revenue generation mechanisms – and the overall sustainability of the solutions as well as their readiness to scale from the providers' perspective.

The case studies include a balanced mix of start-ups (9) and consolidated enterprises (11). The majority (13) has or will have (some cases have not started commercializing their solution) **business-to-consumer** models in place, followed by **business-to-business** models (TraSeable Solutions, Igara Tea, Hortikey, Food Autonomy). In seven cases, both models are utilized (e.g. TROTRO Tractor, Tun Yat, Aerobotics, Abaco, ioCrops) and three cases also include service contracts with farmer associations and government agencies (Abaco, CropIn, TraSeable Solutions).

Most digital solution providers employ **software-as-a-service** (SaaS) as a revenue model. Providers of machinery and automated solutions sell them directly to clients (e.g. Lely, UrbanaGrow, Atarraya, Hortikey) and usually accompany them with **dedicated digital solutions** (marketed as SaaS). In some cases, the revenue model applied is **device as a service** (TROTRO Tractor, tractor-as-a-service, Hortikey, robot-as-a-service), or **machine pay-as-you-go/harvesting as a service** (Harvest CROO Robotics). **Innovative models** are in place for protected cultivation, such as the case of Food Autonomy (**farming-as-a-service** [FaaS] and **plants-as-a-service** [PaaS] models), where providers operate the farm on behalf of the client or offer dedicated production capacity. Similar arrangements apply in the Atarraya aquaculture case.

Seven of the informants indicated that their solutions have proven profitable or are financially sustainable. With one exception (Igara Tea), these solutions originated or were commercialized in either high- or upper-middle-income countries. Most solution providers serve large-scale farmers. The exceptions are Abaco, Igara Tea (which serve both medium- and small-scale farmers, keeping in mind the varying definitions of such in different contexts) and TraSeable Solutions which serves all farmers. As is to be expected all are mature or scaling solutions on the readiness scale. There is a mix of disembodied solutions (e.g. TraSeable Solutions and Igara Tea), disembodied with the use of UAS, remote sensing and modes (e.g. SOWIT), fully automated for livestock (Cattler, Lely) and whole farm digitalization solutions (Egistic, Abaco, ioCrops and Food Autonomy).

While not disclosing the economic sustainability of their solutions, several informants cited their ample outreach and ability to attract private investment (e.g. Atarraya and several UAS-based services with advanced intelligence solutions). One provider indicated that they are still transitioning from donor funding to a more commercial model (GARBAL, the solution for pastoralists, to eventually be funded by mobile operators). The remaining solution providers are not commercializing or are in the early stages of commercialization (mostly protected cultivation like UrbanaGrow, Food Autonomy and Hortikey, as well as a few UAS-based services); the financial sustainability of these providers is still to be proven.

We looked at evidence for **readiness to scale** the solutions, as defined in Section 2.7. There is a balanced mix of solutions: two are at the pilot stage (GroboMac and Seed Innovations), several are close to market (e.g. Harvest Crop Robotics, Atarraya, UrbanaGrow, Food Autonomy, Hortikey), or scaling (e.g. Cattler, TROTRO Tractor, Aerobotics, SeeTree, SOWIT, Tun Yat, CropIn, ioCrops), and five can be considered as already mature (Lely, ZLTO, Abaco, Egistic and Igara Tea).

Most solutions (14) originated (11) or are deployed (3) in high-income countries.[8] The remaining 12 are in lower-middle-income countries. The solutions at the mature stage typically relate to livestock automation and whole-farm digitalization. Solutions at the scaling stage belong to a variety of categories: disembodied with digital solutions only; with UAS and remote sensing; mechanization solutions; solutions for protected cultivation. Solutions that

8 Interestingly, several solutions were initially developed in lower-middle-income countries (Cattler in Argentina, Atarraya in Mexico and Aerobotics in South Africa) and later commercialized successfully in high-income countries, especially in the United States of America.

are close to market include different typologies: mostly automation for protected cultivation and aquaculture, as well as those based on advanced application of UAS for decision-making and active use of UAS. Solutions at the pilot stage are for automated open field and protected cultivation.

As anticipated, a comparison across farm types is difficult due to country-specific conditions and the varying definitions of production orientation. In general, the solutions at the scaling and mature stages tend to be concerned with medium-scale farms.

5.2 Drivers and barriers to adoption

Table A3 (see Annex 2) summarizes the adoption drivers and barriers perceived by our key informants. It is important to distinguish between the perspectives of solution providers and those of the users of those solutions: adoption drivers for one group could be considered barriers by others and vice-versa. However, for solutions that have not yet been commercialized, we can only investigate adoption in terms of the perspectives of providers.

This section is divided into several themes identified by the key informants. They are ordered according to the number of times they were mentioned in the interviews.

5.3 Operational, economically viable and easy to implement solutions

This theme was raised 17 times. It was usually identified as a driver for adoption in that the solution has proven to be actionable, solving concrete farming operations such as harvesting on time, milking, feed yard management, and mechanization of operations in general (Lely, Harvest CROO Robotics, Cattler, Tun Yat, SOWIT, TROTRO Tractor, GroboMac). Another positive consideration is that the solution is easy to use (ZLTO: "Farmers have little time to invest in familiarizing with such solutions"; "Farmers adopt them when sensors are already in-built in machinery").[9] This point was often mentioned with reference to medium- to large-scale farms (e.g. by SOWIT), while different drivers (mostly related to costs and skills) motivate small-scale producers. Demonstrated return on investment, reduction of farming costs and value addition in general were identified as drivers by four solution providers (Cattler, SOWIT and Egistic).[10] Solutions that bundled different services, for example, market linkages, advisory services, insurance and financial services, among others, were indicated as important drivers, although with different perspectives (TraSeable Solutions, SOWIT, Seed Innovations, GARBAL, CropIn, Abaco). For large-scale farming in high-income countries, the preference is for "one-stop-solutions" (SeeTree, SOWIT, Aerobotics), while producers in lower-middle-income countries (Innovation Seeds, TraSeable Solutions) are more interested in reducing costs and ensuring the sustainability of the business model. The costs of investing in an unclear added value was seen as a barrier to the adoption of VRT by ZLTO in the Netherlands.

5.4 Farmer's attitude, capacity and skills

This theme was cited in 13 interviews and generally seen as a barrier (in nine cases). Informants identified lack of digital literacy, lack of awareness and knowledge, scepticism, ageing, reluctance to change and lack of trust of the proposed solutions as barriers. Interestingly,

9 Global positioning system (GPS) devices for examples are already included with tractors for sale.

10 Costs (capital investment and operation costs) were considered as the top barriers to mechanization, digitalization and automation according to the online survey that supported McCampbell's paper, which particularly focused on small-scale producers in lower-middle-income countries (McCampbell, 2022). This is seldom mentioned in our report, probably because service providers would not emphasize such costs as a barrier.

these responses cut across world regions and farm types. For example, a lack of digital literacy was mentioned as a barrier by Tun Yat (Myanmar) and Seed Innovations (Nepal) but also by Abaco (Europe, Central Asia and South America) and SeeTree (with reference to the United States of America). Skepticism, lack of awareness and trust by farmers also cuts across regions, farm types and solutions. They are mentioned by TraSeable Solutions and Seed Innovations with reference to smallholders in lower-middle-income countries and for relatively simple farm advisory solutions, as well as by IoCrops in the Republic of Korea regarding protected cultivation: “Farmers in Korea are not very welcoming because high-tech solutions (and the capital they are attracting) is seen as a competition with the conventional growers.”

The number of farmers is decreasing and ageing, and this is perceived as a key barrier, for example by ZLTO, for the Netherlands. Generational change was also indicated (four times) as a driver for adoption. Young farmers are perceived as instrumental for transforming the family farming business towards digitalization and automation. For example, Atarraya and Cattler, with reference to the United States of America, as well as ioCrops in the Republic of Korea indicate that young farmers, both “Millennials” and “Generation Z”,[11] are much more open to innovation then are their parents, the “Boomers”.[12] This is especially evident when it comes to digitalization and automation. Cattler and Aerobotics also indicated that Argentinian and South African large-scale farmers are more dynamic and open to digital solutions than farmers in the United States of America, likely because they need to be more competitive on the international market. Capacity building is generally seen as a cross cutting driver for adoption.

5.5 Labour availability, costs, drudgery and safety

This theme was prioritized in 12 interviews. It was mostly mentioned as a driver in terms of the positive effect of a solution responding to lack of labour and to seasonal labour gaps. For example, Harvest CROO Robotics in the United States of America, with reference to for strawberries, noted that:

> By the early 2000s it was becoming evident to me that less and less workers were showing up at the farm gate to do work in the fields. And by the late 2000…, it was getting to critical stages where we were abandoning fields early in the season because there wasn’t enough harvest labour (interviewee, Harvest CROO Robotics).

The case studies that prioritized labour issues span many production orientations and solutions: Harvest CROO Robotics for strawberries, GroboMac for cotton, ZLTO for multiple production orientations, TraSeable Solutions for crops and IoCrops for protected farming. TROTRO Tractor in Ghana and other countries in sub-Saharan Africa expressed particular concern in relation to women farmers. Labour cost reduction was also mentioned by Harvest CROO Robotics, IGFT for tea farming and Lely in relation to milking robots. Decreased drudgery was cited as a driver by Lely and SOWIT. Labour was mostly prioritized as a driver in high- and middle-income countries (eight times) and, to a lesser extent, in lower-middle-income countries (by four respondents: Igara Tea, TROTRO Tractor, GroboMac, SOWIT). TROTRO Tractor indicated labour as an adoption driver, particularly for women. Bearing in mind the different concepts of farm scale across countries and production orientations, labour was prioritized by large-scale producers in two cases (Harvest CROO Robotics,

11 Millennials refer to people born between 1981 and 1996. Generation Z refers to people born between 1997 and 2012.

12 Baby boomer is a person born between 1946 and 1964. The baby boomer generation makes up a substantial portion of the world's current population, especially in developed nations.

GroboMac) and by medium-scale farmers in five cases (GroboMac, TROTRO Tractor, SOWIT and Lely). ZLTO addresses all farm types. Small-scale farmers are especially addressed by TraSeable Solutions and IGFT, although these also offer their solutions to medium-scale farmers and large estates.

5.6 Public policies, regulatory framework and investments

Ten case studies cited public policies, regulations and public investments outside the environmental sphere (which is covered in the next section). This theme was seen as a driver for adoption by some informants, for example IoCrops in the Republic of Korea, which indicated that the government invests in high-tech farming systems that can be used for experiments and demonstrations and provides talented people with targeted capacity building. Seed Innovations in Nepal noted that national policies on insurance favour the scaling of their solutions. Seven cases cited policy as a barrier, noting, for example, bureaucratic restrictions on drone flights (Aerobotics in South Africa) and the import of drones and IoT devices (by Igara Tea and SOWIT), and the lack of policies on data sharing and infrastructure (GARBAL for West-Africa, etc.) Several respondents indicated that there are no or insufficient public policies (e.g. CropIn operating from India) or incentives, for example on innovation (SOWIT) and public-private partnerships (Egistic in Kazakhstan). In two cases, the lack of regulations was indicated as positive since regulations would have just added to ineffective bureaucracy (Atarraya, operating in Mexico). In one case (Lely, with reference to the Netherlands), the existence of subsidies for the purchase of milking robots was perceived negatively, since the farmers often prefer to wait until they are made available through the European Union or national schemes before buying them with own funds.

5.7 Environment and climate change

Eight interviewees (all in high-income countries) confirmed that a solution meeting environmental policy and regulatory frameworks, as well as preferences from customers and retailers towards more sustainable products, was a key adoption driver. Meeting environmental reporting needs (according to SOWIT, this is becoming a “top management priority over finance”) and carbon credit market opportunities (Cattler in the United States of America) was also seen as an important driver in high-income countries, particularly in the European Union (Abaco, Hortikey, Food Autonomy) and countries that export to Europe (e.g. by SOWIT), as well as Chile (UrbanaGrow) and the United States of America. (Atarraya). UrbanaGrow observed that, “In the United States of America, supermarkets make the rules on environmental compliance.” According to Lely, environmental regulations in the European Union have “moved from nice-to-do to must-do.” For Lely, new regulations in the European Union, such as those related to free animal movement, may become a barrier to adoption.

In some cases, environmental sustainability is seen as a driver that goes beyond respecting regulations or accessing new markets or subsidy opportunities; it is a genuine aspiration of the farmers. This especially concerns the younger generation of solution providers, who want to be seen as having a positive impact on the environment (ZLTO).

In some cases, a solution is seen as suitable for environments that are not suited for open field agriculture, and could mitigate the risk of crop failure due to climate change. This was mentioned especially in the case of protected cultivation solutions (UrbanaGrow, Food Autonomy), but also in open cultivation settings in the context of advanced solutions for precision farming (e.g. SOWIT).

5.8 Infrastructure development

Infrastructure was prioritized by seven solution providers and mostly seen as a barrier. Infrastructure gaps include a lack of connectivity and electricity (GARBAL in West Africa), internet connectivity in rural areas (Egistic in Kazakhstan) and transport logistics (Atarraya in Mexico). Interestingly, the rapid mobile phone penetration was cited as a favourable driver by TraSeable solutions (in Fiji and neighbouring countries) and Tun Yat (in Myanmar).

5.9 Market orientation and consumer behaviour

Five interviewees cited consumer behaviour and market orientation as either a driver or a barrier. Organic farming is mentioned as a market segment by Abaco (in Italy). A negative consumer attitude towards protected cultivation was mentioned in three interviews. For example, ZLTO indicated that consumers do not necessarily prefer food grown from precision agriculture. Hortikey, referring to protected cultivation, noted that "indoor farming is not perceived as natural by consumers," a view that is shared by Food Autonomy, which also indicated a non-favourable policy environment in the European Union around these solutions. ZLTO observed that, despite efforts by many farmers to adopt environmentally sound practices through PA, "We don't necessarily connect with the heart of the consumer."

As seen previously, private sector compliance and reporting based on environmental standards and "zero kilometre" solutions were seen as a positive driver in a few cases, particularly by providers of protected cultivation solutions.

5.10 Local engagement, networking, ecosystem support

This theme was mentioned in four interviews and was seen equally as a driver and a barrier. GARBAL cited the need for local engagement and contextualization: "If we are scaling into a new geographical area, just as the local partners will be different, the strategy will also be different." GARBAL also emphasized the need for trust building: "Public-private-partnership model, engaging with a large mobile network operator and the Ministries of Agriculture and Livestock in both countries was key for the acceptance of the solution." Although operating in a totally different context (traditionally high-income countries and now moving to middle-income countries), Lely indicated that a strong driver of adoption lies in the local commercial networks: "We have Lely centres with advisors who can also suggest the best solutions." SeeTree noted that networking and word-of-mouth were key scaling mechanisms in the United States of America: "Entering a new market of big growers with networking among other growers has a ripple effect." For Atarraya, the enabling environment promoted by the State of Indiana is a key support for implementing and distributing innovations for agriculture.

5.11 COVID-19 pandemic

The COVID-19 pandemic was mentioned in three interviews. On the one hand, it was seen as a driving factor because people refrained from having physical contact and the value of digital solutions across sectors became more evident. For TROTRO Tractor, which operates in a number of countries in sub-Saharan Africa, the pandemic actually drove the uptake of the platform. It allowed production to continue, while minimizing manual labour and direct interaction users of the platform. TraSeable Solutions also cited the pandemic as a factor in the adoption of their solutions, since: "It has shown the value of digitalization creating a lot of interest." On the other hand, the pandemic was perceived as a barrier. SOWIT indicated that: "It has reprioritized and delayed government investments to the detriment of digitalization in agriculture."

5.12 Other drivers and barriers

Several additional drivers and barriers to adoption were identified by key informants:

- The ability of protected vertical farming to produce food with higher safety and quality standards on the spot (zero-kilometre solutions) was seen as a driver (mentioned by UrbanaGrow, Food Autonomy).
- Animal well-being is considered an adoption driver especially in Europe (Lely).
- The barn management techniques by Lely make the dairy automation solutions independent from external energy sources, since they use solar and wind energy to power the robotic products. This was seen as an important driver by Lely.
- A barrier is encountered in some countries due to the security situation (GARBAL in West Africa).
- Lack of standards, such as for machine data, was seen as barrier (ZLTO, with reference to Europe).
- The lack of coordination between donors in lower-middle-income countries was seen as barrier (by CropIn).
- Limited interest from private investors in robotic solutions, due to their long lead time,[13] when compared with digital solutions (barrier by GroboMac).

5.13 Implications for sustainability

Table A3 (see Annex 2) summarizes the views of key informants on the dimensions of economic, environmental (including climate change) and social sustainability. The third dimension considers implications in respect to labour, gender, youth, smallholder producers, minorities and other vulnerable groups.

For economic sustainability, we turn to the **perspective of the farmer** (and other final users if relevant) as reported by the key informants. Ten of the informants claimed that the farmers will definitely improve their financial sustainability – through gains in productivity, efficiency, return on investments, new market opportunities – by adopting their solutions. However, we only have quantitative evidence for two of these claims. Igara Tea in Uganda reported that the tea leaves delivered by more than 7 000 farmers to the two processing plants increased by 57 percent over five years. Tun Yat in Myanmar indicated that farmers generate around USD 120 in additional income per season, or USD 240 annually, as a result of using their services. This is primarily due to the more modern machines, which give a higher threshing quality with less post-harvest loss, and because Tun Yat operators drive more slowly than local operators, resulting in an addition five baskets of rice paddy/acre.

In three cases, the farmers were already paying for the solution, based on subscription fees, transaction-based services, or other mechanisms under a B2C business model, indicating its sustainability.[14] This was the case for GARBAL (solutions for livestock-pastoralists) and TROTRO Tractor (mechanization platform for crop production), both deployed in sub-Saharan Africa, and for SeeTree in high-income countries. In five cases, evidence of sustainability may be inferred only from the number of producers currently reached or the investments that the company has been able to attract. Figures on the customers reach were provided for example by Cattler, Aerobotics, SOWIT, Egistic and Lely. Harvest CROO Robotics referred to a high interest from the client sector addressed (strawberries in the United States of America). Atarraya pointed to the investments they had been able to attract.

13 The time interval necessary for a service provider to satisfy a customer request.

14 More solid evidence would require confirming the data over several years. This was not possible in the context of this research.

In the case of B2B business models, the evidence is less clear. There is an assumption that the many agribusinesses or other organizations paying for the agricultural automation services (through freemium models, etc.) ensure the solutions are sustainable for farmers.[15] This is, for example, the case for IoCrops in India. Finally, several of the solutions have not yet been commercialized, thus the positive economic impact on the farmer can only be conjectured, regardless of the intended revenue models.

Most of the informants (12) reported that **environmental sustainability** was an intentional goal of their businesses. The reported advantages of the precision agriculture solutions range from reduced used of agrochemicals, fertilizers and irrigation water (SOWIT, Seeds Innovation, Aerobotics), reduced emissions (Lely), improved carbon footprint (Cattler), to full environmental control (as for several solutions for protected cultivation and Atarraya for aquaculture). In some cases, a specific contribution to climate change was also mentioned (mostly in the European-related cases, such as ZLTO and Abaco, but also UrbanaGrow in Chile and for SOWIT in Northern Africa).

Finally, in terms of **social sustainability**, young people were most often cited (six cases) as the driver of generational change in the management of family enterprises and ultimately as the driver of adoption. This applies across regions. The interviewers expressed their reflections on the effect of automation and mechanization on labour in three cases, mostly indicating a positive shift from unskilled to more qualified jobs (UrbanaGrow, GroboMac). Gender was not usually taken into consideration explicitly, except for in solutions deployed through development projects in lower-middle-income countries (Tun Yat, CropIn), or by ZLTO, which has policies addressing women's roles in farming in the Netherlands. Nor was much attention given to implications for small-scale producers and vulnerable (indigenous) communities, mentioned in only two interviews (Tun Yat and Atarraya).

15 Under a B2B model, free services are offered to farmers; however, the data collected by some of these digital and automation technologies can then be sold for profit, such as to insurance companies.

