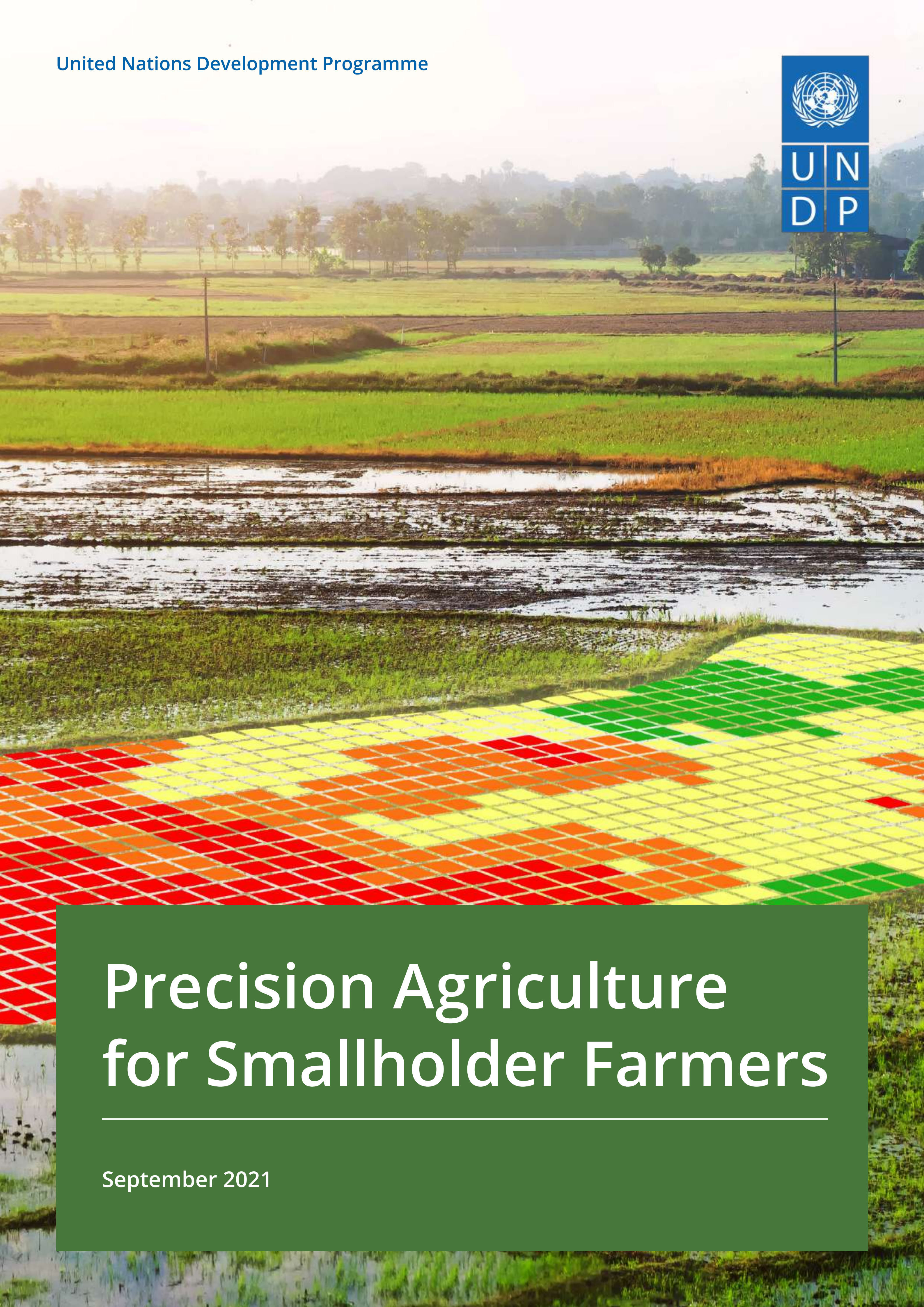
United Nations Development Programme



Precision Agriculture for Smallholder Farmers

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Preface

Global agri-food systems are under immense pressure. The world's population is estimated to increase to almost 10 billion people by 2050 and feeding it would require increasing current food production by 59–98 percent. Agriculture accounts for more than 70 percent of the global freshwater use, about half of which gets wasted. Globally, about a third of the food produced gets lost of wasted. Agriculture is a major contributor to the climate crisis and is also impacted by it—particularly in developing countries. Moreover, the COVID-19 pandemic has disproportionately affected the most vulnerable stakeholders, including smallholder farmers worldwide, and has put a spotlight on the several systemic issues in the sector.

Agriculture, however, is undergoing a 'Digital Revolution', with immense potential for improving the lives and livelihoods of farmers around the world. Precision Agriculture for Smallholder Farmers aims to contextualise and map the various innovations emerging in the area of digital farming. With a focus on smallholder farmers in developing countries, the report gives an overview of the technologies driving digital or data-driven farming, highlights the key challenges preventing their large-scale adoption, and provides recommendations and important considerations for overcoming them.

The intended audience of this report are project managers and development practitioners working on existing or planning new agricultural initiatives. Policymakers in the areas of agriculture and technology are the secondary target audience and will find policy recommendations on several challenges described in the report, particularly in the final section. While the report is quite technical, it has been developed as a guidebook for navigating this exciting and emerging space. It is not aimed at describing detailed workings of individual technologies or their applications. Interested readers may make use of the references provided throughout the report for exploring particular topics in greater detail.

Digitalisation is transforming all stages of agri-food supply chains—from production and processing to distribution and consumption. The use of data often transcends the boundaries between these stages. Farm-level data has uses beyond the objectives of precision agriculture; it can be leveraged by supply-chain actors other than farmers such as input suppliers, credit and insurance providers, and retailers to improve their service offerings to farmers. The scope of this report, however, is limited to precision agriculture—particularly crop farming—and the use of farm-level data to improve productivity and yields.

Agri-food systems are at the heart of the 2030 Agenda and impacting all 17 Sustainable Development Goals. Across the globe, UNDP is sharing climate-smart agricultural tools and practices, promoting livelihood diversification, new policies and transformative changes in social traditions to empower the ones left behind. UNDP's Strategic Plan 2022-25 envisages digitalisation as an enabler for maximising development impact. We hope that this report contributes to the acceleration of efforts to create a new paradigm of agricultural production, based on resilient, equitable, healthy and inclusive sustainable agri-food systems.

Contents

List of Abbreviations

AEW	Agricultural extension workers
AI	Artificial intelligence
ARaaS	Agricultural robots-as-a-Service
ARVI	Atmospherically resistant vegetation index
AWD	Alternate wetting and drying
B2B2C	Business-to-business-to-consumer
B2C	Business-to-consumer
B2G	Business-to-government
CAVIS	Clouds, aerosols, vapours, ice, and snow
CGIAR	Consultative Group on International Agricultural Research
CSO	Civil society organisation
DEM	Digital elevation models
ESA	European space agency
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GEO	Geosynchronous Equatorial Orbit
GPS	Global Positioning System
ICT	Information and communications technology
IoT	Internet of Things
ITU	International Telecommunications Union
IVR	Interactive voice response

LEO	Low Earth orbit
LMICs	Low- and middle-income countries
LPWAN	Low-power wide area network
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NBR	Normalised burn ratio
NDVI	Normalised difference vegetation index
NIR	Near infrared
NPK	Nitrogen, Phosphorus and Potassium
PxD	Precision Development
RGB	Red, Green and Blue
ROI	Return on investment
SDGs	Sustainable Development Goals
SMS	Short message service
SWIR	Short-wave infrared
TIRS	Thermal infrared sensor
UAV	Unmanned aerial vehicle
UNDP	United Nations Development Programme
USGS	United States Geological Survey
USSD	Unstructured supplementary service data
VRT	Variable rate technology

Executive Summary

In the coming decades, world agriculture will need to undergo a major transformation to meet the future demands of a growing population. By 2050, the food industry will have to face the daunting challenge of feeding about 10 billion people by almost doubling its food supply in a sustainable way.

Smallholder farmers in developing countries—who constitute about 90 percent of all farmers worldwide—will be a major part of the global food security equation. However, several challenges prevent them from turning farming into a viable and sustainable source of livelihood. Smallholder farmers suffer from low farm productivity and yields as well as lack of access to inputs, credit, and markets. They are also disproportionately vulnerable to shocks such as extreme weather events, now increasingly frequent due to climate change.

Precision agriculture is a farm management approach that uses data and technology to make farming simpler, more efficient, and more productive. Precision agriculture reduces the need for agricultural inputs like water, fertilisers, and pesticides, thereby reducing costs and the environmental footprint of agricultural production. The use of technology also cuts down the need for physical labour and improve productivity, ultimately enhancing the profitability of farming as a source of livelihood.

Digital technologies are making precision agriculture solutions increasingly affordable and accessible to even smallholder farmers in developing countries. These include mobile phones, remote sensing using satellites and unmanned aerial vehicles (UAVs), and sensors and the Internet of things (IoT)—all enabled by advances data processing and analytics. The adoption of these technologies is also driven by the growing mobile phone and Internet penetration and the falling costs of data worldwide.

The mobile phone is perhaps the most transformative technology enabling precision agriculture for smallholder farmers. Mobile phones enable two-way communication between farmers and experts, real-time monitoring, and the digitisation and easy collection of field data. Smartphones with cameras, GPS, various sensors, and a processor offer additional capabilities. Cost-effective and scalable mobile phone-based farming advisory services are already helping millions of farmers worldwide, overcoming the challenges with conventional agricultural extension. Through mobile phones, farmers can receive customised and localised advice on what, when, and how to grow, as well as alerts on weather, pests, and diseases.

Remote sensing using satellites is also supporting precision agriculture. This is made possible through the increasing availability of high-resolution imagery from satellites. Satellite imagery provides a snapshot of a large area of farmland in a single image. This imagery can be analysed—including through use of machine learning (ML) algorithms—for applications like nutrient status and crop health monitoring and yield estimation for individual farms.

Albeit less scalable than satellites, UAVs also offer remote sensing capabilities and high resolutions that satellite imaging, enabling additional applications like weed and pest detection. Based on this, variable rate maps can be generated specifying the amounts of inputs (e.g., fertilisers, pesticides, weedicides) required in different parts of the farm, thereby helping avoid their excessive application. In addition to remote sensing, UAVs can also be used for precise application of these inputs, substantially reducing the amount of physical labour required. While the technology remains unaffordable for individual farmers, contractors can leverage 'drone-as-a-service' business model to cater to a large number of farmers through farmer groups or cooperatives.

Various onsite sensors can also be used to collect accurate farm-level data (e.g., soil moisture and pH, temperature, humidity) to help farmers make decisions related sowing, irrigation, fertiliser application, and harvesting. This is enabled by advances in wireless networking technologies like Low-Power Wide Area Network (LPWAN) and cloud computing.

Adoption of precision agriculture by smallholder farmers is still at a nascent stage and is limited by several factors. In addition to high costs of some of the above solutions, other key barriers include the lack of digital infrastructure like Internet and electricity, lack of awareness and digital skills among farmers, and societal barriers like gender.

Overcoming these challenges requires cross-sector collaboration among the public and private sectors, civil society, and the academia. Solutions should be user-centred and designed considering the local context such as language, social and political barriers and inclusion challenges. An open approach (e.g., open source, open standards) to designing digital solutions will increase collaboration among stakeholders, ensure interoperability between solutions, and prevent duplication of efforts.

Availability of digital infrastructure is a major bottleneck in scaling precision agriculture solutions, particularly in rural and remote areas. Public-private partnerships and technological innovation will play an important role in making available at least basic Internet coverage for all farmers. Enabling policies addressing issues of data ownership and management, privacy and cybersecurity are essential for spurring innovation in the agritech sector and scaling the adoption of digital solutions.

Finally, lack of digital skills and literacy among smallholder farmers remains a major barrier in leveraging the potential of digital technologies. The public and private sectors can partner with civil society organisations (CSOs) and leverage their on-ground presence (e.g., agricultural extension workers) for delivering hands-on trainings and building digital capacities of farmers.

Introduction

Introduction

By 2050, the world's population is projected to increase to almost 10 billion people and feeding them will require increasing food production by up to 98 percent.[1] Smallholder farmers[2] are expected to play a crucial role in this. Already, an estimated 80 percent of the food produced in Asia and sub-Saharan Africa comes from small farms.[3]

About 90 percent of the world's farmers are smallholders, owning less than two hectares of land.[4] Farming is often the primary (and only) source of revenue for smallholder farmers, making them vulnerable to price fluctuations and extreme weather events. Smallholder farmers not only suffer from a lack of access to resources (e.g., financing, land, water) but also from various asymmetries in markets, including in power structures and information access. Improving the productivity and livelihoods of smallholder farmers is thus vital for achieving United Nations Sustainable Development Goals (SDGs). Yet, small farm size poses several challenges for farmers. It makes technological investments to enhance productivity and yields infeasible and acts as a barrier to benefiting from economies of scale.

Agriculture has radically transformed in the previous century. The electro-mechanical revolution in the early-20th Century brought farm mechanisation, reducing the need for physical labour. The Green Revolution in the mid-20th Century increased crop yields substantially and ensured the supply of enough food for the rapidly growing world population. However, the over adoption of Green Revolution techniques and technologies led to several adverse impacts, including loss of soil fertility, depletion and pollution of water resources, and increased incidence of livestock and human diseases.[5]

Agriculture is now on the cusp of another revolution—the digital revolution—which could help address several issues faced by the sector. Digitalisation is impacting all stages of agri-food supply chains—from planning, growing and harvesting to marketing, consumption and waste disposal. The use of digital technologies at the growing stage also does not pose the kinds of environmental harms that resulted from the Green Revolution.

This digital revolution is a key foundation for precision agriculture—a farm management approach that uses data and technology to make farming simpler, more efficient and more productive. It enables agricultural inputs like water, fertilisers and pesticides to be applied in precise amounts to get increased average yields compared to traditional cultivation techniques.[6] The birth of precision agriculture has often been linked to the introduction of Global Positioning System (GPS) guidance for tractors in the early 1990s.[7] Yet, its adoption was largely limited to large farms in developed countries owing to high costs and technological limitations.

1. Maarten Elferink and Florian Schierhorn, "Global Demand for Food Is Rising. Can We Meet It?" Harvard Business Review, April 7, 2016, https://hbr.org/2016/04/global-demand-for-food-is-rising-can-we-meet-it.

2. There is currently no universal definition of a smallholder farmer. The term is frequently used interchangeably with "small-scale farmer" and "subsistence farmer". "Smallholder" usually refers to having agricultural landholding of less than two hectares. In this report, smallholder farmers are those having "limited resource endowments compared to other farmers in the sector." (see Clara Aida Khalil, Piero Conforti, Ipek Ergin, and Pietro Gennari, "Defining Small-Scale Food Producers to Monitor Target 2.3. of the 2030 Agenda for Sustainable Development," FAO Statistics Working Papers Series ESS 17-12, http://www.fao.org/3/i6858e/i6858e.pdf.)

3. Elferink and Schierhorn, "Global Demand for Food Is Rising. Can We Meet It?"

4. Food and Agriculture Organization of the United Nations, "Smallholder family farms," available at http://www.fao.org/economic/esa/esa-activities/smallholders/en/.

5. Saidur Rahman, "Green Revolution in India: Environmental Degradation and Impact on Livestock," Asian Journal of Water, Environment and Pollution 12, no. 1 (2015): 75–80, 2015.

6. Amit Kumar Mungarwal, SK Mehta, "Why farmers today need to take up precision farming," Down to Earth, 21 May 2019, available at https://www.downtoearth.org.in/blog/agriculture/why-farmers-today-need-to-take-up-precision-farming-64659.

7. Remi Schmaltz, "What is precision agriculture?" AgFunderNews, 24 April 2017, available at https://agfundernews.com/what-is-precision-agriculture.html.

However, advances in various technologies (particularly digital technologies) and their growing affordability are now making precision agriculture available to smallholder farmers in developing countries. Precision agriculture has evolved as data-driven farm management that focuses on managing crop production inputs like seeds, water, fertilisers and pesticides to increase production, reduce waste and protect the environment.[8]

Data is essential for precision agriculture. Various kinds of data relevant for farming (e.g., soil parameters, weather data, crop health, geographical location) can be collected through various means including on-site sensors, remote sensing using satellites and drones,[9] and weather stations. This data can be integrated and analysed to generate customised, actionable information and insights that meet the needs of individual farms and farmers and delivered to them via accessible technologies like mobile phones.

Precision agriculture solutions powered by digital technologies can improve productivity and crop yields, help protect the environment by reducing chemical inputs, foster gender inclusion and help make farming profitable for smallholders.

