The Sustainable Agriculture Transition:

Technology options for low- and middle-income countries

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Executive Summary

Worldwide, food and agriculture systems face three complex challenges. First, demand for nutritious food continues to rise globally. Second, food and agriculture systems are having to adapt to changing weather and ecological conditions, while reducing the harm they cause to the environment. And third, farmers and farmworkers face economic precarity and vulnerability, with too many living in poverty and chronic hunger. The challenges are immense, but there are technologies that can make a positive difference. This report looks at innovations in three areas of technology, particularly how the declining costs and increased availability of renewable energy can make a difference. The report looks at how off-grid electrification using solar photovoltaics (PV), dramatic improvements in battery capacity and performance, and the data revolution in information and communication technology (ICT) can each strengthen the resilience and sustainability of food and agriculture systems in low-and middle-income countries.

History teaches us that the introduction of new technologies has unpredictable effects. Policy-makers need to anticipate potential risks to ensure technologies do not undermine public policy objectives. New technologies open the possibility of bringing an affordable and reliable supply of energy to rural communities everywhere. For this to work, it is important to understand the challenges. For example, a number of the innovative technologies considered here are associated with high upfront costs, even though the running costs are negligible. If this is understood in advance, governments can work with end users and financial services providers to protect inclusive access. Another challenge is the need for effective privacy laws and regulations to manage data gathering and data use by private firms and government agencies. This remains a work in progress in both rich and poor societies, but it is a challenge that countries without strong legal institutions might hesitate to take up. Yet affordable energy from renewable sources is critical to realizing the UN Sustainable Development Goals (SDGs), not least SDG 2, which is the goal to end hunger sustainably, with improved nutrition, increased small-scale food producer income, and better environmental outcomes. This paper looks at answers to the question, "How can disruptive technologies help?"

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1.0 Introduction

The world's food and agriculture systems face three linked challenges. First, they need to meet rising global demand for nutritious food (Food and Agriculture Organization of the United Nations [FAO], et al., 2017). Second, all food and agriculture systems have to adapt to changing weather and ecological constraints, while some must at the same time significantly reduce their contribution to environmental degradation (Foley et al., 2011). Industrialized agricultural systems are a significant source of greenhouse gas emissions and must do their part to mitigate climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). Third, food and agriculture systems need to reduce the precarity of farm work, particularly in low- and middle-income countries. Hundreds of millions of small-scale food and agriculture farmers and workers depend on agriculture, and they are among the most vulnerable populations on earth (International Labour Organization [ILO], 2013).

The challenges are immense, but there are technologies that can make a positive difference. Innovations in three areas of technology could contribute to meeting the challenge. The featured technologies are all "disruptive," which can be defined as a technology that either displaces an established technology and shakes up the industry or creates a new industry altogether (Christensen, 2015). The three technological innovations examined in the paper are: i) affordable off-grid renewable energy systems made possible with the significant fall in the costs of solar photovoltaics (PV); ii) the rapid and dramatic evolution of battery technology that has exponentially increased batteries' usefulness as an energy source; and, iii) the evolution of information and communications technology (ICT) resulting from the expansion of big data.

The potential of these technologies to increase productivity at reduced environmental cost is well established. Reliable power for high-efficiency irrigation systems, dramatic reductions in fertilizer runoff through the use of precision tools, mechanized equipment that does not require oil or gas—all of these applications bring significant productivity gains, supporting higher yields, reduced inputs, and lower costs. The challenge is also how to make these technologies accessible and useful to more farmers. How can adopting technologies for multiple scales at affordable prices support diversified production systems, especially those that already outperform more intensive production with regard to the productivity of the land and meeting high environmental standards.

In the UN 2030 Agenda for Sustainable Development, governments articulated overarching objectives for agricultural and food systems. Adopted by the UN General Assembly in 2015, the Agenda sets out 17 Sustainable Development Goals (SDGs). If the deployment of renewable energy and information and communications technology in low- and middle-income countries is accompanied by sustainable improvements in small-scale producer and worker productivity and income, then the technologies will contribute to the achievement of a range of SDGs, including the elimination of poverty (SDG 1) and hunger (SDG 2); affordable and clean energy (SDG 7); decent work and economic growth (SDG 8); industry, innovation and infrastructure (SDG 9); and climate action (SDG 13) (United Nations General Assembly, 2015). The opportunity is too important to let pass.

The paper is divided into four parts. Part One provides a brief description of the challenges facing food and agriculture systems. Part Two presents the three technologies. Part Three considers how the technologies are transforming (or could transform) food systems, using three applications of the technologies to illustrate the point: solar-powered irrigation, precision agriculture, and vertical farming. The fourth and concluding part contains recommendations.

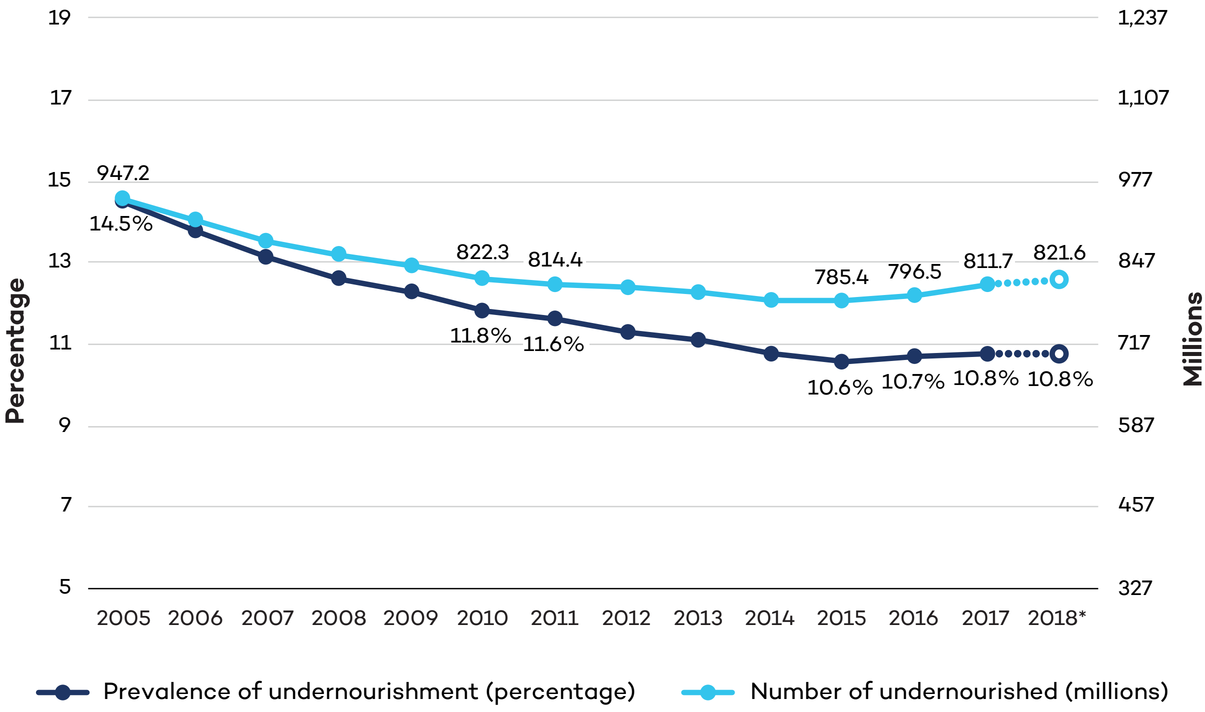
Throughout the paper, specific examples of products or companies that use the technologies are described. Where possible, these examples have been drawn from applications by producers in low- and middle-income countries. Where helpful, examples from large-scale agriculture or high-income countries are also provided, where the example is thought to illustrate the potential for the technology's adoption by smaller-scale producers in low- and middle-income countries. The focus is on the potential of the technologies and their applications to bring transformative change. The challenge for policy-makers and investors is to see the potential for the public good and to harness it.