6 Discussing the future of precision agriculture solutions based on the case studies

KEY MESSAGES

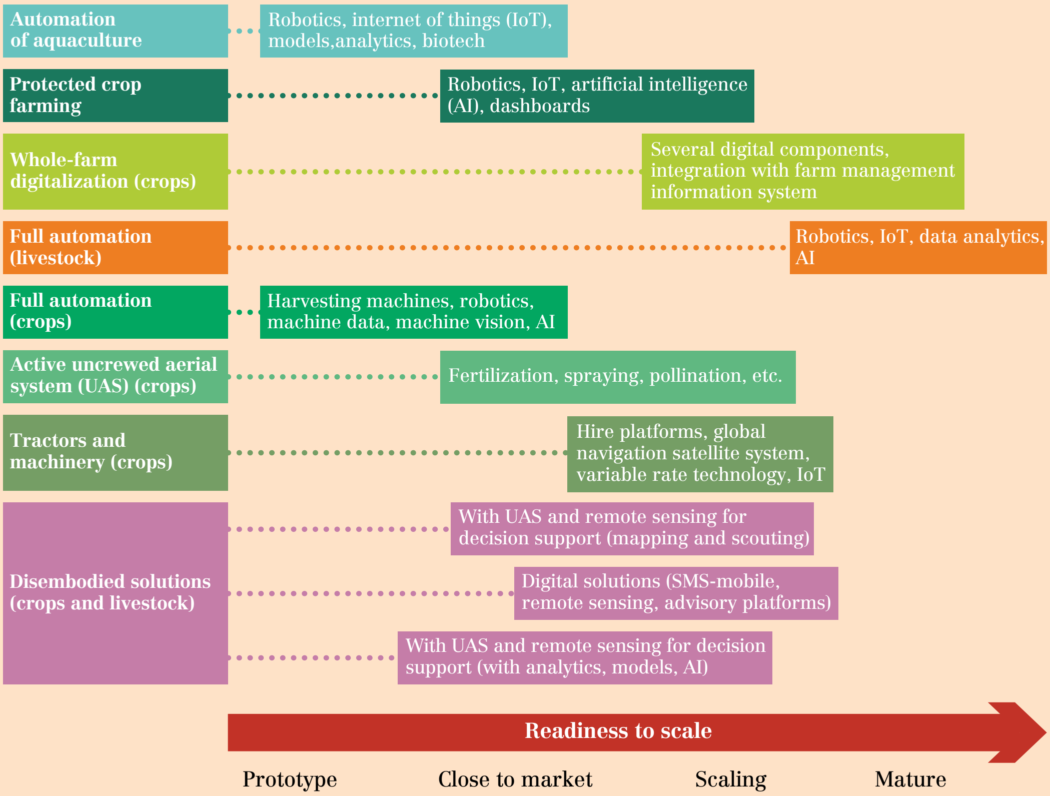
- Disembodied digital solutions, including remote sensing and simple mobile devices, are rapidly scaling, including in low-and middle-income countries. More advanced solutions, such as big data analytics, AI and machine learning, are also expected to be further developed and applied.
- The development of machinery hire services is expected to expand access to automation technologies by small- and medium-scale agricultural producers in low- and lower-middle-income countries.
- Agricultural robots (e.g. drones for fertilizing crops) are still mostly used in high-income countries, with limited examples in upper-middle-income countries.

Robots for precision livestock farming, especially milking robots, on the other hand, are more vastly used, including by medium-scale farms. Their success has also made it possible to gradually introduce other robots such as automatic feeders and automated solutions that allow whole-farm management. In this section, we discuss possible future trends for the different precision agriculture solutions.

The trends are seen from the perspective of readiness to scale, as described in Section 3.7 and are organized along the spectrum of PA solutions presented in Section 5.1. This is shown in Figure 4 in a schematized way and further elaborated in the next sections with regard to specific production orientations, world regions and farm types.

Readiness to scale is assumed to reflect adoption trends by farmers. In the following sections, we have complemented this notion of readiness with reflections on adoption drivers and barriers as well as sustainability (in its three different dimensions), as discussed in Sections 6.3 and 6.13.

FIGURE 4 Precision agriculture solutions and their readiness to scale



Source: Authors' elaboration.

6.1 Disembodied digital solutions

A few cases (TraSeable Solutions, GARBAL) fall under the category of disembodied solutions. As discussed in the paper by McCampbell, such cases are mostly deployed in lower-middle-income countries and usually address small- and mid-scale producers (McCampbell, 2022). This indicates a good level of penetration of feature phone-based services coupled with unstructured supplementary service data (USSD) and call centres. These services rely on web-based platforms and smart phones with more advanced delivery and feed-back services. The penetration of smart phones, however, varies by location: it is less prominent in sub-Saharan Africa than in Asia and the Pacific, Latin America and the Caribbean, and other high- and middle-income countries.[16] Solutions are often supported by remote sensing and other digital geodata, including weather forecasts, vegetation indices, land use and crop maps, land demarcation and farmers' data when available. All this information is useful for farm advisories and farm alert services. It can also be bundled with additional services such as digital marketplaces and price information, input procurement and access to credit.

There are several reports indicating that these solutions are rapidly scaling across all lower-middle-income countries: the CTA-Dalberg *Report on the digitalization of African agriculture* (Tsan *et al.*, 2019), FAO-ITU (2017, 2022), and the Digital Agri Hub (undated), among others. There are also cases where simple mobile tagging devices are introduced

[16] According to GSMA (2020), by the year 2020, 69 percent of the population in Latin America and the Caribbean, 64 percent in Pacific Asia, and 45 percent in sub-Saharan Africa had access to a mobile phone, although the penetration of smartphone in Africa is much less (for example, 4G accounts for 15 percent of connections).

as part of product tracing solutions (TraSeable Solutions and Aquaconnect in McCampbell [2022]). Tracking allows more steps along the value chain to be digitized, including handling and processing. Handheld equipment can also be considered as part of this category.

When assessing possible adoption drivers, barriers and trades-off for disembodied solution in terms of precision agriculture, we would like to highlight a few considerations.

Drivers. From the user's perspective, there are very limited investment costs involved and operational costs are also limited/affordable for most producers. Indeed, such costs are often covered by donors and governments (as for CropIn) through B2C models or based on B2B and other innovative business models where other actors in the value chain (e.g. agrodealers) pay for the services. Adding tagging to tracking solutions is a further, very promising development in several consumer markets of high- and middle-income countries that are looking for product traceability. Overall, the potential outreach of disembodied solutions across all world regions is vast.

Barriers. Connectivity and other enabling infrastructures (electricity, data infrastructures and related policy and data interoperability[17] issues) remain a challenge in many lower-middle-income regions. For very small farmers (usually those with holdings below 1–2 ha) the quality/level of contextualization of the data and of the advisory generated may be questionable, especially in multiple and low-input cropping systems. There are known difficulties related to scaling due to low literacy and digital skills, as well as insufficient access to solutions by women and other vulnerable groups.[18] Trust around farmers' data sharing, i.e. the non-existence of data privacy and protection regulations in many countries, is also emerging as an issue. Since there is only limited control of environmental variables with disembodied solutions, their contribution to precision agriculture is relatively small. But given the potential outreach, the overall impact in terms of achievements of the PA goals as defined in Section 1.2 could be substantial.

6.2 Disembodied digital solutions with remote sensing and uncrewed aerial system for decision-making

Disembodied digital solutions that involve UAS and remote sensing are starting to scale globally, including in lower-middle-income countries, although their uses are mostly limited to data collection, scouting and decision support (e.g. Igara Tea). Solutions that add more advanced applications, including **big data analytics**, **dedicated models** (including based on AI and ML) and **machine vision**, have been successfully deployed and are expected to develop further in many application fields, starting from fruit and nut crops (SeeTree, SOWIT, Aerobotics) and to eventually include other high value crops and, in time, large-scale arable crops. Applications include water stress and irrigation network monitoring, nitrogen needs determination, yield forecasting irrigation, and pest and disease scouting. These solutions are mostly adopted by large-scale farms for high value crops because the costs of directly operating unmanned aerial vehicles (UAVs) and collecting and processing data (e.g. with photo geotagging, IoT enabled sensors, and machine learning-based predictive modelling) or resorting to third party services are still high.

Drivers. Advancements in data analytics and modelling and their integration with satellite and other data sources (e.g. photo geotagging) are expanding the potential for precision agriculture applications. There are limited investment costs involved for providers.

17 A typical case of data interoperability relates to machine data, which can be useful information for precision agriculture when exchanged, for example, with FMIS. Machine manufactures have established their own data standards, which need to be harmonized, i.e. made interoperable. For further details, see, for example, the work done in the context of the NIVA project (European Commission, 2022a).

18 See, for example, UNDP (2021) and FAO (2018).

IoT-enabled devices are also becoming relatively inexpensive. This makes the cost of the services increasingly affordable for large- and medium-scale farmers. The shared use of UAS or hiring services may expand their use by smaller scale farmers, as in the case of Igara Tea and SOWIT. The objective of the latter is to offer free advisory services to small-scale producers, basing their business model on the income they generate from the sale of the big data they collect.[19] The potential for this type of solutions is growing across all world regions.

Barriers. Regulations governing the import of high-end technology (UAVs, sensors, weather stations, etc.) in many lower-middle-income countries are quite restrictive and suffer from heavy bureaucracy (as reported for example by Igara Tea, SOWIT and Aerobotics). For UAVs, restrictions for flight permits are also a barrier. Some agronomic models are still in their infancy (e.g. those related to pest and diseases with more complex biology and ecology). Costs are prohibitive for individual small-scale producers in lower-middle-income countries, although research in Rwanda (Niyitanga, Kazungu and Mamy, 2020), Burkina Faso (Pouya *et al.*, 2020) and Ghana (Annor-Frempong and Akaba, 2020) points to the willingness of farmers **growing the same crop on contiguous areas**[20] to share UAS-based advisory services. With reference to high-income countries, SeeTree observed that they are working with small-scale olive growers in Greece, organized through cooperatives.

6.3 Mechanization

With regard to mechanization for open-field crop production, two perspectives are considered: mechanization for PA, and digital tools and services to facilitate access to mechanization. The first perspective addresses the role of mechanization to support PA applications (mostly evident in high- and middle-income countries), while the latter addresses access to mechanization (lower-middle-income countries).

The advent of global positioning systems (GPS) and GNSS is widely accepted as a key enabler of PA, since these technologies allow precise positioning of farm operations such as levelling, sowing, spraying and fertilization. As reported by Rose (2022) and confirmed by our case studies in Europe (ZLTO), and Central Asia (Egistic), adoption rates for GNSS, are relatively high across high- and middle-income countries. Positioning remains key for precision agriculture, but the key trends are towards spatial mapping and linkage of observations and measurements for the deployment of VRT. The adoption rate for VRT has been slow, even in Europe as reported in Rose (2022) and confirmed in our case study by ZLTO. This is also corroborated in a recent survey, which showed that some PA technologies (such as guidance systems, automatic section control and yield monitoring) are being adopted more quickly than others (such as soil mapping, variable rate fertilizing and variable rate seeding) (Nowak, 2021). One of the reasons cited is the lack of evidence of the profitability of VRT (Lowenberg-DeBoer, 2022) and, more particularly, a lack of validated agronomic models informing the application maps (Zarco-Tejada, Hubbard and Loudjani, 2014). As discussed in more length in the paper by McCampbell (2022), cooperative mechanization hiring services based on digital platforms are expected to develop further, especially in the context of lower-middle-income countries. This Uber-like business model, which relies on a commission earned by the intermediary, is illustrated by the cases of TROTRO Tractor in Africa, and Tun Yat in Asia. It is advantageous, both for the farmer (who is served more rapidly) and the owners of the equipment who can maximize and closely monitor its use and fuel consumption, offering more competitive rates. The beneficiaries are small- and medium-

19 To ensure the protection of farmers' data, these are duly anonymized, and an informed consent is obtained beforehand.

20 Services tend to be more easily shared, with the support of government programmes, on contiguous areas. We refer, for example, to the Ministry of Agriculture Agricultural Transformation Agency promoted Agricultural Commercialization Clusters (ACC) in Ethiopia, or areas under the Crop Intensification Program (CIP) in Rwanda.

scale farmers as well as factories and companies involved in contract farming. Potentially this implies a progressive adoption of GNSS for accurate positioning and advanced machine control, with prospects for developing further precision agriculture through VRT in lower-middle-income countries.

Drivers. The "sensor-enhanced" mechanization we have described above allows, in principle, an ever-increasing amount of data to be gathered. This employs a variety of different sensors carried by ground vehicles (data acquired at the highest spatial resolution, with either low spatial coverage or at lower speed than aerial observations), integrating them with satellite data (low resolution data but high spatial coverage, with data acquired at regular intervals), and UAS (higher resolution data but lower spatial coverage). As highlighted by McCampbell (2022), changing models around conventional machinery (from individual to shared ownership, rental and pay-as-you-go services) is expected to facilitate the scaling of these solutions in lower-middle-income countries. Precision agriculture will benefit from this "Uberization" trend both indirectly (through enhanced data collection) as well as through direct intervention in several farming operations ("on-the-go" via VRT).

Barriers. Large agricultural machinery is not adapted to small, irregular fields. Although the use of mechanization for VRT has long been championed for enabling PA, the cost/benefit of advanced VRT applications is still unclear. Data-sharing of machine sensors is still a challenge due to lack of interoperability.

Mechanization for **precision livestock farming and aquaculture** will be covered in the following sections on automation. It is noted that milking robots have long been part of the sector and are at a very high maturity level on the readiness scale.

6.4 Full automation and robotics for crops

Robotic solutions (both semi and completely autonomous) exhibit different degrees of readiness to scale, depending on the production orientation, farm type and whether they were developed as protected or open field farming solutions. Such solutions are particularly evident in high-income countries, with limited examples in middle-income countries.

There is limited evidence that robots for **crop-arable farming** can successfully generate a market. There is prototypical evidence of the use of autonomous field robots by large and small corporations (see Harvest CROO Robotics in the United States of America, GroboMac in India) but the application appears limited to trial cases or research and test farms. However, this sector is strongly supported by private investments (including by growers and farmer cooperatives), which demonstrates strong confidence in the role these technologies may play on the farms of the future.[21]

In lower-middle-income countries, the farms run by smallholders are usually designed for manual labour; the robots designed for high-income country farms are not adapted to such conditions. For example, automated cotton harvesting machines in high-income countries are highly efficient, but are suited for one-time harvesting of synchronous bloom cotton. The harvesting operation damages the crop, but the harvest is complete. Such a solution would not be appropriate for traditional farms in India or West Africa, where cotton is a high-quality multibloom crop with a season of about 150–160 days. During this period, cotton is picked three to four times. GroboMac developed a robot that is designed to take the local context into account, so that the plant is not damaged and can be harvested multiple times. There are few examples of robotic solutions being developed in middle-income

21 This is confirmed by Lowenberg-DeBoer (2022) who reports that only 4 percent of agricultural input dealerships use robots for crop scouting services and 2 percent use them for weeding services. A substantial growth by 2024 is foreseen, however, with 18 percent expecting to offer robotic crop scouting and 13 percent expecting to offer robotic weeding.

countries. These solutions target crops and cropping systems that have traditionally been designed for manual work. They are tailored to local contexts and challenges, requiring minimal to no change in the current farm structures.

The drivers of these solutions are also socioeconomic, with lack of seasonal labour featuring prominently. Better access to education, migration to cities, social stigma and government policies to support the jobless have all been reported as trends leading to diminishing interest in manual (and poorly paid) labour on MIC farms. Case studies indicate two key challenges for middle-income countries: lack of investment (this is significantly different from trends in digitalized solutions in lower-middle-income countries), and difficulty in retaining talent in the organizations developing the solutions, since these are small enterprises competing against large companies.

Drivers. The key drivers of robotic solutions are:

- labour shortages, especially the need to overcome the lack of peak seasonal labour;
- reduced undesired variability introduced by human error and further increase of environmental control through protected cultivation;
- In high-income countries, there is strong industry interest in robotic solutions to automate on-farm tasks (irrigation, pest scouting, harvesting, weeding, etc.) and address the lack of labour. For example, 70 percent of the strawberry industry in the United States of America has already invested in Harvest CROO Robotics’ strawberry harvesting robot.

Barriers. There is only anecdotal evidence of autonomous field robots being operational, let alone information on their cost effectiveness. This is regardless of region considered but more evident in middle-income countries. The strategies for scaling up the manufacture of hardware and software are not mature, as they rely on technology adoption. High investment costs are also a barrier, independent of the world region. In contrast to high-income countries, robotic solutions have not attracted significant investment in lower-middle-income countries, as these technologies are perceived as high-risk investments.

6.5 Active use of unmanned aerial vehicles as flying robots

The use of UAVs for spraying crops is widespread in high-income countries, in Eastern and South-eastern Asia. China, Japan and the Republic of Korea have been active in the commercial use of UAS for plant protection spraying for over 30 years (OECD, 2021). In Australia and the United States of America, the use of UAS is permitted and the trend is towards using larger application volumes and low drift nozzles (OECD, 2021). In lower-middle-income countries, farmers in Benin, Ghana,[22] Mali, Togo and Zimbabwe are showing a growing interest in the service. In Europe, aerial spraying by drones is considered risky due to the potential drift of agrochemicals and is therefore not allowed. As mentioned previously, the technology has increasingly been adopted in sub-Saharan Africa.

Interviewees observed that there is a growing market for multitier service solutions (SeeTree, SOWIT, Aerobotics) but no mention was made of the need to ensure interoperability of systems across service platforms. Nevertheless, examples of converging efforts are emerging, such as where agrochemical industries tailor pesticides and micronutrients for high density distribution via spraying drones, for example.

[22] In 2021, AcquaMeyer Drone Tech sprayed a total of 8 700 hectares of maize, rice, cowpea, pineapple, mango and papaya for pest and weed control and micronutrient applications. Ninety percent of the serviced areas belonged to commercial farmers and 9 percent to medium- scale farmers (Acquah, personal communication, 2022).

Seed Innovations in Nepal offers a solution that actively uses UAVs to address **agroforestry** challenges. As also reported in the paper by McCampbell (2022), the other agroforestry solutions we have identified are usually limited to detecting and counting plants. Seed Innovations has developed this further to encompass disease scouting and, although at a pilot stage, the active use of UAVs for fertilization. However, it appears that applications in the agroforestry field are still in their infancy and that there is considerable potential for development.

Drivers. When UAVs are used for direct input applications, they can be seen as a variant of VRT, hence contributing "on-the-go" to precision agriculture.

Barriers. The European Union restricts the active use of UAVs for pesticide spraying due to the risk of drift.

6.6 Full automation and robotics for livestock

Robots for precision livestock farming, especially milking robots, are at a very high maturity level on the readiness scale, employed mostly on medium- to large-scale farms. The adoption rate for this solution is high (e.g. 40 percent of Dutch farmers, according to ZLTO),[23] the demand remains high (milking robots are scaling also in Asia and Latin America and the Caribbean as reported by Lely), there are multiple successful business models (which include local after-sale service centres), and there is production capacity to meet current demand. The experience of milking robots has also made it possible (according to Lely) to gradually introduce other robots for manure cleaning and feeding as well as for automating barn management, as well as sensors for monitoring health, fertility, well-being and, more recently, gas emissions. Similar solutions have been developed (by Cattler); these are less mature than the previous example but are scaling. These solutions cover all operations related to feedlots, from automatic feeding to diet and health monitoring for individual animals. However, anecdotal evidence from one case study (Lely) points to the consolidation of dairy farms in Northern Europe as the underlying cause of the falling numbers of milking machines resulting from technology replacement and greater economies of scale.

Drivers. Mature and promising solutions address issues of labour availability, costs and drudgery, as well as environmental compliance. New solutions allow a move to full automation and more precise livestock farming. Solutions also improving energy efficiency.

Barriers. Do not make the solutions practical for small-scale livestock farmers and in lower-middle-income countries particularly, where adapted, cheaper solutions are needed. New regulations, such as on free animal movement, will introduce the need for adapting current technologies (also potentially interesting for lower-middle-income countries).