Digitalisation is transforming all stages of agri-food supply chains—from production and processing to distribution and consumption. The use of data often transcends the boundaries between these stages. Farm-level data has uses beyond the objectives of precision agriculture; it can be leveraged by supply-chain actors other than farmers such as input suppliers, credit and insurance providers, and retailers to improve their service offerings to farmers. Access to farm-level data could also enable informed policymaking and help governments address various agricultural issues, including threats from climate change and pests, farmer livelihoods, food security and food safety. However, the scope of this report is limited to precision agriculture and the use of farm-level data to improve productivity and yields.

The theme of this report is the use of technology in crop farming. However, by definition, 'agriculture' also includes the rearing of livestock.[10] Precision livestock farming is also witnessing significant developments wherein technology is used to improve results, including the use of cameras and sensors to track and monitor individual animals and robotics to optimise production. Nevertheless, this is out of the scope of this report.

In the subsequent sections, we will provide an overview of the technologies spurring the development of precision agriculture, particularly for smallholder farmers. We will highlight key precision agriculture applications (with examples) using these technologies and provide recommendations for project managers looking to incorporate them in ongoing or future projects.

8. Gerard Hoogendijk, "Progression of Precision Agriculture," Possibility (Teledyne Imaging), 11 October 2018, available at https://possibility.teledyneimaging.com/progression-of-precision-agriculture/.

9. A 'drone' in this report refers to an unmanned aerial vehicle (UAV).

10. "Agriculture," Merriam-Webster, https://www.merriam-webster.com/dictionary/agriculture.

1 NO POVERTY

Target 1.1

By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day.

Role

Increases incomes of smallholder farmers—some of the poorest people in the world.

15 LIFE ON LAND

Target 15.1

By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.

Role

Reduces the chemical runoff from farms into water bodies.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Target 12.2

By 2030, achieve the sustainable management and efficient use of natural resources.

Target 12.4

By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.

Role

Reduces the need for use of natural resources like water and improves usage efficiency of chemical inputs such as fertilisers and pesticides.

10 REDUCED INEQUALITIES

Target 10.1

By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average.

Role

Increases incomes of smallholder farmers.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Target 9.3

Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets.

Role

Enhances the integration of smallholder farmers into value chains through access to customised information and better service delivery. Enable informed policymaking through access to farm-level data.

Target 2.3

By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through sec Reduces chemical runoff from farms into water bodies and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.

Role

Improves agricultural productivity of smallholder farmers through technology and data.

Target 3.9

By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.

Role

Helps farmers produce better quality and healthier food using fewer chemical inputs.

Target 5.b

Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women.

Role

Reduces the need for physical labour and enhances productivity of women farmers.

Target 6.3

By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

Role

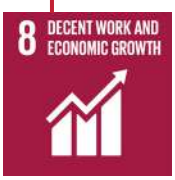
Reduces chemical runoff from farms by reducing the need for chemical inputs.

Target 6.4

By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.

Role

Reduce the need for water in farming.



Target 8.2

Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors.

Role

Reduces chemical runoff from farms by reducing the need for chemical inputs.

Technologies Driving Precision Agriculture for Smallholder Farmers

Technologies Driving Precision Agriculture for Smallholder Farmers

A few key technologies like mobile phones, satellites, drones and on-site sensors are driving the adoption of precision agriculture. While not all of these are new, their growing affordability and availability make them increasingly accessible to all farmers. Yet, despite the overall positive outlook, smallholder farmers face several barriers in adopting these solutions. The 'Five A's of Technology Access'—availability, affordability, awareness, ability and agency—provides a useful framework for analysing these diverse challenges.[11]

In many regions, precision agriculture solutions might be simply unavailable due to issues such as the lack of digital infrastructure (e.g., electricity, Internet) to support them. Even if they are available, many farmers might not be able to afford them. For example, farmers might not be able to afford a smartphone with an Internet subscription, which is an essential requirement for many precision agriculture applications.

Where solutions are available and affordable, farmers might not be aware of them. This is also true for several other digital services offered by the public and private sectors. Additionally, farmers might lack the literacy and digital skills required to use the solutions. According to a GSMA survey, this was the main bottleneck for Internet adoption among respondents in low- and middle-income countries (LMICs) who were aware of mobile Internet.[12] Finally, farmers from disadvantaged groups (e.g., women farmers) might lack 'agency' owing to various sociocultural barriers, preventing them from accessing technological solutions.

Addressing these barriers requires interventions at multiple levels, including at programmatic and policy levels. These include designing user-centred solutions, innovative and inclusive business and service delivery models, and enabling policies to support digitalisation of the sector. The complexities of the barriers also underscore the need for increased collaboration between diverse stakeholders—public and private sectors, civil society, and academia—to scale up adoption of digital technologies by smallholder farmers.

In this section, we provide an overview of the key technologies relevant for precision agriculture, their applications, and highlight important considerations for each technology to facilitate their increased uptake.

11. Tony Roberts and Kevin Hernandez, "Digital Access is not Binary: The 5'A's of Technology Access in the Philippines," The Electronic Journal of Information Systems in Developing Countries 85, no. 4 (2019), available at https://doi.org/10.1002/isd2.12084.

12. Kalvin Bahia and Anne Delaporte, The State of Mobile Internet Connectivity 2020 (London: GSMA, 2020), available at https://www.gsma.com/r/somic/.

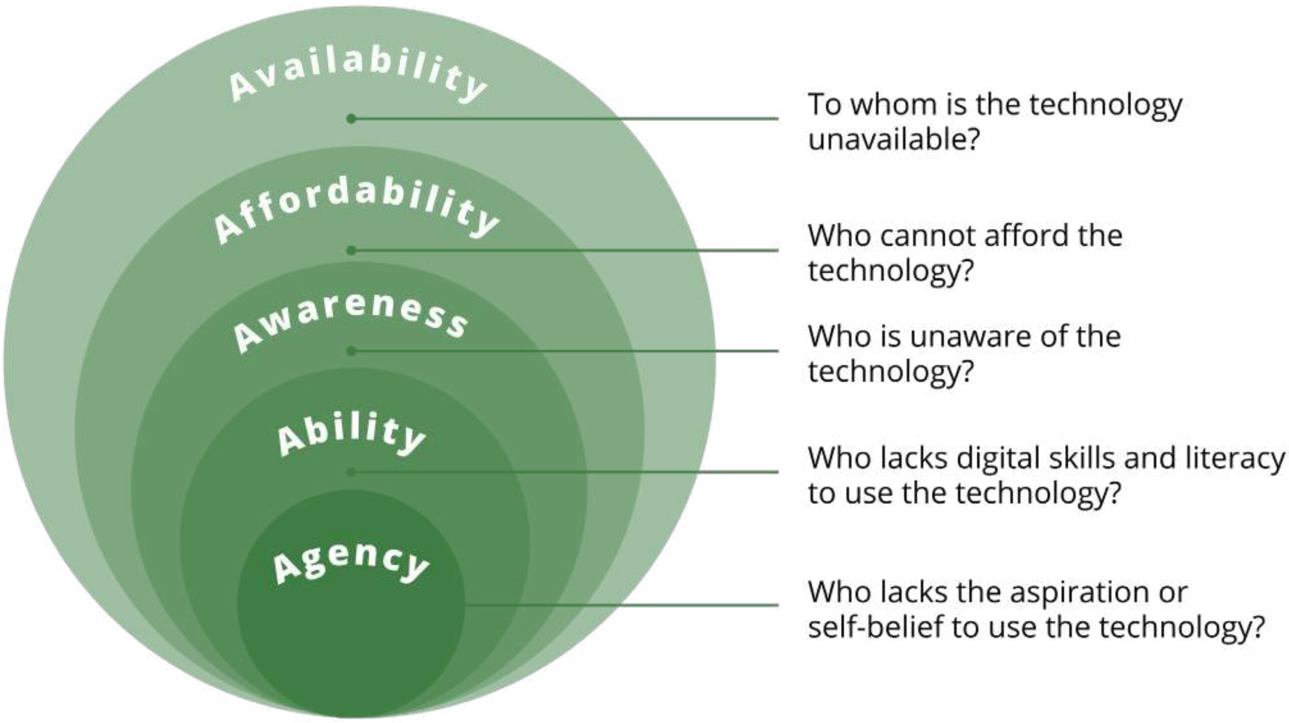


Figure 1: The five A's of technology access[13]

13. Adapted from Roberts and Hernandez, "Digital Access is not Binary: The 5'A's of Technology Access in the Philippines."

Mobile phones

Overview

The mobile phone is perhaps the most impactful technology for making precision agriculture accessible for smallholder farmers. Mobile phone penetration has grown rapidly over the last decade. Close to seven out of ten households around the world today have a mobile phone.[14] In low- and middle-income countries (LMICs), more than 80 percent of the rural population has some mobile coverage (at least 2G).[15]

Growing mobile phone penetration has rapidly scaled up access to the Internet in developing countries. By 2019, almost 65 percent of urban and 28 percent of rural households in developing countries had access to the Internet.[16] Mobile phones accounted for over 87 percent of all Internet broadband connections in low- and middle-income countries.[17]

14. The World Bank, World Development Report 2016: Digital Dividends (Washington, DC: World Bank, 2016), available at https://openknowledge.worldbank.org/handle/10986/23347.

15. International Telecommunications Union (ITU), Measuring Digital Development: Facts and Figures 2020 (Geneva: ITU, 2020), available at https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx.

16. Ibid.

17. Bahia and Delaporte, The State of Mobile Internet Connectivity 2020.

Use in precision agriculture

Numerous mobile phone-enabled services for agriculture (also known as 'm-Agri services') have spawned, enabled by growing mobile phone and Internet penetration. These include providing farmers with access to inputs, credit, insurance and markets to sell their produce.

Mobile phones enable two-way communication between farmers and experts, real-time monitoring capabilities, and digitisation and easy collection of field data.[18] GPS-enabled smartphones can help collect accurate location data and enable delivery of tailored information to farmers. Mobile phones are a highly accessible medium for disseminating information and insights generated using other technologies like satellites, Unmanned Aerial Vehicles (UAVs), and on-site sensors (described later in this section). Even a phone with basic functionality and lacking 'smart' capabilities (feature phone) offers multiple capabilities for farmers to access customised information, allowing farmers who cannot afford a smartphone or those living in areas with limited or no Internet connectivity to avail precision agriculture services.

Mobile phone-based farming advisory services (also called 'digital extension')[19] are the most common precision agriculture solution, currently helping millions of farmers worldwide. They can overcome many limitations of agricultural extension workers (AEWs), such as their lack of numbers, limited demonstrated effectiveness and distrust among farmers about their recommendations.[20] Although the effects of advisory services alone are modest,[21] they are a highly cost-effective intervention for improving farming outcomes. For instance, a study suggested a benefit-cost ratio of up to 10:1 from farmers applying lime to their crops to increase yields following SMS-based advisories.[22]

18. Fritz Brugger, Mobile Applications in Agriculture (Basel: Syngenta Foundation, 2011), available at https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2011/12/Syngenta_Report_on_mAgriculture_abridged_web_version.pdf.

19. See "What We Know About Digital Extension" on the "Our Learning" page, available at https://precisionag.org/our-learnings/learning/.

20. Raissa Fabregas, Michael Kremer, and Frank Schilbach, "Realizing the potential of digital development: The case of agricultural advice," Science 366, no. 6471 (2019), available at https://doi.org/10.1126/science.aay3038.

21. While there is scope for more research on the subject, mobile phone-based advisory by itself has been shown to have a modest but significant effect on adoption of good farming practices. For instance, a meta-analysis found that farmers who received SMS advisory promoting the use of lime adopted the practice at a rate 11.3 percent higher on average than the control groups. (see Raissa Fabregas et al., "SMS-Extension and Farmer Behavior: Lessons from Six RCTs in East Africa," Working Paper (2019), available https://www.dropbox.com/s/guiog3ief0hnwl7/textfarmers.pdf.)

22. Ibid.

Mobile phones and their use in precision agriculture

Camera

Cameras are useful for capturing visual data of farm conditions for analysis. Plantix (https://plantix.net/en/) is a crop diagnosis app with 80 percent of its 1.1 million monthly active users in India. By sending a picture of their infected crop on WhatsApp, farmers are connected to a 'crop doctor', who replies with a diagnosis and recommended treatments.

Short Message Service (SMS)

SMS allows farmers to send queries and receive advisories and alerts. Farmer-focused social networking platforms have also been developed with SMS as the main medium for communication to accommodate users with limited Internet connectivity. An example is WeFarm, an SMS-based social networking platform in East Africa that allows farmers to interact with peers, exchange ideas, and sell or trade agricultural equipment and supplies.[23]

Unstructured Supplementary Service Data (USSD)[24]

USSD is similar to SMS but slightly different in that users can select a customised advisory from a menu. For example, Tigo Kilimo in Tanzania provides real-time information through USSD. By referring to a USSD menu, they can obtain information about weather, crop prices and agronomy techniques of 10 different crops.[25]

23. Ingrid Lunden, "Wefarm adds $11M to expand its network for independent farmers, now at 2.5M users," TechCrunch, March 9, 2021, available at https://techcrunch.com/2021/03/09/wefarm-adds-11m-to-expand-its-network-for-independent-farmers-now-at-2-5m-users/.

24. USSD is another messaging protocol like SMS. Unlike SMS, messages are sent to and from a network entity. Users need to use a feature code starting with a '*' and ending with a '#', with digits in between to query information. Common uses include network requests and callback services. (see Nicholas Congleton, "What Is USSD?" Lifewire, August 4, 2020, https://www.lifewire.com/what-is-ussd-4689194.)

25. GSMA, Tigo Kilimo: Impact Evaluation (London: GSMA, 2015), available at https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2015/09/GSMA_Tigo_Kilimo_IE.pdf.

Interactive Voice Response (IVR)[26]

IVR is used mainly to deliver pre-recorded agricultural advisories to farmers. Solidaridad, an international civil society organisation (CSO), used IVR to continue providing agricultural extension services to smallholder farmers in West Africa when COVID-19 safety measures were in place. In 2019, they used IVR to share agricultural best practices to over 40,000 farmers, workers and producers.[27]

Position Sensors

Position sensors help locate a device's position and include magnetometers, GPS and orientation sensors. They help provide location data for crop mapping and alerts on disease and pests.[28] MachineryGuide (https://machineryguide.hu/index) is an Android-based GPS guidance system that allows farmers to receive precision location guidance with their smartphones. With the MachineryGuide's application and antenna package, farmers are shown the cultivated area and overlap on their smartphones. The application also guides farmers to perform consistent fieldwork by providing reference lines.

Motion Sensors

Motion sensors measure the user's movements and include accelerometers, gyroscopes, gravity sensors and rotational vector sensors. By tracking the user's movements, they help inform farmers if they are performing farm activities optimally. Using the accelerometer in the mobile phone, researchers from the TCS Innovation Lab have designed an algorithm that can detect if farmers are performing a farm activity like sprinkling fertiliser in the most optimal manner.[29]

Mobile Processors and Applications

Mobile processors enable on-site calculation of optimal decisions without the need to connect to cloud servers. The Fertilizer Optimization Tool developed by the Consultative Group on International Agricultural Research (CGIAR) is a mobile application that allows extension workers to input crop and acreage data, fertiliser cost, and forecasted crop price to output the optimal amount of fertilisers to be used for each crop, the expected yield improvement, and calculated return on investment (ROI). This involves linear optimisation techniques that cannot be supported with a feature phone's processing power.[30]

26. IVR is an automated voice response system that interacts with callers using voice and keypad input.

27. Solidaridad, "Deploying Digital Tools for Agricultural Extension Support Amid COVID-19," 21 May 2020, available at https://www.solidaridadnetwork.org/news/deploying-digital-tools-for-agricultural-extension-support-amid-covid-19/.

28. Steven Schriber, "Smart Agriculture Sensors: Helping Small Farmers and Positively Impacting Global Issues, Too," Tech Briefs, 1 June 2019, available at https://www.techbriefs.com/component/content/article/tb/supplements/st/features/applications/34585.

29. Somya Sharma, Jabal Raval, and Bhushan Jagyasi, "Mobile sensing for agriculture activities detection," 2013 IEEE Global Humanitarian Technology Conference (GHTC) (October 2013): 337–342, available at https://doi.org/10.1109/GHTC.2013.6713707.

30. Platform for Big Data in Agriculture (CGIAR), "Fertilizer Optimization Tool (FOT)," available at https://bigdata.cgiar.org/digital-intervention/fertilizer-optimiation-tool-fot/.

Key Considerations

Mobile phones are the foundational technology for making precision agriculture widely accessible to even smallholder farmers. Thus, it is important to be mindful of the challenges that might inhibit their use by farmers.

Initially, it is important to determine whether a solution would require a smartphone or if a feature phone would suffice. Median smartphone ownership in emerging markets is still low at 37 percent, although it rose almost 50 percent between 2013 and 2015.[31] The average cost of an entry-level, Internet-enabled device in low- and medium-income countries stood at 34 percent of monthly income in 2019.[32] This means that some capabilities described earlier may not be readily available to all farmers. Project designers must be mindful of technological considerations as well as the accessibility of smartphones when planning initiatives.