2.0 Challenges for Food and Agriculture Systems

The world's food and agriculture systems face complex and interconnected challenges. These are presented here under three broad headings: food security and nutrition; climate change and environmental degradation; and farm and food worker livelihoods.

Food security and nutrition: For much of the past 30 years, the incidence of hunger has been in decline. Yet 2015 marked a return to rising levels of global hunger (see Figure 1), driven primarily by conflict, economic recession, and climate change (FAO et al., 2017). The problem of malnutrition is larger still: in addition to the hungry, almost two billion people suffer from micronutrient deficiencies that contribute to physical and mental underdevelopment, and two billion are overweight or obese (FAO et al., 2019: p. xiv). Some people suffer from micronutrient deficiencies and excessive calorie intake simultaneously (WHO, 2020). The UN predicts that the global population will increase to over 9.8 billion people by 2050, increasing by 83 million people per year (UN, 2017). Much of that increase will occur in regions that are already facing food deficits.

Figure 1. The number of undernourished people in the world has been on the rise since 2015, and is back to levels seen in 2010–2011.



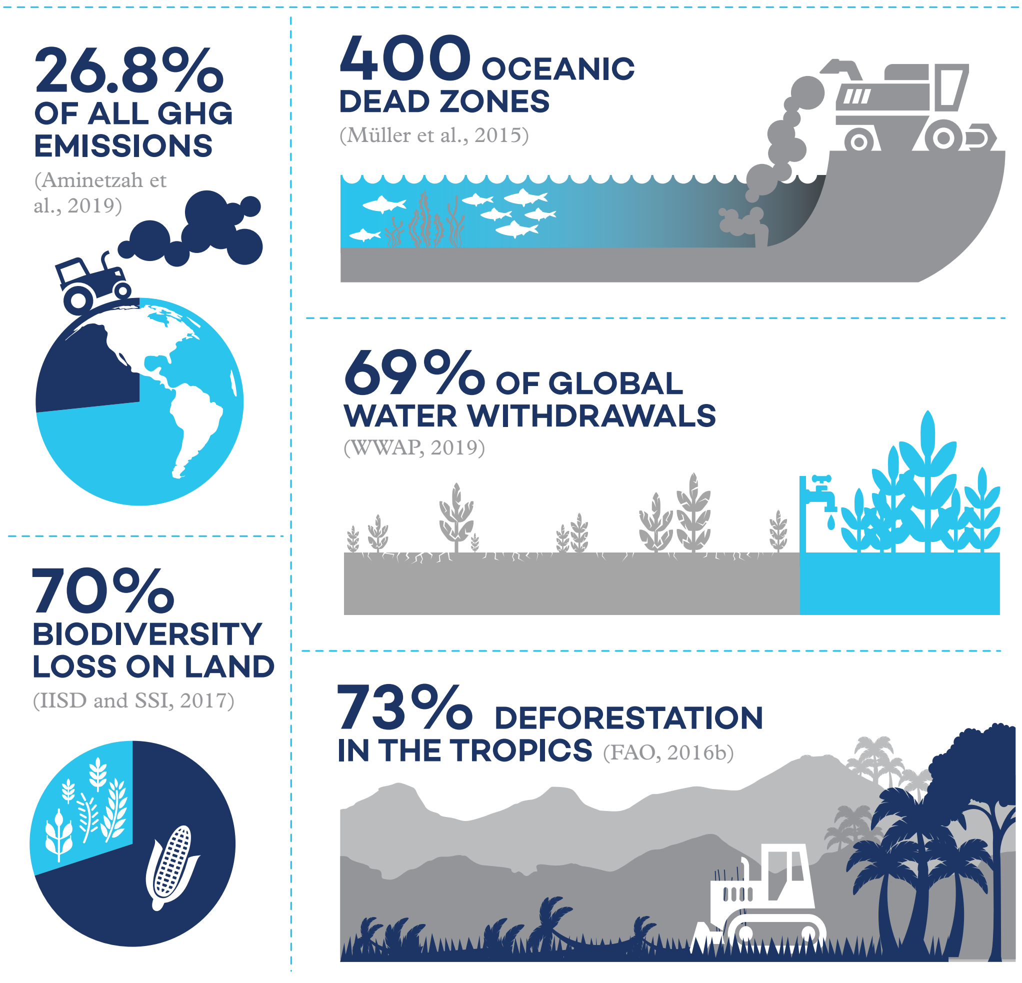
* Values for 2018 are projections as illustrated by dotted lines and empty circles. The entire series was carefully revised to reflect new information made available since the publication of the last edition of the report; it replaces all series published previously.

Source: FAO et al., 2019, p. 6

Climate Change and Environmental Degradation: Food and agriculture systems contribute significantly to global greenhouse gas emissions. The largest sources of these emissions linked to agriculture are deforestation from land clearing for cultivation or grazing, methane emissions from livestock and rice production, and nitrous oxide from the heavy use of synthetic fertilizers (IPCC, 2019). Agriculture has contributed to 70% of biodiversity loss on land (Secretariat of the Convention on Biological Diversity, 2014, p. 10). It is estimated that 69% of annual water withdrawals globally are for agriculture (UNESCO World Water Assessment Programme [WWAP], 2019, p. 13). Since 1960, global inorganic nitrogen fertilizer use has increased almost nine-fold (IPCC, 2019). With continued population growth and land degradation, the FAO estimates that the amount of arable, productive land per person in 2050 will be under half of 1960 levels (Bruinsma, 2011, p. 234).