6.7 Full farm digitalization solutions

Full farm digitalization solutions have been developed in high- and middle-income countries (see, for example, Abaco in Italy, and Egistic in Kazakhstan) as well as in lower-middle-income countries as well (CropIn in India). The examples cited are already scaling to mature (except for the integration with FMIS) although the solutions integrating several datasets and models are very limited.

Drivers. These solutions contribute to greater environmental control and precision in open field agriculture, as they can monitor different aspects of production and how these are integrated.

[23] More detail on how automation has evolved in this sector and current levels of adoption can be found in Lowenberg-DeBoer and Erickson (2019) and Rose (2022).

Barriers. Quality data and data infrastructure availability and interoperability, connectivity and availability of validated agronomic models are among the most important factors limiting adoption. A lack of skills for handling complex digital solutions is also a key barrier.

6.8 Full automation protected cultivation

Protected cultivation (or controlled environment agriculture, CEA) is another area where robotics is increasingly prevalent. This is particularly evident in greenhouse production environments. These solutions have yet to strongly penetrate the market and the adoption rate is low. Nevertheless, investors are bullish on these technologies and private investment appears to be driving the sector, as confirmed by ioCrops, Hortikey and UrbanaGrow. Protected cultivation, especially in modern greenhouses and vertical farms, involves extremely controlled environments with multiple automated processes, including decision-support systems. A key advantage and a possible enabler for the adoption of robots is a potentially rapid integration into existing control and decision-support processes.

Drivers. CEA can ensure horticulture production in urban areas as well as in environments that are not suitable for crop production or are likely to become unsuitable in the face of climate change. UrbanaGrow observed that protected cultivation is the only environmentally and economically sustainable solution in two difficult environments in Chile (Atacama Desert in the north and Tierra del Fuego in the south). Other drivers of the solution include its ability to ensure environmental benefits and compliance with environmental regulations and, at the same time, to support the production of high quality “zero kilometre” food, distribution efficiency, lower transportation costs and less food waste. Food Autonomy, for example, operates a vertical farm adjacent to a salad production company, providing locally-produced, chemical-free and consistent quality microgreens. Full control is the maximum expression of precision agriculture. A shortage of expertise for large-scale production management is another driver. Hortikey offers the Plantalyzer robot to make production capacity estimates in tomato greenhouses, a solution built to address the shortage of expertise and standardization on how to grow tomatoes, especially on a large scale. Labour shortages in high-income countries remain a strong driver for automation and robotics in protected cultivation.

Barriers. Rigorous evidence is lacking on the financial returns on investment (ROI) and the environmental benefits (energy, water, carbon footprint etc.) of such solutions. There is also insufficient evidence that production can always take place under totally aseptic conditions and without the use of pesticides. Moreover, protected cultivation is not perceived as natural by consumers (mentioned by UrbanaGrow and Food Autonomy). It is also not usually favoured in sectoral public policies (mentioned by Food Autonomy). Conventional growers are not very welcoming as this is seen as a competition from new actors (as indicated by IoCrops). Such solutions also have high investment costs.

6.9 Full automation aquaculture

We regard this type of solution (offered by Atarraya) as similar those ones discussed under the protected cultivation of crops. This applies to potential drivers and barriers and to their contribution to precision agriculture.

7 Conclusions and recommendations

7.1 Conclusions

It is generally accepted that precision agriculture is an inevitable fact, as new digital solutions and underlying technologies will impact agriculture worldwide. What we do not know is which solutions will be adopted, at what speed and with what eventual environmental, economic and social implications.

Returning to objectives of this paper, we will try to answer two overarching questions:

- Are automation and digitalization leveraging precision agriculture?
- Are their promises of productivity and efficiency gains, environmental sustainability and climate resilience met?

From our findings, automation and digitalization, to which we add mechanization given the important interdependencies, are instrumental for the adoption of precision farming. Different solutions contribute to PA in different ways: from disembodied digital solutions that leverage data, models and expert judgement, to machinery and robots that support on-the-go precision farm operations, to fully automated solutions (in open field or protected conditions) offering the highest possible control over environmental variables and thus, in principle, also the maximum expression of precision agriculture.

We have analysed the solutions based on their readiness to scale, which we assume to reflect adoption trends by farmers. We have complemented this with considerations on adoption drivers and barriers elicited from key respondents, as well as on their sustainability from economic, environmental and social perspectives. Solutions have different scaling prospects, which largely depend on farm type and location. As observed in the paper by McCampbell (2022), **disembodied digital solutions** most characterize the trends in progress **in lower-middle-income countries and for small-scale producers**. We suggest that such solutions, coupled with remote sensing, UAS and IoT sensors, have the **greatest potential to contribute to PA across all world regions**. This is evidenced by the emphasis on digitization and digital tools in the upcoming common agricultural policy (CAP) of the European Union, for example the mandatory use of the Farm Sustainability Tool for Nutrients (FaST) (European Commission, 2022b).

Mechanization (the **embodiment of digital solutions and sensors for tractors, equipment and drones**) is likely to become critical for gathering and integrating an ever-increasing amount of data using different proximal sensors, satellite and UAS data and carrying an array of sensors and actuators. Precision agriculture will benefit from these rich datasets as well as from more precise operations (e.g. by means of VRT). Scaling solutions, such as VRT, is expected to improve in high- and middle-income countries, due to advancements in the quality of underlying data and models, and an overall better understanding of crop responses to specific environmental factors. Again, following the conclusions in McCampbell' s paper, changing models around conventional machinery may facilitate the scaling of mechanization in lower-middle-income countries, acting as a potential driver for more advanced PA applications (McCampbell, 2022).

The prospects for scaling **fully automated solutions** are highly dependent on production orientation; these are more likely in precision livestock farming and still very limited in arable farming, especially in middle-income countries. As one of the most advanced solution providers in Kazakhstan put it, “Farm mechanization will become a major trend in the coming 4–5 years. However, full farm level automation may take 5–10 years." Similar considerations apply to automation in protected cultivation and aquaculture systems, where there is, however, a lot of interest from investors, and possibly an added incentive due to a deterioration of climatic conditions.

Turning to the second question, we argue that all of the proposed solutions contribute effectively to the three dimensions of sustainability. There is, however, a lack of sufficient and compelling evidence on positive returns to investment and the overall costs and benefits of the different solutions. Addressing these knowledge gaps is an important recommendation of this paper.

It should be noted that energy and farm input costs are likely to become a more prominent driver of sustainable solutions due to the Ukraine war and therefore, farmers are likely to prioritize PA in terms of gained efficiency and cost reduction.

How do these solutions affect social sustainability, considering any trades-off in terms of labour and inclusion? Who are the eventual winners and losers?

With a few exceptions (e.g. farmers' organizations or providers that are active in development projects), **social concerns** are not critical to the mandate and thinking of our key informants. The conclusions that have emerged on the impact of automation are therefore likely to be influenced by these views. A farmers' organization emphasized the fact that the agricultural population is shrinking and ageing, and that automation appears inevitable, not only in the Netherlands but also in Africa. Overcoming labour shortages and reducing labour costs labour particularly drive adoption in h, although shortfalls in the labour force is a known challenge in several lower-middle-income countries due to the ageing population in rural areas and the outmigration of the younger generations.

Interviewees cited the positive **impacts on labour** arising from precision agriculture solutions, including reduction of drudgery and increased safety. Automation was cited by several respondents as the reason for shifting the workforce to more highly skilled jobs. How many workers are positively affected by automation, and the policies and actions needed to support it varies across different world regions. Rose (2022) indicates, for example, that some rural employees may find it easier to retrain and learn new skills than others (women often receive fewer educational opportunities). He further points to the fact that horticulture is more likely to incur manual labour losses, as thus far it has only relied in manual labour but slowly it will start to be automatized, and therefore requires less manual labour..

Farmers or agricultural workers in lower-middle-income countries and with lower **literacy skills** are likely to become more vulnerable, but a lack of **digital skills** is likely to represent a barrier across regions in the world. Basic digital literacy is considered as an essential capacity for farmers intending to practice precision agriculture in lower-middle-income countries, while the necessary skills level increases in relation to the complexity and sophistication of the deployed solutions. The propensity to test and adopt precision agricultural practices seems also to be linked to age and level of technical education.

Young, educated farmers appear to be the first to embrace technical innovations. They are perceived as instrumental for transforming the family farming business through digitalization and automation. Young people are very often indicated as the winners of the digitalization transformation because of their interest in this type of agriculture (as was mentioned by UrbanaGrow and ioCrops regarding protected, fully automated farming).

Social benefits are likely to be spread unevenly in relation to **data sharing**, where there is a risk that data (and solution) providers retain (without obtaining prior informed consent) information originating from farmers. There is also the risk that precision agriculture and data-driven approaches will emerge that, bundled with, for example, agriculture insurance, would lead to top-down, prescriptive recommendations.

As mentioned by one of our key informants from a farmers' organization in the Netherlands:

> Data management, sharing, ownership is key: future farming could follow a positive path, i.e. from calendar farming to clever farming. But can also go wrong: from free farming to "bound" farming, where Big Tech[24] would put everything in recipes that farmers will be forced to follow. Farmers should be given the option to choose (interviewee).

Therefore, precision agriculture yes, but prescriptive agriculture, no.

7.2 Recommendations

Based on the conclusions of this study, we offer a few recommendations for consideration by governments, development actors, the research community and other stakeholders interested in promoting precision agriculture. The aim is to highlight specific areas for policy and investment, regulatory frameworks, research and innovation that can help PA to achieve its economic, environmental and climate goals in an inclusive manner. The order in which the recommendations are presented suggests the degree to which, in the authors' opinion, they should be given priority.

- A major conclusion concerns the essential role that **digitalization can play to support precision agriculture** across the whole spectrum of available solutions, with special attention to disembodied solutions integrated with machinery, sensors and drones in order to achieve impact at scale. **National data policies**, including data protection and privacy regulations, data sharing, and data protection and privacy are key enablers of digital solutions and therefore need to be developed and supported in all countries. "Privacy by design"[25] approaches to the development of solutions are also important for respecting the needs and gaining the trust of farmers. Where applicable, there is much scope for supporting the development of national policies for the responsible and progressive **digitalization of the agricultural sector**, in line with the efforts of FAO-ITU (International Telecommunication Union) in some world regions (FAO and ITU, 2017).
- A more specific action is to develop and support **national data infrastructure**, including the definition of technical and legal interoperability[26] and other standards. Technical or semantic interoperability is vital for data sharing, as is legal interoperability because it defines the regulatory framework in which data can be exchanged and at the same time, protects aspects such as privacy and secrecy.
- We also believe that a strong **human capital development/capacity building agenda is needed**, with investments in scaling literacy and basic and digital skills. This would target farmers as well as other actors in the value chain that need to embrace automation and digitalization and would hopefully support the transition from low skill to higher skill job profiles.
- A specific agenda for promoting **agricultural digitalization and automation among young people** should be prioritized in government policies and investments. The aims would be to attract them, empower them and build competencies among young farmers and entrepreneurs in agrifood value chains.

24 Big Tech collectively describes the most important technology companies in today's marketplace.

25 Behind this approach is the idea that data protection is most effective when it is integrated in the design phase of digital solutions.

26 This term is commonly used to denote accurate and reliable communication among machines.

- Funding for precision agriculture solutions should **target investments in enabling infrastructures**, such as the creating of core public datasets (e.g. accurate weather forecasts, land demarcation, information on crop calendars and requirements) and broadband internet connectivity as well as electrification and roads in the rural areas.

We believe that a research and innovation agenda is a priority in areas such as:

- Impact studies to assess the impacts of specific PA solutions in terms of their different dimensions: economic (e.g. studies on the profitability from the perspective of different farm types and regions, overall cost/benefit analysis), environmental (including carbon, water and energy footprints), and social (implications for labour availability and safety, inclusion of women and other vulnerable groups). Studies with specific reference to protected, highly controlled agriculture are especially important given less than positive perceptions of some consumers and decision-makers in this type of solution.
- Development and validation of specific agronomic models to allow a better understanding of crop response to specific precision farming technologies (e.g. VRT).
- The use of (big) agricultural data and analytics as a public good to offer (free) advisory services to farmers.
- The development of adapted (to specific regions, countries, production orientation and farm types) mechanization and automated solutions.

We have documented examples of disembodied digital solutions – with and without UAS – that are applicable across different production orientations, regions and farm types. The adaptation of solutions related to mechanization and automation is less straightforward. Crop examples include the small mechanization equipment (e.g. tea leaf pickers) developed in Uganda and the automated cotton harvesting machines developed for high-quality multibloom crop in India and West Africa. These are currently used by medium- and large-scale farmers but are expected to eventually be accessible to small-scale farmers through custom hiring centres, following the examples documented for tractors in sub-Saharan Africa and Myanmar. For precision livestock, the business and the service models developed for the milking robot product lines have valuable lessons for other production orientations in terms of production scaling, service and maintenance, and business models. Some of the milking robots can be adapted to smaller-scale indoor farms and pasture-based free cow movement installations, which is potentially relevant across different regions.

In the realm of protected cultivation, there are examples of greenhouses in high- and mid-income countries where a level of automation is almost always present (especially for climate control). The trend towards full automation is mainly noted in HICs, although robotic solutions in protected cultivation have suitability beyond a certain geography and our informants aim to offer such solutions in Chile, Mexico, the Netherlands, Saudi Arabia, among others). This bodes well for the robotic industry aiming to target greenhouse production, because it opens up global possibilities.

Yet, it is not only public policies and investments, research and innovation agendas that, in our view, need to be prioritized.

Regardless of where they operate, solution providers have highlighted the importance of building partnerships. In West Africa, for example, our informant stressed the fact that their public-private-partnership model, engaging with a large mobile network operator and the Ministries of Agriculture and Livestock, was key for the acceptance of the pastoralist monitoring solution. Another informant pointed out that networking and word-of-mouth are key scaling mechanisms for drone and satellite-based solutions for citrus farms in the United States of America. A favourable ecosystem for digital innovations is a key scaling element, for example, in the case of aquaculture solutions in the United States of America.

Many interviewees (from India to Kazakhstan) emphasized the fact that they want to become an "ecosystem connector" by bundling services such as market linkages, farm machinery hire, advisory services and capacity building.

The **entire ecosystem around precision agriculture** should be therefore encouraged. This can be done, for example, by consolidating specific thematic networks for the exchange of information (e.g. through e-discussion groups) and promoting collaboration among interested stakeholders. Hackathons could be organized where developers of precision agriculture digital solutions meet innovators in the field of IoT, robotics, biotechnologies, etc. Matchmaking events[27] can be organized to bring together different stakeholders, such as solution providers with governments, impact investors, donors, farmers' organization, agribusinesses.

Awareness raising and communication are also important. Once again, we borrow the words of one of our key informants:

> Consumers think in a very old fashion(ed) way… when we (especially younger farmers) show evidence of efficiency gains, environmental sustainability, animal welfare, through precision farming and livestock, we don't necessarily connect with the heart of the consumer (interviewee).

That is to say that low-input farming, often associated with seminatural environments, often resonates better than precision agriculture when it comes to influencing consumers' perceptions of environmental sustainability and climate resilience.

When it comes to vertical cultivation, our informants pointed out that it is not just about consumers' attitudes. Citing the case study in Hungary, an informant observed, "Regulations do not define vertical farm productions as bio…if plant is not in contact with the ground, the produce is not considered biological."

There is therefore work to be done on several fronts so that the whole spectrum of precision agriculture solutions are considered in light of their benefits. This brings us back to need to rigorously document evidence of the impact of precision agriculture across the dimensions of economic, environmental and social sustainability. Policies can help by prioritizing the action points we mentioned earlier, promoting specific forms of certification for precision agriculture, providing incentives and focusing on consumer awareness and communication.

Ultimately, if precision agriculture is to keep its ambitious promises to improve the lives of all agricultural stakeholders, we will need to establish a lasting dialogue across the entire food system.

27 These events can be supported by "partner finder tools", including directories of relevant stakeholders and searching/matching solutions based on partner type, solution focus and geographic location.

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Annexes

Annex 1. Glossary

Actuator: component of a device or machine that helps it to achieve motion by converting energy, often electrical, air or hydraulic, into mechanical force.

Agricultural automation: the substitution of physical activities and human decision-making by machinery and equipment in the performance of agricultural operations, reducing or eliminating direct human intervention and improving their precision. Examples include tractors (both traditional and fully automated) that pull, push or put into action a range of implements, equipment and tools to perform farm operations, as well as more advanced options, such as weeding robotics that can spray a precise amount of herbicides only where needed, or drones that remotely monitor conditions and apply fertilizers, pesticides and other treatments from above.

Agricultural motorization: the application of all types of mechanical motors or engines, regardless of energy source, to activities associated with agriculture.

Artificial intelligence (AI): the ability of computer programs or computer-controlled devices to perform tasks commonly associated with intelligent beings. AI includes programs that behave like humans, operate like humans, think like humans or have their own rational way of processing information and/or behaviour, including the ability to learn from experience.

Automated equipment: systems where some (partly automated) or all (fully automated) elements have the capacity to work without human intervention.

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

Blockchain technologies: a distributed ledger technology that records the provenance of a digital asset promoting decentralization, transparency and data integrity.

Business-to-business (B2B) model: sales between companies.

Businesses-to-customer (B2C) model: the process whereby a business sells products and services directly to end-users.

Business-to-government (B2G) model: the sale of goods and services to federal, state or local government agencies.

Climate-smart agriculture (CSA): an approach to transforming and reorienting agricultural production systems and food value chains so that they support sustainable development and can ensure food security under climate change.

Controlled traffic farming (CTF): cultivation system built on permanent wheel tracks such that the crop zone and traffic lanes are permanently separated.

Data interoperability: addresses the ability of digital solutions that create, exchange and consume data to have clear, shared expectations for the content, context and meaning of that data.

Digitalization for agriculture (D4Ag): the use of digital technologies, innovations and data to transform business models and practices across the agricultural value chain and address bottlenecks in, *inter alia*, productivity, postharvest handling, market access, finance and supply chain management.

Digitization in agriculture: part of the agricultural automation process, it refers to the use of different sorts of data generated by sensors, machines, drones, and satellites to monitor animals, soil, water, plants, and humans to perform agricultural tasks. It encompasses digital devices or tools that are embodied in agricultural machinery and *equipment* (such as precision agriculture tools) or *disembodied* devices (such as smart phones or tablets) or software tools.

Disembodied solutions: primarily software-based solutions that require limited hardware resources, generally a smartphone, or tablet, or software tools, such as advisory applications, farm management software and online platforms. Disembodied solutions may include remote sensing and/or unarmed aerial systems (UAS) but are limited to data for decision support and scouting.

Drone: remote-controlled pilotless aircraft that – depending on the mounted sensor(s) – have many applications for agricultural field surveillance and remote diagnostics of agronomic conditions such as plant and crop diseases, water resources and soil quality. See UAV and UAS.

Embodied solutions: disembodied digital solutions that interact with the environment through a physical element such as agricultural machinery and equipment. The ability to interact involves direct action, not just observations and decision support.

Farming-as-a-service (FaaS): agricultural services provided on a pay-per-use or subscription-based model.

Farm management information system (FMIS): a management system designed to assist farmers to perform various tasks, ranging from operational planning, implementation and the documentation of field work.

Feed yard or feedlot: a type of animal feeding operation that is used in intensive animal farming, notably of beef cattle.

Freemium: a business model in which a service provider offers basic features to users at no cost and charges a premium (based on a paid service) for supplemental or advanced features.

Geodata: information about a geographical location held in a digital format; also called geospatial data and information, georeferenced data and information and geoinformation.

Geotagged photo: a photograph that is associated with a specific geographic position.

Global navigation satellite system (GNSS): a constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. The receivers use this data to determine the location of, for example, a field boundary or of a machine. GNSS are used for precision positioning and advanced control of tractors and other farm machinery.

Global positioning system (GPS): a GNSS that shows the exact position of an object on earth using satellite signals. GPS is the most commonly used GNSS technology at present.