Basic digital infrastructure is necessary for making the best use of available precision agriculture solutions, particularly access to at least 3G mobile connectivity. Although the coverage gap[33] in mobile connectivity has declined rapidly—from 10 percent in 2018 to just 7 percent in 2020—about 600 million people worldwide still live in an area not covered by mobile networks.[34]

It is thus important to know the extent of digital infrastructure in an area where precision agriculture interventions are planned. A 2G connection can provide farmers with a variety of farm advisory services through SMS, USSD, and/or IVR. While these can help cater to the needs of a farm as a whole, at least a smartphone with Internet connectivity is required for more advanced applications to address intra-farm variability.

Lack of literacy and digital skills can be a major barrier. While access to mobile phones and the Internet is growing rapidly, more than half of the world's population still does not use mobile Internet. Lack of literacy and digital skills remains the primary bottleneck for Internet adoption in LMICs.[35] It is thus crucial to know the level of digital skills (e.g., use of SMS, mobile applications or social media, for instance) and functional and digital literacy among targeted farmers.

Special attention needs to be given to the inclusion of women farmers. In addition to resources like land, water and credit, women also lack access to mobile phones compared to men. Despite fast-growing mobile phone penetration in LMICs, compared to men, women are 7 percent less likely to own a mobile phone, 15 percent less likely to own a smartphone, and 15 percent less likely to use mobile Internet.[36] Moreover, women use a narrower range of mobile services than men and feel less able to learn a new activity by themselves.[37] Awareness of such barriers can help in designing more inclusive interventions.

Use of mobile phones also presents an opportunity for overcoming traditional gender-related barriers faced by women farmers. For example, AEWs in developing countries are predominantly men, while the agricultural workforce consists largely of women.[38] Multiple studies have shown that having access to female AEWs resulted in greater participation and satisfaction among women farmers compared to male AEWs.[39] Extension services delivered through mobile phones (e.g., demonstration videos) customised to the farmer's gender can help ensure their better uptake.

31. Madeleine Karlsson et al., Accelerating affordable smartphone ownership in emerging markets (London: GSMA, 2017), available at https://www.gsma.com/mobilefordevelopment/resources/accelerating-affordable-smartphone-ownership-in-emerging-markets/.

32. GSMA, The State of Mobile Internet Connectivity 2020.

33. Coverage gap refers to the percentage of population which does not live within the footprint of a mobile broadband network.

34. Bahia and Delaporte, The State of Mobile Internet Connectivity 2020.

35. Ibid.

36. Isabelle Carboni et al., The Mobile Gender Gap Report 2021 (London: GSMA, 2021), available at https://www.gsma.com/r/gender-gap/.

37. Ibid.

38. B.A.N. Lahai, P. Goldey, and G.E. Jones, "The gender of the extension agent and farmers' access to and participation in agricultural extension in Nigeria," The Journal of Agricultural Education and Extension vol. 6, no. 4 (1999): 223–233, https://doi.org/10.1080/13892240085300051.

39. Ibid.; also, Santa BahadurGhartiMagar, "An Assessment of Men and Women Farmers' Accessibility to Governmental Agriculture Extension Program: A Case of Arghakhanchi District, Nepal," Master's thesis (Wageningen: Wageningen University and Research, 2011), available at https://edepot.wur.nl/192651.

Due consideration must be given to the local context where services will be offered. Particularly, access to information in local languages can be a driving factor in the uptake of mobile-based precision agriculture services by farmers. Factors like these can be identified by adopting participatory approaches and involving targeted farmers in designing solutions; not doing so can result in failures. For example, a mobile e-wallet solution in Rwanda witnessed low uptake because SMS messages were sent in English instead of Kinyarwanda, the preferred language of the target community.[40]

Finally, there is limited willingness to pay among farmers for mobile phone-based advisory services. Once a farmer receives information, they can easily share it with other farmers, thus reducing the number of potential paying customers for the service. Also, farmers do not readily know the value of information sold to them and assessing its quality can be difficult. These issues make it difficult for pure subscription-based business models to reach farmers at scale.[41]

'Freemium' models offer a potential solution wherein farmers only pay after they are convinced of the value of the service. In the case of a contract farming arrangement, a large buyer may operate a digital extension service and provide information freely to farmers with the motive of increasing the supply of inputs for processing. Another business model is to include advertising for agricultural inputs with the freely shared information. However, this model risks supplying false or misleading information and an undersupply of useful information, particularly related to farming techniques that do not involve purchasing inputs.[42]

The above challenges make a case for the provision of advisories as a public good, provided that governments can design user-friendly services and are receptive and attentive to user feedback.[43]

40. The World Bank, Future of Food: Harnessing Digital Technologies to Improve Food System Outcomes (Washington DC: World Bank, 2019), available at https://openknowledge.worldbank.org/handle/10986/31565.

41. Fabregas, Kremer, and Schilbach, "Realizing the potential of digital development: The case of agricultural advice."

42. Ibid.

43. Ibid.

Mobile-based advisory during monsoon in Odisha, India[44]

Precision Development (PxD) is an international non-profit providing digital extension across ten countries in Africa, Asia, and Latin America.[45] In India, PxD's provides mobile-based customised farm advisory service named 'Ama Krushi' during the monsoon season, serving 1.3 million farmers in the Odisha state, out of which 97 percent grow paddy.

The monsoon in South Asia typically begins in the second last or last week of June. The agronomy team at PxD sends out pre-planting advisory on optimal planting practices, fertilizer application, nursery best practices, and disease/pest monitoring in early June. At the end of the rice growing season around November, the team sends post-harvest advice about crop storage, market prices, and on planting non-paddy crops.

PxD's messages are customised based on district location, dialect preference, crops planted, land types, and availability of irrigation. District location is important because the monsoon season begins at vastly different time in the west versus the state's coast in the east. The advisory is customised for 17 crop types including paddy, black gram, bitter gourd, cauliflower, red gram, and more. Land type is classified into low, medium, and upland. Each of the three has different impact on seed choice and farming practices. In the peak period, the team may broadcast up to 24 different messages in a week.

PxD's agronomists structure the season's advisory activity by deciding the intervals at which content is pushed and by prioritising crops which might need more attention. They also determine which farming practices should be spotlighted. Thereafter, the different agronomists are assigned to a few crops each and begin penning a set of crop-specific advisory. To prioritise their content effectively, the team focuses on identifying low cost and risk farming practices which are proven to increase yield by evidence.

To ensure consistency of their messages, PxD uses the following standard template for the messages, which are sent via IVR, SMS, WhatsApp, or Telegram:

1. Who is this message from?
2. What is this message about?
3. How should I act in response to this message?
4. Why should I change what I'm doing?
5. How should I act in response to this message?
6. How to follow up for more information?

44. Tarun Pokiya et al., "Kharif in Odisha: A Monsoon of Information," Precision Development, 15 July 2021, available at https://precisionag.org/kharif-in-odisha/.

45. Precision Development, "Our Motivation," available at https://precisionag.org/what-we-do/our-motivation/.

Satellites

Overview

Satellite imaging can play an important role in scaling up precision agriculture. Satellite imagery provides a snapshot of a large area of farmland in a single image. The information in that image is analysed and used to monitor changes in soil conditions and crop health, detect pest infestations and can be used for better land management.

Resolution of satellite imagery

The resolution of satellite imagery is an important consideration for different applications of precision agriculture. There are three types of resolution in remote sensing: spatial, spectral and temporal.[46]

Spatial resolution refers to the size of the smallest feature that can be represented in a pixel of the satellite image. For instance, a 30m spatial resolution means that each pixel corresponds to 30m×30m on Earth's surface. Spatial resolution, as per current capabilities, can be broadly divided into three categories:[47]

- Low-resolution: > 60m per pixel
- Medium-resolution: 10m-30m per pixel
- High- and very high-resolution: 30cm-5m per pixel

Spectral resolution refers to the range of wavelengths in the electromagnetic spectrum that the satellite sensor can capture. The ranges of spectrum to which a sensor is sensitive are called its 'bands'. A sensor can have multiple bands of varying wavelength widths. For instance, a pan-chromatic image from a sensor consists of a single wide band encompassing a wide spectral range whereas a hyperspectral image consists of many narrower bands spread across the electromagnetic spectrum.[48]

Temporal resolution refers to the revisit time taken for a satellite to orbit and return to the same field of observation.

46. Satellite Education for Geoscience Education, "Spatial Analysis," Online course, available at https://cimss.ssec.wisc.edu/sage/remote_sensing/lesson3/concepts.html.

47. Earth Observing Systems, "Satellite Data: What Spatial Resolution Is Enough?" 12 April 2019, https://eos.com/blog/satellite-data-what-spatial-resolution-is-enough-for-you/.

48. University of Southampton, "Spectral resolution," Online course, available at https://www2.geog.soton.ac.uk/users/trevesr/obs/rseo/spectral_resolution.html.

Satellite technology has evolved greatly over the decades. Spatial resolution has improved from 80m in the 1970s to submetre resolutions available today. Similarly, temporal resolution has improved from 18 days to 1–2 days. Spectral bands have doubled from four to eight. Raw satellite imagery from governmental and intergovernmental space programmes, such as the National Aeronautics and Space Administration (NASA)'s Landsat or the European Space Agency (ESA)'s Sentinel, is made freely available. Moreover, a host of downstream analytics capabilities are made available almost real-time by the agencies (e.g., United States Geological Survey (USGS)'s EarthExplorer and ESA's Copernicus). The improved resolution and increased availability of satellite data have enabled its use for precision agriculture.[49]

The private sector presence in this space has also greatly improved over the last two decades. New ventures include companies like Planet Labs, Maxar Technologies, Capella Space and Orbita Aerospace. Unlike traditional agencies who launch constellations (tens of satellites) of large geosynchronous equatorial orbit (GEO) satellites, the new players are aiming to launch constellations (hundreds to thousands of satellites) of small low Earth orbit (LEO) satellites. LEOs have the advantage of faster orbit times and continuous coverage. Moreover, small satellites use commercial off-the-shelf technology, which fundamentally changes the economics of launching space missions and reduces the barriers of entry for an increasing number of private ventures.[50]

49. Babankumar Bansod et al., "A comparison between satellite based and drone based remote sensing technology to achieve sustainable development: a review," Journal of Agriculture and Environment for International Development vol. 111, no. 2 (2017): 383–407,available at http://www.jaeid.it/index.php/JAEID/article/view/690.

50. Herbert J. Kramer and Arthur P. Cracknell, "An overview of small satellites in remote sensing," International Journal of Remote Sensing vol. 29, no. 15 (2008): 4285–4337, available at https://doi.org/10.1080/01431160801914952.

Currently, private sector players in satellite imaging offer daily imagery with higher spatial resolution than government satellites. This high frequency of data access allows farmers to react to issues, such as crop stress, in a timely manner. A comparative overview of free and paid satellite data is given in the table below.

Table 1: Comparison between free and paid satellite data sources[51]

Data Source Type	Description	Examples
Free	• Primarily from government agencies like NASA and ESA. • Usually requires an entire swath[52] to be downloaded and requires atmospheric corrections	• USGS/NASA's Landsat series • ESA's Sentinel series
Commercial	• Usually requires a minimum order area, paid either on a per tile or square kilometre basis • Discounts are usually given if a larger swath is purchased • Pre-processing is different across providers and is offered at different price points	• Airbus Defence and Space's SPOT 6 and 7 • Maxar/DigitalGlobe's WorldView 2, 3, and 4

51. Nikita Marwaha Kraetzig, "A Definitive Guide to Buying and Using Satellite Imagery," UP42, 15 January 2021, available at https://up42.com/blog/tech/a-definitive-guide-to-buying-and-using-satellite-imagery.

52. Swath refers to the width that the satellite sensor can observe Earth's surface. A swath of 100 km means that full-scene images will be 100 km in width.

Use in Precision Agriculture

Spectral data from satellites can generate spectral index maps that visualise farm health and inform the farmer which parts of the farm to focus on. Some commonly used spectral indices include the Normalised Difference Vegetation Index (NDVI), Normalised Burn Ratio (NBR), and Atmospherically Resistant Vegetation Index (ARVI). NDVI measures the greenness of vegetation and can be used as a proxy for understanding crop health across the field.[53] NBR assesses burn extent and is deployed for monitoring active fires.[54] ARVI tracks particulate matter and allows users to identify areas with pollution or even slash-and-burn practices.[55]

Farm maps showing intra-farm variability in crop health as well as farm-specific advisory can be delivered to farmers over mobile phone apps. Satellite data can also be integrated with other data like weather, on-site sensors and farming records (e.g., fertiliser use, planting dates) then processed with machine learning algorithms to generate even more accurate information for individual farmers. Several start-ups, including CropIn, OneSoil and Agrosmart, provide precision agriculture services such as fertiliser application advice and yield estimation based on satellite imagery.

Another capability offered by satellites is geopositioning. Satellite-based navigation systems such as GPS help collect georeferenced data and help identify accurate field locations for precise placement of seeds and agrochemicals, manage the efficient use of water and assist in overall farm management practices.[56] The combination of satellite and navigation systems characterise the farms' soil and crop variability, allowing for more intensive and efficient cultivation practices. For example, IDEO.org, a non-profit design studio, is testing a GPS-guided smartphone app in Myanmar that helps farmers accurately map their fields and thus estimate the right amounts of inputs for their farms.[57]

High-resolution satellite imagery is also useful for other actors in agriculture. For instance, insurance companies in India are using it to assess the extent of crop damage and settle claims.[58] Yield estimations based on satellite imagery can be used for making various policy decisions. However, these do not fall under the ambit of precision agriculture and are not explored in this report.

53. OneSoil, "What the NDVI index is and how it makes a farmer's life easier," Medium, 11 May 2019, available at https://medium.com/onesoil/what-the-ndvi-index-is-and-how-it-makes-a-farmers-life-easier-d6e900d91c9f.

54. Earth Observing System, "6 Spectral Indexes To Make Vegetation Analysis Complete," 22 February 2019, available at https://eos.com/blog/6-spectral-indexes-on-top-of-ndvi-to-make-your-vegetation-analysis-complete/.

55. L3Harris Geospatial, "Vegetation Analysis: Using Vegetation Indices in ENVI," available at https://www.l3harrisgeospatial.com/Learn/Whitepapers/Whitepaper-Detail/ArtMID/17811/ArticleID/16162/Vegetation-Analysis-Using-Vegetation-Indices-in-ENVI.

55. BIS Research, Global Precision Agriculture Market – Analysis and Forecast, 2018–2025 (2018), available at https://bisresearch.com/industry-report/global-precision-agriculture-market.html.

56. IDEO.org, "Connecting Smallholder Farmers to Low-Cost Sensors," available at https://www.ideo.org/project/sensor-sensibility.

57. Nick Measures, "How satellite imagery is helping precision agriculture grow to new heights," Eco-Business, 2 March 2021, available at https://www.eco-business.com/news/how-satellite-imagery-is-helping-precision-agriculture-grow-to-new-heights/.

58. Earth Observing Systems, "Satellite Data: What Spatial Resolution Is Enough?"

Key Considerations

Low- and medium-resolution imagery is available freely through governmental and intergovernmental satellite missions such as NASA's Landsat (30m) and ESA's Sentinel (10m). These are two of the most widely used sources of satellite data.[59] However, high- and very high-resolution imagery is only available through commercial satellite operators such as Planet Labs and Maxar Technologies.

Choosing the appropriate resolution depends largely on the application objective, the size of the agricultural field and the ability of farm equipment to use this data. Typically, precision agriculture applications such as yield estimation require a spatial resolution of 1–3 m. Variable-rate fertiliser and irrigation applications require a spatial resolution of 5–10m. Generally, these are the resolution requirements for precision agriculture applications:[60]

- Spatial resolution should correspond to the average agricultural field size (<30m)
- Temporal resolution should correspond to crop development cycles (once a month)[61]
- Spectral resolution should correspond to the spectral bands required for relevant vegetation indexes calculation (from 450 nm to 900 nm)

Resolutions offered by popular satellite imagery providers are given in the following table.

59. Earth Observing Systems, "Satellite Data: What Spatial Resolution Is Enough?"

60. Marco Sozzi et al., "Benchmark of Satellites Image Services for Precision Agricultural use," in EuAgEng proceedings: New Engineering Concepts for Valued Agriculture, European Society of Agricultural Engineers, 2018, available at http://hdl.handle.net/11577/3272211.

61. Graciela Metternicht, "Use of remote sensing and GNSS in precision agriculture," June 2006, UN-Zambia-ESA Regional Workshop on the Applications of GNSS in Sub-Saharan Africa, available at https://www.unoosa.org/documents/pdf/psa/activities/2006/zambia/presentations/04-01-01.pdf.