At the same time, climate change poses significant risks to food and agriculture systems. These risks include rising sea levels and the risk of coastal inundation, changing and less-predictable weather patterns, and an increase in the incidence of extreme weather events. The spread of new pests and crop diseases as average temperatures change is another risk (IPCC, 2014). Rising temperatures have expanded arid climate zones around the world, in turn affecting the range, abundance, and seasonable behaviour of both animal and plant species (IPCC, 2019).

Figure 2. Agriculture's footprint



Employment and Livelihoods: The ILO estimates that in 2019, just over 28% of global employment was in the agriculture sector, equating to roughly 2.1 billion people (World Bank, 2020). Of the approximately 570 million farms in the world, more than 475 million farms are smaller than 2 hectares, and more than 500 million are family farms, meaning that the farm household provides the majority of the labour on the farm (Lowder et al., 2016, p. 27). Small-scale producers are estimated to be responsible for producing over one third of the world's food supply, and that global average masks significant regional variations (Ricciardi et al., 2018). For example, one recent study estimated that small-scale producers provide up to 80% of the food supply in Asia and sub-Saharan Africa (FAO, 2012, p. 1). The International Fund for Agricultural Development estimates that roughly half of all youth (aged 15–24) in developing countries live in rural areas (IFAD, 2019, p. 14). They represent a tremendous opportunity for their countries' social and economic development.

3.0 Three Technologies Driving Change

Technological change has always played a central role in the history of agriculture. Some changes have been incremental, such as gradual improvements in soil drainage. Other changes have been revolutionary, such as the introduction of mechanized plowing tools or synthetic fertilizers and chemical pesticides. Today, a number of new technologies have the potential to drive revolutionary change in agriculture. Three of them are the subject of this paper: PV energy, longer-life batteries, and new applications for ICT. Simple but effective ICT systems, powered by renewable energy and smaller, cheaper, longer-lasting batteries, can now be deployed anywhere in the world at a very low cost. Together, these technologies could help boost agricultural productivity while dramatically reducing the demand for water, chemical inputs, and land.

None of these technologies is new. But the sharp decline in what it costs to use them is opening new markets and new applications. The technologies are already widely diffused in high-income countries. They are now being introduced in developing countries, through demonstration projects and in forms adapted for deployment on smaller-scale farms and in resource-poor rural settings. This section reviews the current status of these technologies and the potential to expand their use.

Solar Photovoltaics

Solar photovoltaic (PV) technology allows electricity to be produced directly from sunlight almost anywhere in the world. The technology allows for off-grid electrification. The panels themselves require almost no maintenance (other than cleaning) and can last more than 30 years. For several decades, solar PV has been used in a variety of contexts in low- and middle-income countries, including to power irrigation systems and drinking water pumps for animals, electric fencing, pest control, drying units, cold storage, egg incubation, and aeration for aquaculture (van Campen et al., 2000). Despite its many uses, however, uptake of solar PV has been limited. The main barrier in poor rural areas was cost. This has now changed, with a dramatic fall in prices that makes the technology cost-effective in an increasing range of applications. The cost of solar PV fell by 88% between 2009 and 2018, from USD 359 per megawatt hour (MWh) to USD 43 per MWh (Lazard, 2018, p. 7). One MWh is equivalent to a million watts per hour.

These low prices are not limited to countries with established solar industries. In 2019 a solar auction in Zambia was awarded at USD 40 per MWh, which approaches the record low prices seen in India, where, due to the country's large established solar PV market, prices can be as low as USD 35 per MWh (Singh, 2019). Falling costs have resulted in global installed capacity of solar PV soaring from 40 gigawatts (GW) in 2010 to 480 GW in 2018 (IRENA, 2019, p. 48). One GW is equivalent to a billion watts, or 1,000 MW. In 2018 alone, global solar PV capacities increased by 97 GW, accounting for approximately half of the growth in installed renewable power generation capacities (IEA, 2019).

These prices apply to grid-connected solar PV. Note, these grids use a smaller measure, the kilowatt hour or kWh, which is equivalent to 1,000 watts per hour. Off-grid systems have higher prices due to the higher per-kWh costs of installation, and the need for inverters and storage. However, prices for off-grid solar PV have also declined dramatically. The levelized cost of energy for new off-grid or grid-tied distributed solar, including storage, is now below USD 0.20 per kWh, compared to USD 0.60 per kWh for small diesel and petrol generators (Crown Agents, 2018, pp. 6–7; Hossain et al., 2019, p. 2). Tesla recently opened a solar PV plant equipped with batteries to supply electricity to the Hawaiian island of Kauai at USD 0.14 per kWh (Golson, 2017), a price well below conventional alternatives on the island.

The dramatic fall in the cost of PV solar could be a game-changer because it offers small-scale producers, who typically lack access to a reliable electricity supply, with the electricity needed for mechanization and ICT equipment. Mechanization can increase yields through improved irrigation, planting, weeding, and harvesting technologies. The energy is also important for the prices farmers receive because it makes processing and storage cost-effective as well, boosting demand for their product (Robertshaw et al., 2016). An affordable energy supply will reduce post-harvest losses through improved cooling, chilling, and drying solutions. Machines or generators that run on diesel are relying on an expensive and polluting fuel that is not always available in off-grid settings.

Batteries

A second transformative development, closely linked to solar PV, is the quickly decreasing cost and increasing storage capacity of batteries. Batteries to power small devices and lead-acid batteries (used for solar PV power storage, among many other things) have existed for many years. But recent developments in the technology have made batteries more affordable, increased their storage capacity and useful lifespan, and decreased size and maintenance requirements. These developments have led to new uses, for example, the launch of the first electric tractor in 2016 by John Deere, signalling the beginning of the electrification of farm machinery (Lambert, 2016). Of particular significance are the developments regarding so-called "advanced batteries," such as those that use lithium-ion (Svarc, 2019). Compared to lead-acid batteries, they are generally smaller and lighter for the amount of power they can store, they can discharge more of their stored energy without compromising the battery life, they have low losses while charging and discharging (making them more efficient), and they have a longer lifespan (Svarc, 2019).