Global System for Mobile communications (GSM): a digital mobile network that is widely used by mobile phone users in Europe and other parts of the world.

Hackathon: a social event that brings computer programmers and other interested people together to improve upon or build a new software program.

High-income country: defined by the World Bank in 2022 as having a gross national income (GNI) per capita exceeding USD 12 056.

Internet of things (IoT): a system in which devices, such as mobile phones, sensors, drones and satellites, are connected to the internet.

Machine learning (ML): an application of AI that enables systems to improve and learn from experience without being explicitly programmed. Deep learning an ML method based on artificial neural networks.

Machine vision (MV): a technology that enables computers to visualize objects through images and videos. In precision agriculture, MV supports plant phenotyping, crop selection and yield estimation, plant pest and disease detection, animal welfare assessment, etc.

Mechanization: the use of all levels of technologies, from simple hand tools to more sophisticated and motorized equipment, to ease and reduce hard labour and labour shortages, improve productivity and the timeliness of agricultural operations and the efficient use of resources, enhance market access and contribute to mitigating climate related hazards. There are three types of power sources in agricultural mechanization: hand-tools, draught-animals and motorized tools (powered by engines and or motors).

Middle-income country (MIC): highly diverse in terms of size, population and income level. Lower middle-income countries have a per capita GNI (in 2022) between USD 1 036 and USD 4 045, upper middle-income countries between USD 4 046 and USD 12 535.

Mobile tagging: the practice of creating visual elements (e.g. bar codes) that can be recognized by smart phones. These can be placed on agricultural products and activated when the user captures them with the camera on a mobile device. The tag directs the user to online resources and information, permitting to trace the product back to its production site.

Multitier service: a service in which different decision-support systems (e.g. tree inventory, irrigation, fertilization, yield estimate, etc.) are organized in tiers to provide desired levels of actionable information.

One-stop-solution: the provision of a comprehensive range of services by a single service provider.

Plants-as-a-service (PaaS): the provider operates a facility – usually for protected cultivation or automated aquaculture – on behalf of the client or offers a dedicated production capacity.

Precision agriculture (PA): a management strategy that gathers, processes and analyses temporal, spatial and individual data to support improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production. PA includes precision livestock farming (PLF) and equivalent approaches in aquaculture and agroforestry.

Precise irrigation: a system that supplies crops with water and nutrients (if used for fertigation) at the right time and place and in optimal quantities that allow the growth and development of crops by using irrigation sensors.

Protected cultivation: cultivation of high-value vegetables and other horticultural crops in greenhouses and on vertical farms, allowing farmers to grow cash crops on small plots in marginal, water-deficient areas where traditional cropping may not be viable.

Remote sensing: process of gathering information about objects on Earth using aircraft, satellites or other platforms carrying sensors.

Software-as-a-service (SaaS): licensing service model in which the user is connected to cloud-based applications or software over the internet. Saas is often subscription based. It is also known as on-demand-software.

Technology readiness level: a measurement system used to assess the maturity level of a particular technology.

Unmanned aerial system (UAS): a system that includes an aircraft (drone or UAV), mounted sensor(s), a ground control station operated by the pilot and the software used to analyse the data gathered by the sensor(s).

Unmanned aerial vehicle (UAV): an unmanned aerial vehicle (i.e. aircraft piloted by remote control or onboard computers), usually referred to as a drone.

Unstructured supplementary service data (USSD): a protocol used in GSM networks for sending short text messages. It is similar in format to SMS, however, it can be used for receiving background information about weather, etc., in the subscriber's region.

Variable rate technologies (VRT): an area of technology in PA that focuses on the automated application of materials (e.g. fertilizers, chemicals and seeds). The way in which the materials are applied is based on data that is collected by sensors, maps and GPS.

Vegetation indices: mathematical combinations of several spectral bands obtained from remote sensing. They are simple and effective algorithms for quantitative and qualitative evaluations of vegetation and crop cover, vigour and growth dynamics, among other aspects.

Vertical farming: an environmentally-controlled indoor farming system that allows crops to be grown vertically year-round.

Zero km food: food produced, sold and eaten locally, having travelled zero kilometres.

Annex 2. Case study overview tables

TABLE A1 Overview of the case studies presented in interviews with key informants

No.	World region	Country	Income group	Case name	Production orientation	Spectrum of technologies and solutions	Description of the solution offered	Farm type(s) targeted
1	Northern America	**United States of America**	High	Harvest CROO Robotics	Crop production (strawberry)	Full automation (crops)	Development of automated harvesting robots for strawberry harvesting in open fields	Large-scale strawberry farmers (>25 acres, i.e. >10 ha)
2	Latin America and the Caribbean	**Mexico**, United States of America	Upper-middle	Atarraya	Aquaculture (shrimp)	Full automation (aquaculture)	"Shrimpboxes" with microbiotic control of the growing environment, minimizing environmental side effects (limited use of water, nitrogen build up, diseases). Aquaculture equivalent of vertical indoor farming	The equivalent of small- and medium- scale poultry raisers in the United States of America, with investments in the order of 500–800 000 American dollars.
3	Latin America and the Caribbean	**Chile**	High	UrbanaGrow	Crop production (horticulture)	Automated protected cultivation	Technology for modular, vertical protected growing units with controlled environment	Producers running modules of 4 to 77 m^3 (200 to 3 000 lettuces/month)
4	Latin America and the Caribbean	**Argentina**, United States of America	Upper-middle	Cattler	Livestock (beef)	Full automation (beef)	Precision livestock farming platform integrating feedlot management, feeding, health monitoring, etc.	Medium-scale beef livestock farmers with 2 000 to 40 000 heads
5	Sub-Saharan Africa	**Mali, Burkina Faso**	Low	GARBAL	Livestock (pastoralist)	Disembodied without UAS	Call, SMS and IVR services for pastoralist livestock and crop producers using satellite intelligence as data input	Large-, medium- and small-scale livestock and agropastoralists, small-scale crop producers
6	Sub-Saharan Africa	**Ghana**, Togo, Benin, Nigeria, Zimbabwe, Zambia	Lower-middle/ Low (Togo, Benin)	TROTRO Tractor	Crop production (not crop specific, primarily staple crops)	Mechanization hire service for IoT devices and GNSS	Third party mechanization equipment and drone sharing service accessible via digital platform, mobile phones, USSD	Small- and medium-scale producers as well as factories and companies for contract farming

TABLE A1 (cont.) Overview of the case studies presented in interviews with key informants

No.	World region	Country	Income group	Case name	Production orientation	Spectrum of technologies and solutions	Description of the solution offered	Farm type(s) targeted
7	Sub-Saharan Africa	**Uganda**	Low	Igara Tea	Crop production (tea)	Disembodied with UAS for decision support	Farmer-owned tea factory using simple digital tools to optimize tea leaf collection, farm input quantification and delivery and payments to farmers	Small-scale producers and large estates
8	Sub-Saharan Africa	**South Africa**, United States of America, Spain, etc.	Upper-middle	Aerobotics	Crop production (fruit trees such as citrus, grapes, etc.)	Disembodied with UAS and remote sensing for decision support plus analytics, models, AI	Farm advisory services through web applications based on drones, aerial imagery, data analytics, machine learning algorithms to optimize crop performance	Very large-scale citrus and other fruit and nut tree farmers
9	Northern Africa and Western Asia	**Morocco**, Ethiopia, Senegal, Tunisia	Lower-middle	SOWIT	Crop production (fruit trees and annual crops)	Disembodied with remote sensing and UAS for decision support, plus analytics, models, AI	Fruit tree water stress detection, nitrogen needs determination, yield forecasting using satellite imagery, UAS, ML and irrigation automation	Medium- and large-scale fruit tree and arable crop farmers and large agribusinesses. Minor but potentially growing role for small-scale producers
10	Northern Africa and Western Asia	Brazil, Chile, Greece, **Israel**, Mexico, Portugal, South Africa, Spain, United States of America	High	SeeTree	Crop production (fruit trees)	Disembodied with remote sensing and UAS for decision support, plus analytics, models, AI	Fruit trees yield forecasting and health monitoring using satellite imagery, UAS, IoT, etc.	Citrus and other fruit tree farmers, primarily big growers (> 5 000 ha) but also cooperatives with small growers (100 ha and above)
11	Europe	Europe (**Italy**), Central Asia, South America	High	Abaco	Crop production, livestock production	Whole farm digitalization	Integrated platform connecting IoT devices, machinery data and other data sources	Medium- (> 50 ha) and small-scale (< 50 ha) producers

TABLE A1 (cont.) Overview of the case studies presented in interviews with key informants

No.	World region	Country	Income group	Case name	Production orientation	Spectrum of technologies and solutions	Description of the solution offered	Farm type(s) targeted
12	Europe	**Netherlands**	High	ZLTO	Crop production, livestock production	Whole farm digitalization, mechanization with IoT devices and GNSS	Mechanization/ automation and use of machine data for farm management/ advisory services	All scales, with horticulture ranking first in terms of automation, followed by dairy (40 percent have milking robots), then poultry, pig husbandry; arable is more complicated with up to five crops in rotation
13	Europe	Europe (**Netherlands**), Northern America, Australia	High	Lely	Livestock production (dairy)	Full automation for livestock (dairy)	Milking, manure and feeding robots and new barn solutions (e.g. automatic barn hygiene); grass harvesting robots	Medium- to large-scale farmers with > 100 cows
14	Europe	**Netherlands**	High	Hortikey	Crop production (horticulture, such as tomato and peppers)	Automated protected cultivation	Robotic, sensing and data-driven system for plant and fruit growth and crop forecasting	Medium- to large-scale greenhouses > 10 ha in size
15	Europe	**Hungary**	High	Food Autonomy	Crop production (horticulture)	Automated protected cultivation	Complete vertical farming solutions, from LEDs to climate chambers, production layers and control software	Small (100 m^2), medium (180 m^2) and large farms (540 m^2)
16	Central Asia	**Kazakhstan**	Upper-middle	Egistic	Crop production (annual crops)	Whole farm digitalization and mechanization	Solution for precision agriculture	All types. Average farm size 20 000 ha, ranging from 5 000 to 1 000 000 ha
17	Southern Asia	**Nepal**	Lower-middle	Seed Innovations	Agroforestry and crop production	Disembodied with UAS for decision support (active, but experimental), plus analytics, models, AI	Solution for precision agriculture including for nitrogen fertilization on crops, banana, Longan tree, (agroforestry), irrigation management, pest and disease scouting (banana)	Small- (< 2 ha), medium- and large-scale crop and agroforestry oriented

TABLE A1 (cont.) Overview of the case studies presented in interviews with key informants

No.	World region	Country	Income group	Case name	Production orientation	Spectrum of technologies and solutions	Description of the solution offered	Farm type(s) targeted
18	Southern Asia	Global presence (primarily **India** and sub-Saharan Africa)	Lower-middle	CropIn	Crop production (various crops)	Whole farm digitalization	Several solutions, ranging from whole farm digitization for management to credit risk assessment and business intelligence, to farm-to-fork traceability, compliance, quality control	In principle, all farm sizes and all crops
19	Southern Asia	**India**	Lower-middle	GRoboMac	Crop production (cotton and horticulture crops)	Full automation (crops)	Autonomous machines for harvesting; can be customized to do other labour-intensive tasks like weeding, pruning and spraying	Medium- and large-scale (> 5 ha) cotton growers, with later possibility to include small-scale farmers
20	Eastern and South-eastern Asia	**Myanmar**	Lower-middle	Tun Yat	Crop production (primarily rice, mung bean, sesame, groundnut, maize)	Mechanization with digital, IoT devices and GNSS	Mechanization equipment service accessible via smartphone applications, targeting smallholder farmers	Medium-scale (5 to 15 acres) growers, with small-scale (0 to 5 acres) as primary clientele
21	Eastern and South-eastern Asia	**Republic of Korea**	High	IoCrops	Crop production (tomatoes and bell peppers)	Automated protected cultivation	AI-driven data monitoring systems for crop management in indoor-farming conditions and IoT sensors to diagnose and forecast various environmental conditions using gathered data	Medium-scale (>1 ha) to large-scale growers (>2 ha)
22	Oceania	**Fiji**, Cook Islands, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu	Upper-middle	TraSeable Solutions	Crop production, fisheries (tuna), timber	Disembodied without UAS	Advisory and blockchain-ready software-as-a-service (SaaS) platform for backward traceability of agriculture products and fish	Mostly small-scale but also medium- scale

Note: The country in bold denotes where the solution was developed; the other countries listed are where it is currently deployed.

Source: Authors' elaboration.

TABLE A2 Overview of business models, economic sustainability and readiness to scale

No.	Case name	Type of entity	Stage	Business and revenue model	Economic sustainability of the solution provider	Readiness to scale
1	Harvest CROO Robotics	Solution provider	Start-up	Not yet commercial; will be B2C with a pay-as-you-go/ harvesting-as-a-service model	Funds from private investors and financial institutions; minor role for government grants; 70 percent of the strawberry industry in the United States of America has invested in the company; growers are highly interested in the solution	Close to market
2	Atarraya	Solution provider	Enterprise	Not yet commercial; will be B2C and is exploring several service models: direct operation, contract farming, direct selling of the Shrimpboxes	Evidence of growing interest from investors; is already attracting venture capital	Close to market
3	UrbanaGrow	Solution provider	Start-up	Just about to go on the market. Will be B2B and B2C, with direct sale of the modular farms tied to a subscription service	UrbanaGrow had seed money (not grants) at first; now first pilot units are self-sufficient, and they believe they can pay for themselves; they believe that they can expand throughout Latin America and eventually	Close to market
4	Cattler	Solution provider	Enterprise	B2C; subscription fee-based	90 million heads of cattle in the United States of America alone and good prospects for scaling in Brazil, etc.; the solution is already sustainable	Scaling
5	GARBAL	Non-governmental organization	Not applicable	B2C; fee-based (revenue generated by airtime)	Generates revenues but not near break-even point; grant funds amount to 30 percent	Scaling
6	TROTRO Tractor	Solution provider	Enterprise	B2C and B2B; TROTRO Tractor retains commission percentage on the cost of the service	Grant funds amount to 15 percent; the solution is becoming sustainable	Scaling
7	Igara Tea	Farmer-owned company	Not applicable	B2B	No grant funds; the solution is already sustainable	Mature

TABLE A2 (cont.) Overview of business models, economic sustainability and readiness to scale

No.	Case name	Type of entity	Stage	Business and revenue model	Economic sustainability of the solution provider	Readiness to scale
8	Aerobotics	Solution provider	Enterprise	B2C and B2B (insurance companies and agribusinesses); mostly subscription fee and pay a per acre fee for insurance policies	They served 200 000 hectares in 2021	Scaling
9	SOWIT	Solution provider	Start-up	B2C; subscription fee-based; grants are 25 percent of its turnover	They served 72 000 hectares in 2021; the service is already sustainable	Scaling
10	SeeTree	Solution provider	Start-up	B2C; subscription fee-based	Outreach numbers not disclosed but large	Scaling
11	Abaco	Solution provider	Enterprise	B2C; mostly freemium with subscription fee depending on the farmer type; offers service contracts with farmer associations (B2B) and governments	Already sustainable	Mature
12	ZLTO	Farmers' organization	Not applicable	Not applicable	Not applicable	Mature
13	Lely	Solution provider	Enterprise	B2C; sales of milking, manure and feeding robots and new barn solutions; service contracts offered abroad	Outreach numbers not known but very large; providers indicate that solution uptake is booming worldwide: South Europe, South America, and Asia for example; market grows faster than they can deliver; the solution is sustainable	Mature
14	Hortikey	Solution provider	Enterprise	B2C; sales of robots and software with a monthly subscription fee or service contract	Outreach numbers not known but the solution is scaling; development is supported by investments from the shareholders	Scaling
15	Food Autonomy	Solution provider	Start-up	B2C; FaaS (farming-as-a-service) and PaaS (plants-as-a-service) model, where provider operates the farm on user's behalf or offers dedicated production capacity to the client	Solution is not yet commercialized; internal investments cover current developments	Close to market

TABLE A2 (cont.) Overview of business models, economic sustainability and readiness to scale

No.	Case name	Type of entity	Stage	Business and revenue model	Economic sustainability of the solution provider	Readiness to scale
16	Egistic	Solution provider	Start-up	B2C based on sustainable business attracting investors	Outreach not disclosed but the solution is scaling; it is a sustainable business attracting investments and interest from agribusinesses	Mature
17	Seed Innovations	Solution provider	Enterprise	B2C and B2B (insurance)	To be demonstrated; grant funds cover 40 percent	Pilot
18	CropIn	Solution provider	Enterprise	B2C and B2B based on SaaS; sustainable business with over 225 clients (farming companies, seed production, agri-input companies). Revenue: 60–65 percent from enterprise sector (B2B) and 30–35 percent from development sector	Very large outreach: seven million acres of farmland, four million farmers, this suggests sustainability of the solution	Scaling
19	GRoboMac	Solution provider	Start-up	Not yet commercial. Will offer direct sales to farmers and, in the longer term, to operators and service providers	Not yet operating; supported by personal investments and small grants	Pilot
20	Tun Yat	Solution provider	Enterprise	B2C and B2B	In the past they attracted grants and venture capital investments; currently, revenues are rising	Scaling
21	IoCrops	Solution provider	Start-up	B2C and B2B	B2B-based services with more than 200 costumers; outreach suggests solution is becoming sustainable; most of the investment (more than 70 percent) from venture capital funds, and limited contribution from subsidies	Scaling
22	TraSeable Solutions	Solution provider	Enterprise	B2B; farmers' organizations, agribusinesses, fisheries and processing plants pay a tier-based subscription for accessing the services; free for farmers	The outreach is limited (approximately 14 000 registered, 2 000 active users) but the B2B model ensures sustainability	Scaling

Source: Authors' elaboration.