Table 2: Resolutions offered by popular satellite imagery providers[62]

Satellite Service Provider	Type	Resolution		
		Spatial	Spectral	Temporal
Landsat (NASA)	Public	15m, 30m, 60m, 100m, 120m	Natural colour (Visible, NIR), Coastal aerosol, SWIR 1/2, Panchromatic, Cirrus, TIRS 1/2[63]	16-18 days
Sentinel (ESA)	Public	5m, 10m, 20m, 60m	C-band, Natural colour (Visible, NIR, SWIR)	1-5 days
Planet	Private	0.72m, 3m, 4.77m, 6.5m	Natural colour: Blue, Green, Red, Red-Edge, NIR	12 hours - 5 days
Maxar	Private	0.3m, 0.4m, 0.5cm, 0.6m, 1.2m, 2.0m	Panchromatic, 8 NIR bands (RGB, near-IR1/2, coast, yellow, red-edge), 8 SWIR bands (for haze, fog, smog, etc.) 12 CAVIS bands (for clouds, ice, and snow)	1-2 days

Publicly available satellite imagery tends to be lower resolution and is thus less suitable for precision agriculture applications.[64] Beyond considerations of resolution, other factors such as the sensor position, GPS receiver, viewing angle, cloud condition, sun position and the sensor type used for image acquisition can also affect the quality of remotely sensed images.[65]

The information and advisory generated using satellite imagery are shared with farmers through mobile phones. Thus, the challenges faced by smallholder farmers as end users are the same as those with anyone using mobile phones. Particularly, smartphones are needed for making the most of the capabilities afforded by the availability of high-resolution imagery. Consequently, lack of awareness, literacy and digital skills remain major barriers.

62. United States Geological Survey, "What are the band designations for the Landsat satellites?" available at https://www.usgs.gov/faqs/what-are-band-designations-landsat-satellites; Rajendra P. Sishodia, Ram L. Ray, and Sudhir K. Singh, "Applications of Remote Sensing in Precision Agriculture: A Review," Remote Sensing vol. 12, no. 19 (2020): 3136, available at https://doi.org/10.3390/rs12193136; Jordan Fraczek, "Aerial Imagery Provider Comparison – Satellite and Airborne," AppGeo, available at https://www.appgeo.com/imagery-comparison-satellite-aerial/; William Johnson, Imagery at a Glance: Industry News and Updates for 2020 (AppGeo, 2020), available at ; Maxar Technologies, "Constellation," available at https://www.maxar.com/constellation.

63. Near Infrared (NIR); Short-Wave Infrared (SWIR); Thermal Infrared Sensor (TIRS).

64. Sishodia, Ray, and Singh, "Applications of Remote Sensing in Precision Agriculture: A Review."

65. Metternicht, "Use of remote sensing and GNSS in precision agriculture."

Unmanned Aerial Vehicles (UAVs)

Overview

With recent technological advances, the payload capacity of unmanned aerial vehicles (UAVs, colloquially known as 'drones') has increased substantially, allowing them to carry a variety of payloads (e.g., sensors, cameras, spray equipment) for various precision agriculture applications.[66] Drones allow much higher resolutions than satellites in remote sensing. In addition, they can also be used for the precise application of pesticides and herbicides.

Many governments have gradually implemented favourable regulatory policies supporting the use of drone technology in agriculture. For example, with supportive regulatory frameworks and subsidy-backed purchase models, China—a leader in drone manufacturing—is one of the most drone-friendly countries having over 50,000 agricultural drones in operation.[67] Owing to these favourable regulatory and technological tailwinds, the Association for Unmanned Vehicle Systems International has estimated that 80 percent of the future UAV market will be in the precision agriculture segment.[68]

66. Jaime del Cerro et al., "Unmanned Aerial Vehicles in Agriculture: A Survey," Agronomy vol. 11, no. 2 (2021): 203, available at https://doi.org/10.3390/agronomy11020203.

67. CGTN, "How drones help improve agricultural productivity in poverty-stricken areas," 2 October 2020, available at https://news.cgtn.com/news/2020-10-02/Agricultural-productivity-flies-high-with-drones-in-poverty-hit-areas-UgaQ3MXWhO/index.html.

68. Francisco Klauser and Dennis Pauschinger, "Entrepreneurs of the air: Sprayer drones as mediators of volumetric agriculture," Journal of Rural Studies vol. 84 (May 2021): 55–62, available at https://doi.org/10.1016/j.jrurstud.2021.02.016.

Use in Precision Agriculture

In combination with other technologies such as In combination with other technologies such as various sensors and variable rate technology (VRT), drones are used in multiple stages of the crop growth cycle—from soil analysis, seed sowing or crop spraying to deciding the right moment for harvesting. They serve two broad uses: sensing and labour reduction. When equipped with cameras and sensors, drones enable real-time aerial monitoring and provide a bird's eye view of the farm. Drone payloads, like spraying systems, can reduce the physical labour involved in farm activities such as scouting and applying fertilisers, pesticides and herbicides. The following figure gives an overview of the various kinds of payloads used with drones and their applications for precision agriculture.

Various Drone Payloads and Their Applications[69]

RGB Camera

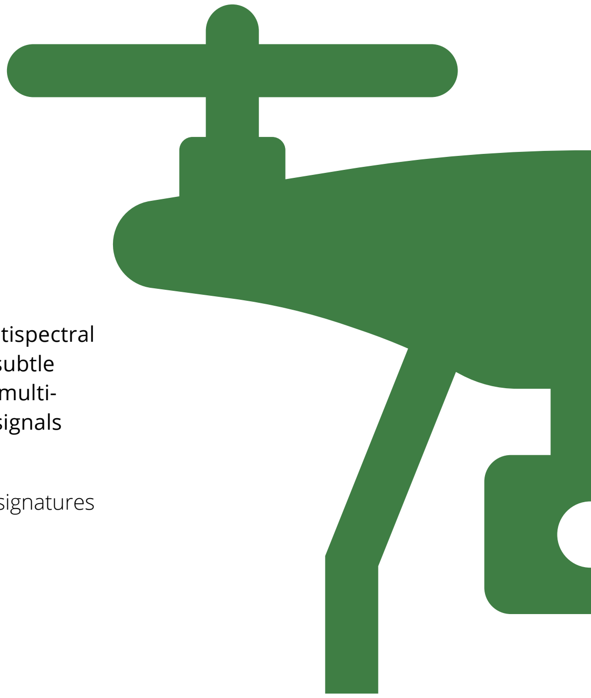
Only able to capture the wavelengths of the visible spectrum.

- Monitoring plants outer defects, greenness and growth
- Calculating a range of vegetation indices
- Creating high-resolution digital elevation models (DEMs)
- Mapping vegetation height

Multispectral Camera

Able to capture wavelengths beyond the visible spectral range, usually through 3-15 bands.[70]

- Monitoring and mapping crop diseases and weeds
- Estimating the vegetation state
- Detecting nutrient deficiency
- Mapping vegetation height



Hyperspectral Camera

Has more and narrower spectral bands compared to multispectral (They are most suitable when there is a need to identify subtle differences in signal along a continuous spectrum. Since multi-spectral cameras sample larger wavebands, these small signals may not be detected)[71]

- Distinguishing different plant species with similar spectral signatures
- Identifying plant biochemical composition
- Quantifying soil vegetation
- Calculating chemical attributes

Thermal Camera

Infrared radiation to form a heat zone image, operating at wavelengths of ~14,000 nm

- Evaluating water stress and assessing irrigation uniformity
- Calculating vegetation indices
- Calculating chemical attributes

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69. Adapted from "Applications of Remote Sensing in Precision Agriculture: A Review."

70. GISGeography, "Multispectral vs Hyperspectral Imagery Explained," 9 June 2021, available at https://gisgeography.com/multispectral-vs-hyperspectral-imagery-explained/.

71. Edmund Optics, "Hyperspectral and Multispectral Imaging," available at https://www.edmundoptics.com.sg/knowledge-center/application-notes/imaging/hyperspectral-and-multispectral-imaging/; Jaylond Cotten-Martin, "Hyperspectral and Multispectral Imaging," Photonics Media, available at https://www.photonics.com/Articles/Hyperspectral_and_Multi-spectral_Imaging/a65595.

Lidar (Light Detection and Ranging)

Uses laser beams to create a 3D representation of the surveyed environment

- Creating high-resolution digital surface models of terrain and elevation
- Measuring canopy heights, coverage, tree density, location and height of individual trees

Position Sensors

Includes inertial navigation systems, GPS, magnetometer

- Finding the physical location of the UAV

Chemical Sensors

- Measuring and detecting quantities of various chemical agents

Biological Sensors

- Identifying various forms of microorganisms

Meteorological Sensors

- Measuring weather-related indicators such as wind speed, temperature and humidity

Spraying System or Similarpayloads

- System consisting of pumps and sprinklers for spraying chemical inputs

Key Considerations

The technical considerations for UAV solutions include battery life, line-of-sight, customs regulations for imported solutions and UAV flight regulations. Regulations regarding airspace are particularly important for autonomous and beyond-line-of-sight drone solutions, though they are more common for cargo delivery than precision agriculture.[72]

The key considerations for using UAVs for smallholder farmers are technical capacity, business models and affordability. Drones are scalable if applied to a group of farms together through cooperative farming or virtual land consolidation.[73] A complete drone solution (including the analytics software, training modules and charging equipment) could amount to $5,000, which is unaffordable for most farmers in low- and lower middle-income countries. In developing countries, drones are being made available for smallholder farmers at affordable prices through business models that support their use. The high initial investment cost of drones makes them an expensive technology to use.

However, in developing countries, a service model where drones are rented out to farmers via a subscription is gaining traction; it offers a more affordable option where the investment cost is spread across multiple farms by the contractors or drone service providers. This service model for drones is ideal as the service providers can also provide technical know-how and training for farmers to use the technology. Such an asset-sharing business model can make drones an accessible and affordable technology.

For instance, Nongtian Guanjia (which means 'farmland manager' in Mandarin) is a Chinese start-up offering a platform where drone operators can connect with farmers to provide agricultural services. The company's app allows farmers to book a range of services, from field data sharing to pesticide spraying. The farmer is usually paired with a drone service operator who is nearest to their field.[74]

In addition, the drone industry has fine-tuned its offerings for smallholder farmers based on affordability and prerequisites of smallholder farmers. For example, for farms in Asia, a drone from a leading manufacturer could cost as little as $400.[75] The low starting price makes it an affordable option for drone service providers and contractors. Companies have also considered prerequisites such as the electric power cost needed to run these drones. For example, an eight-rotor drone could use $1.20 worth of electrical power to move 30 km with a payload of 10 kg.[76] A study of Ghanaian farmers showed that 80 percent of the farmers surveyed were willing to pay between $1.50 and $7 for drone application of pesticides.[77]

Satellites and drones are often compared because they are both a form of remote sensing technology. The following table highlights the considerations for choosing one over another.

72. Andy Lockhart et al., "Why Rwanda Beat Tanzania in UAV Drone Regulation and Experimentation," ICTworks, 3 June 2021, available at https://www.ictworks.org/tanzania-rwanda-uav-drone-regulation/.

73. Virtual land consolidation refers to a group of adjacent farms synchronizing their farming efforts (e.g., type of crop, sowing time, irrigation), so that these farms can be collectively treated as a single farm for application of technologies such as drones and robots for applications such as pesticide spraying.

74. Yon Heong Tung, "Gobi Partners leads US$7M round in Chinese drone sharing startup that serves farmers," e27, 9 June 2017,available at https://e27.co/gobi-partners-leads-us7m-round-chinese-drone-sharing-startup-serves-farmers-20170609/.

75. BIS Research, Global Agriculture Drones and Robots Market – Analysis & Forecast, 2018-2028.

76. Ibid.

77. Festus Annor-Frempong and Selorm Akaba, Socio-Economic Impact and Acceptance Study of Drone-Applied Pesticide on Maize in Ghana (Wageningen: The Technical Centre for Agricultural and Rural Cooperation (CTA), 2020),available at https://www.cta.int/en/digitalisation/issue/socio-economic-impact-and-acceptance-study-of-drone-applied-pesticide-on-maize-in-ghana-sid0f9beb2e1-aafd-483b-85bd-92e66451a0b7.

Table 3: Comparison between satellites and drones for remote sensing applications in precision agriculture[78]

Considerations	Satellites	UAVs
Cost	Satellite imaging tends to be cheaper, especially when area to survey is large. No purchase and maintenance costs for hardware as well.	Usually more expensive per square metre. Requires purchase of hardware (drones) as well as software solution required to process and analyse data captured by drone.
Accompanying analytics software	Satellite data providers usually also provide analytics capabilities on their platform.	UAV suppliers might only provide the hardware and require separate software to analyse collected data.
Need for on-demand service	Possible today with more advanced satellite design and availability of satellites.[79]	Possible because drones can be sent for surveying any time.
Spatial resolution	Generally lower resolution than UAV resolution, especially for publicly available satellites like Landsat and Sentinel. Ranges from 0.3 m to 120 m.	Finer and more granular data: < 5 cm in resolution.
Weather	Not affected by wind conditions but affected by cloud conditions.	Not affected by cloud conditions (fly under clouds) but affected by wind conditions.
Regulations	Usually, no regulations for users for purchasing satellite imagery from providers.	Flying drones require licences in some countries and may even be forbidden if the farm is near airspaces.

78. Earth Observing System, “Drones In Agriculture Make Way For Satellite Monitoring,” 24 October 2019, available at https://eos.com/blog/drones-in-agriculture-make-way-for-satellite-monitoring/; Jonathan Barnes, “Drones vs Satellites: Competitive or Complementary?” Commercial UAV News, 11 April 2018, https://www.commercialuavnews.com/infrastructure/drones-vs-satellites-competitive-complimentary; Patrick C. Gray et al., “Integrating Drone Imagery into High Resolution Satellite Remote Sensing Assessments of Estuarine Environments,” Remote Sensing vol. 10, no. 8 (2018): 1257, available at https://doi.org/10.3390/rs10081257.

79. Capella Space, “Capella Space Unveils Advanced Satellite Design to Deliver High Resolution On-Demand Earth Observation Data,” Cision (PR Newswire), 21 January 2020, https://www.prnewswire.com/news-releases/capella-space-unveils-advanced-satellite-design-to-deliver-high-resolution-on-demand-earth-observation-data-300989916.html; FluroSat, “New in Flurosense: on-demand high-resolution satellite imagery,” available at https://flurosat.com/news/new-in-flurosense-on-demand-high-resolution-satellite-imagery.

Sensors and Internet of Things (IoT)

Overview

The International Telecommunications Union (ITU) defines the Internet of Things (IoT) as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies."[80] In simpler terms, it refers to the multitude of "physical devices around the world that are now connected to the Internet, all collecting and sharing data."[81] Central to IoT for agriculture are on-site sensors that can monitor farm-level parameters such as soil moisture, pH and temperature. This accurate ground-level data can complement data from other sources for informing farmers' decisions.

The agricultural IoT market has strong growth momentum with an expected annual growth rate of 15.2 percent until 2027, when the market is expected to be worth $32.75 billion.[82] This is driven by multiple trends, including the growing availability of low-cost sensors, increasing broadband penetration that enables devices to transmit data to the cloud for aggregation and analysis, and reducing installation costs as sensor providers offer easier assembling of IoT equipment.[83] For example, the IoT sensor array by Fasal, an agritech start-up in India, can be installed in less than 15 minutes.[84]

80. International Telecommunications Union (ITU), "Internet of Things Global Standards Initiative," available at https://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx.

81. Steve Ranger, "What is the IoT? Everything you need to know about the Internet of Things right now," ZDNet, 3 February 2020, available at https://www.zdnet.com/article/what-is-the-internet-of-things-everything-you-need-to-know-about-the-iot-right-now/.

82. Meticulous Market Research Pvt. Ltd., "Agriculture IoT Market Worth $32.75 Billion by 2027 – Market Size, Share, Forecasts, & Trends Analysis Report with COVID-19 Impact by Meticulous Research®," GlobeNewswire, 22 March 2021, available at https://www.globenewswire.com/en/news-release/2021/03/22/2196690/0/en/Agriculture-IoT-Market-Worth-32-75-Billion-by-2027-Market-Size-Share-Forecasts-Trends-Analysis-Report-with-COVID-19-Impact-by-Meticulous-Research.html.

83. Technavio, "Low Cost of Sensors to Boost the IoT Market in Smart Farming," Business Wire, 15 November 2017, available at https://www.businesswire.com/news/home/20171115005848/en/Low-Cost-of-Sensors-to-Boost-the-IoT-Market-in-Smart-Farming-Technavio.

84. Richard Martyn-Hemphill, "India's Fasal raises $1.6m seed funding to build out precision ag across SE Asia," AgFunderNews, 30 October 2019, available at https://agfundernews.com/breaking-indias-fasal-raises-1-6m-seed-funding-to-build-out-precision-ag-across-southeast-asia.html.