Price is often seen as one of the main challenges to the use of lithium-ion batteries in low- and middle-income countries, but the costs are decreasing rapidly. According to BloombergNEF (2019), the cost of lithium-ion battery storage has decreased by 87%, from USD 1,100 per kWh in 2010 to USD 156 per kWh in 2019, with a further predicted decrease to USD 100 per kWh by 2023. By 2030, batteries are expected to be significantly cheaper per kWh than conventional electricity (Chip Register, 2015; Knupfer et al., 2017). The combination of solar PV technology and lithium batteries at affordable prices creates an attractive alternative to fossil fuel-based generators in off-grid areas. The introduction of a low-cost decentralized energy source would bypass the prohibitive costs and infrastructure requirements of connecting remote areas to a regional electricity grid, improving rural communities' access to power for irrigation systems, water pumps, and other equipment.

Information and Communications Technology (ICT)[1]

ICT is already revolutionizing the agricultural sector in high-income countries. Farmers now have better access to information on weather forecasts, crop and livestock varieties, production techniques, farm conditions, available services, storage costs, processing options, prices, and markets than ever before (World Bank, 2019). ICT is being used to save time and labour, and, using data-driven assessments, to reduce input use through targeted applications that can now be extremely precise. Sensors and mapping technologies allow farmers to monitor and respond to changing growing conditions as they arise. Many farmers are using automated systems in some form, demonstrating the potential for increased productivity.

Small-scale producers in low- and middle-income countries traditionally get their information from experience, by word of mouth, and from local leaders (World Bank, 2019). This is changing. A recent World Bank (2011) study cites five factors that are making ICT accessible to smaller-scale food producers: 1) reduced costs, 2) increased prevalence of the technology, 3) advances in data storage and exchange, 4) innovative business models and partnerships, and 5) democratization of information, including the gains achieved by open access movements and the spread of social media.

The changes in technology prevalence and affordability are particularly relevant. The International Telecommunications Union estimates that at the end of 2019, over half the global population (some 4.1 billion people), was using the Internet (International Telecommunication Union, n.d.). There were 5.1 billion unique mobile users in the world as of July 2019 (Kemp, 2019). In low- and middle-income countries, Internet users reached 45% of the total population at the end of 2018, up from 7.7% in 2005 (International Telecommunication Union, 2018). The relative price of information processing has fallen by almost 96% since 1970 (Wolf, 2017). These trends combine to increase the availability of ICT for small-scale producers.

The next step is to consider how ICT can be applied to improve the productivity and incomes of food and farm workers while also improving food system sustainability. An important contribution of ICT is its capacity to deliver information to farmers that they previously would not have been able to access and to connect them to services that are otherwise out of reach (see Table 1). Even the most rudimentary radio or telephone can be effective in conveying information. For example, one study found that 80% of households in a rural area in Mongolia, where the primary activity is livestock management, listened to weather forecasts daily to inform their farming practices (van Campen et al., 2000, p. 19). Table 1 lists some of the important services that ICT offers to smaller-scale producers.

[1] ICT is an umbrella term that encompasses any device, tool, or application that permits the exchange or collection of data through interaction or transmission.

Table 1. Potential benefits of ICT for supporting smaller-scale producers

Information or service	Technology	Benefits
Education and awareness	Radio, mobile phones (smartphones, SMS or voice messages), Internet	• Real-time knowledge regarding weather, long-term climate trends, best practice, improved crop varieties, pest or disease outbreaks, natural disaster warnings
Commodity prices, market information, and sales	Mobile phones or Internet	• Direct access to prices in regional markets to inform decision making. • Virtual marketplace allowing farmers to deal directly with buyers and secure the highest prices.
Mapping	Geographical information systems (GIS), global positioning systems (GPS), satellite imagery, aerial imagery, data from sensors	• Data on soil depth and quality, water, temperature, nutrients and other variables provide farmers with new and dynamic information about their farm and can reduce the use of water, land, energy and chemical inputs, or improve their efficiency. • Potential to improving legal land rights if mapping results are integrated in ownership documentation.
Data collection and analysis	Computing applications that can collect and process vast amounts of data (commonly called "big data")* from mapping, sensors, and directly from farmers via communications technologies	• Improved practices, policies, products, and interventions that reduce the use of water, land, energy, and chemical inputs, or improve their efficiency.
Electronic financial tools and services	Mobile phones or Internet	• Direct money transfers, lending and insurance, including government payments • Development of borrower profiles based on yield and sales data from app-based systems

* "Big data" is a term for volumes of data so massive and complex that special tools are required to capture, store and analyze them.

ICT is increasingly embedded in more industrialized farm management practices, through robotics, remote sensors, mapping and geomatics technologies,[2] data analysis, telemetry, positioning technologies, and automated decision-making technologies (Pivoto et al., 2018). When connected to the Internet, these embedded technologies link agriculture to what is known collectively as the "Internet of things" (Pivoto et al., 2018, p. 21). For now, these applications are generally only employed by large-scale and wealthy farmers. The explosion of ICT applications, however, suggests that the barriers to the adoption of these technologies by smaller-scale producers are melting away. A number of newer ICT technologies, such as banking by mobile phone, are already well established in a number of low- and middle-income countries (see Box 1).

[2] "Geomatics" consists of products, services and tools involved in the collection, integration and management of geographic data (Applied Geomatics Research Laboratory, 2019).

Box 1. Examples of projects that use advanced ICTs in low- and middle-income countries

- In 2007, Reuters Market Light established an SMS service providing Indian farmers with tailored information on prices, commodities, and advisory services from a database of 150 crop varieties and 1,000 markets (Burwood Taylor, 2017; World Bank, 2011: p.5). By 2010, the service was reported to have generated USD 2–3 billion in new wealth for the farmers and contributed to a reduction in agricultural input costs for over 50% of subscribed farmers (World Bank, 2011, p. 5). Since then, the service has developed into an app that offers farmers seasonal, detailed advice and decision-making support, as well as providing a national online marketplace (Burwood Taylor, 2011).
- Loop is an app-based system in India that allows farmers to arrange transport for their crops from a pool of local drivers, to browse and select the best market price from participating buyers, and to get paid electronically after delivery (Get Loop App, 2018). Farmers can use the app to organize the sale and shipment of their crops without leaving their farms.
- Hello Tractor is a sharing platform for farm machinery founded in 2014. The platform connects tractor owners to farmers through a digital app, reaching more than 250,000 small-scale African farmers (Foote, 2018). This benefits both the small-scale producer farms who can plant 40 times faster and for a third of the cost, and the owners of compact tractors, who often purchase such machinery as an income-generating business opportunity (Foote, 2018).
- The Zimbabwe Farmers Union (ZFU) and Econet Wireless Zimbabwe provide information and services to small-scale producers through the ZFU EcoFarmer Combo programme (Kuipa & Mozhendi, 2019). For USD 1.10 per month, the service offers farming advice, weather-based insurance, accurate location-based weather reports, and funeral insurance. The subscription price is directly deducted from the farmers' electronic wallets (EcoCash) on their mobile phones (Kuipa & Mozhendi, 2019).
- FarmDrive is a Kenyan data analytics firm that helps small-scale African farmers access credit from local banks (Cosgrove, 2017). Many small-scale producers did not qualify for loans because they did not have a credit history or collateral, or because they were illiterate. FarmDrive generates credit scores for farmers by combining data input by farmers into its mobile app—designed to help farmers track their revenues and expenses—with satellite, agronomic and local economic data (Cosgrove, 2017).
- Big data is being used by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to develop tools to share information with small-scale producer farmers using basic ICT devices, such as tablets and mobile phones (ICRISAT, n.d.). These tools share basic weather data as well as more complex recommendations from other farmers and policy-makers (Rao et al., 2019).