TABLE A3 Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
1	Harvest CROO Robotics	Labour shortage and cost of labour Provides the operational solutions farmers need	Need for scaling-up manufacturing hardware and software to support solution	Growers are highly interested in the solution		There are acute labour shortages, especially in the peak harvest season	
2	Atarraya	Environmental motives Favourable business ecosystem Generation shift (Generation Z)	Generational attitude (Boomers) Difficult logistics in Mexico, remoteness of shrimp production sites Traditional views on aquaculture	Atarraya believes, but needs to demonstrate, that this will become a sustainable alternative for small- and medium- scale poultry raisers in the United States of America and elsewhere	The intersect between automation and biotechnology, microbic farming reduces the environmental footprint of aquaculture Circular bio-based production solutions; no negative impacts on mangroves	Not directly in their scope, although in Mexico, they are working with local/ indigenous communities	
3	UrbanaGrow	Producing in hostile environments for horticulture and in the face of climate change Environmental compliance: Government of Chile is supportive; in the United States of America, supermarkets make the rules regarding environmental compliance Provides or enables clients to produce high quality food on- the-spot (zero kilometres)	Lack of awareness of potential benefits	Targets mostly retailers and supermarkets	In these environments (and in general, in the future?), impossible or much more expensive to grow outside Less use of fertilizers, water, pesticides	Skilled workforces replace unskilled Young people love this type of agriculture but do not want to leave cities: this solution attracts them	Food security can be achieved in areas not suitable for agriculture
4	Cattler	Ability to manage barns and animals Return on investment is a factor Analytics helps but comes later Argentinian farmers are dynamic and open to digital solutions	Policy depends on the country; in Argentina very problematic and uncertain; in the United States of America, given the Farm Bill, there is too much protection	Current outreach suggests that the solution is sustainable for the farmers	Precision livestock farming that can potentially make feed yard systems more sustainable Carbon credit market in the future	Not in their scope, but young people are instrumental for the digital transformation of this sector	

TABLE A3 (cont.) Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
5	GARBAL	Public-private-partnership model, capacity and trust building, local level engagement	Need to contextualize and co-design solutions Investments in infrastructure (electricity, connectivity, etc.) Security situation	Farmers are paying for the services although GARBAL still depends on donor funds; progressively involving mobile operators	More informed management of grazing land and water resources in face of climate change	No really proactive/ intentional actions	
6	TROTRO Tractor	Reliable and timely Mechanization services COVID-19 created interest in the platform	Need to access loans to buy mechanization equipment Affordability, accessibility, reliability Lack of labour and drudgery (especially for women)	Large- and medium-scale farmers and other users (private companies and factories) are already paying for the services			
7	Igara Tea	Provides access to credit	Labour cost Real-time feedback to farmers is needed	Farmers are shareholders and do not pay for services			
8	AEROBOTICS	Operational service that solves problems In South Africa, (commercial) farmers are ready to adopt digital solutions	Restrictive drone regulations in South Africa	The current outreach suggests that the solution is sustainable for farmers	Reduces irrigation water losses, use of pesticides	In the United States of America, young people are instrumental for adoption	
9	SOWIT	Profitability (cost reduction) Environmental reporting (top management priority over finance) Comfort in working conditions (drudgery, paperwork) Climate changes forces provider to be more efficient	Imported technologies (drones/IoT sensors) No subsidies for technology COVID-19 response de-prioritized/ caused delays For smallholders, a lack and cost of connectivity/ infrastructure and trust For large-scale, advisory needs to be actionable	Evidence of sustainability for large- scale producers, not yet for medium- and small-scale producers; for the latter, cost needs to become close to zero, or alternatively, insurers will pay the bill	Precision agriculture (nitrogen applications, irrigation water delivery) is key for climate change and reduced carbon footprint.	Cost reduction needed to include small-scale producers Company has 40 percent women and 100 percent youth staff	

TABLE A3 (cont.) Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
10	SeeTree	Networking, word of mouth	Skepticism of growers around adopting digital technologies on their farm Lack of digital literacy Growers expect “a one-stop shop” for implementing data-driven decision-making Weak market linkages among input suppliers	Users pay for the services already		Younger farmer generation is key	
11	ABACO	In Europe, the number one driver is the environment: CAP regulations Regulations on use of pesticides EC Green Deal	Lack of farmers’ capacity Lack of information technology infrastructure in Africa Need to translate the service into many local languages In Africa also, need to descale technologies (adapting solutions to the much simpler feature phones)	Not always known to the provider	Major focus in the near future	Not considered explicitly	
12	ZLTO	Education and familiarity with ICT Can be easily used if machinery already has in-built sensors	Farmers are fewer and ageing. Farmers’ reluctance to investing in innovations Consumer preferences do not favour precision agriculture Lack of standards, such as for machine data Lack of trust when it comes to sharing farmers’ data	Farmers are cautious investors when it comes to automation; a recent survey shows that 30 percent of farmers would invest EUR 30 000 in the next five years on sensors and robotics; however, it is not clear yet for farmers what this extra investment will bring	Major focus of the European Union on new CAP and Green Deal	Female farmers are very important (30 percent) and so are youth for generational shift	

TABLE A3 (cont.) Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
13	Lely	Provides the operational solutions needed Labour cost Labour drudgery Environmental regulations: from nice to do to must do Energy efficiency	Farmers wait for subsidies before investing in automation Environmental regulations Dairy cattle free movement regulations (upcoming in the European Union?)	Provider indicates that solutions already help farmers' profitability	The solutions reduce emissions	Reduce labour drudgery; lack of labour has been addressed with milking robots	Animal wellbeing
14	Hortikey	European Union environmental regulations Environmental reporting by private sector (retailers, etc.)	Indoor farming not perceived as natural by consumers	Yet to be proven Scaling, and this implies sustainability for farmers	Controlled protected cultivation reduces use of chemicals	Not considered explicitly	
15	Food Autonomy	European Union environmental regulations Private sector environmental reporting	Consumer behaviour	To be proven	They feel they are contributing environmentally-sound solutions	Not considered explicitly	
16	Egistic	High return on their farm investments due to savings on fuels for farm machinery	No policies on private-public partnerships Bad internet connectivity in the rural areas	Mature, and this suggests sustainability for farmers			
17	Seed Innovations	Bundled solutions National insurance policies	Farmers' scepticism in following advisory and adopting digital solutions Lack of digital skills. Culture is a barrier to adoption	Being at pilot stage, sustainability for the farmers cannot be confirmed	Precision agriculture optimizes use of fertilizers and irrigation water	Important and an explicit request when it comes to development projects	
18	CropIn		No government enabling policies Donors disconnected	Mostly B2B, hence difficult to assess economic sustainability for the farmers		This is a focus only with development projects	

TABLE A3 (cont.) Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
19	GRoboMac	Labour availability at the farm gate	Limited interest from private investors in "hard" robotic solutions (long lead time, when compared with digital solutions)	Not known as yet		Labour force not necessarily reduced as it can be easily shifted if tasks become automated (e.g. tasks changing from picking to seeding, weeding, spraying)	
20	Tun Yat	Access to reliable and affordable mechanization services is a top need of farmers Huge smartphone penetration Because of the pandemic in the last two years there has been more use of applications	Prices for inputs and fuel Farmers and equipment owners can bypass the matchmaker service once they know each other Low digital literacy Connectivity, especially for data Low levels of trust, for example in mobile payment Low uptake of agricultural applications In remote areas farming is still done manually, primarily by women	Impact assessment showed that farmers generate additional income when using Tun Yat services		Focusing on employment of women and youth	
21	IoCrops	Government support: investing greatly to increase high-tech greenhouses; also attracting talented people to this market Educating high-tech greenhouse operators and companies Lack of labour	Traditional farmers in the Republic of Korea are not very welcoming because is seen as a competition with the conventional growers As conventional growers became worried about increasing competition due to digitalization, the government pushed against the automation process	No evidence as yet		No explicit statistics, but ioCrops estimates that < 10 percent of greenhouses are owned by women and < 30 percent greenhouse owners are youth (< 40 years old)	

TABLE A3 (cont.) Overview of adoption drivers, barriers and sustainability dimensions

No.	Case name	Drivers	Barriers	Sustainability dimensions			
				Economic sustainability (for the farmer/ final user)	Environmental sustainability/ climate resilience	Social sustainability and Inclusion	Other dimensions mentioned
22	TraSeable solutions	COVID-19 created a lot of interest Increased internet penetration Cost/lack of labour force (seasonal to Australia for fruit picking)	Lack of awareness and skills Organizations do not value data enough	It is a B2B model, paid by agribusinesses and farmers associations			

Source: Authors' elaboration.

Annex 3. Interview questions

A. For service providers (i.e. enterprises, start-ups, NGOs or research organizations)

The aim of this interview is to learn more about your digital, mechanization or automation solution and each question should be seen from that perspective.

Organization and service in general

1. Can you briefly explain what your organization is and what you do as an organization?
2. What services do you offer, based on which technologies?
3. For what purpose are those services used?
4. Can you briefly explain the geographic market that you serve with your solution?

Unique selling points of intervention/technology/service covered in case study

1. Why do think your solution/s is needed?
2. What sets your solution apart from the competition?

Customers and business model

1. What types of customers do you have (small-scale producers, medium-scale producers, large-scale producers; individual farmers or farmer cooperatives) and/or (service providers/extension agents/governments/agri-business/agroprocessors/…)
    a. Can you briefly explain how different types of customers leverage (take advantage of) your solution/s?
    b. Do you maintain statistics about women and youth users? If yes, can we access them?
2. Are there additional types of clients or users that you'd like to become your customers?
3. Can you briefly explain the business model behind your solutions/services. Does this currently result in a profitable business, and, if not, how do you cope with financial sustainability?
4. What percentage of your 2021 turnover relied on grants?

Adoption drivers

1. What are the scaling trends for your solution (in context/country/ region)?
2. What are, in your experience, the factors that drive the adoption of your solution?
3. Is there any national policy that established an enabling environment for your solution to be deployed?
    a. If yes, please cite it.

Adoption barriers

1. Did or do you still experience barriers to the adoption and use of your solution due to national and international policies, rules and regulations?
    a. If yes, please explain.
2. Did or do you still experience other barriers for the adoption and use of your solution by your target clientele/users?

(If time permits) Future vision

What is your future vision for your solution in <enter the context/country/region>

B. For farmers’ associations or cooperatives

The aim of this interview is to learn more about the digital, mechanization or automation solution(s) and services that the association/cooperative is using and providing to farmers, and each question should be seen from that perspective.

Organization and service in general

1. Can you briefly explain what your organization is and what you do/produce as an organization?
2. How would you describe your farm/farmer organization in terms of, for example, size, market orientation, partnerships with other producers and service providers?
3. What is/are the geographic market(s) that you serve with your production?

Use of mechanization, digital, and automation solutions

1. What mechanization, digital, and automation solutions and services do you use?
   a. Which service providers offers these solutions?
   b. Why did you choose the solutions of this/these service providers?
2. Can you briefly elaborate the purposes for which these solutions are used?
3. What made you decide that you needed these solutions?

Unique selling points of intervention/technology/service covered in case study

1. Do these solutions give you a competitive benefit over other farmers?
   a. If so, how?

Customers and business model

1. In your opinion, what type(s) of producers can take advantage of and benefit from the kind of solutions that you are using?
   a. <if a farmer cooperative/multiple user> Do you maintain statistics about women and youth users? If yes, can we access them?
2. Can you briefly explain the business model behind the solutions/services that you are using? For example, have you purchased them or are they on loan? Does some other entity pay for it? Do you pay monthly membership fees? Do you pay for maintenance?
   a. <if farmer has invested him/herself> How did/do you finance your investment in these services?
   b. <if farmer has invested him/herself> What is your expected return on Investment?

Adoption drivers

1. What trends do you observe in relation to mechanization, digitalization and automation (in context/country/ region)?
2. What problems/challenges could your company address by adopting mechanization/digitalization/automation solutions?
3. Is there any national policy or financial mechanism that supports investment in and/or deployment of these solutions (in context/country/ region)?
   a. If yes, please cite it.

Adoption barriers

1. Did or do you still experience barriers to the adoption and use of the solutions that you use due to national and international policies, rules and regulations?
   a. If so, please explain.

2. Did or do you still experience other barriers for the adoption and use of the solutions that you use?

(If time permits) Future vision

What is your future vision for mechanization, digitalization and automation on your farm/in your farmer cooperative?

Annex 4. Case studies

Abaco

Year of establishment: 2013

Operates in: Europe (based in Italy), Central Asia and South America

Current number of users: Not disclosed

Target agricultural sector: Crops, forestry and livestock

Interviewees: Giovanna Roversi and Fabio Slaviero

Biography: Giovanna Roversi is the private sector lead at Abaco for Italy. She is a former Microsoft employee with a focus on retail and consumer goods. Roversi joined Abaco with the goal of assisting players in the agrifood industry to face the challenges of digital transformation, with a focus on precision agriculture, in order to build a more sustainable digital future.

Services

Abaco provides web/app-based solutions based on several sources of open data and connected to sensors and equipment for additional *in situ* data acquisition. Abaco Farmer is an innovative platform that exploits territorial, agricultural and weather data. Rebranded as Demetra, the solution is now offered by the largest farmers' organization in Italy – Coldiretti – to its 1.6 million members. Other applications are offered for the organic farming sector, as well as territorial management for national and local governments. There is also an "off-the-shelf" version dedicated to small farms under 50 ha: Abaco Farmer R2U (ready-to-use).

Target customers and users

Farmers' organizations, individual farmers (both small- and large-scale) and national and local governments are Abaco's target clients. Other target groups include insurance companies, soil laboratories and UAV operators.

Why Abaco needed to digitize/automate

Precision farming and environmental compliance are the two main objectives of digitalization for agriculture and Abaco's solutions support both.

Business model and financial sustainability

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

Scaling target

Abaco's future vision is to expand into new sectors, including forestry and the environment, and to offer new functionalities in the dairy sector. In addition, Abaco has several ongoing projects that are studying how to apply precision agriculture in protected environments such as greenhouses. Other areas of interest are the design of agronomic models that can be used in different environments and the development of a scoring system for farming practices. Different objectives can be indicated (e.g. maximization of yields, cost minimization, etc.) and the highest score represents the best practice to achieve the goal. Abaco aims to make data entry as automated as possible. Abaco is also working on machine learning, whose automation require the resolution of problems related to interoperability between data standards used by different machine vendors.

In the recent past, Abaco ran several projects on robotics for selective weed spraying but considers the deployment of its robotics solutions to be at the infancy stage.

Abaco's core business is based in continental Europe, while Central Asia (Azerbaijan, Georgia, Turkey) and South America (Argentina and Brazil) are growing markets. Pilots of Abaco's services are also ongoing in the Netherlands.

Drivers

The main drivers for the adoption of Abaco's products are the demand for precision agriculture technologies and the need to comply with environmental standards and regulations, especially within the European Union. These include the Common Agricultural Policy regulations, regulations on use of pesticides and the European Green Deal. Small-scale producers have the incentive of using Abaco services free-of-charge for a limited period.

Barriers

Time is needed to learn how to operate the platform. The need to translate the platform into different languages for scaling in other countries is also a challenge. In some countries, for example in Africa, low penetration of smartphones and limited IT infrastructure are barriers.

Policy as a barrier or enabler

No policy-related adoption barriers are noted. As noted, policy-related adoption drivers are environmental standards and regulations, as well as regulations on pesticide use, which incentivize adoption.

Top quotes

"We have nearly exhausted any potential application… what else should Abaco do?"

"Farmers love to see on a map their farms in the first place: this, as Google Maps does, is the entry point and connected to that, data and services that Abaco can provide."

Aerobotics

Year of establishment: 2014

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

Current number of users: 300

Target agricultural sector: Fruit and nut trees

Interviewee: Benjamin Meltzer

Biography: Benjamin Meltzer is the co-founder and Chief Technology Officer (CTO) of Aerobotics, a South Africa-based company that uses aerial imagery to help farmers identity problems and optimize farming performance. He is responsible for the product development area of the business, designing and building predictive, automated insights that farmers can use to easily make decisions through a range of web and mobile applications.

Services

Aerobotics offers remote sensing – primarily aerial imagery from drones, satellites and fixed-winged airplanes – that enables the early detection of pests and diseases, as well as irrigation, fertilizer and nutrition requirements, in addition to measuring tree growth and performance. Aerobotics' other services include estimating yields and planning for harvest. The company offers growers a spatio-temporal view of the crops on demand; this combines high resolution drone imagery with satellite imagery captured on a weekly basis. The service also detects variability in terms of irrigation distribution uniformity to support irrigation system design or maintenance. It identifies flow/pressure variations and detects dripline and emitter issues, thereby allowing for targeted maintenance recommendations.

Target customers and users

Target customers are large-scale fruit and nut farmers in 18 mostly high-income countries, insurance companies for farmers and fruit juice processors and commercial businesses, such as agrochemical corporations or irrigation companies, that are selling solutions to growers who can use Aerobotics data to help better understand the value of their products.

Why Aerobotics needed to digitize/automate

In South Africa, where the company started its operations, citrus is grown on large family-owned estates. Managing large swathes of land where they can take real-time, location-specific informed decisions on crop management has been a challenge has been a challenge for farm managers. The use of drones, sensors and analytical software became an avenue for addressing this challenge. Entering the market in the United States of America, the value of the approach became even more evident, as the areas planted with tree crops under single management are vast in the United States of America.

Business model and financial sustainability

The main business model is based on an annual multitier services subscription. Growers pay Aerobotics on a per-hectare or per-acre basis, at yearly or monthly intervals. Different services are bundled according to the needs of the customer, with the cost of the service depending on the features required. A different business model applies to crop insurance companies, which pay a per-acre fee to collect data for inspection or auditing purposes. Some 95 percent of the company's revenue is generated in the United States of America, 40 percent of which comes from the crop insurance market. Investment in the company has so far been in the form of private equity.

To acquire high resolution “red, green and blue” (RGB) or multispectral imagery, Aerobotics relies on selected third parties that own and are licensed to fly drones. At present, Aerobotics works with approximately 150 companies in the countries where it operates, which fly drones on its behalf. The companies are responsible for obtaining flight permits from the competent authorities. In many cases, Aerobotics has invested in training drone pilots. In some cases, long-term customers acquire their own drones and sensors, and fly the drones themselves. Aerobotics has developed an ad hoc solution for these customers to make their task of data acquisition as straightforward as possible.

Scaling target

Rather than acquiring new customers, especially in the United States of America, Aerobotics aims to eventually serve a higher percentage of the orchards managed by existing customers.

Drivers

Demand for variable rate applications of agrochemicals, thus economizing their distribution and mitigating their negative environmental impacts, is an important driver of the service. In the United States of America, farmers embrace technological innovations and digital solutions such as those offered by Aerobotics.

Barriers

Benefits from the solution are not yet entirely perceived by farmers, which has slowed adoption.

Policy as a barrier or enabler

In the United States of America, regulations regarding drones are clear and favour their use, while in South Africa, compliance with the regulations can be very expensive.

Top quotes

“…[T]ypically … in South Africa, … there will be a younger sort of manager of the farm, the farmer’s son or daughter or whoever it is who’s taken over, and they’ll be our sort of route into the farm. Having said that, in South Africa, we’ve actually found the farmers are very sort of tech savvy … [and] open to experimenting. We haven’t been that limited. In the United States, it’s been a lot more of a challenge. There we’ve got a much higher success rate with younger guys and then older ones.”

Atarraya

Year of establishment: 2019
Operates in: Mexico, United States of America
Current number of users: Unknown
Target agricultural sector: Aquaculture (shrimp)
Interviewee: Daniel Russek

Biography: Daniel Russek is the Chief Executive Officer (CEO) and co-founder of Atarraya Inc. Enterprise, whose mission is to use technology and a market-oriented perspective to shrink our ecological footprint. Russek has a solid foundation in economics, augmented by hands-on experience in business analytics, software systems and business model creation.

Services

Atarraya has developed an automated and controlled shrimp farm ("Shrimpbox"), enclosed in a shipping container. Each container uses sensors, machine learning, big data, biotechnology (microbic farming) and robotics to control aquaculture operations, including nutrition intake, water quality and oxygen content.

Target customers and users

The company's targets are mostly shrimp producers, but they also target poultry farmers who have a similar business dimension and are interested to switch to shrimp farming. Additional targets are restaurants, universities, corporations and consumers that wish to provide and access fresh and sustainable seafood. Some of the target restaurants are partners of Atarraya.

Why Atarraya needed to digitize/automate

The high demand for shrimp worldwide and the damaging traditional practices of cultivating shrimp led Atarraya to develop this solution Traditional shrimp farms are prone to high losses due to rapidly spreading diseases. Such farms also have a serious negative impact on the environment, due to the pollution coastal waters and the destruction of mangrove forests, which are an important source of carbon sequestration worldwide.[1]

Business model and financial sustainability

The solution is not yet profitable because it is still in the early phase. The company previously relied on subsidies from the Government of Mexico, however, there is growing interest from private investors. The business model is still to be decided. Atarraya is not keen on operating the solution directly due to difficulties in scaling. Contract farming is the preferred option, where Atarraya leases the solution. However, the technology transfer should be smooth to make this option attractive. Some clients (from China) would like to buy the Shrimpboxes, but Atarraya is not yet ready for this model.

Scaling target

The scaling target for Atarraya is to expand further to the United States of America, starting in the state of Indiana.

Drivers

The Shrimpbox innovation was driven by the high global demand for shrimp, coupled with the environmentally-harmful practices of most shrimp farming. Current practices are associated with high losses triggered by rapidly spreading diseases and also cause the

[1] According to the interviewee, 50 percent of mangrove forests globally are destroyed due to shrimp farming.

destruction of mangrove forests, which are an important source of carbon sequestration. The service provided by Atarraya improves the sustainability and flexibility of shrimp production by, for example, not requiring the proximity of an ocean. A critical and promising factor for increased adoption is the generational shift: young farmers are much more open to implementing new technologies.

Barriers

Scepticism by established shrimp producers, coupled with remoteness of the shrimp farms, are driving the resistance to changes in business methods. In Mexico, poor road infrastructure is an important barrier, given the logistics required to operate a Shrimpbox.

Policy as a barrier or enabler

Public research and development grants from the Government of Mexico helped in the early stages but have come to an end. Indiana in the United States of America has a favourable ecosystem for implementing and distributing innovations for agriculture.