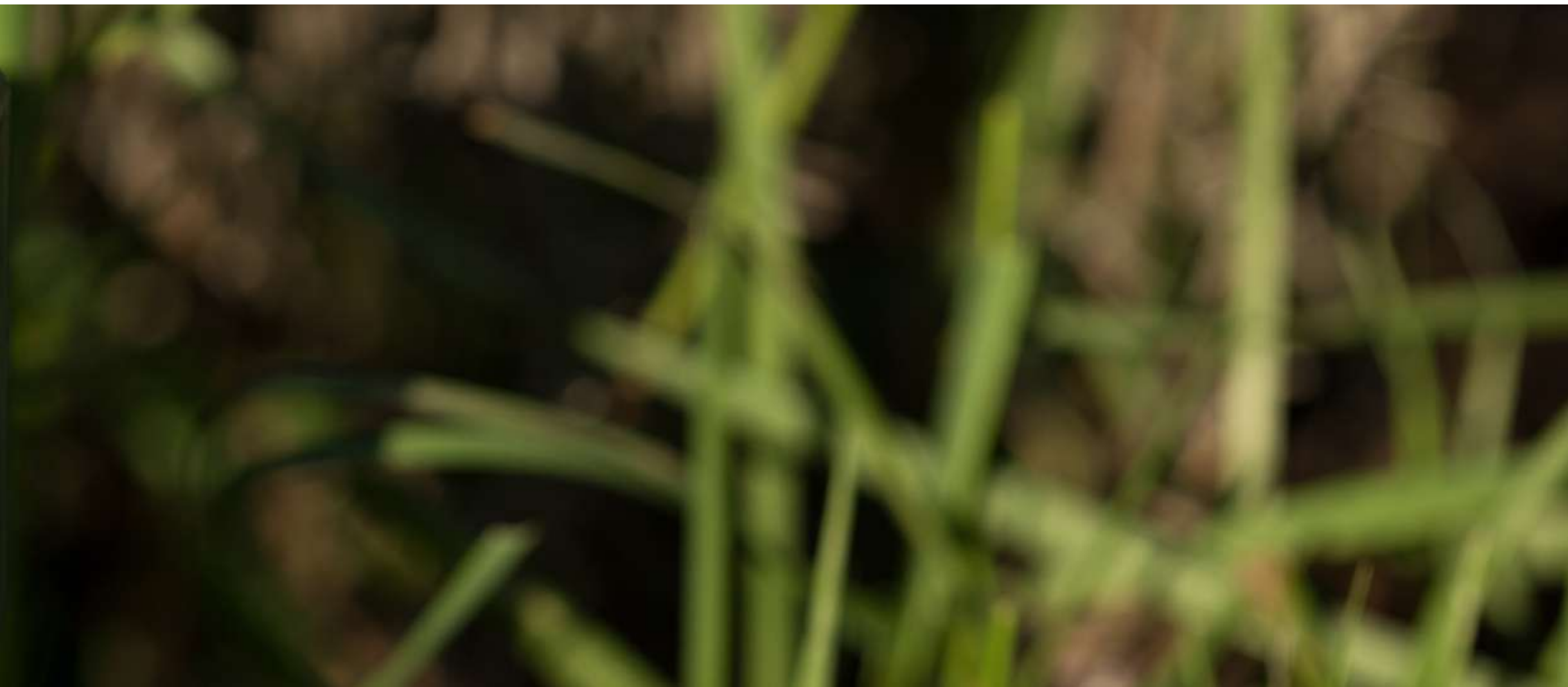
Use in Precision Agriculture

On-site sensors measure field and crop characteristics with high accuracy, which growers can use to make farming decisions. Sensors are used in pest monitoring, soil monitoring, smart irrigation, yield monitoring, weather monitoring, and precision planting and spraying applications. The most commonly used sensors are listed in the table below.

Table 4: Types of on-site sensors for precision agriculture[85]

Group	Sensors
Soil	Moisture, temperature, nitrogen, phosphorous, potassium, carbon, pH
Plants	NDVI, chlorophyll, plant health, plant water demands, sugar content
Atmospheric	Temperature, humidity, wind speed, rainfall, pressure, precipitation
Water	pH, temperature, turbidity, water depth, conductivity, dissolved O_2

85. Anish Paul Antony, Jennifer Lu, and Daniel Sweeney, Seeds of Silicon: Internet of Things for Smallholder Agriculture (Comprehensive Initiative on Technology Evaluation, Massachusetts Institute of Technology, 2019), available at https://d-lab.mit.edu/resources/publications/seeds-silicon-internet-things-smallholder-agriculture.



For on-site sensors to communicate and transmit data, they need a set of rules that govern inter-device communication. This set of rules is known as a network protocol. Different wireless networking technologies have different ranges and sizes of transmission and are thus suitable for different purposes. The following table provides a comparison:

Table 5: Comparison of different wireless networking technologies[86]

	Bluetooth Low Energy Technology	Wi-Fi	Z-Wave	IEEE 809.15.4 (Zigbee, Thread)	LTE-M	NB-IoT	Sigfox	LoRaWAN
Range	10m – 1.5km	15m –100m	30m – 50m	30m –100m	1km – 10km	1km – 10km	3km – 50km	2km – 20km
Throughput	125kbps – 2Mbps	54 Mbps – 1.3 Gbps	10 kbps – 100 kpbs	20 kpbs – 250 kpbs	Up to 1 Mbps	Up to 200 kpbs	Up to 100 bps	10 kbps – 50 kpbs
Power Consumption	Low	Medium	Low	Low	Medium	Low	Low	Low
Ongoing Cost	One-time	One-time	One-time	One-time	Recurring	Recurring	Recurring	One-time
Module Cost	Under $5	Under $10	Under $10	$8-$15	$8-$20	$8-$15	Under $5	$8-$15
Topology	P2P, Star, Mesh, Broadcast	Star, Mesh	Mesh	Mesh	Star	Star	Star	Star
Shipments in 2019 (millions)	~3500	~3200	~120	~420	~7	~16	~10	~45

86. Mohammad Afaneh, "Wireless Connectivity Options for IoT Applications – Technology Comparison," Bluetooth®, 21 April 2020, available at https://www.bluetooth.com/blog/wireless-connectivity-options-for-iot-applications-technology-comparison/.

Low-Power Wide-Area Network technology (LPWAN) is being widely adopted for agricultural IoT usage. LPWAN is best suited for smart devices to communicate over a large distance but only need to transmit small amounts of data. LoRaWAN[87] and NB-IoT[88] are examples of LPWAN network technologies. Apart from a long range of coverage (up to 20 km), they also have low power consumption, and thus the batteries that power the sensors can last up to 15 years.[89] LoRaWAN is more commonly adopted for agricultural use because it does not rely on 4G and GPS (while still offering strong data transmission and geolocation).[90] This means it is more suitable for rural areas with limited 4G coverage.[91]

87. LoRaWAN® is an LPWAN protocol "designed to connect battery operated 'things' to the Internet in regional, national or global networks". (see LoRa Alliance, "What is LoRaWAN® Specification," available at https://lora-alliance.org/about-lorawan/.

88. NarrowBand-Internet of Things (NB-IoT) is a "standards-based low power wide area (LPWA) technology developed to enable a wide range of new IoT devices and services." (see GSMA, "Narrowband – Internet of Things (NB-IoT)," available at https://www.gsma.com/iot/narrow-band-internet-of-things-nb-iot/.

89. Actility, "IoT enables precision agriculture and smart farming," available at https://www.actility.com/precision-agriculture/.

90. Eric Hewitson, "Revolutionising smart agriculture with LoRa and LoRaWAN," Wyld, available at https://wyldnetworks.com/staging/8929/smart-agriculture-with-lora-and-lorawan/.

91. Art Reed, "NB-IoT vs. LoRa: It's an Ecosystem, Not a Race," LinkedIn, 14 July 2017, https://www.linkedin.com/pulse/nb-iot-vs-lora-its-ecosystem-race-art-reed/.

Key Considerations

Connectivity and affordability issues hinder adoption of IoT technology. On-site sensors require Internet connectivity, which can be a challenge in rural areas. Also, while the cost of sensors is falling, data transmission networks and protocols powering these technologies use significant power and bandwidth, thus causing the overall price to be high for smallholder farmers.[92] Some companies are also investing in local production of sensors to avoid paying high prices for imported components from developed markets.[93]

Overall, sensors are less scalable because multiple farms would require multiple sensors, which may not be economically favourable. Small farms often do not have much variability in soil parameters, such sensors may not provide significant insights. Given this, the benefits of sensors do not currently justify the cost for the smallholder farmers.

As such, efforts have been made to replace on-site sensors with smartphone sensors. For instance, Microsoft is developing a solution that uses a smartphone's Wi-Fi chipset instead of a network of sensors, thereby eliminating the cost of purchasing standalone sensors. The technology analyses the 'time of flight'[94] to determine the soil moisture and conductivity (this correlates well with physical and chemical properties that indicate soil health). This informs the farmers on how much input and fertiliser to use.

92. U.S. Agency for International Development, Low-cost sensors for agriculture (USAID, 2016), available at https://static.globalinnovationexchange.org/s3fs-public/asset/document/USAID%20Sensors4Ag%20Key%20Findings%20FINAL_FOR%20DISTRIBUTION.pdf.

93. Abbie Phatty-Jobe, Digital Agriculture Maps: 2020 State of the Sector in Low and Middle-Income Countries (London: GSMA, 2020), available at https://www.gsma.com/r/digital-agriculture-maps/.

94. Rajat Agrawal, "How Microsoft is building new tech to bring precision agriculture to the world's poorest farmers," Microsoft, 11 March 2020, available at https://news.microsoft.com/en-in/features/microsoft-farmbeats-building-tech-precision-agriculture-world-poorest-farmers/.

Agricultural field intelligence through IoT

Arable Labs (https://arable.com), a startup from the United States, produces IoT devices that provide on-site climate and plant data. Their devices can track more than 40 weather and plant measurements (such as ambient temperature, humidity, precipitation, NDVI and photosynthetic active radiation), offering insights on climate variability, crop health, event timing and irrigation.

An interesting public-private partnership project is enabling the provision of accurate weather data for smallholder farmers. Due to poor infrastructure, local weather stations are often far from farms and do not provide localised information.

In Kenya, the University of California, Santa Barbara and Mpala Research Centre, a Kenyan private conservation organisation worked with AEWs to install and maintain Arable Labs' IoT equipment to help farmers address the above challenge.[95] The AEWs would also communicate the project's expected benefits and results to the farmers. Farmers, on their own, could also access the real-time insights through a mobile application.

Arable device installed on a farm in Kenya. Photo by Massachusetts Institute of Technology (MIT) D-Lab

95. Paul Antony, Lu, and Sweeney, Seeds of Silicon: Internet of Things for Smallholder Agriculture.

Other Technologies

Technologies like variable rate technology (VRT) and farm robotics and automation are aiding precision agriculture. However, high costs, absence of viable business models, and the need for technological know-how make them currently infeasible for adoption by smallholder farmers.

Robotics and Farm Automation

Farmers around the world are using robotics in varied forms such as autonomous tractors, weeding robots, harvesting robots, and crop monitoring bots to reduce multiple trips for farm monitoring, reduce crop damage and losses, improve farm yield and reduce fuel consumption. The biggest constraint to adopting agricultural robots in developing countries is their high cost. For instance, in 2017 robotic crop scouting was estimated to require an upfront cost of more than $9,000 and an annual operating cost of $18 per hectare. Other small mobile robots for pruning and weeding could easily cost between $15,000 and $30,000.[96]

However, different business models are being explored to make robotics an affordable option. For example, Ambit Robotics has developed a crop-spraying robot specially for Southeast Asian small farms. The business model adopted involves using 'Agricultural Robots-as-a-service (ARaaS)'. This model offers smallholder farmers a comfortable financial option by paying for the use of farm robots.[97]

96. Frank Tobe, "The Ultimate Guide to Agricultural Robotics," Robotics Business Review, 1 January 2017, available at https://www.roboticsbusinessreview.com/agriculture/the_ultimate_guide_to_agricultural_robotics/.

97. Putu Agung Wija Putera, "Ambit Robotics: Automated crop spraying for Southeast Asia's smallholder farmers," CompassList, 25 September 2020, available at https://www.compasslist.com/insights/ambit-robotics-automated-crop-spraying-for-southeast-asias-smallholder-farmers.

Low-cost robotics designed by the University of Sydney[98]

The Australian Centre of Field Robotics (ACFR) of the University of Sydney has designed a farm robot called 'Digital Farmhand'. It is made of two wheels that allow it to travel unmanned over rows of crops. It has a hitch that allows sensors, sprayers or weeders to be attached to it. The robot's design is intentionally simple so farmers in rural areas can easily find off-the-shelf parts to repair it. It can be powered either by batteries or micro solar cells.

Digital Farmhand allows farmers to assess plant health, conduct pesticide spraying and weeding activities autonomously, and even collect farm data for crop analytics. An interesting innovation is that farmers can attach their smartphones to the robot. The robot can collect data about the farm and process this data using the smartphone's chipset. As an example of its application, the smartphone may identify a certain fungus and trigger the sprayer on the robot to automatically apply the appropriate fungicide.

Digital Farmhand. Photo by University of Sydney

The product has been trialled in Fiji and Samoa. Some of the key lessons that the university team derived are:[99]

- Pest identification and disease monitoring are two of the most appropriate applications of farm robotics for small farms.
- A service model would be most suitable in delivering products like Digital Farmhand.
- Working with non-profit organisations and AEWs who are locally known is useful for training farmers to use the product.
- In-person demonstration of the product on crop rows was the most effective in illustrating how the product works.

98. University of Sydney Faculty of Engineering, "Digital Farmhand boosts food security in the Pacific," 3 August 2018, available at https://www.sydney.edu.au/engineering/news-and-events/2018/08/03/digital-farmhand-boosts-food-security-in-the-pacific.html; The University of Sydney, "The robot revolution that will help farmers all over the world," available at https://www.sydney.edu.au/research/research-impact/the-robot-revolution-that-will-help-farmers-all-over-the-world.html.

99. Salah Sukkarieh, "AI Powered Robots for Smallholder Farmers in Fiji and Samoa," The University of Sydney Australian Centre for Field Robotics, available at https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2020/Digital%20Agriculture%20Solutions%20Forum%202020%20for%20Asia%20and%20the%20Pacific/DASF_2020_ASP/AI%20Powered%20Robotics%20Sukkarieh%20FAO%20Final.pdf.

Variable Rate Technology

Factors that influence crop yield are seldom uniform across a field. Also, the uniform application of inputs does not allow for optimum yield and profitability. Variable rate technology (VRT) involves customizing and varying rates of inputs, such as fertilisers, chemicals and seeds, in appropriate zones throughout the field to help maximise input efficiency and, thereby, the yield and profitability of individual fields.[100]

Variable-rate capable equipment (e.g., sprayer, spreader) is fitted to vehicles such as drones, tractors or other agricultural robots for delivery. Such equipment is usually expensive (costing between $150,000 and $250,000 in 2020)[101] and complicated for farmers to learn and implement, making it infeasible for smallholder farms.

100. BIS Research, Global Precision Agriculture Market – Analysis and Forecast, 2018 – 2025.

101. Phillip Clancy, "Making Your Variable Rate Technology Pay," CropLife, 8 July 2020, available at https://www.croplife.com/precision/making-your-variable-rate-technology-pay/.

Data Analytics and Precision Agriculture

Data forms the digital resource layer enabling precision agriculture. With the development of stronger computational power, advanced analytics and new techniques to interpret unstructured data, big datasets can now be cost-effectively and widely leveraged. Moreover, the sheer volume of hyper-local agriculture data from satellites, sensors, and various other data sources and the prevalence of mobile devices are making big data applications for smallholder farmers a reality.[102]

The following figure shows a 'data chain' for precision agriculture, which best describes the lifecycle of a dataset.[103]

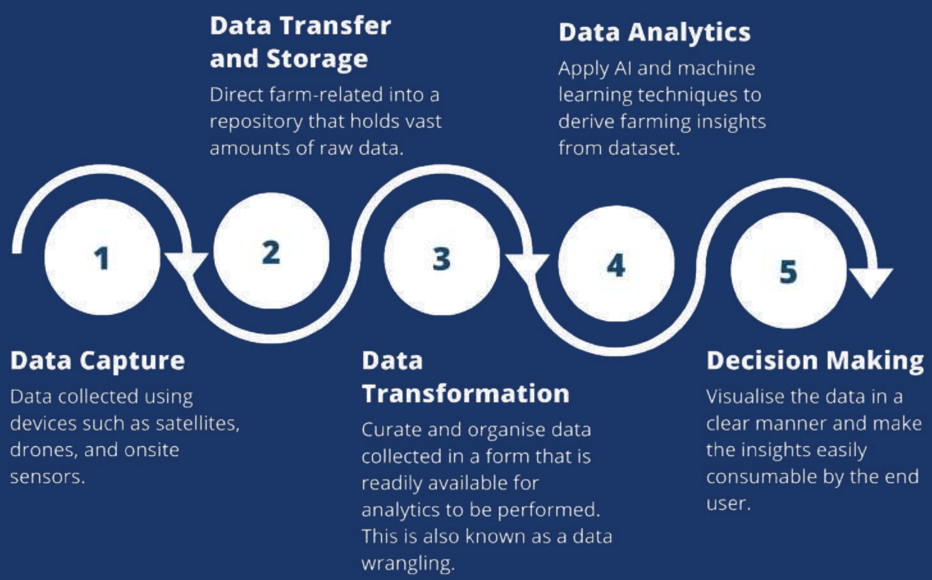


Figure 2: Data chain for precision agriculture

The data collected from farmers could be used for building farmer profiles. A farmer profile would typically include information about farm size, crop type, income levels, physical assets and demographic information. Farmer profiles allow government agencies, private sector players (e.g., financial service providers, input suppliers, wholesalers, agricultural processors), non-profits and others to offer products and services that improve farming efficiency, farmers' financial inclusion and farmers' integration into agricultural supply chains.[104] In fact, "as digital management of farmer profile data becomes the norm, the farmer becomes only one of many sources of that data and only one of its many users."[105]

102. Brett Drury, "Smallholder. Big data," CGIAR Platform for Big Data in Agriculture, 12 April 2018, https://bigdata.cgiar.org/smallholder-big-data/.