4.0 Transformative Applications for Solar PV, Batteries, and ICT

This section considers the potential of three agricultural practices that are made possible by the technologies described above: i) irrigation powered by solar PV, including systems that use desalinated water; ii) precision agriculture, and iii) soil-free indoor farming. Each of these agricultural practices is already operational in well-financed and high-input settings, whether large-scale or for niche markets. They are beginning to be deployed in resource-poor settings, too. Each could revolutionize food production by raising productivity while improving sustainability. They could support food production on marginal or degraded land. They could support farmers to make more efficient use of inputs, while reducing environmental harm through the use of more sustainable inputs (such as renewable energy) and reducing the overuse or misapplication of inputs, especially those that are potentially polluting, such as synthetic fertilizers.

Solar-Powered Irrigation

Irrigation systems are a prime application for low-cost solar energy. Solar irrigation pumps were first installed in the 1970s, but the price of solar panels began to decline significantly only in 2009 (Hartung & Pluschke, 2018). Prices have continued to drop since then, and there is now great market potential for both small- and large-scale solar-powered irrigation systems. Such potential is furthered by the consistent development of more powerful and efficient systems, and larger pumps that can withdraw water from greater depths (Hartung & Pluschke, 2018).

Despite falling prices, there is still a high upfront cost to the installation of off-grid solar pumps, which is an important barrier to their uptake in low- and middle-income countries. It is estimated that the average upfront cost of a solar pump is 5 to 15 times more than diesel equivalents (Beaton et al., 2019, p.7). In the long term, however, solar pumps are cost-effective because they cost so little to run and maintain. It is estimated that over a 10-year period, the net cost of installing and running a solar PV pump is roughly two thirds of the cost of a similar diesel pump (Beaton et al., 2019, p.7). A solar pump capable of irrigating 5 hectares of land in India costs 10 times more than a conventional pump to install (Jain, 2015). Once installed, however, it costs half as much to operate (Jain, 2015). Given that solar pumps typically last 15 to 20 years, they are cost-effective over time. A study from India that compared the cost of pumps powered by solar PV with those powered by electricity from the grid also found that despite solar pumps being more costly, farmers may still opt for solar PV because on-grid electricity supply (both its quality and duration) is so unreliable in some parts of the country (Agrawal & Jain, 2016).

One of the solutions to the barrier of high upfront costs is to provide financing for solar PV systems that spreads the capital cost over time. For example, ICT can be used to allow regular (and reliable) transfers of electronic funds, which reduces risks for the lender and lowers the overall cost of the financing. Off-grid solar companies in low- and middle-income countries are increasingly using digital payment systems to provide energy on a "pay-as-you-go" basis (Waldron & Faz, 2016, p.1). The companies can protect their loan because they have the ability to remotely disable devices if a farmer falls into arrears (Waldron & Faz, 2016). Digital payments allow farmers to pay small amounts more frequently, which suits low-income households (Waldron & Faz, 2016). It also removes the need to travel from remote rural areas to a physical bank to make cash payments (Tellez & Waldron, 2017).

Targeted subsidies are another way to help small-scale producers overcome the high initial capital costs of investing in off-grid power generation. An example of this is the KUSUM Scheme developed by the Government of India, which uses a combination of subsidies and financing to encourage a transition from diesel pumps and pumps that rely on grid electricity to solar PV powered systems (Government of India, 2019). The KUSUM scheme has three components: i) the addition of 10 GW of decentralized ground-mounted grid-connected solar PV power plants for agricultural irrigation; ii) the installation of 1.75 million stand-alone solar-powered agriculture pumps; and, iii) the transition of 1 million existing grid-connected agriculture pumps to solar PV (Beaton et al., 2019, p. 17). The scheme will receive INR 34,442 crore (USD 4.8 billion) to add 26 GW of solar PV capacity, in an attempt to transform the agriculture sector's electricity consumption, which accounts for 17% of India's electricity use (IISD, 2019, p. 2).

Benefits of Solar-Powered Irrigation

Solar-powered irrigation systems have important advantages for small-scale producers. For those who do not already use some form of irrigation, affordable solar pumps make irrigation accessible, with strong positive benefits for agricultural productivity and incomes. Irrigation can improve yields on existing cropped lands, allows farmers to expand the total cropped area, and makes it possible to produce a greater diversity of higher-value crops. In some cases, irrigation can even create the possibility of adding an extra crop cycle into the year. In Bihar, India, for example, irrigation allows for a third crop—rice paddy, maize, or vegetables—in the summer season (Beaton et al., 2019, p. 9). A World Bank (2018) project in West Bengal estimates that micro-irrigation projects have been able to more than double farmers' income. In Zimbabwe, a study found that solar PV booster irrigation pumps increased yields by an average of 4 to 5 tonnes of maize per hectare for 270 small-scale producers (Magrath, 2015, p. 4).

For farmers who already use some form of conventional water pump for irrigation, a shift to solar-powered systems can increase incomes in the medium to long terms because of the low recurring costs associated with the technology. Solar–diesel hybrid drip-fed irrigation systems (which water plants with a small regular stream) can be operated for less than half the cost of diesel-only systems (Carroquino et al., 2015). For the same reason, farmers can use solar PV systems to run pumps for longer hours than previously (sunlight or battery storage permitting), with benefits for productivity and incomes. Rooftop solar panels have also been used to power cold storage and solar charging facilities. One study found that a solar-powered drip-irrigation system in Benin farmed by a women's cooperative saved each woman up to four hours per day in labour and produced on average an additional 2 tonnes of produce each month (IRENA, 2016, p. 16). The reliable income flows from this production helped the women to independently feed, educate, and provide medical care to their families. The project was expanded to directly benefit an estimated 3,352 individuals, with another 66,000 benefiting from produce grown in the gardens (IRENA, 2016, p. 16).