Top quotes

"Make shrimps the most popular source of protein, replacing chicken in an environmentally sustainable way."

"With Atarraya, you become ocean-saving farmers."

Cattler

Year of establishment: 2019

Operates in: Latin America and the Caribbean and United States of America

Current number of users: Unknown, but the solution has reached 90 million heads of cattle in the United States of America, 200 million in Brazil and 50 million in Argentina

Target agricultural sector: Livestock

Interviewee: Ignacio Albornoz

Biography: Ignacio Albornoz is the CEO and co-founder of Cattler Corporation. He is an entrepreneur in farming and renewable energy technologies, with experience in a variety of subjects and countries (Argentina, Brazil, Chile, Colombia, Mexico, United States of America) and in starting new ventures in the field of the Internet of things (IoT) and machine vision for agribusiness.

Services

Cattler started with two products: i) an animal weight predictor and ii) the automation of barn management. The company then developed a complete automated cattle farm management system, whereby sensors, satellite imagery, electronic tagging and feeding systems perform operations from automatic feeding to predicting daily growth rates and nutrition, to health scans and diagnosis, among others.

Target customers and users

Targets are mainly medium- and large-scale cattle farmers with between 2 000 and 40 000 heads of cattle that operate in the beef (feed-yard) sector. The company is now also targeting operators in the cow-calf and rangeland-based stocker segments.

Why Cattler needed to digitize/automate

Farmers in the sector need to perform their operations in a more integrated way to improve their efficiency. The potential afforded by data analytics to gain more insights is a significant add-on benefit.

Business model and financial sustainability

Money is still generated from sales of the two stand-alone products described above, although the company is currently focusing on the complete automated system. To operate the system, Cattler switched to a freemium model, with an entry level that is free. If users want to add devices or features, they must pay a subscription, which depends on what functionalities are included.

Scaling target

For commercial reasons, Cattler does not want to spread itself too thin. The company is happy to work in places with a similar business environment as in the United States of America, but it will not limit its presence to that country. It is now receiving some interest from Canada and will eventually consider Brazil.

Drivers

Demand is growing for the Cattler solution, since automating several operations in the beef livestock sector reduces costs significantly. Farmers in the sector are increasingly keen to perform these operations in a more integrated way to improve their efficiency.

Barriers

Farmers in the United States of America tend to be slower adopters than in Argentina. The reason given is that Argentinian farmers need to be more dynamic and competitive on the international market.

Policy as a barrier or enabler

Easy access to credit by farmers is an enabler. Political uncertainty in Argentina is a barrier, while in the United States of America, the Farm Bill is protective of traditional farming to the extent that, in some cases, it discourages farmers from adopting new solutions.

Top quotes

"We are looking for a balance between oversimplification (one product and market only) and hyper customization (stretched over too many applications)."

"Youth are seen taking over from the parents, the Boomer generation. They are more inclined towards digital (otherwise they will get bored in the farm, they would think of another career). Also, new business processes that are embedded, emerge with digitization."

CropIn

Year of establishment: 2010

Operates in: Primarily in India and sub-Saharan Africa

Current number of users: 225 clients (e.g. farming companies), enriching the lives of nearly 4 million farmers

Target agricultural sector: All crops

Interviewee: Arjun Goyal

Biography: Arjun Goyal is Director of Development and Programmes at CropIn Technology Solutions BV, a leading agritech business that has partnered with UN agencies and multilateral institutions, governments and foundations. CropIn is based in the Hague, the Netherlands. Goyal won the Global environment Facility's Challenge Program for Adaptation Innovation Challenge at the UN Framework Convention on Climate Change (UNFCCC)'s COP 26 in Glasgow for CropIn.

Services

CropIn offers a software platform that provides a complete farm management system. It uses technologies, such as big data analytics, artificial intelligence, IoT sensors and remote sensing, to provide insights across different aspects of the value chain and helps managers make better decisions. CropIn's product offerings also include: 1) an AI-ML powered technology platform that leverages data for risk mitigation and forecasting intelligence for credit risk assessment and business intelligence; 2) a comprehensive solution for packhouse, processing and export companies that enables farm-to-fork traceability, compliance, quality control and flexible inventory management; 3) a solution covering all aspects of sales – creating farmer loyalty, customer relationship management application, and decision-making on sales planning and forecasting; 4) a B2B farmer engagement application that helps businesses to reach, educate, promote and establish a direct connection with growers; and 5) an AI-powered risk mitigation solution for agricultural lending and crop insurance.

Target customers and users

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

Why CropIn needed to digitize/automate

There are significant data and information gaps at different levels of the agroecosystem, leading to information asymmetry throughout the value chain. CropIn seeks an opportunity to create a transparent end-to-end agribusiness supply chain and well-informed data-driven decisions, backed by a data-powered platform.

Business model and financial sustainability

Most revenue is generated from the enterprise sector (60–65 percent) and the remainder from the government and the banking, insurance and development sectors.

Scaling target

CropIn aims to reach twenty million farmers by the end of 2022. Being an ecosystem connector, CropIn wants to scale impact towards smallholder farmers, while building effective partnerships with investors and donors.

Drivers

Significant data and information gaps lead to information asymmetries throughout value chains and call for well-informed data-driven software.

Barriers

Barriers include a lack of digital assets, literacy and connectivity and risk aversion.

Policy as a barrier or enabler

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

Top quotes

“Farmers do not pay for services in the development sector. When you're depending on the grants, programmes by governments and humanitarian agencies such as World Bank, it is not a sustainable model. The banks, financial institutions and market off-takers need to have subsidized or incentivized the farmers to avail their offerings through CropIn’s digital platforms.”

“CropIn provides solutions and service delivery on a single integrable digital platform for every stakeholder in the value supply chain. So that's one of our greatest unique selling points.”

Egistic

Year of establishment: 2018
Operates in: Azerbaijan and Kazakhstan
Current number of users: Almost 1 500
Target agricultural sector: Crops
Interviewee: Zhandos Kerimkulov

Biography: Zhandos Kerimkulov has a master's degree in Automatization and Control Systems from Eurasian National University and a bachelor's degree in IT engineering from Satbeyev University. He is the CEO of Egistic.

Services

Egistic provides integrated solutions for monitoring and managing crop areas using remote sensing technology, high-precision satellite navigation, geoinformation systems and machine learning technologies. Services include analytics (yield forecast, crop rotation history); satellite images of fields; digital advisory services; GPS monitoring systems combined with tractors and harvesters; management of agricultural activities; and agrochemical soil analysis.

Target customers and users

Primary customers are large-scale farmers with landholding sizes varying from 5 000 to 1 million hectares. Users also include agriproducers, food distributors, agrochemical suppliers and fertilizer companies. Most registered users of the Egistic's services are in the 18–45 age group.

Why Egistic needed to digitize/automate

Farmers with large landholdings struggle with paper-based recordkeeping. Egistic's services provide them with an opportunity to digitally collect, store, analyse and visualize information to support data-driven decision-making. Egistic hopes to eventually become an ecosystem-level service provider by introducing market linkages for farm machinery and an e-commerce platform for agribusinesses. Also planned are capacity-building services, such as podcasts, videos and learning materials.

Business model and financial sustainability

Revenues are generated through annual subscription fees. In 2021, Egistic received its last round of grants and, since 2022, it has been financially sustainable and is attracting investors. The subscription also covers technical support, such as webinars, videos and a user guide.

Scaling target

To expand its market outreach, Egistic wants to focus on large-scale farmers with an average landholding of 20 000 ha. It also hopes to expand its clientele internationally to the rest of Central Asia, Canada and the United States of America.

Drivers

Large-scale farmers increasingly demand automated farm management solutions. This promises a high return on farm investments due to fuel savings for farm machinery.

Barriers

Poor internet connectivity in rural areas is the main barrier to adoption.

Policy as a barrier or enabler

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

Top quotes

"We are the only company in Kazakhstan, probably in the whole of Central Asia that works with remote sensing and provides farm management solutions as software-as-a-service (SaaS)."

"I interact with my customers in Kazakhstan on a regular basis. We believe farm mechanization will become a major trend in the coming 4–5 years. However, full farm-level automation may take 5–10 years."

Food Autonomy

Year of establishment: 2018

Operates in: Hungary

Current number of users: 2

Target agricultural sector: Microgreens, leafy greens, seedlings, cosmetic plants in vertical farming settings

Interviewee: Zoltan Sejpes

Biography: The CEO of Food Autonomy Kft., Zoltan Sejpes has over 20 years of leadership experience with large and diverse multinational teams and has achieved proven results in manufacturing engineering, LED lighting development, establishing complex manufacturing processes, quality assurance and works with different areas of the supply chain. He holds a master's degree in chemical engineering and business administration.

Services

Food Autonomy offers various crop production technologies and the corresponding hardware and software solutions for vertical farming. It provides full-scale, remotely controllable modular vertical farms for industry and research applications. All technologies are available as separate services, as well as being completely integrated into vertical farms.

Target customers and users

Clients include different sizes of farms – ranging from very small (30 m^2) to large (540 m^2) – for germination, research and production.

Why Food Autonomy needed to digitize/automate

The goal of Food Autonomy is to produce chemical-free crops, at high volume and with consistent quality and taste, while being affordable. Vertical farming has the potential to deliver this goal. Automation and digitization are central to this mission, where automated control of the entire vertical farm operation is needed.

Business model and financial sustainability

Current funding flows to the vertical farming business of Food Autonomy are primarily supported via internal investment from its indoor plant cultivation lighting business arm. The research farm facility of Food Autonomy has also been supported by a grant from the Government of Hungary. There are two business models: FaaS (farming-as-a-service), where Food Autonomy operates the farm on the user's behalf, and PaaS (plants-as-a-service), where it offers dedicated production capacity to the client.

Scaling target

Food Autonomy is currently in the process of developing a scaling strategy.

Drivers

Drivers include the increasing demand for organic, sustainable, high-quality and affordable produce; increasing interest in vertical farming; low energy and water use; and the possibility of producing food locally close to cities and in arid regions.

Barriers

There is a high initial investment cost.

Policy as a barrier or enabler

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

Top quotes

“The interest is huge, enormously big. We're … thinking about setting an entrance fee to our farm and establishing a visitor centre because of so many visitors. We like that because I think more and more people should be aware that this technology is not something that is artificial and produced in some kind of unnatural way, producing unnatural outcomes, so we are happy to do … [these] kind of visits.”

“I think the government should subsidize some way farmers to use these technologies, which are providing … environmentally-friendly, chemical- free, locally grown, fresh, tasty products.”

Garbal

Year of establishment: 2017
Operates in: Burkina Faso, Mali and soon Niger
Current number of users: More than 500 000
Target agricultural sector: Livestock (pastoralists) and arable crops
Interviewee: Catherine Le Come

Services

Garbal offers an integrated digital solution that provides smallholder farmers and pastoralists in the Sahel region with highly contextualized information about suitable grazing lands, herd migration, weather, farming practices and markets. The solution makes use of satellite and other data. It also includes a digital marketplace for obtaining fodder and selling milk and cereals. The service is available through a call centre or interactive voice response.

Target customers and users

Targets include small-scale farmers and pastoralists. Women represent between 22–30 percent of Garbal's users. Traders and herd owners are also targeted.

Why Garbal needed to digitize/automate

Agriculture and livestock are the backbone of people's livelihoods and food security in the Sahel. Climate change, uncertainty about the weather and market access and political unrest are challenging the traditional knowledge of farmers and herders and threatening their livelihoods. This solution has the potential to improve their access to markets, making the markets more inclusive, and to support their resilience and adaptation to shocks.

Business model and financial sustainability

The business model is based on a public–private partnership, which is crucial for overcoming the risk aversion of donors and funders towards developing innovative digital solutions in fragile contexts. The operational funding of GARBAL relies primarily on donor funding and contributions from project partners. Revenues come from calls made to the call centre, or modest payments to use the USSD service (cost based on airtime). Despite the revenue, which is reinvested in the solution, GARBAL is nowhere near the break-even point. The business strategy is to generate new revenue streams through the digital marketplace and a digital finance solution, which can help improving access to credit, such as by assessing clients' risk faster and at a lower cost.

Scaling target

The GARBAL solution can be adapted to the specific contexts and needs of smallholder farmers and pastoralists throughout sub-Saharan Africa, depending on opportunities and partnerships. The company acknowledges that scaling comes with challenges due to the need for contextualization.

Drivers

The GARBAL solution has the potential to improve farmer access to markets and to support their resilience and adaptation to shocks. The fact that Garbal is a public–private partnership has proved critical to acceptance of the solution by end users. Capacity building and the widespread use of mobile phones – despite these not predominantly being smartphones – has also enabled adoption. Finally, face-to-face engagement with local farmers, pastoralists and their organizations has been critical to gaining trust and increasing outreach.

Barriers

The barriers to adoption differ by country, reinforcing the need to adapt the solution to the national context. Political unrest and insecurity in some countries is a challenge, as is accessibility of the service since the internet regularly shuts down. Other barriers include a lack of infrastructure for digital solutions (for example, energy, connectivity, smartphones), lack of skills and awareness of the benefits of the technology and lack of data quality and data management.

Policy as a barrier or enabler

Support from local ministries has been instrumental; this includes sharing databases and providing content for the advisory services. However, political unrest and insecurity hamper investments in the current client countries.

Top quotes

“If we are scaling into a new geographical area, just as the local partners will be different, the strategy will also be different. So, it's all linked to ‘do you know your market?’ What are the key features of your markets and the end-users’ needs and habits?”

“Due to the scarcity of the mobile network, … [pastoralists and smallholder farmers] already know where they can get the network and when they are making calls to families, they often also make calls to the GARBAL service just to check for up-to-date information. So that's what we also learn from our evaluation, that the GARBAL service is not replacing traditional knowledge. It's being used as an additional source of information to cross check.”

GRoboMac (Green Robot Machinery)

Year of establishment: 2014

Operates in: India

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

Target agricultural sector: Multibloom cotton

Interviewee: Manohar Sambandam

Biography: Manohar Sambandam, founder and CEO of GRoboMac, is an active farmer and owns nearly 7 ha of farmland in the Thiruvarur District of Tamil Nadu, India. He has been farming since 2009, primarily growing cotton, paddy and legumes. With his background and interest in robotics, Manohar developed a cotton-picking robot. He is an executive member of United Progressive Farmers Forum and a member of India Farmers Network, a forum of progressive farmers in India.

Services

GRoboMac offers an electrically-powered, semi-autonomous precision machine that can pick cotton without damaging the crops, using high-speed robotic arms assisted by computer vision and artificial intelligence technology. It allows precision harvesting of multibloom cotton in multirow cropping systems.

Target customers and users

The initial target is medium- and large-scale cotton growers (greater than 5 ha), with the potential to eventually include small-scale farmers. In the longer term, the machine can be run by farm producer organizations, farmers' collectives and custom hiring centres – service organizations being promoted in India to run farm operations on a pay-per-use model.[2] The machine is intended to be primarily operated by women, who are the main workforce involved in cotton picking in India.

Why GRoboMac needed to digitize/automate:

A shortage in peak-time farm labour made GroboMac want to digitize.[3]

Business model and financial sustainability

The solution has not yet been commercialized. The company is mostly supported by personal investments and grants. In the future, the aim is to sell individual robots directly to customers and, in the longer term, to operators and service providers.

Scaling target

GroboMac intends to focus mainly on India, but the model may also serve West African countries, where cotton is becoming an increasingly popular crop and where farming practices are very similar to those of India.

Drivers

The main adoption driver is the lack of manual labour during peak seasons.

[2] The India Digital Ecosystem of Agriculture (IDEA), established by the Ministry of Agriculture and Farmers Welfare, has developed major digital applications to boost technology adoption among farmers and value chain actors. This has involved encouraging enterprises (private and NGOs) to innovate their business models in order to effectively work with smallholder farmers.

[3] The National Mission on Agricultural Extension and Technology (NMAET, 2020) has released a standard operating procedure for various forms of mechanization and automation in agriculture. This has become an adoption driver for enterprises working with precision agriculture.

Barriers

The benefits of the technology are still to be fully perceived by investors; return on investment can take a long time.

Policy as a barrier or enabler

The Government of India encourages agricultural start-ups by providing grants. GRoboMac was awarded a grant of about USD 30 000. The company also submitted a proposal for a grant following a Request for Proposals for Robotics-as-a-service in the southern Indian state of Telangana.

Top quotes

“Rain came and washed out my whole crop. I knew the rain was coming, but I couldn't get farm labour and that is what triggered me to start finding a solution for this. I went across the country and saw what's happening. And then I saw that cotton as a crop is completely manual in India. And so, I thought maybe this is the right calling for me and I should go ahead and solve this problem.”

“Much of my cost is on human resources and I'm competing with the best of the industry in vision, AI and robotics. But multinationals in India and a lot of other companies are picking them. Whenever I offer a job, the people stay on for 6–18 months, and they learn the trade and trade skills and then they move on. So that's a very fundamental problem I have. Unfortunately, I'm competing with the best in the industry for the best skills, robotics and AI and vision and those things.”

Harvest CROO Robotics

Year of establishment: 2013
Operates in: United States of America
Current number of users: Unknown
Target agricultural sector: Strawberries
Interviewee: Gary Wishnatzki

Biography: Gary Wishnatzki is the co-founder of start-up robotic company Harvest CROO Robotics (HCR) based in the United States of America. Its mission is to solve the problem of labour shortages through automation. The first project was the development of a robotic strawberry picker. Wish Farms – also owned by Gary – supports Harvest CROO Robotics and is a year-round berry supplier to supermarket chains throughout the United States of America and Canada. The company markets strawberries, blueberries, raspberries, blackberries and pineberries.

Services

Harvest CROO Robotics offers a complete manual labour replacement for strawberry growers. Each HCR Harvester is a single robot, with 16 independently working robotic arms and the vision systems needed to execute picking, inspecting, cleaning and packing operations on 16 rows simultaneously. The Harvester can navigate through a farm autonomously.

Target customers and users

Targets are large-scale strawberry farmers (greater than 10 ha) and marketing companies that work with farmers.

Why Harvest CROO Robotics needed to digitize/automate

For decades, labour shortages and increasing labour costs have been a challenge for strawberry growers. The problem became extremely serious in the 2000s and, in 2012, the Government of the United States of America established the H2A programme to enable the temporary employment of foreign agricultural workers as a temporary solution. Thereremains, however, is an urgent need to address this issue on a long-term basis. Robotic harvesting presents an attractive option. Yet any such solution must address all aspects of harvesting, including detection, inspection, picking, packaging and navigational autonomy. The HRC Harvester was designed to bring hardware, software, AI and data analytics together in a single platform for this purpose.

Business model and financial sustainability

The solution has not yet been commercialized. Funds were obtained from private investors and financial institutions, with the public sector playing a minor role. The business model is a “pay-as-you-go” service, where payments depend on the volume harvested (also known as the “harvesting-as-a-service”). In the event of high demand, it is projected that early contributors to the investment will have priority.

Scaling target

Harvest CROO’s target is to begin commercialization.

Drivers

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

Barriers

Scaling the manufacturing of required hardware and software is considered a barrier.

Policy as a barrier or enabler

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

Top quotes

“Our tagline is we're making farming fun again.”

“By the early 2000s it was becoming evident to me that less and less workers were showing up at the farm gate to do work in the fields. And by the late 2000s, it was getting to critical stages where we were actually abandoning fields early in the season because there wasn't enough harvest labour.”

”I compare our technology right now to the cellphone of the 1980s. It was this big brick that you held, and it was only to make calls. But nobody back then, including myself, imagined a smartphone of today and all the things you could do with that technology. So I mean right now growers just want to make that phone call. If you ask any grower, I just want to get my berries picked, you know. I don't care about all that other stuff [referring to by-products of HCR robot, such as advisory, forecasting, etc.], but all of that other stuff is coming.”

Hortikey

Year of establishment: 2015
Operates in: Netherlands
Current number of users: Undisclosed
Target agricultural sector: Tomato
Interviewee: Andreas Hofland

Biography: Andreas Hofland has been General Manager at Hortikey since 2016. He holds a master's degree in System Engineering, Policy Analysis and Management from the Technical University of Delft.