103. Edward Curry, "The Big Data Value Chain: Definitions, Concepts, and Theoretical Approaches," in New Horizons for a Data-Driven Economy, ed. J. Cavanillas, E. Curry, W. Wahlster (Cham: Springer, 2016): 29–37, available at https://doi.org/10.1007/978-3-319-21569-3_3.

104. Steve Hollingworth, "Big data and smallholder farmers," Grameen Foundation, 17 April 2018, available at https://grameenfoundation.org/stories/blog/big-data-and-smallholder-farmers.

105. Bobbi Gray et al., Digital Farmer Profiles: Reimagining Smallholder Agriculture (USAID, 2018), available at https://grameenfoundation.org/partners/resources/digital-farmer-profiles-reimagining-smallholder-agriculture.

An important consideration is to always apply data privacy and security principles such as data minimisation and storage limitation. Leading data governance frameworks include the General Data Protection Regulation (GDPR), which is a set of data privacy regulations that offer European Union residents more control over their data.[106] The FAIR Guiding Principles[107] —which recommend that data should strive to be findable, accessible, interoperable and reusable—are useful when approaching data for research purposes.

While legal and regulatory frameworks around the sharing and governance of agricultural data are nascent in developing countries, practitioners should work with service providers to ensure data privacy per international standards. This includes ensuring that terms and conditions of data licences are clearly explained to farmers. Farmers in industrialised countries sometimes resist adopting big data technologies because they are unsure how their data is governed and shared.[108] They are cautious about precision agriculture data feeding into credit and insurance companies and personalised products leveraging opaque decision support algorithms.

Biophysical parameters in agriculture (like soil nutrients, soil organic carbon, soil moisture, digital elevation models, photos of pests, yield, etc.) are non-personal data and hence less relevant to data privacy. However, farmer's socio-economic data would be considered personal data. Implementing privacy best practices ensure that the rights of smallholder farmers are not infringed, and in turn, encourage greater adoption of these technologies when farmers feel protected.

Other challenges with data analytics and big data for precision agriculture include data fragmentation and bandwidth constraints. Data fragmentation refers to the problem of aggregating data across multiple equipment (sensors, drones, etc.) in an interoperable and usable format to give a holistic picture of the farm. Bandwidth constraints describe the challenge of running machine learning algorithms in the cloud with limited Internet connectivity, especially in rural and less developed areas. Project designers should thus consider if data analytics platforms can be designed without cloud computing as a prerequisite.[109]

106. Danny Palmer, "What is GDPR? Everything you need to know about the new general data protection regulations," ZDNet, 17 May 2019, available at https://www.zdnet.com/article/gdpr-an-executive-guide-to-what-you-need-to-know/.

107. Mark D. Wilkinson et al., "The FAIR Guiding Principles for scientific data management and stewardship," Scientific Data vol. 3, no. 160018 (2016), available at https://doi.org/10.1038/sdata.2016.18.

108. Michael Kassner, "6 reasons why farmers are losing sleep over big data security," TechRepublic, 1 March 2016, available at https://www.techrepublic.com/article/6-reasons-why-farmers-are-losing-sleep-over-big-data-security/.

109. Casey Kinsey, "The 5 Biggest Digital Challenges for Precision Agriculture," Lofty, available at https://hirelofty.com/blog/product-and-strategy/5-biggest-digital-challenges-precision-agriculture/.

Key Applications

Key Applications

A range of precision agriculture applications is made possible by various combinations of technologies described in the previous section. This section describes some important applications of precision agriculture that are benefiting smallholder farmers.

Most precision agriculture applications can be divided into three broad stages:

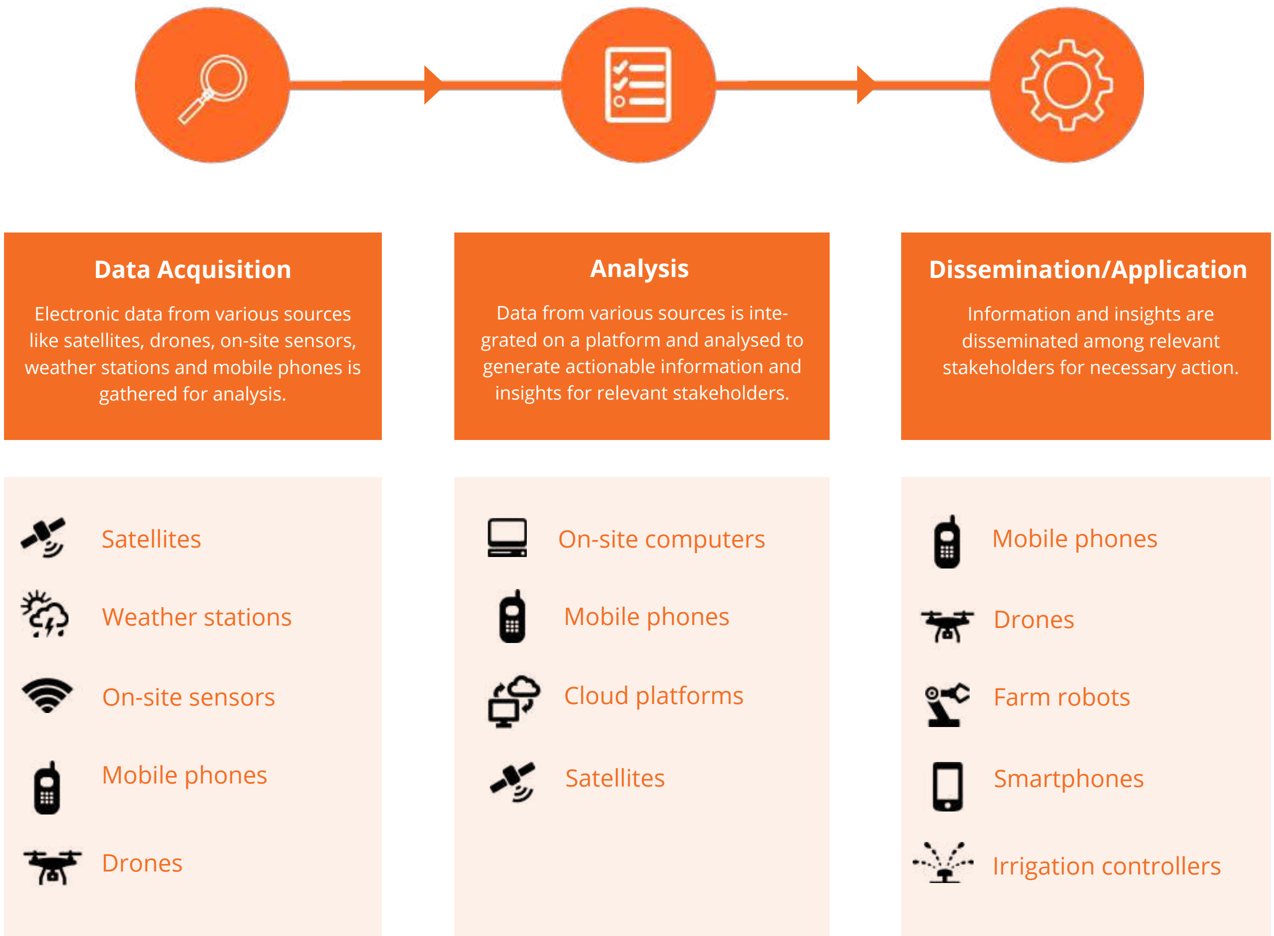


Figure 3: Three stages of a precision agriculture solution and the technologies involved

Weather Monitoring

The Food and Agriculture Organization of the United Nations (FAO) estimates that the agriculture sector in developing countries absorbs 25 percent of the total damage and losses caused by climate-related disasters, such as droughts, floods and storms. In financial terms, natural disasters alone have been responsible for more than $200 billion of economic losses since 2016.[110]

Weather monitoring involves the continuous study and analysis of key weather parameters such as temperature, moisture, pressure and wind velocity to make informed planting, harvesting and irrigation decisions. For example, if a crop were expected to be at peak quality in a week, but there was a forecast for heavy rain tomorrow, a farmer could decide to harvest today and avoid the risk of crop damage.

Typically, weather information comes from centralised sources where meteorologists make predictions for a large geographical area. In fact, the data that informs these predictions may be collected by a weather station nearest to farmers' location but could still be relatively far away.

Weather conditions can vary significantly over even a few kilometres, and farm activities can be considerably affected with even a few degrees of difference in temperature or millimetres of rainfall.[111] Other problems with current weather information include conflicting information from multiple sources, poor integration with farmer operations and not being tailored for a farmers' individual decisions.[112]

Weather monitoring solutions for precision agriculture can be categorised into either software- or hardware-based solutions.

- **Software-based weather monitoring**

  Software-only solutions aggregate weather information on temperature, precipitation, humidity and wind speed from many private and public networks of observers, automatic weather stations or buoys. Through proprietary algorithms, companies can then offer farm-level weather advisory and analytics to users.

- **Hardware-based weather monitoring**

  Hardware-based solutions deploy sensor technology and physical weather stations closer to farms to capture weather signals that best represent local conditions. Users will need to purchase the sensing equipment.

110. Naveen Kumar Arora, "Impact of climate change on agriculture production and its sustainable solutions," Environmental Sustainability vol. 2, no. 2 (June 2019): 95–96, available at https://doi.org/10.1007/s42398-019-00078-w.

111. Croptracker, "On Farm Weather Stations in Precision Agriculture," available at https://www.croptracker.com/blog/on-farm-weather-stations-in-precision-agriculture.html.

112. William P. Mahoney III, "Advanced Weather Prediction Capabilities & Precision Agriculture," 28 August 2014, http://ral.ucar.edu/csap/events/agriculture-climate-across-scales/file_attach/William_Mahoney.pdf.

Weather service built on virtual weather stations

aWhere delivers weather-based agricultural intelligence with its 1.9 million virtual weather stations and advanced analytics. Its millions of weather stations put farmers within 6.4 km of a local weather station. Built using billions of data points generated each day from a variety of sources, these "virtual stations" mimic what a physical weather station would collect. aWhere has accumulated historical data from 2006 and have built climate forecast models on more than 20 critical weather variables. This advisory service is available as an API integration.

Weather monitoring mobile app for farmers

IBM and Yara have jointly developed the FarmWeather mobile app, which provides farmers with hyperlocal and reliable weather insights within a 3–4km radius. The app leverages data from IBM's The Weather Company and Global High-Resolution Atmospheric Forecasting System (IBM GRAF). Advisory messages are communicated to farmers without mobile broadband access through SMS. [113]

Low-cost weather stations to overcome lack of weather tracking infrastructure

Kukua is a social enterprise that has developed weather stations serving smallholder farmers in sub-Saharan Africa, where there is a dearth of weather tracking infrastructure. Powered by hand-sized solar panels, these weather stations are relatively cost-effective and upload weather data to the Internet every 15 minutes. Weather information is sent to farmers on their mobile phones.[114]

113. Peter Rylander, "Helping smallholder farmers predict the weather can transform the global food system," IBM Nordic Blog, 23 February 2021, available at https://www.ibm.com/blogs/nordic-msp/helping-smallholder-farmers-predict-the-weather-can-transform-the-global-food-system/.

114. F6S, "Kukua Weather Services," available at https://www.f6s.com/kukuaweatherservices; Food and Agriculture Organization of the United Nations, "Kukua: Weather Data and forecasting services for local farmers in Africa," E-Agriculture, 9 November 2017, available at http://www.fao.org/e-agriculture/news/kukua-weather-data-and-forecasting-services-local-farmers-africa.

Publicly available weather information is typically freely provided by governments, while insights derived from such data are usually provided by companies for a fee. An advantage of such services is index-based insurance. Index insurance pays out benefits to farmers according to indices that correlate strongly to agricultural production. Index data could include rainfall, yields, and temperature, which can be obtained via remote sensing.[115] Once the threshold for an index is exceeded and farms are expected to be adversely affected, farmers can automatically receive insurance pay-outs, sometimes through mobile wallets. This arrangement overcomes the need to physically verify loss by insurance companies, which can be challenging when smallholder farmers are dispersed across a vast area and where infrastructure is poor.[116]

115. Radost Stanimirova et al., Using Satellites to Make Index Insurance Scalable: Final IRI Report to the ILO Microinsurance Innovation Facility, Release 2.0.0 (International Research Institute for Climate and Society, 2013), available at https://iri.columbia.edu/resources/publications/using-satellites-scalable-index-insurance-iri-ilo-report/.

116. Research Program on Climate Change, Agriculture, and Food Security (CCAFS), "Index-based insurance," available at https://ccafs.cgiar.org/research/index-based-insurance.

Soil Monitoring

Healthy soil is essential for producing healthy crops. However, unsustainable agricultural practices such as the indiscriminate use of chemical fertilisers and deforestation degrade soil quality and adversely affect crop yields. The 2015 Status of the World's Soil Resources report[117] identified nutrient imbalances and loss of organic carbon as two of the most severe threats to soil health globally. About a third of the world's soil is already degraded, according to FAO.[118]

Soil monitoring is the measurement and monitoring of soil's physical and biochemical attributes such as nutrients, microbes, and water. Particularly, maintaining a proper balance of soil NPK levels[119] is important for maximising yields. Knowledge of these parameters allows farmers to avail advice on the types and amounts of fertilisers to be applied to match the needs of their farms. Soil monitoring not only helps save unnecessary expenditure on inputs but also helps avoid soil degradation due to excessive use of chemical fertilisers.

Soil testing is usually done using on-site sensors. Information collected from these sensors is usually fed into variable-rate enabled devices for precise application of farm inputs. It could also be deployed with GPS and data analytics to generate field maps that visualise and track soil health, especially during the harvest season.[120]

Soil sensors are presently uneconomical for small farms. In Africa, for instance, the adoption of soil monitoring solutions stands at only 3–18 percent. Most of the time, sensors are confined to commercial and large farms.[121] Thus, soil monitoring solutions for smallholder farms often come in the form of advisory services because they spread the cost of data collection across multiple farms and are sometimes publicly funded.

117. FAO report available at http://www.fao.org/3/i5199e/I5199E.pdf.

118. Chris Arsenault, "Only 60 years of farming left if soil degradation continues," Reuters, 6 December 2014, available at https://www.reuters.com/article/us-food-soil-farming-idUSKCN0JJ1R920141205.

119. NPK stands for Nitrogen, Phosphorus, and Potassium—the three macronutrients used by plants.

120. Research and Markets, "Worldwide Precision Farming Industry to 2026 - Soil Monitoring is Expected to Hold a Significant Share of the Market," GlobeNewswire, 17 February 2021, available at https://www.globenewswire.com/en/news-release/2021/02/17/2177033/28124/en/Worldwide-Precision-Farming-Industry-to-2026-Soil-Monitoring-is-Expected-to-Hold-a-Significant-Share-of-the-Market.html.

121. Dominik Klauser and Christine Negra, "Getting Down to Earth (and Business): Focus on African Smallholders' Incentives for Improved Soil Management," Frontiers in Sustainable Food Systems vol. 4, article 576606 (2020), available at https://doi.org/10.3389/fsufs.2020.576606.