Box 2. Affordable desalination in arid coastal regions and small-island developing states

Solar PV could also be used to power desalination plants. Turning large amounts of seawater or brackish groundwater into fresh water is currently a high energy-cost undertaking. Most desalinated water is reserved for drinking as a result. If prices fall low enough, however, desalination has the potential to dramatically increase production for small-scale producers in arid coastal regions and small-island developing states, where water shortages threaten agricultural production and food security (Beltran & Koo-Oshima, 2004). Increased water supplies through affordable sustainable desalination could transform food deficit areas such as the Arabian Peninsula and North Africa into centres of agricultural production (Beltran & Koo-Oshima, 2004).

The technical viability of renewable energy-powered desalination systems is already proven and competitive with fossil fuel-powered systems (Caldera et al., 2016). It is not yet, however, cheap enough to make sense in the context of small-scale agriculture. A case study in a remote coastal area of Egypt found that for a 1,000 m^3 per day seawater reverse osmosis system, the estimated water cost for desalination using solar PV was about USD 1.21 per m^3 (Shouman et al., 2015, p. 230). This compared favourably to a cost of between USD 1.18–1.56 per m^3 for desalinated water using a conventional generator powered with fossil fuel (Shouman et al., 2015, p. 230). The hope is that further improvements in solar PV technology will eventually reduce costs enough to provide affordable desalination at the right scale.

Risks of Solar-Powered Irrigation

Solar-powered irrigation systems are not without drawbacks. The high upfront costs pose a financial risk to low-income households (Hartung & Pluschke, 2018). When farmers take out loans to meet the high upfront cost of solar PV installation, they must trust their production and income will increase sufficiently to cover the debt. If their income does not increase for any reason (which could include factors not related to irrigation such as pests), the loan will cause financial hardship. In addition, there is a scale risk that decentralized irrigation could be too successful; if productivity in a region rises for a large population of farmers, the resulting increase in yields could depress prices unless farmers are able to access new markets for the increased supply. Financial institutions need to work with farmers to assess these risks and to plan risk-management strategies to cope with financial stress if it arises.

An expansion of irrigation could also increase pressure on already stressed natural resources, including by encouraging over-extraction of water resources, and harming soil health either with increased demands on existing land (for example to produce an additional crop in the rotation) and/or enabling an expansion of production to more marginal lands (Hartung & Pluschke, 2018). If solar pumps extend the use of irrigation into previously unirrigated areas, there could be negative repercussions on greenhouse gas emissions, soil health, and an increased risk of salinification and eutrophication (FAO, 2017).

One of the confusing signals for producers is that the extremely low recurring costs of solar-powered pumps and the failure to meter or charge for water use mean there is no economic incentive to irrigate conservatively (Beaton et al., 2019). This can lead to water withdrawals putting stress on existing water resources. A review of international experiences found that this risk is generally inadequately evaluated in feasibility studies (Closas & Rap, 2017). In practice, the extent to which solar pumps increase water stress is dependent on many factors: regional water availability, cropping patterns, time horizons (whether water extraction now affects future availability due to over-extraction), regulation and enforcement of water access, and whether farmers can store excess electricity or sell it to the grid or neighbours (such as through a mini-grid) (Beaton et al., 2019). To limit the risk of overuse, governments could consider introducing incentives and infrastructure to encourage farmers to sell excess power, install drip irrigation, and otherwise curtail water extraction (Hartung & Pluschke, 2018).

Precision Agriculture

Precision agriculture describes a range of applications that gather and analyze data to optimize and automate agricultural processes on a specific site. Data can be gathered using satellites and other aerial imagery, and by the use of on-the-ground sensors. Together, these provide detailed maps of farm conditions that may include soil conditions (depth, moisture, temperature, salinity, pH), surface conditions (sunlight levels, humidity, wind speed, rainfall), and the characteristics of the crop (such as the size of plant stems, and height) (Libelium, 2015). Monitors attached to livestock and the machinery the animals interact with (feed bins, water troughs, milking machines) can similarly provide a detailed view of an individual animal's health, habits, and productivity. GPS systems can create detailed maps of farms. GPS technology is becoming more prevalent because all smartphones and tablets have distributed GPS transmitters that allow for locational data to be integrated into every activity on the device. GPS transmitters have also been integrated into some farm equipment, on-farm sensors, and supply chain equipment, all of which enable spatial and locational analysis of various data generated by these systems. Other tracking systems monitor the weather. Precision agriculture also works with drones, which can be programmed to deliver specific amounts and kinds of inputs on specific locations.

Benefits of Precision Agriculture

Precision agriculture provides farmers with the ability to: (i) map farm characteristics, (ii) vary inputs and management practices (called "variable rate technology"), (iii) build guidance systems for farm equipment and (iv) track livestock or fish schools using GPS. Data from sensors and GPS can be used to tailor agricultural practices or inputs to specific locations on the farm. Variable rate technology can allow farmers to greatly improve the precision of their input use, raising efficiency. The result is to reduce the cost of inputs by limiting their use, while also limiting leakages into the wider environment due to excess application. These systems have already been demonstrated to be very effective in commercial, large-scale agribusiness in high-income countries. Industry estimates suggest there will be nearly 12 million agricultural sensors installed globally by 2023, linking farms to the Internet (Meola, 2020). The table below provides examples of the benefits of precision agriculture techniques.

Box 3. Applications showing the benefits of precision agriculture

- In drought-affected California, several farms of high-value but water-intense crops, such as almonds, use cloud-based computer systems to minimize water use (Carr, 2016). Data on soil moisture is collected by sensors and used to calculate the right amount of water and fertilizer to be dispensed, which is done so automatically by the irrigation system (Carr, 2016). It was predicted that the use of precision agriculture technologies could reduce water use in Canada by up to 22% while maintaining productivity (Pacific Institute, 2014, p. 6).
- Using a precision agriculture approach on a maize and soy farm in South Africa, the soil was tested to determine which elements were present; available (some elements may be present but are only available to the plant in the presence of another element that may be missing); and to determine the level of micro-bacterial activity in the soil (soil organisms produce nitrogen and phosphate that the plants can use) (Gray, 2018). The information not only allows much more precise use of inputs such as fertilizers, but also informs the farmer if other elements need to be added instead of fertilizers (Gray, 2018).