Services

Hortikey offers an integrated farming system comprising a self-driving robot equipped with cameras, smart software that uses algorithms and artificial intelligence to provide reliable data and crop estimations, including the number and ripeness of tomatoes, through daily measurements and with no need for additional infrastructure. The insights from the data, combined with climate and meteorological data, are used for business-specific harvest forecasts from one to four weeks into the future.

Target customers and users

Target customers are medium- to large-scale commercial tomato growers (with farms greater than 10 ha) in controlled environments (such as greenhouses).

Why Hortikey needed to digitize/automate

The current benchmark for tomato crop forecasting is manual, and only a very small sample of the overall crop can be monitored manually in a greenhouse. This process of forecasting is like the technique used 100 years ago, while farm sizes have grown tremendously since then. A company that in the past owned 5 000 m^2 of land now owns 500 000 m^2 and longer feasible to use the traditional methods. A rethinking of process deployment is necessary, where monitoring can be automated, standardized and scaled up for crop forecasting.

Business model and financial sustainability

Revenues are generated from the sales of robots and monthly subscription fees for the software. Otherwise, both are available for a total monthly fee under a service contract. Development is supported with investments from the shareholders.

Scaling target

Hortikey is currently in the starting phase of commercialization and expansion in Western Europe, Northern America and the Middle East.

Drivers

Crop forecasting provides valuable information for growers; variability in tomato prices calls for accurate estimates of production capacity. There is a need for expertise in tomato growing as farm sizes increase.

Barriers

Some tomato growers are sceptical regarding the technology. Confidence can only be built over time.

Policy as a barrier or enabler

The Dutch Knowledge and Innovation Agenda promotes investment in innovation (Topsector Agri & Food, 2022). However, some countries have laws that prevent data sharing abroad, which makes it difficult to expand into certain markets.

Top quotes

"The benchmark, so how people are working right now is they count on their own, so it's manual counting of tomato plants. But the problem is that it's processed in a way it was done like 100 years or so. In time, the companies have been growing. So they used to have, for example, in the old days, a company of 5 000 square metres. But now they own a company of 500 000 square metres. They are stretching their way of working, but it's in the end impossible to continue in that way. So, if the companies are getting bigger and bigger, you need to rethink about how you are deploying your processes in the company."

Igara Tea

Year of establishment: 1969. In 2017, Igara Tea started to invest in digital solutions

Operates in: Uganda

Current number of users: More than 7 000

Target agricultural sector: Tea

Interviewee: Hamlus Owoyesiga

Biography: Hamlus Owoyesiga is the Manager of Digital Solutions at Igara Growers Tea Factory Ltd. (IGTF). He is a certified unmanned aerial systems (UAV) operator. Previously, he served as Igara Tea's information technology (IT) systems administrator for eight years and concurrently managed the implementation of European Union-funded digitalization projects (2017–2020).

Services

Using digital technologies, Igara Tea acquires and manages information on tea farmer profiles, farm boundaries, land use and cover; tracks, traces and monitors the production and delivery of tea leaves to the processing plants; assesses the health status of tea plants and simulates production capacity; supplies inputs commensurate with profiled farms; provides tailored advice and e-extension services; and enables access to credit. In the future, small mechanization devices are envisaged, to improve precision and reduce the labour of tea leaf pickers.

Target customers and users

Igara Tea's targets are primarily smallholder tea farmers (1.5–2 ha), who are shareholders of Igara Tea. About 18 percent of users are women and 65 percent of farm labour is done by young farmers. Women and youth comprise more than half of the workforce involved in processing tea leaves. Banks and credit providers are also targeted as customers.

Why Igara Tea needed to digitize/automate

Digitalization was necessary since Igara Tea had no way to trace its 7 000 farmer shareholders. Igara Tea had no information about their precise location, size of farm, production and financial capacities, nor any means of calculating input requirements, etc. Additionally, traceability of the tea leaves was a problem, as was data on farm productivity. Digitalization started with support from the Technical Centre for Agricultural and Rural Cooperation (ACP-European Union) in 2017. In 2018, Igara Tea started mapping and profiling its tea farmers, established a farmers' database complemented by a geographic information system, and acquired UAS capacities. Further improvements included the issuance of farmers' cards, the deployment of digital scales and point of sale devices at collection points for tea leaves.

Business model and financial sustainability

Today, Igara Tea acts as a provider of technical assistance, advance input supplier, buyer, processor and seller of tea. It sells tea on local and international markets on behalf of its shareholders (tea farmers), who sell their raw material to the company. Digitalization helps to optimize the procurement process, saving up to 70 percent of costs associated with receipt books, pens, paper, etc. The payback time for investments in digital hardware and software was 1.5 years. Today, the company invests – without grant funding – in both hardware and software.

In 2016, Igara Tea farmers delivered a total of 25 623 metric tonnes of tea leaves to processing plants. In 2021, once the digitalization of the value chain from farm to processing plant had been completed, delivery increased by 56.6 percent, reaching 42 000 metric tonnes of tea leaves.

Scaling target

Currently, the company is limited by the capacity of its two processing plants. Igara Tea has been approached by the Government of Uganda and by stakeholders involved in procuring and processing other cash and export crops in that country (such as coffee, cotton, other tea processors) to share its experiences in digitalization.

Drivers

Demand for increased certainty, transparency and timeliness for the buyer (Igara Tea), farmers and loan providers are the main factors driving adoption of Igara Tea's solution. Increased labour costs are driving the development of tea leaf pickers.

Igara Tea has invested in awareness building through radio programs and face-to face meetings and has introduced a policy on data protection. Its extension officers (data collectors) have been trained in the use of digital tools and data. An important factor that helped to convince farmers to register was the prospect of improved access to customized services.

Barriers

Limited tea leaf processing capacity is hindering expansion. Other barriers include low tea prices worldwide and lack of financial capacity of farmers to invest in machinery. Igara Tea is looking into developing a sharing scheme for mechanization.

Policy as a barrier or enabler

The Government of Uganda is determined to advance the use of technological solutions to solve the country's development challenges. However, it is still difficult to obtain financial support from government sources. High levels of bureaucracy, which translate into higher costs, act as barriers as does a lack of clear regulations and policies on using drones.

Top quotes

"Farmers were double dealing in several banks … using the same property as a collateral."

"Before we could introduce the system,[4] there was no way that you could … [refuse to register a farmer] because everything was really by the use of eyes. So, you would not really reject to say, 'I'm not going to enroll you based on the fact ABC', because in the first place you do not know the boundary of the father and the son [if each has their own land]. So, the only choice you had was to issue both of them a number [and register the same farm twice in the system]."

"If you look at the graph of our production right now, the trend is moving up and up and up. In 2017, we were receiving about 28 million [kg of tea leaves]. Last year we received 43 million. This is such a significant progress because of the trust and the confidence created on the on the side of the farmers, who are really suppliers of the raw material to this company."

[4] This refers to a geographic information system fed with georeferenced data gathered during the profiling process.

ioCrops

Year of establishment: 2018

Operates in: Republic of Korea

Current number of users: More than 200

Target agricultural sector: Indoor crops (such as greenhouses for tomato and bell pepper)

Interviewee: JinHyung Cho

Biography: JinHyung Cho is co-founder and CEO at ioCrops Inc. He has been a researcher at the Korean Institute of Science and Technology. He holds a master's degree from Pohang University of Science and Technology.

Services

ioCrops offers autonomous crop management solutions, including climate monitoring on indoor farms; a data analysis and decision-making platform; crop management advisories and forecasts; automated cultivation; remote farm operations allowing the management of farms across the world from a distance, without the need for specialized greenhouse managers at each farm.

Target customers and users

Targets include medium- (> 1 ha) to large-scale (> 2 ha) greenhouse growers, primarily in the Republic of Korea. It is estimated that in the Republic of Korea fewer than 10 percent of greenhouses are owned by women, and fewer than 30 percent by young people.

Why ioCrops needed to digitize/automate

The goal of ioCrops is to increase profitability and scalability, and this objective has steered the company towards providing digitization and automation solutions, for example:

- supporting non-expert growers by making use of data rather than experience;
- supporting expert growers as their farm sizes increase; and
- using (and maturing) ioCrops solutions to bring revenue to ioCrops, as the company itself becomes a producer of indoor crops.

Business model and financial sustainability

The company's revenue is generated by the sale of sensors and web-based solutions. ioCrops also rents out automated greenhouses and controls the complete greenhouse plant operations, ranging from climate and crop management to labour and post-harvest logistics management. Most of the investment flow is from venture capital funds, with limited contributions from subsidies.

Scaling target

The focus is on the Republic of Korea's market in the near term, but with the ambition to expand globally.

Drivers

Growers increasingly require automated solutions as their farm sizes increase. The area devoted to greenhouses is growing, as are the number of large-scale producers. The younger generation is more open to IT solutions. Wages are increasing and labour supply is declining.

Barriers

Some farmers are sceptical about high-tech solutions; there is also the risk that this technology will push smaller producers out of business.

Policy as a barrier or enabler

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

Top quotes

"At the beginning, our approach was that only experienced growers could make profit and people who weren't very good at growing the greenhouse still remain on that site. But people who are making profit there, they could increase in their [production] area. So that's where we've seen there was an opportunity if data could increase their profitability and then that can help."

"So small-scale growers are not any more sustainable in terms of economics. Small-scale growers are decreasing … because they're getting older and then many people don't want to work in agriculture, and they want to have more … [fancy] jobs. I think that agriculture is the fanciest job."

Lely

Year of establishment: 1948

Operates in: Europe (especially the Netherlands), Northern America and Australia

Current number of users: More than 25 000

Target agricultural sector: Dairy

Interviewee: Martijn Bruggeman

Biography: Martijn Bruggeman is Senior Subsidy Advisor at Lely. He is responsible for the subsidy/grant department and is the main contact with knowledge institutes. His broad experience in tech companies and analytical abilities makes him a valuable specialist in advising organizations on financial/economic issues.

Services

Lely delivers robotic and software solutions for dairy farming. Specifically, it provides stationary milking, manure and feeding robots, and is developing a barn management solution to control gas emissions, as well as grass harvesting robots to optimize grass production and feeding of cows. Additionally, Lely's management software provides information and advisory services on all farm operations, including animal health and welfare.

Target customers and users

Target customers include medium-to large-scale dairy farmers with more than 100 cows, but not the very largest.

Why Lely needed to digitize/automate

Lely's solutions respond to labour constraints and the need to reduce tough and repetitive work. The company aims to assist farmers to follow environmental regulations, reduce emissions from the barn, which is especially important in the European Union, and finally, to improve animal welfare – with the goal of a clean, low-emission barns – and ensure that milking machines do not cause harm to animals.

Business model and financial sustainability

Revenue is generated through sales of the Lely's solutions and service contracts. Lely also offers financial and lease solutions, which lead to greater adoption by farmers. It receives funding through grants (national and European Union). Turnover is estimated at EUR 650 million, and a significant share of this is reinvested in research and innovation.

The sector is booming worldwide particularly in South Europe, South America, and Asia for example. The market is growing faster than the company can deliver.

Scaling target

The company aims to move beyond the markets they reach today, especially in Asia and South America.

Drivers

Drivers include a demand for more flexible working schedules and less drudgery; labour shortages; the need to comply with environmental regulations (such as emission reductions on dairy farms); concerns about animal welfare; provision of financial services; gains in energy efficiency and the use of renewable energy sources. Lely offers solutions that are easy to integrate into conventional farms.

The energy efficiency of Lely's solutions is the highest amongst its competitors, as others are less focused on this. Given the rising cost of chemical waste, chemical use reduction is becoming increasingly relevant. Similarly, increased climate awareness has prompted an interest in reducing emissions in barns. Lely's solutions are independent of external energy sources, since they use solar and wind energy to power the robotic products.

Barriers

None were mentioned.

Policy as a barrier or enabler

Policy-related adoption drivers are environmental and animal welfare regulations and subsidy programmes to invest in barn solutions for reducing emissions. However, adoption can be delayed, because farmers often wait for subsidies to arrive before investing. Discussions in Europe on regulations for free animal movement and natural behaviour need new strategies for adapting the milking solutions offered at present.

Top quotes

"Medium-scale farmers are the best adopters, not the largest."

"Farmers are more interested in robustness and easiness than in [a] lot of features in the solution."

"We also have grass harvesting robots; but farmers at times prefer to mow on their own, riding the tractor on a nice summer day."

Seed Innovations

Year of establishment: 2019
Operates in: Nepal
Current number of users: 1 500
Target agricultural sector: All crops
Interviewee: Suman Ghimire

Biography: Suman Ghimire is an agritech entrepreneur on a mission to help farmers in developing countries make climate-smart and satellite-based agricultural decisions on their farms. Suman is the CEO/founder of Seed Innovations Pvt. Ltd. Before his entrepreneurial journey, he worked as a researcher at the department of Environmental and Natural Resources Management, University of Patras in Greece. He possesses a strong interest in geospatial technologies, machine learning, entrepreneurship, agriculture and food security.

Services

Seed Innovations offers an android application providing farmers with satellite-based analytics to monitor crop performance, including the identification of threats such as water and nutrient deficiencies or surplus, and to access and exchange agronomic information. Services also include nitrogen and plant moisture calculators, farm calendar notifications, expert assistance, weather information and ability to farmers to register data about their farm.

Target customers and users

Seed Innovations targets mostly medium- to large-scale farmers for satellite-based advisory services and market-oriented smallholders for generic advisory services.

Why Seed Innovations needed to digitize/automate

Access to advanced technologies (such as satellite-based intelligence) was until recently mostly available to researchers and scientists. Seed Innovations' PlantSat application facilitates data-driven agriculture by making such information directly available to farmers. This enables them to optimize the use of resources such as water and fertilizers, and to make farming more sustainable and profitable.

Business model and financial sustainability

Currently the solution is free for farmers. The plan is to sell annual subscriptions to insurance companies, which will give them access to data, enable them to monitor crop and farmer performance, and make farmers eligible for insurance (pay outs). Approximately 40 percent of current funding comes from grants.

Scaling target

India (2025), South Asia (Bangladesh, Pakistan) thereafter, eventually all of the Global South.

Drivers

PlantSat is a bundled service solution, integrating various functionalities that a farmer can use independent of the crop produced. The application was also made as simple as possible for farmers, reducing the need for data connectivity (offline data entry is possible) and the cost of operations (for example by limiting the server space required to store data points).

Barriers

Scepticism towards new technologies is a barrier to adoption.

Policy as a barrier or enabler

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

Top quotes

"Everyone was so excited and they were saying … this is a very big breakthrough … But when it came to actual implementation, we can't force them [to use PlantSat] and they're sceptical and they don't [use the application]."

"[Farmers] are sceptical about this kind of technology, so they don't use it … often."

"We can't force them to do the task or we can't force them to like … top dress[5] … But insurance companies, they have that capability."

"So, then I realized insurance is a very key thing. That we need to enter into that channel, because farmers are obliged to follow or obliged to do the works that insurance companies tell them so."

"You see like what happens when farmers get engaged in insurance or they are insured is they can take more risks. […]."

5 Top-dressing is applying fertilizer to the soil surface in the proximity of a plant.

SeeTree

Year of establishment: 2017

Operates in: Brazil, Chile, Greece, Mexico, Portugal, South Africa, Spain and United States of America. Data analysis, research and development are carried out in Israel.

Current number of users: More than 3 000

Target agricultural sector: Fruit and nut trees

Interviewee: Israel Talpaz

Biography: Israel Talpaz is co-founder and CEO of SeeTree. A leader and a highly skilled strategist, he is an expert in constructing and applying operations, technology and analytic processes. Talpaz is active in the international arena, running complex campaigns in specialized domains of expertise and coping with different cultures and environments.

Services

SeeTree offers digital solutions through its data intelligence platform to monitor tree health, fruit optimization and growth; manage inventory and production; estimate yield, track farming operations and measure their impact.

Target customers and users

Target customers are mainly large-scale growers and fruit cooperatives that reach small-scale growers.

Why SeeTree needed to digitize/automate

Growers with large orchards invest significant amounts of input resources (fertilizers, pesticides) and manpower hours. Without the precision application of resources, farm productivity and profitability decline, thereby increasing uncertainty around yield as well as market price speculation. The artificial intelligence data from the SeeTree platform is validated by machine learning and local agronomists have a strong potential to make tree farming cost-efficient and to conduct interventions for smart marketing.

Business model and financial sustainability

SeeTree's business model is based on an annual subscription fee that enables clients to access the services of the data intelligence platform, either via a web-based or a mobile-based application. The services help growers to ensure the precise application of resources, as well as to effectively manage inventory and ensure the efficiency of staffing hours. The platform generates an annual revenue of USD 30–100 per hectare. The larger the landholding, the lower the per hectare price.

Scaling target

Have global scope. Australia, India and Indonesia are potential markets in the near future. The company also hopes to scale its intelligence platform across additional farming sectors, including tea, cacao, rubber and timber.

Drivers

There is a huge demand by large-scale growers with substantial landholdings for ways to increase productivity and resource-use efficiency and reduce uncertainty regarding yield and market prices. There is also a growing interest in sequestering carbon to obtain carbon credits.

Barriers

One of the main barriers to adoption is the scepticism of growers around digital technologies. In addition, the lack of or limited digital literacy hinders understanding of the value of the solution. Furthermore, growers expect “a one-stop shop” for implementation of the recommendations (on tree health, fruit optimization and growth, etc) made by data-driven decision-making and networking with local supply chain actors. However, in some locations, weak market linkages between input suppliers are also slowing adoption and preventing some growers from accessing and implementing SeeTree’s solutions.

Policy as a barrier or enabler

Nothing was mentioned.

Top quotes

“Big growers know each other. Their word of mouth is one of the biggest adoption drivers.”

“When you want to do something with the trees, we want you to contact SeeTree.”

“Growers subscribed to our platform to buy fewer chemicals and not only to reduce the negative environmental impact, but also to reduce their carbon footprint by precise inventory and farm management.”

SOWIT

Year of establishment: 2017
Operates in: Ethiopia, Morocco, Senegal and Tunisia
Current number of users: 17 490
Target agricultural sector: Fruits, cereals and rapeseed
Interviewee: Hamza Rkha Chaham

Biography: Hamza Rkha Chaham is the co-founder of SOWIT, a start-up that provides decision-support systems to African farmers. SOWIT is incorporated in France, Morocco and Senegal and leverages all the power of remote sensing, AI and agronomy to provide key insights to farmers, enabling them to optimize crucial operations such as fertilization or harvest. Chaham is co-author of a landmark report published by the African Union in 2018: *Drones on the horizon: transforming Africa's agriculture*.

Services

SOWIT offers digital solutions that provide decision-support tools and information insights to farmers on citrus, olive, apple, cereals and rapeseed, mainly regarding irrigation, fertilization, crop health and yield estimation. An additional service monitors the dry matter content of forages, taking into consideration intraplot heterogeneity to optimize harvest and ensilage quality.

Target customers and users

SOWIT's targets are large-scale agribusinesses and medium- and small-scale farmers (directly or via aggregators), government agencies and financial institutions. In Morocco, more than 20 percent of the company's farmer clients are women. SOWIT staff also includes a large share of women (44 percent), and everyone falls within the youth category.

Why SOWIT needed to digitize/automate

Climate change and other factors are increasingly impacting the availability of water for irrigation. The resource is dwindling and costly. A system that offers daily location-specific recommendations on irrigation delivery is an effective solution. Likewise, the cost of fertilizer has been increasing and farmers need to optimize their use of inputs. One of SOWIT's solutions enables farmers to deploy variable rate applications of nutrients, especially nitrogen.

Farmers need more affordable crop insurance policies. SOWIT offers an alternative to index-based insurance since it is in the position to provide yield estimates based on the actual situation. A farmer insures their crop for a specific expected yield, which is compared with average yields in in the different agroclimatic zones. If the farmer anticipates a lower yield, they trigger a digital assessment, the results of which are compared by the insurance company with their data sets. If due, a compensation payment from the insurance company to cover the losses is released.