Soil Health Cards in India

The Soil Health Card Scheme is an initiative by the Government of India to offer farmers field-level soil condition information, fertiliser and crop recommendations, and land management tips. The motivation for this is to solve the inefficient application of fertilisers. Often, farmers only discover the optimal fertiliser and crop to invest in through trial and error.[122]

Government staff and volunteers collect soil samples from farms using GPS and revenue maps. For irrigated areas, soil samples are drawn every 2.5 ha; for rain-fed areas, every 10 ha.[123] A Soil Health Card is a printed card displaying the health of a farmer's land, based on indicators of macronutrients, secondary nutrients, micronutrients, and physical parameters.[124] The government has also launched an online tool[125] to recommend optimal amounts of fertilisers based on soil test results (NPK and organic carbon content) and parameters like crop type, soil type, and availability of irrigation.

Since the scheme's launch in February 2015, more than 150 million farmers have received their Soil Health Cards. These cards are re-sent every three years to reflect changes in field conditions.[126] According to the National Productivity Council of India, the scheme has reduced the use of chemical fertilisers by 8–10 percent and raised productivity by 5–6 percent.[127]

However, the scheme has faced multiple criticisms. Farmers have complained that the cards contain too many technical terms and could not be easily understood without assistance.[128] There are also criticisms about the sampling methodology and the accuracy of tests.[129] Farmers' participation in trainings was also found to be lower in less developed states of the country.[130]

122. Divya Nair et al., "Improving India's soil health card scheme and agricultural markets," IDinsight, 25 May 2021, available at https://www.idinsight.org/project/improving-indias-soil-health-card-scheme-and-agricultural-markets/.

123. "Soil Health Card," Vikaspedia, https://vikaspedia.in/agriculture/policies-and-schemes/crops-related/krishi-unnati-yojana/soil-health-card.

124. National Portal of India, "Soil Health Card," available at https://www.india.gov.in/spotlight/soil-health-card.

125. Government of India Department of Agriculture and Farmers Welfare, "Soil Health Card," available at https://www.soilhealth.dac.gov.in/calculator/calculator.

126. Nair et al., "Improving India's soil health card scheme and agricultural markets."

127. Rituraj Tiwari, "Soil health card reduces fertiliser use by 10%," The Economic Times, 5 February 2020, available at https://economictimes.indiatimes.com/news/economy/agriculture/soil-health-card-reduces-fertiliser-use-by-10/articleshow/73957634.cms.

128. Vartika Singh and Sujata Ganguly, "Designing a better Soil Health Card for farmers in India," International Food Policy Research Institute (IFPRI), 19 March 2018, available at https://www.ifpri.org/blog/designing-better-soil-health-card-farmers-india.

129. Jyotika Sood, "Unearthing the loopholes in Modi government's Soil Health Card scheme," DNA, 7 October 2015, available at https://www.dnaindia.com/analysis/column-unearthing-the-loopholes-in-modi-government-s-soil-health-card-scheme-2132191.

130. A Amarender Reddy, "The Soil Health Card Scheme in India: Lessons Learned and Challenges for Replication in Other Developing Countries," Journal of Natural Resources Policy Research vol. 9, no. 2 (2019): 124–154, available at https://www.jstor.org/stable/10.5325/naturesopolirese.9.2.0124.

Pest Surveillance and Disease Monitoring

According to FAO, pests account for 20 to 40 percent of annual global crop loss yearly. In monetary terms, the annual economic damage attributable to invasive insects is $70 billion, while plant diseases account for about $220 billion.[131] The monitoring of farms for insects and other pests is thus critical to improving farm production. The most common disease and pest detection method today is visual diagnosis by a human expert.[132] This is not only challenging to scale, but it can also be expensive for smallholder farmers to hire an expert to come to their field for inspection.

Pest and disease monitoring solutions employ simple hand-held devices, remote sensing and on-site sensors to provide timely and reliable advice for integrated pest management. Depending on the disease and pest, different sensor technologies are appropriate. Optical sensors are most useful for diseases that occur in patches and cause considerable changes to the crops' shape, size or colour. Image sensors with pheromone and acoustic sensors are used to gather on-site information about soil-dwelling insects and other pests.[133]

Remote sensing capabilities have been more successful for diseases that infect in clusters and result in significant changes to the foliage. Such diseases include root-knot nematodes, Late Blight on tomato, Northern Leaf Blight on corn and diseases on perennial and orchard crops.[134] For diseases like the Cotton Root Rot, which often reoccur in the same area in the field, disease maps plotted in the preceding harvest season can be used for early prevention and pesticide application.[135]

Because of the ubiquity of smartphones, innovators have developed mobile applications which allow farmers to snap a picture of the infected crop and receive an immediate diagnosis. These applications typically use the processing power of the smartphone to run the computer vision and machine learning algorithms underlying the application. They are sometimes combined with SMS services to send alerts to other farmers in the community when a disease or pest is detected.[136]

131. Food and Agriculture Organization of the United Nations, "New standards to curb the global spread of plant pests and diseases," 3 April 2019, available at http://www.fao.org/news/story/en/item/1187738/icode/.

132. A.-K. Mahlein et al., "Hyperspectral Sensors and Imaging Technologies in Phytopathology: State of the Art," Annual Review of Phytopathology vol. 56, no. 1 (2018): 535–558, available at https://doi.org/10.1146/annurev-phyto-080417-050100.

133. Erich-Christian Oerke, "Remote Sensing of Diseases," Annual Review of Phytopathology vol. 58, no. 1 (2020): 225–252, available at https://doi.org/10.1146/annurev-phyto-010820-012832; Richard W. Mankin et al., "Methods for Acoustic Detection of Insect Pests in Soil," Proceedings of the Soil Science Society of America Conference on Agroacoustics, Third Symposium (1998), available at https://www.ars.usda.gov/ARSUserFiles/3559/publications/agroacoust3pp3-8.html.

134. Daniel P. Roberts et al., "Precision agriculture and geospatial techniques for sustainable disease control," Indian Phytopathology vol. 74 (2021): 287–305, available at https://doi.org/10.1007/s42360-021-00334-2.

135. Chenghai Yang, "Remote Sensing and Precision Agriculture Technologies for Crop Disease Detection and Management with a Practical Application Example," Engineering vol. 6, no. 5 (2020): 528–532, https://doi.org/10.1016/j.eng.2019.10.015.

136. Pennsylvania State University, "New mobile app diagnoses crop diseases in the field and alerts rural farmers," Phys.org, 6 October 2017, available at https://phys.org/news/2017-10-mobile-app-crop-diseases-field.html.

The data collected could include information on soil fertility, pathogen and pest presence, and soil fertility. These data points are then analysed using big data analytics, digital signal processing, image processing techniques and computer vision. Insecticide spray programmes, for instance, use such data to precisely administer insecticide where pest infestation is severe. Some monitoring solutions are even paired with camera-equipped traps, which would either automatically or semi-automatically remove these harmful pests.[137] These solutions promise to reduce pesticide, water and fertiliser usage. In some cases, savings on fertilisers can be as much as 15–20 percent.[138]

Pest management solutions using remote sensing and hand-held devices are more suitable for smallholder farmers in low- and medium-income countries. For instance, AgrioShield, a mobile app for pest alerts by Israeli start-up Saillog, currently costs $2 per month.[139] Due to higher costs, camera-equipped automatic traps are not widely adopted by smallholder farmers. They are generally used by farming cooperatives who can spread the costs and enjoy added benefits of sharing data on pests.[140]

137. Michele Preti, François Verheggen, and Sergio Angeli, "Insect pest monitoring with camera-equipped traps: strengths and limitations," Journal of Pest Science vol. 94 (2021): 203–217, available at https://doi.org/10.1007/s10340-020-01309-4.

138. BIS Research, Global Precision Agriculture Market – Analysis and Forecast, 2018-2025.

139. NoCamels, "Israeli Startup Launches AI-Powered Alert App to Help Farmers Save Crops from Disease, Pests," 3 April 2018, available at https://nocamels.com/2018/04/saillog-ai-app-farming-disease/.

140. Preti, Verheggen, and Angeli, "Insect pest monitoring with camera-equipped traps: strengths and limitations."

Leveraging artificial intelligence (AI) to tackle pink bollworm infestation for cotton in India[141]

Cotton is a major cash crop in India, providing livelihood to about 6 million farmers. However, 20–30 percent of the crop is destroyed annually due to pests like the pink bollworm. The worms are larvae of insects who eat the seeds and damage the cotton fibres. An Indian non-profit Wadhwani AI and Google.org, the philanthropic arm of Google, have developed a mobile app called 'CottonAce' to provide quick advice to farmers to tackle the menace.

Person taking a photo of a pest trap. Photo by Google

Using the app, a few tech-savvy 'lead farmers' in a community can take images of the worms caught in a pest trap. The images are analysed using the AI model in the app, which instantly predicts the trajectory of infestation and advises on ways to counter the menace, including spraying of pesticides. If infestation is not severe, farmers may be advised to spray biopesticides, allowing them to save costs and avoid the indiscriminate spraying of chemical pesticides.

141. Talib Visram, "Google.org is helping deploy AI to prevent pests devastating Indian crops," Fast Company, 27 May 2021, available at https://www.fastcompany.com/90640843/google-is-helping-deploy-ai-to-prevent-pests-devastating-indian-crops.

eLocust3: FAO's solution for locust monitoring and forecasting[142]

eLocust3 is a data logging and transmission solution for monitoring and forecasting locust outbreaks. It is designed specifically for monitoring in areas where there may not be an Internet connection. eLocust3 is a tablet integrated with monitoring software that allows field workers to log field conditions and upload the data to national locust centres through the satellites. Information that may be logged includes data on pests, rainfall, vegetation, safety, etc. The tablet even provides satellite imagery for ground officers to better survey and navigate remote areas. The product currently covers 19 countries across West and East Africa, the Arabian Peninsula and Southeast Asia.

Since 2013, all six major locust outbreaks have been contained. eLocust3's software enabled the pest control team to identify areas of infestation and quickly manage the spread. Not only does this imply more efficient pest control operations, but it also means pesticide application can be more targeted, thus reducing the costs of treatment.

First, the eLocust3 device had been tested multiple times and with many potential users to ensure that the hardware remained functional in the harshest conditions, such as high temperatures. Second, the product designers were mindful that the device and software was user-friendly for smallholder farmers. They also standardized the user experience across all 19 countries to simplify the technical support demanded of field staff. Finally, the team gave sufficient focus on teaching users how to use the device. After experimenting with both written user manuals and training videos, they realized visual tutorials were better because they were easier to understand and did not require translation into local languages.

142. Keith Cressman, Alice Van der Elstraeten, and Clare Pedrick, eLocust3: An innovative tool for crop pest control (FAO, May 2016), available at http://www.fao.org/resilience/resources/resources-detail/en/c/437998/.

PlantVillage

PlantVillage (https://plantvillage.psu.edu/) is a digital platform for farms to obtain advice on pest and plant disease management. All farmers need to do is to snap a picture of their crops, upload them and await diagnosis from a plant disease expert. The platform has aggregated over 50,000 infected plant images and has since become the world's largest open-access library of crop health knowledge. Moreover, the application has forum rooms to facilitate peer-to-peer discussion and information-sharing.

On top of the digital platform, PlantVillage has developed a digital assistant application called Nuru. Farmers can upload a picture of an infested plant leaf to Nuru and receive an AI identification of the suspected disease. The application is able to diagnose diseases in cassava, maize, potato and wheat without an Internet connection.[143] It does so by running machine learning models using the smartphone's processing power and an offline database of images collected and annotated by crop disease professionals. All farmers need to input is crop type, location and planting date.

Photo by PlantVillage

The application is proven to be twice as accurate as extension workers. More than 18,000 plant disease reports have been generated on the platform by users across 40 nations. The application has also been integrated with the West African viral epidemiology platform to extend services to West and Central Africa. The aim is to use it to combat cassava brown streak disease in that region.[144]

143. Food and Agriculture Organization of the United Nations, Advanced agricultural technology for smallholder farmers in Africa: PlantVillage (FAO, December 2019), available at http://www.fao.org/food-chain-crisis/resources/success-stories/detail/en/c/1256210/.

144. Stefanie Neno, "PlantVillage Nuru," CGIAR Platform for Big Data in Agriculture, 7 June 2020, available at https://bigdata.cgiar.org/divi_overlay/plantvillage-nuru/.

Yield Monitoring

It is forecasted that a growing population and rising incomes will lead to an increase in demand for agricultural products by 35–50 percent between 2012 and 2050, exerting even more pressure on the world's arable land. Arable land is decreasing, accelerating the need to find solutions to grow more with fewer resources and do so in an environmentally sustainable manner.

Yield monitoring and mapping uses a combination of GPS technology and on-site sensors to track crop yields. Yield maps display the spatial and temporal variability in crop yields. The data can be collected for either a specific load or field, thus enabling farmers to compare yield performance across different test plots or crop varieties. Smallholder farmers can use yield data to get insurance and loans at a lower price since the banking companies would have reliable farm data to back their loans and insurances.

To ensure conclusions from yield maps are not affected by unusual weather conditions or other unforeseen factors in each harvest period, it is generally preferred to collect at least five years of yield maps before drawing firm conclusions about yield patterns.[145] In fact, yield variability over time turns out to be much greater than that over space for annual and perennial crops.[146]

Yield monitors are typically attached to farm equipment used by farmers; hence, monitors must be compatible with the equipment owned by farmers. A basic, entry-level yield monitor is typically priced at $2,000 and becomes increasingly expensive with more in-depth and advanced systems. The basic yield monitor only provides information on yields, whereas advanced systems can provide deeper insights on how yields in specific areas of the field can be increased.

Measuring yields of small farms in Kenya using satellite imagery. Image by World Bank

145. University of Nebraska Institute of Agriculture and Natural Resources "Yield Monitoring and Mapping," CropWatch, available at https://cropwatch.unl.edu/ssm/mapping.

146. Aspexit, "Yield maps in Precision Agriculture," 3 January 2020, available at https://www.aspexit.com/en/yield-maps-in-precision-agriculture/.

Smart Irrigation

Fresh water is a fast-depleting resource, particularly for agriculture. According to FAO, 1.2 billion people live in agriculture areas with very high levels of water stress or very high drought frequency.[147] Agriculture accounts for more than 70 percent of the global freshwater use. Unfortunately, much of it is wasted.[148]

A smart irrigation system can help substantially improve water-use efficiency. It involves using technology to assess and cater to the needs of the farm. Such a system requires an irrigation controller, which is typically an electronic device. A smart irrigation system can be either weather-based or soil sensor-based.[149]

Soil sensors placed in the farm can be used to monitor soil moisture levels. The number and location of sensors in the farm can be varied for precision and can be connected through wired or wireless networks (e.g., LoRaWAN). When the soil moisture level falls below a certain threshold, an alert can be generated through a mobile phone app. The farmer can then decide the optimal time to irrigate the farm and the amount of water to apply.

Alternatively, a weather-based system depends on the phenomenon of evapotranspiration (ET), through which water evaporates from soil and plants.[150] Local weather stations can calculate ET based on factors including temperature, sunlight, wind and humidity. An irrigation controller can provide appropriate amounts of water to the farm based on ET rates.

Smart irrigation may involve on-site sensors and irrigation controllers, which can make it expensive for smallholder farmers. This is compounded by the requirement of having Internet connectivity at the farm. Further, in many settings where smallholder farmers pay little or nothing for irrigation water, there may not be enough incentive for them to save water.[156]

147. FAO, The State of Food and Agriculture 2020: Overcoming water challenges in agriculture (Rome: FAO, 2020), available at https://doi.org/10.4060/cb1447en.

148. WIRED, "Farms Waste Much of World's Water," 19 March 2006, available at https://www.wired.com/2006/03/farms-waste-much-of-worlds-water/.

149. HydroPoint, "What Is Smart Irrigation?" available at https://www.hydropoint.com/what-is-smart-irrigation/.

150. GardenSoft, "Weather Based and Smart Irrigation Controllers," California Friendly Landscaping, available at https://www.ladwp.cafriendlylandscaping.com/Garden-Resources/SmartControllers.php.

Smart irrigation for paddy fields in Vietnam[151]

Alternate wetting and drying (AWD) is a technique in which paddy fields are irrigated 1–10 days after the disappearance of ponded water. This helps reduce the irrigation water consumption without affecting yields.[152]

In Vietnam, the Korea-World Bank Partnership Facility funded a pilot test for the feasibility of applying smart irrigation to the AWD technique for smallholder paddy farmers. A sensor measured the water level in the field and uploaded the information to a cloud-based online platform. Using a mobile app, the farmer could monitor the current water level against the recommended level. Based on this, the farmer could determine the optimal time and quantity to irrigate the field.

By applying smart irrigation practices, farmers were able to save 13–20 percent of the irrigation water compared to conventional AWD.