The high cost of large-scale precision agriculture makes it largely inaccessible to small-scale producers in low- and middle-income countries, especially in areas lacking electricity and ICT infrastructure. The cost barrier is coupled with skills and knowledge deficits, limited awareness of the possibilities the new technologies offer, and evidence of a level of skepticism and mistrust of precision agricultural technologies among farmers (Schumpeter, 2014). The technology to date has been aimed at larger and more highly capitalized farms.

Reductions in the cost of solar PV and the near-ubiquitous use of mobile devices around the globe will reduce these barriers. Rural communities in low and middle-income countries are among the populations most at risk from natural disasters (FAO, 2016a). The ability to monitor and anticipate climate-related and environmental changes, as well as to better track water and nutrient input needs for crops, are important advantages for small and medium-sized producers. Technologies that give farmers access to this data enhance their ability to protect their crops and thus their ability to protect their incomes and safeguard their food security. Limiting waste in the application of water, fertilizer, and pesticides also reduces costs. The box below provides examples of how precision agriculture techniques are currently being applied in low- and middle-income countries.

Box 4. Examples of the use of mapping and sensors in low- and middle-income countries

- A prototype of an easy-to-use soil sensor is being tested in Tanzania. The sensor uses LED signals to tell the farmer when to irrigate. It can send data to an internet-based platform where it is analyzed in real-time. The sensor does not require calibration based on soil type, making it very easy to use. The sensor unit is cheaper than similar technologies without sacrificing many of the advantages offered by more sophisticated (and expensive) versions (Sim et al., 2015).
- Kitovu is a Nigerian-based online decentralized warehousing system that uses location and soil information collected by the mobile app to provide advice on correct fertilizer and seedling inputs to different small-holder producer farmers (Balachandran, 2018).
- In Myanmar, small-scale producers are testing three basic sensors. The first tests for water levels in rice fields, the second helps check moisture levels in betel nut crops, and the third is a mobile app that uses GPS to provide detailed maps of farmers' fields and anticipates the correct amount of inputs needed (IDEO, 2019).
- Colombian researchers analyzed 10 years of weather and rice crop data to generate planting advice. It is estimated that the farmers who followed the advice avoided drought-induced economic losses of USD 1.7 million (Urrea, 2017).
- A prototype real-time variable rate fertilizer application system was recently developed in Mexico as an add-on kit to conventional farm machinery (Van Loon et al., 2018). Nitrogen sensors immediately assess the plant nutrient status and automatically adjust the amount of fertilizer deposited accordingly (Van Loon et al., 2018). At USD 5,000, the system was cheaper than large-scale alternatives, but still expensive for small-scale producers. Efficient ICT sharing technology could allow farmers to rent such services.

Risks of Precision Agriculture

Aside from the cost barriers, precision agriculture techniques are associated with several further risks. They include: unresolved questions over data ownership; the importance of providing farmers with training and support so they can make full use of the information that is generated by the technology; and the threat to rural workers as the demand for agricultural work changes. There are also very practical and immediate risks, such as the possibility that sensors will be stolen from the fields. A conflict of interest may arise if a software designer or data provider has to choose between providing the best possible information to its users (the farmers) and protecting the profits of its shareholders (who might be agricultural input suppliers).

The increased use of precision technology in small-scale agriculture creates new uncertainties and potential risks around who owns the data generated (Wiseman & Sanderson, 2019). To date, regulation in industrialized countries has not kept pace with the technologies, creating significant concerns over privacy and ownership (Ferris, 2017). It seems unlikely low- and middle-income countries will do better without active and deliberate policy interventions. This will require national legislation, eventually, and public debates in which rural voices—and particularly the voices of small-scale producers and farm workers—may struggle to be heard, particularly if those voices are female.

Agriculture will not be exempt from the effects that automation is having on employment across economies around the world. The uncertainty over the extent to which low- and even high-skilled labour will be displaced is a reason to temper technological optimism. Yet ICT has the potential to counter consolidation, too. For example, apps that allow the efficient sharing of technology and services, such as Hello Tractor, give small-scale producers access to the benefits of mechanization on small plots of land without having to buy expensive equipment, reducing some of the disadvantages they face compared to larger farms. Yet the availability of technological hardware and software is not likely to improve productivity unless farmers have the skills to understand and use the data. The investment in both time and money needs to be financially worthwhile if farmers are to adopt precision agricultural practices.

Indoor Agriculture: Soil-free and vertical farming

Indoor agriculture refers to both soil-free agriculture (also known as hydroponics) and vertical farming (Impey, 2019). Plants are grown in optimized, controlled environments to avoid unwanted environmental hazards such as bad weather, pests, weeds, and disease, and to target and reduce the use of water, fertilizers, and pesticides (Benke & Tomkins, 2017). The controlled environment prevents the leakage of inputs into the wider environment. Soil-free agriculture uses drip irrigation to grow plants in a nutrient solution rather than soil (Despommier, 2009). The systems can be very sophisticated, with continuous monitoring and temperature optimization sensors controlling light, water, and nutrients, or they can be simpler, with fertilizers applied manually. For now, indoor agriculture is predominantly practiced in high-income countries, but its use is evolving quickly.

Vertical farming grows food at very high densities in vertically stacked layers using soil or hydroponic or aeroponic (growing plants in a mist environment) methods. Vertical farming is becoming increasingly popular in densely populated urban settings in Japan, China, and the United States (Al-Kodmany, 2018; Benke & Tomkins, 2017). The ability to produce food in the city without depending on land shortens the supply chain. Vertical farms are being built in otherwise derelict, former industrial spaces in urban and peri-urban areas with the effect of reducing pressure on agricultural land (Al-Kodmany, 2018). Some businesses and non-governmental organizations are exploring the use of vertical farming in remote regions, for example in Canada's North, where food insecurity levels are high and the land is not arable (Green Iglu, n.d.).

The Benefits of Indoor Agriculture

The important benefit of soil-free and vertical farming is that it enables food producers to overcome limitations in their natural environment, such as land or water scarcity. The technologies have important potential applications in environments suffering the effects of climate change as well. Food production with little or no need for soil can reduce land degradation and support efforts to rehabilitate land.

Vertical farms are reported to be commercially viable in some developed country markets (Benke & Tomkins, 2017). One of the world's largest vertical farms, AeroFarm, in New Jersey, covers 70,000 square feet in a former steel plant (Frazier, 2017). The farm sells leafy salad greens to corporate customers and local retailers, and has since received upwards of USD 50 million in investment (Frazier, 2017). The table below provides examples of large-scale hydroponic agriculture.