Business model and financial sustainability

SOWIT's main business model is based on an annual multitier services subscription. The price per hectare varies (between USD 10–70 per ha per year) depending on the number of decision-support tools requested and including both mobile and web-based multilingual access interfaces. SOWIT has secured financial resources through equity fundraising and grants from development agencies such as the United States Agency for International Development. In 2021, grant funding represented 25 percent of turnover.

Scaling target

SOWIT aims to have the 100 top African agricultural organizations as its clients. New target countries include Côte d'Ivoire, the Democratic Republic of the Congo, Egypt and Gabon.

The company aims to build a virtuous circle for agricultural data in Africa that would enable smallholder farmers to access free information about their farms, including multiple crops. In turn, this data would assist SOWIT's paying clients (agribusinesses, insurance, financial institutions, government agencies) to obtain more precise and aggregated data about their own clients, the farmers, to better serve them.

Drivers

Climate change and other factors affect the availability of water for irrigation and increase the need to optimize its use. Hence, a system offering daily location-specific recommendations on irrigation delivery is needed. Another solution offered by SOWIT can optimize fertilizer use, whose cost is also on the rise.

The solutions are available in different languages (Arabic, English and French) and are designed to be accessible to less literate people via smartphones or the internet.

Barriers

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

Policy as a barrier or enabler

In Morocco, the government is investing in innovating the agricultural sector, for example by promoting agricultural entrepreneurship among young people, reinforcing the role of agricultural cooperatives and developing new subsidies for digital solutions. In particular, the country's Generation Green 2020-30 Strategy aims to connect two million farmers to digital platforms, including SOWIT. On the other hand, the absence of regulations on the use of drones is a barrier to development of the technology. For this reason, SOWIT has switched to satellite remote sensing.

Top quotes

"Privacy has been taken into consideration by design. I mean, if you don't do it by design, even if we felt it was painful at the beginning, but I believe that there is a certain virtue in doing it this way because then you get the trust of all stakeholders. We couldn't have signed the research agreement with CIRAD[6] if we were not also up to date on this aspect."

[6] CIRAD is the French agricultural research and cooperation organization, which works for the sustainable development of tropical and Mediterranean regions.

TraSeable Solutions

Year of establishment: 2018

Operates in: Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga, Cook Islands and Vanuatu

Current number of users: More than 2 000

Target agricultural sector: Crops, tuna and soon timber

Interviewee: Kenneth Katafono

Biography: Kenneth Katafono is Founder and Managing Director of TraSeable Solutions Pte Ltd – Fiji. Katafono launched the company to help address the issue of illegal, unregulated, and unreported fishing by making cutting-edge technology for digitalization and traceability accessible and affordable.

Services

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

Target customers and users

Targets are mostly smallholders, although some are medium-scale. The company also works with farmers' organizations and agribusinesses, mainly those involved in exporting commodities. Women and young people represent approximately 40 percent and 15 percent of users respectively. Additional customers of TraSeable Solutions include development organizations. These are interested in data, mainly on a regional scale.

Why TraSeable Solutions needed to digitize/automate

There are a great many gaps in the agricultural value chains of the Pacific, and a solution such as that offered by TraSeable Solutions can help to bridge such gaps.

Addressing illegal, unregulated and unreported fishing of tuna required a user-friendly mobile system that could facilitate monitoring activities. A digital solution based on a range of technologies is now in use.

Business model and financial sustainability

The solution for farmers can be downloaded at no cost, but farmers' organizations, agribusinesses, fisheries and processing plants pay a tiered-based subscription fee to access the services. The company also provides consultancy services, which represent the bulk of its revenue. The company has received grants to fund its business.

Scaling target

The TraSeable Solutions application was released in 2020. The growth of downloads has been remarkable, probably in part due to limitations on face-to-face contacts imposed by COVID-19 restrictions. The challenge is to maintain momentum, keep registrants engaged and stimulate use. The company monitors use of the app. The market price function has been one of the most widely used. Young people are most interested in information on how to grow crops, while more entrepreneurial farmers have used the app to generate profit-and-loss statements so as to be in a position to apply for financing.

The company aims to increase its customer base to include East Timor, the Federated States of Micronesia, Marshall Islands and New Caledonia, and plans on growing the subscription model to be the primary revenue earner.

It is also working on a traceability solution for high-value timber used to manufacture musical instruments.

Drivers

Drivers of adoption include: an increasing interest by producers – especially exporters – in collecting data in a cheaper and more effective way; a growing interest by farmer organizations in capacity-building and advisory services; and the need to comply with food safety regulations and traceability. The COVID-19 pandemic has accelerated interest and uptake of digital solutions. Development agencies consider the capacity of TraSeable Solutions in networking across the region and data gathering as an interesting value proposition.

Barriers

Strict data regulations impede the creation and management of digital solutions. Digital literacy is low among farmers.

Policy as a barrier or enabler

Not mentioned.

Top quotes

"I think a lot of organizations, large and small in the Pacific, also don't value data as much as they probably should. It's not something that they used to collect and use in the decision processes."

"We have small populations; the cost of labour is increasing. It's very difficult to get farm labour. A lot of people are joining the seasonal worker programmes in Australia and New Zealand … This leaves big gaps in the Pacific. I think there is a place for these [mechanization and automation solutions] in the future."

TROTRO Tractor

Year of establishment: 2016
Operates in: Benin, Ghana, Nigeria, Togo, Zambia and Zimbabwe
Current number of users: 75 000
Target agricultural sector: Arable crops
Interviewee: Kamal Yakub

Biography: Kamal Yakub is co-founder of TROTRO Tractor. He is an experienced CEO with a history of working in the technology and financial services industry. He is skilled in strategy, business management, business development and financial accounting, with a strong start-up mentality.

Services

TROTRO Tractor offers a digital rental platform that matches smallholder farmers with a vast range of agricultural machinery and equipment and the owners of that machinery, who provide hire services. Recently, TROTRO Tractor has also included drone owners, who offer their services in mapping and spraying. All machines are equipped with TROTRO Tractor's IoT tracking devices. Customers can access the service through a smartphone application and an unstructured supplementary service data (USSD) service.

Target customers and users

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

Why TROTRO Tractor needed to digitize/automate

Most farmers in Africa are smallholders, who cannot buy a tractor and often cannot even afford to rent a tractor for a full day. TROTRO Tractor makes tractors and other mechanization appliances affordable for farmers to rent by breaking down the use-cost to the hectare or acre level.

Business model and financial sustainability

TROTRO Tractor's main revenue stream is the matchmaker fees (10 percent per transaction) that the company receives for each agricultural machinery service that is contracted. Additional revenue is generated by selling tracker devices, which are mandatory for owners renting out equipment. The company is profitable in all countries where it operates, except for Ghana, where only about 40 percent of registered users recur as clients each season. The company partly relies on grant money, which is mostly used to expand the business.

Scaling target

The vision is to scale to a level where TROTRO Tractor has decentralized mechanization centres in every farming community in the countries where it operates.

Drivers

Most small-scale farmers cannot afford to buy a tractor and must resort to rental markets if they are to mechanize their farming operations. TROTRO Tractor's solution enables transparency and reliability of access, which was not possible in the context of traditional market mechanisms. Women farmers are progressively using the service, thus allowing them access to mechanization that they otherwise would not be due to social norms. Young farmers also prefer the service, as they are more dynamic and open to innovative solutions. Some young people have trained as machine operators. The COVID-19 pandemic accelerated the digitalization of agriculture and gave a push to this solution. The adoption of drone services is being driven by growing demand from farmers to have accurate land data, since this can help them to obtain finance, credit and insurance.

Barriers

Barriers include an increase in fuel prices, which make the service inaccessible for some farmers, and a lack of credit and finance for operators to buy machinery to rent to farmers. Poor road infrastructure also impedes transport of the machinery and the capacity to make the service available in different places.

Policy as a barrier or enabler

The provision of subsidies and incentives to farmers to produce staple crops has encouraged mechanization, as have investments in infrastructure and digital technologies.

Top quotes

“The pandemic has really shown that I can use my phone to get food. I can use my phone to work. I can do so many things with my phone, the things that we didn't do before the pandemic.”

“These guys [young tractor operators], when they go to the banks to request a loan to buy a tractor, they have 0 credits. … [T]here's no system to allow them to get a tractor to serve farmers, and if we don't have more tractors then we will still get small commissions. And then at some point we just give up and say ‘There's no profit in this business.’ But the more we get service providers on the platform, the more our commissions would also come, and then we can continue to do the business.”

Tun Yat

Year of establishment: 2017
Operates in: Myanmar
Current number of users: More than 20 000
Target agricultural sector: Primarily rice, mung bean, sesame, groundnut, maize
Interviewee: Hujjat Nadarajah

Biography: Hujjat Nadarajah is the co-founder and CEO of Tun Yat. He has skills and experience in agile, lean-start up and change management processes. He has grown many organizations, business units and corporate brands, following processes and strategy to develop vision and know-how and to effect change. His direct experience is with the start-up, retail, advertising, government and non-profit sectors, using a global adaptive leadership style. Nadarajah promotes community engagement from grassroots to boardroom levels.

Services

Tun Yat offers mechanization services targeting smallholder farmers in the delta and dryland regions of Myanmar. Tun Yat maintains its own fleet of five tractors and five combine harvesters and acts as a matchmaker between machine owners and farmers. Services include ploughing, land preparation, seeding, combine harvesting with different headers for different types of harvest (e.g. mung beans or maize) and picking (e.g. sesame or groundnut).

Target customers and users

Targets are mainly smallholder farmers (0–2 ha), although medium-scale farmers (2–6 ha) or farmer groups with medium-scale consolidated farms (>6 ha) are also targeted. Approximately 30 percent of clients are women, and 25–30 percent are young people below the age of 30. The company targets farmers who do not own and cannot afford to buy a tractor. It makes modern and more advanced mechanization technologies accessible as a service – for example, laser levelling of land surfaces.

Why Tun Yat needed to digitize/automate

Widespread mechanization in the form of two-wheel tractors is available, but most households cannot afford them. Four-wheel tractors have been introduced in recent years and are growing in numbers, but their availability was fragmented, and the service delivery was unreliable, so better aggregation and organization were needed.

Business model and financial sustainability

Revenue is generated through payments for the service; the payments vary on a per-acre or per-hour basis. The highest margins are generated from providing direct services with their own fleet. Smaller margins come from matchmaking services. Tun Yat also generates revenue by conducting research in South-eastern Asia on matters related to their business.

Scaling target

In the long term, the plan is to offer a bundled service platform that includes the sale of seeds and fertilizers as well as machinery, and to make the service available across South-eastern Asia and beyond.

Drivers

Farmers are mostly unable to afford their own machinery yet demand for reliable and affordable mechanization services is high. Other drivers include unreliable service delivery of such machinery and increased penetration of mobile and smartphones, which allows users to access the digital platform.

Barriers

Barriers include: increasing prices for inputs and fuel; the fact that users can bypass Tun Yat's matchmaker service once they know each other; limited digital literacy and connectivity; low levels of trust, for example in mobile payment. There is a need for technological handholding and capacity building.

Policy as a barrier or enabler

The Government of Myanmar is committing to digital policies, but the current uncertain political environment hampers innovation and investment. Furthermore, existing policies related to digitalization and data use are more focused on cyber security and surveillance, which can also slow adoption.

Top quotes

"As mechanization increases as an upward trend across the country, farmers move from a hanging-in to a stepping-up stage of development. When this happens, groups of farmers (or relatives) then pool money together to buy a tractor, where four or five families join and chip in to buy a tractor. When that happens, then they no longer need an external service provider like Tun Yat and then themselves use their machines to till/harvest their own lands and rent these out to other villagers in their area. So then, we work ourselves out of this first level of service and look at more complexity – where we supply other inputs, more specialized precision equipment like laser levelers, and start linking harvested crops to off takers, or process it ourselves, and move towards tech-enabled solutions that link transactions of inputs to credit profiling and financial institutions interested in financing inputs for these farmers. Therefore, as the cluster grows and becomes more complex, our level of services multiplies and penetrates further, to meet their needs and assist with their growing response and capacity."

"[An i]nteresting point for Myanmar is that there was a huge smartphone penetration in the last couple years. So, we have a very high rate of smartphones, even among farmers, like at least one [person] in every household has got a smartphone."

UrbanaGrow

Year of establishment: 2019
Operates in: Chile
Current number of users: Unknown
Target agricultural sector: Leafy green vegetables
Interviewees: Maricruz Larrea, Eduardo Vásquez

Biography: Maricruz Larrea is the co-founder and CEO of UrbanaGrow, a vertical farming start-up. She is an accomplished, results-driven operations manager with nearly 15 years of project management experience throughout Latin America and the United States of America. Larrea has direct responsibility for strategic planning, selecting and training teams, and managing budgets and budget cycles.

Services

UrbanaGrow offers modular units for vertical farming in a highly controlled environment. Products are mostly leafy greens, such as lettuce and basil. The farms use light-emitting diode lights and sensors to control temperature and humidity, in addition to a water recycling system to minimize water consumption. Production is tailored to the needs of clients.

Target customers and users

Clients include all operators at the end of food supply chain, such as retailers, supermarkets, restaurants, consumers and occasionally governments, who want to produce fresh vegetables for sale or consumption.

Why UrbanaGrow needed to digitize/automate

This solution seeks to provide reliable food production, independent of weather conditions to mitigate the effects of climate change. In this way it contributes to both food security and food safety. The eventual aim is to run entirely on green (solar) energy, and to set up operations in remote areas that are difficult to provide with food and where agriculture is not feasible due to extreme climate conditions (such as the Atacama Desert or Tierra del Fuego). The company would like to see the solution placed in general stores, making it possible to grow food anywhere on Earth.

Business model and financial sustainability

The service is still at an early stage, but it will soon be commercially available. It is supported through international collaboration (such as with the German Fraunhofer Institute). UrbanaGrow is planning to sell modular farms for controlled environments, with everything needed for the crops to grow, according to the type and quantities of vegetables required by the client.

Scaling target

The company is about to launch its first commercial solution to the retail sector. If that goes well, it would like to expand throughout Latin America, and eventually globally.

Drivers

Increasing demand for fresh produce, especially in remote areas where agriculture is not feasible due to climate conditions, is an important driver for the solution. The technology also responds to growing demand for environmentally sustainable and high-quality, safe and fresh produce. Increasingly widespread adoption of 5G will work as a facilitator since connectivity is essential to use UrbanaGrow.

Barriers

The scepticism of some agricultural producers and consumers around controlled agriculture can be a barrier. There is also insufficient awareness about climate change and other environmental issues, thereby discounting the value-added of the service.

Policy as a barrier or enabler

Increasing environmental standards in agriculture drives adoption. However, unclear regulations on agrochemicals enable competitors to produce food – albeit of lesser quality – at cheaper prices.

Top quotes

"Some people, when they have seen our technology, they laugh, and they say but this is a solution for the moon."

ZLTO (*Zuidelijke Land en Tuinbouw Organizatie*)

Year of establishment: 2013
Operates in: Netherlands
Current number of users: 13 000
Target agricultural sector: Horticulture, livestock (including dairy), arable crops
Interviewees: Peter Paree and Folkwin Poleman

Biography: Peter Paree is senior programme leader/project developer in agriculture, rural development at *Zuidelijke Land en Tuinbouw Organizatie* (ZLTO). He has worked for 31 years in strategic advice, project and programme management. As project leader, for 25 years he has led more than 200 projects and he now leads ZLTO programmes such as Smart Farming. Paree links farmers' management strategies to their environment and social/business ecosystems.

Services

ZLTO (the Southern Agriculture and Horticulture Organization) is one of three farmers' organizations in the Netherlands. It operates under the umbrella organization LTO and is part of the European farmers' organization CopaCogeca. ZLTO provides technical assistance and advisory services on digitization and data management. It also connects farmers with suppliers and supports innovation processes for farmers, with precision farming and livestock production as core activities.

Target customers and users

Target customers are the members of the organization. The main activities targeted are horticulture, pig husbandry, dairy production and arable crops.

Why ZLTO needed to digitize/automate

ZLTO is very active in providing technical assistance and advisory services (for example, on user rights). It also connects farmers with suppliers (50 percent of their member farmers are organized as independent cooperatives). It supports innovation processes for farmers, so precision farming and precision livestock farming are core activities. The vision is to focus on more automation and robotics in the future.

Digitization is key. In the Netherlands, data on farm parcels (e.g. boundaries and remote sensing data) and soil features are all digitized and accessible according to its open data strategy.[7] Data are critically important for precision applications. Real-time kinematic positioning (RTK) is used to determine precision location of tractors and machinery, with the information coming from the same tractors. All new tractors now have RTK, although differences in standards, depending on the brand, makes interoperability difficult. Precision agriculture, namely variable rate technologies (VRT), is still at a low level of adoption. An estimated five percent of farmers in the Netherlands use VRT. PA requires data integration although it is complicated to integrate all data sets, as shown by the experience of the European Union project NIVA (NIVA, 2022). The challenge is not so much technical, but organizational and related to data standards.

Business model and financial sustainability

ZLTO is not a private company and as such has only an indirect knowledge of the business models and financial sustainability of the solutions for which it provides technical assistance and advisory services for farmers.

[7] ZLTO was an initiator of these applications.

Scaling target

ZLTO only operates in the Netherlands and its scope is to serve its members. It has no further scaling ambitions.

Drivers

The push for precision agriculture comes mainly from environmental compliance and legal prerequisites. Market retailers want clear data on the product that customers are buying. Efficiency is also important: the goal of most farmers is to use half of the inputs and obtain double the harvest.

Labour supply is an adoption driver: there is a lack of unskilled labour that favours robotization and automation, together with an abundance of skilled labour that is willing and able to work with digital technologies.

Familiarity with and interest in ICT on the part of young farmers is another important driver. ZLTO farmers are highly intensive and have a high level of technical knowledge. This is an important driver of innovation adoption, as well as the ability to face environmental challenges (nitrogen emission in the first place, then carbon emissions).

Barriers

A recent survey shows that 30 percent of farmers would be willing to invest EUR 30 000 on sensors and robotics over the next five years. However, it is not yet clear to farmers what such an investment would yield. What is certain is that farmers will need to “go back to school” to learn how to use the new technologies.

Policy as a barrier or enabler

No policy-related adoption barriers have been perceived. In terms of drivers, ZLTO is running dissemination projects to raise awareness of precision agriculture, automation and robotics. The European Union is also promoting an agricultural data-sharing policy and consider making such data a public good.

Top quotes

“The question on why data integration (as a prerequisite for digitization) is important can be asked in five minutes, but the answer took us one year.”

“Consumers think in a very old-fashioned way (Disneyland model, small-scale farmers with olive trees look better): we are really sensitive to public opinion. When we (especially younger farmers) show evidence of efficiency gains, environmental sustainability, animal welfare, through precision farming and livestock, we don’t necessarily connect with the heart of the consumer.”

“Data management, sharing, ownership is key: future farming could follow a positive path, i.e. from calendar farming to clever farming. But [this] can also go wrong: from free farming to ‘bound’ farming, where big tech would put everything in recipes that farmers will be forced to follow. Farmers should be given the option to choose.”

Digital and automation solutions for precision agriculture can improve efficiency, productivity, product quality and sustainability. Nevertheless, barriers to adoption of such solutions – including their cost, lack of knowledge and skills, and the absence of an enabling environment and infrastructure – can prevent producers from realizing these benefits.

Building on findings from 22 case studies worldwide, this study finds that national data policies and infrastructure are key enablers of adoption, as is investment in connectivity (e.g. internet) and electricity in rural areas. Further research and information on the economic, environmental and social impacts of the solutions are also needed to provide evidence on their benefits. So too is investment in human capacity development, particularly digital literacy. To ensure an inclusive process, solutions must be adapted across agricultural production systems, regions and farm types. Partnerships and networks for exchanging information and promoting collaboration will key. Finally, awareness raising and communication are important since consumers can be skeptical about food being produced by new technologies.

In summary, by focusing on a variety of solutions, this study provides a landscape analysis of digital and automation solutions and offers guidance to accelerate adoption for more inclusive, sustainable and resilient agrifood systems.

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