India: SoilSens

SoilSens is a low-cost soil monitoring solution and irrigation recommendation system for smallholder farmers. It was incubated at the Indian Institute of Technology Bombay (IIT-B) and supported by the Indian government.[153] In particular, the SoilSensGo technology, a portable moisture system, is designed for smallholder farmers.[154]

The product is equipped with sensors for soil moisture, soil temperature, ambient humidity and ambient temperature. Farmers can take the SoilSensGo system into their fields and easily measure soil moisture. Based on the information captured, irrigation alerts and recommendations will be given to the farmer.[155]

151. Vikas Choudhary and Karin Fock, "Precision agriculture for smallholder farmers in Vietnam: How the Internet of Things helps smallholder paddy farmers use water more efficiently," World Bank Blogs, 23 April 2020, available at https://blogs.worldbank.org/eastasiapacific/precision-agriculture-smallholder-farmers-vietnam-how-Internet-things-helps.

152. International Rice Research Institute (IRRI), "Saving Water with Alternate Wetting Drying (AWD)," IRRI Rice Knowledge Bank, available at http://www.knowledgebank.irri.org/training/fact-sheets/water-management/saving-water-alternate-wetting-drying-awd.

153. ResearchandMarkets.com, "Worldwide Precision Farming Industry to 2026 - Soil Monitoring is Expected to Hold a Significant Share of the Market," GlobeNewsWire, 17 February 2021, available at https://www.globenewswire.com/en/news-release/2021/02/17/2177033/28124/en/Worldwide-Precision-Farming-Industry-to-2026-Soil-Monitoring-is-Expected-to-Hold-a-Significant-Share-of-the-Market.html.

154. SoilSens, "SoilSensGo," available at https://www.soilsens.com/products/soilsensgo.html.

155. SoilSens, "Solution for Farmers," available at https://www.soilsens.com/solutions/farmers.html.

Precision Spraying

Precision spraying ensures applying an optimum amount of crop protection chemical. It safeguards against spraying in areas with no weeds or pests, significantly reducing the quantity of agrochemicals used and cutting costs.[157] In fact, the use of drones for cotton spraying in China by the company DJI is reported to be 40 times more efficient than manual spraying.[158] This means that after accounting for their cost savings, drone services can be more competitive than traditional farming methods.

Precision spraying is carried out using drone technology and robotics, sometimes combined with GPS, VRT, and sensors. These technologies are usually leveraged by spray contractors or drone service providers who help carry out such services at a marginal cost. For example, in Myanmar, a drone spray service provider would charge $10–12 per hectare for a 20 kg payload capacity.

156. Choudhary and Fock, "Precision agriculture for smallholder farmers in Vietnam: How the Internet of Things helps smallholder paddy farmers use water more efficiently."

157. The Spray Nozzle People, "Precision Spraying Guide," available at https://www.spray-nozzle.co.uk/home/resources/engineering-resources/precision-spraying-guide.

158. Nikola M. Trendov, Samuel Varas, and Meng Zeng, Digital technologies in agriculture and rural areas (Rome: FAO, 2019), available at http://www.fao.org/documents/card/en/c/ca4985en/.

Treating armyworm infestation in China with drones[159]

In August 2019, fall armyworms infested close to a million hectares of crops across 24 provinces in China. These pests could travel 100 km in a night and were therefore able to spread rapidly over the country. The government deployed a drone swarm operation developed by a Guangzhou-based drone maker XAG and the life sciences conglomerate Bayer. The drones carried payloads of low-toxicity insecticide.

The drones removed 98 percent of the fall armyworms. They were highly effective for two reasons. One, they could fly as fast as the fall armyworms and thus be more effective than insecticide sprayers. Two, they could be operated at night when these worms are the most active. Moreover, the drones ensured farmers had no direct contact with the toxic insecticides.

159. Joe Gan, "XAG get its drones upgraded with tie-ups with Bayer and Huawei," AgFunderNews, 25 September 2019, available at https://agfundernews.com/xag-taps-on-bayer-and-huawei-to-help-its-drones-take-off.html.

Challenges and Recommendations

Challenges and Recommendations

The adoption of precision agriculture (and digital technologies in general) by smallholder farmers depends on a variety of factors and challenges. The issues are mainly operational challenges rather than limitations of the technologies themselves.

The Principles for Digital Development (https://digitalprinciples.org)—a set of “nine guidelines to integrate best practices into technology-enabled programs”—provide useful guidance to project managers for planning precision agriculture interventions.

The current section highlights general considerations and potential challenges in implementing digital solutions for smallholder farmers in developing countries. It provides recommendations for project managers as well as policymakers (where relevant) to help address the challenges. The key considerations for adopting specific precision agriculture technologies have been described in Section Two of this report.

User Needs

Solutions should be founded on the needs of the end users. Designing with the users[160] —instead of designing for them—can provide valuable feedback about their needs and nuances related to local context, including society, culture, politics or other barriers that might impede the adoption of technologies by farmers.

For example, low farm productivity and yields are not the only agricultural issues smallholder farmers grapple with. They also suffer from a lack of access to finance and markets: They require reliable and fair access to finance and markets to increase profitability. Digital solutions, particularly involving mobile phones, can make a wide range of solutions available to farmers beyond precision agriculture.

It is important to listen to the voices and views of target beneficiaries to understand their needs and the nuances of the local context. They may know which interventions have succeeded or failed in the past. Co-designing with the users of digital solutions can help build solutions faster and better. Not involving users may lead to the building of solutions that might not work for them and result in failure.[161]

160. Principles for Digital Development, "Design With the User," available at https://digitalprinciples.org/principle/design-with-the-user/.

161. Janet Hughes, "What we mean by "co-design"," Department for Environment, Food & Rural Affairs Future Farming Blog, 11 December 2020, available at https://defrafarming.blog.gov.uk/2020/12/11/what-we-mean-by-co-design/.

Digital Infrastructure

At least 2G connectivity is essential for any precision agriculture application since mobile phones are the bedrock for enabling digital solutions for farmers at scale. A smartphone with Internet connectivity is required for more advanced applications.

Although the coverage gap in mobile connectivity has declined rapidly, about 600 million people worldwide still live in an area not covered by mobile networks.[162] Most of these areas are rural and remote. Deploying mobile broadband in these areas remains commercially unviable due to lower revenues and greater logistical complexities, including providing energy for the base stations.[163] Technological innovations such as backhaul using LEO satellites and solar- or wind-powered cell sites offer possible solutions for remote connectivity.[164]

Moreover, mobile phones usage depends on access to electricity (e.g., for charging). More than 758 million people in the world lacked access to electricity in 2019, with the vast majority in sub-Saharan Africa.[165]

Bringing mobile connectivity to the 600 million people currently unconnected will require setting up a large number of base station sites where expected revenues are low. This is a challenge of economic viability, and technological innovation will offer solutions. However, sound policies are also required to support investments. Two tried and tested examples are making spectrum available in greater quantities and expediting approvals for new deployments. Governments around the world promptly adopted these solutions to support mobile network operators in light of the increased demand for mobile data during the COVID-19 pandemic.[166]

Literacy and Digital Skills

While access to mobile phones and the Internet is growing rapidly, more than half of the world's population still does not use mobile Internet. Lack of literacy and digital skills remains the primary bottleneck for Internet adoption in LMICs.[167] Moreover, women use a narrower range of mobile services than men and feel less able to learn a new activity by themselves.[168] It is thus crucial to know the level of digital skills (e.g., use of SMS, mobile applications, social media) and functional and digital literacy among targeted farmers before planning precision agriculture initiatives.

Access to information in local languages can also be a driving factor for farmers picking up and adopting digital solutions. Factors like this can be identified by adopting participatory approaches and involving targeted farmers in designing solutions. Not doing so can result in failures. For example, a mobile e-wallet solution in Rwanda witnessed low uptake because SMS messages were sent in English instead of Kinyarwanda, the preferred language of the target community.[169]

162. Bahia and Delaporte, The State of Mobile Internet Connectivity 2020.

163. Calum Handforth, Closing the coverage gap: How innovation can drive rural connectivity (London: GSMA, 2019), available at https://www.gsma.com/mobilefordevelopment/resources/closing-the-coverage-gap-how-innovation-can-drive-rural-connectivity/.

164. Ibid.; John Garrity and Arndt Husar, "Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific," ADB Sustainable Development Working Paper Series no. 76 (April 2021), available at https://www.adb.org/publications/digital-connectivity-low-earth-orbit-satellite-opportunities.

165. Tracking SDG7: The Energy Progress Report, available at https://trackingsdg7.esmap.org/results?p=Access_to_Electricity&i=Population_without_access_to_electricity,_millions_of_people_(Total).

166. Bahia and Delaporte, The State of Mobile Internet Connectivity 2020.

167. Ibid.

168. Carboni et al., The Mobile Gender Gap Report 2021.

169. The World Bank, Future of Food: Harnessing Digital Technologies to Improve Food System Outcomes.

Agricultural Extension Workers

AEWs play the crucial role of educating and training farmers on the use of new technologies and techniques. They often act as the link between the farming community and other agricultural stakeholders including researchers, CSOs and the private sector.[170] With the growing use of digital technologies in agriculture, it has become necessary for AEWs to be knowledgeable in their use themselves and train farmers in the same. This, however, remains a challenge. For example, a study in Ghana found that while AEWs use ICTs like mobile phones for personal communications, they do not do so for extension activities.[171] Governments, CSOs and other organisations employing AEWs should thus invest in building their digital capacity. This can be done, for instance, by incorporating education and trainings on digital technologies and applications in the curricula of agricultural universities and research institutes.

Farmer Cooperatives

Cooperatives offer several benefits to farmers, particularly smallholder farmers in developing countries. Farmers in cooperatives benefit from greater bargaining power, easier access to loans, and better access to information and trainings.[172] Being part of a cooperative also allows farmers to share capital and technology, making affordable advanced applications like precision spraying and use of agricultural robots. A study in China found that membership of a cooperative had a significant positive impact on the adoption of agricultural technologies and particularly post-harvest technologies. This was so because post-harvest technologies require collaborative action—a role uniquely suitable for cooperatives.[173]

Governments should formulate enabling policies that promote the formation of farmer cooperatives, following the principle of "support but not interfere". This would mean ensuring that formation of farmer cooperatives is driven by the needs of farmers rather than government priorities. According to a World Bank report, "a core element of a government strategy for supporting [farmer cooperatives] should involve technical support and advice for feasibility studies, economic and market analyses and strategic business planning."[174]

170. Murari Suvedi and Michael Kaplowitz, What Every Extension Worker Should Know: Core Competency Handbook, MEAS Handbook (East Lansing, Michigan, USA: USAID, 2016), available at https://meas.illinois.edu/wp-content/uploads/2015/04/MEAS-2016-Extension-Handbook-Suvedi-Kaplowitz-2016_02_15.pdf.

171. Daniel Ayisi Nyarkoa and József Kozári, "Information and communication technologies (ICTs) usage among agricultural extension officers and its impact on extension delivery in Ghana," Journal of the Saudi Society of Agricultural Sciences vol. 20, no. 3 (2021): 164–172, available at https://doi.org/10.1016/j.jssas.2021.01.002.

171. Massachusetts Institute of Technology, "Small-Farm Cooperatives," available at http://12.000.scripts.mit.edu/mission2014/solutions/small-farm-cooperatives.

173. Shemei Zhang, Zhanli Sun, Wanglin Ma, and Vladislav Valentinov, "The effect of cooperative membership on agricultural technology adoption in Sichuan, China," China Economic Review vol. 62, no. 101334 (2020), available at https://doi.org/10.1016/j.chieco.2019.101334.

174. Achim Fock and Timothy Mark Zachernuk, China - Farmers Professional Association: Review and Policy Recommendations, EASRD working paper series (Washington DC: World Bank, 2006), available at https://documents.worldbank.org/en/publication/documents-reports/documentdetail/539401468218987959/china-farmers-professional-associations-review-and-policy-recommendations.

Business Models

High costs are a major barrier for smallholders' adoption of many precision agriculture technologies like sensors, drones or robots that are not easily scalable. Moreover, farmers are reluctant to invest in new technologies with an unclear ROI. Suitable business models are thus necessary to scale adoption, creating value for farmers as well as additional livelihood opportunities in this sector.

Solutions by the private sector targeting smallholder farmers in developing countries are evolving in two directions[175]:

- Specialised data-driven services that address particular barriers faced by farmers (e.g., access to localised weather information); and
- Bundling solutions for multiple challenges faced by farmers (e.g., mobile phone apps that provide digital extension along with access to input suppliers and financial services).

While the sector requires patient capital investments—from donors and impact investors—a range of viable business models have already emerged. These include business-to-consumer (B2C), business-to-business-to-consumer (B2B2C), and business-to-government (B2G) models.

- In a **B2C** model, the service provider directly serves the farmer. An example could be a contractor offering pesticide spraying using drones as a service to a farmer or cooperatives. The farmers' willingness to pay for such solutions can act as a barrier in scaling up this model.
- In a **B2B2C** model, the service provider offers the service to a value chain actor—such as an agribusiness—who in turn offer the service to farmers as part of a bundle of integrated solutions, thus increasing the likelihood of its uptake. For example, CropIn's (an agritech startup from India) collects data from various sources including weather, satellite imagery, and on-ground data, analyses it using AI algorithms, and sells the insights to financial service providers to help mitigate risks.[176]
- A **B2G** model involves a national or regional governments pay for services on behalf of farmers. An example is PxD providing digital extension to smallholder farmers in multiple countries.[177] In the case of extension and advisory services, smallholder farmers perceive these as public goods to be provided by governments and might not be willing to pay for them. The public sector thus has an important role in making the benefits of precision agriculture widely available at no or a low cost to farmers, especially where the benefits are yet to be demonstrated to farmers.

175. Phatty-Jobe, Digital Agriculture Maps: 2020 State of the Sector in Low and Middle-Income Countries.

176. ADB, "How Technologies Like AI are Transforming Farms Globally," Technology and Innovation Marketplace: Profiles of Technologies Showcased by Exhibitors During the RDFS Forum, available at https://events.development.asia/system/files/materials/2019/10/201910-cropin_0.pdf.

177. Phatty-Jobe, Digital Agriculture Maps: 2020 State of the Sector in Low and Middle-Income Countries.

Data use, Ownership, and Privacy

Farm-level data generated through precision agriculture is a precious resource, not only for an individual farmer but the entire agriculture sector. Monetising this data can be a revenue source for equipment suppliers and contractors. Farm input companies can leverage the data to forecast demand and optimise their supply chains. Insurance companies can offer affordable premiums to farmers through index-based insurance enabled by farm-level data. Such granular data can also aid policy-makers in yield estimation and futures planning.

Project designers should be mindful of the various pitfalls of companies having access to this data, particularly issues of data privacy, ownership and overconcentrating market power among service providers.[178] Regulations and policies regarding data ownership and privacy vary by country and are often inadequate, raising concerns about the misuse of data.

178. Ibid.

Interoperability and openness

The public and private sectors have invested in several digital agriculture solutions in recent years. However, siloed efforts have prevented the development of standards for the industry, particularly regarding the management of agricultural data. Proprietary hardware and software solutions make interoperability between different systems a hurdle, affecting the scalability of precision agriculture initiatives.

Taking an open approach[179] to designing digital interventions, project managers can increase collaboration among stakeholders and avoid duplication of efforts. This includes use of open-source software, open data, and developing and adopting open standards.[180] This can include exploring any open-source solutions exist which have been successful elsewhere[181] or openly sharing project data that would not infringe on privacy.

Gender Inclusivity

In addition to resources like land, water and credit, women also lack access to mobile phones compared to men. Despite fast-growing mobile phone penetration in LMICs, when compared to men, women are 7 percent less likely to own a mobile phone, 15 percent less likely to own a smartphone and 15 percent less likely to use mobile Internet.[182] Designing with the users can highlight such barriers and help in designing more inclusive interventions.

Digital technologies also enable overcoming many existing barriers faced by women. For example, extension agents in developing countries are predominantly men, while the agricultural workforce consists largely of women.[183] Multiple studies have shown that having access to female extension agents resulted in greater participation and satisfaction among women farmers compared to male agents.[184] Digital extension services (e.g., demonstration videos) customised as per the farmer's gender can help improve their uptake.

179. Principles for Digital Development, "Use Open Standards, Open Data, Open Source, and Open Innovation," available at https://digitalprinciples.org/principle/use-open-standards-open-data-open-source-and-open-innovation/.

180. Ibid.; As defined by the Principles of Digital Development, "Open source is software with source code that anyone can view, copy, modify and share. Open data comprise information that can be freely accessed, analysed, and shared, while still maintaining privacy protections. Open standards are publicly available standards with proven implementation success."

181. Principles for Digital Development, "Reuse and Improve," available at https://digitalprinciples.org/principle/reuse-and-improve/.

182. Carboni et al., The Mobile Gender Gap Report 2021.

183. Lahai, Goldey, and Jones, "The gender of the extension agent and farmers' access to and participation in agricultural extension in Nigeria."

184. Ibid; BahadurGhartiMagar, "An Assessment of Men and Women Farmers' Accessibility to Governmental Agriculture Extension Program: A Case of Arghakhanchi District, Nepal."

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