Box 5. Examples of commercially successful large-scale hydroponic agriculture

- Using modified shipping containers, fresh vegetables can be grown in the arctic regions of northern Canada at 25% of the cost of flying them in from urban centres (Finnegan, 2018).
- The largest greenhouse complex in the United Kingdom produces approximately 12% of the tomatoes, 11% of the peppers and 8% of the cucumbers grown in the country (Fletcher, 2013).
- Companies like IKEA and Freight Farms in the United States are selling pre-packed hydroponic kits that make small-scale agricultural production possible anywhere (IKEA, 2017; Freight Farms, 2017). Studies on soil-free farming show the technology can dramatically increase yields, and reduce water use by 92% in lettuce production (Barbosa et al., 2015, p. 6886).

It might seem that such capital-intensive technologies have no place in a paper about agriculture in low- and middle-income countries, but cheaper versions are already coming into commercial use there. Simplified, smaller-scale soil-free and indoor systems, usually requiring manual watering and nutrient monitoring, have been deployed in Cuba, Mexico, Peru, Senegal, Venezuela, and Zimbabwe (Hein, 2007; Orsini et al., 2010). Raised beds for growing produce are constructed from locally available materials, organic fertilizers are derived from bio-waste to limit dependence on purchased inputs, and manual work replaces the pumps and other automated controls that systems in richer countries rely upon (New Agriculturalist, 2007). The reduced use of automation lowers the energy requirements compared to large-scale operations and means more job creation while protecting the benefits of reduced water and land use. The box below provides two further examples of indoor agriculture in low- and middle-income countries. The possibilities for regions already stressed by climate change are clear, even if the scale remains modest, and only a complement to land-based agriculture. Increasing the availability of both pre-packaged systems and tailor-made systems that rely on locally sourced products could expand access to these kinds of technologies in low- and middle-income countries.

Box 6. Examples of indoor agriculture in low- and middle-income countries

- In Uganda, small-scale producers use stacked wooden boxes to grow vegetables (Observers Take Action, 2016). The units have a central vermicomposting chamber in which earthworms transform organic waste into natural fertilizer. Rainwater is collected in water bottles above the unit and filtered through pipes so that irrigation can be continuous or controlled. Using this method, soil use is cut by one third and water by 70% (Observers Take Action, 2016).
- In South Africa, hydroponic fodder production has been found to produce up to 10 times more fodder than conventional methods on the same area of land (Njima, 2016, p. 1). The fodder is grown in trays arranged in shelves inside the hydroponics system. Hydroponics fodder production proved more than 80% more water-efficient compared to growing it in the soil (Njima, 2016, p. 1).

Risks of Indoor Agriculture

Indoor agriculture is energy-intensive and technical. It is suited only to a limited range of crops. Indoor farming is estimated to require 80 times more energy than conventional farming (Barbosa et al., 2015, p. 6886). This is where falling energy prices from solar PV technology play an important supporting role. As with precision agriculture, part of the appeal in industrialized countries is the possibility of reducing labour input. This is not an advantage in most low- and middle-income countries. Farmer indebtedness is also a threat, as with most new technologies. Vertical farming requires significant start-up capital and has significant ongoing costs.

Failure to ensure strong capacity-building for farmers investing in the technology is another hazard. In Mexico, 60% of the installed hydroponic greenhouses failed because the training of the producers was poor, there were too few technicians available to support the investment, and not enough thought had gone into situating the production in relation to markets (2000Agro, 2010). Vertical farming is commercially viable in high-income countries because it can rely on a market for fast-growing, high-margin fresh produce such as herbs and leafy salad greens. It is not a production system geared for staple crops such as grains. It is possible to use the approach for some more calorie-dense crops such as root vegetables, but this has yet to be developed commercially.

5.0 Conclusions and Recommendations

Technological change has been a central driver in shaping agriculture's history. This paper looks at three modern technologies that have the potential to provoke transformative change in agriculture: decentralized energy grids powered by solar PV, high-performance batteries, and ICTs. Simple and affordable ICT systems, powered by solar PV and much-improved batteries, can now be deployed anywhere in the world at a very low cost. These technologies could help dramatically increase the efficiency of agricultural inputs, including synthetic fertilizers, water, and even reducing overall demand for agricultural land. None of these technologies is new. What is new is the sharp and rapid decline in their costs, making them newly accessible to a much larger range of food systems than previously, including food systems in low- and middle-income countries.

Solar-powered irrigation is already improving small-scale producer productivity and incomes. Solar PV and batteries are delivering power for mechanization, transportation, and storage. Small-scale producers are using apps, text messages, and radios to access information and advice on a range of subjects including weather conditions, production practices, and input and sale prices. Innovative new uses of the technologies are emerging all the time, including apps that manage the sharing of farm machinery and transport, virtual marketplaces, and access to financial services. The flow of information is two-way. Governments, companies, and development organizations all have better information than ever before about the communities and clients they serve. There is a huge opportunity for them to develop better policies, products, and interventions for a wider range of rural actors.

Further cost reductions and innovation in these three technologies should be expected in the near future. Inputs are a major cost in agriculture, as is labour in some farm systems. More efficient input use, improved processing and storage capacity, and the gradual automation of some tasks could intensify agricultural production, improve productivity on degraded or marginal lands, reduce food losses and waste, and improve farm-based livelihoods.

Inclusive sustainable food and agriculture systems will not come about by accident. Nor are the new technologies without risk. Agriculture around the world is haunted by the risk of indebtedness. Remunerative on-farm employment is not a given. The technologies bring new risks too—risks that have not yet been well addressed in high-income countries either, such as the potential to appropriate farmers' data without permission. Without effective regulation, environmental degradation will continue to be a feature of food and agricultural systems.

Done right, however, the adoption of these technologies will support the achievement of the UN Sustainable Development Goals, notably those on combatting hunger, poverty, and climate change. Governments have a central role to play to minimize the risks and maximize the potential gains. Here are 10 ideas for how to make this happen.

1. Talk to small- and medium-scale producers about the technologies and their potential, to understand how they are already using them, what other uses they would like to see, and how the design and cost should be managed to protect accessibility.

2. Introduce regulation and enforcement mechanisms to manage the economic, social, and environmental risks associated with new technologies. The expansion of solar-powered irrigation, for example, requires flanking policies to prevent over-extraction and encourage the use of efficient distribution systems (such as drip irrigation).
3. Monitor how the new technologies are contributing to environmental, social, and economic sustainability goals and indicators, as defined in the SDGs.
4. Increase investment in targeted interventions to kickstart the diffusion of new technologies. Specifically, investments in research and development and targeted consumer subsidies for worthwhile products are warranted given high start-up costs coupled with small recurring costs, creating an attractive investment that demands a longer time horizon than many small-scale producers can afford.
5. Support ICT development and adoption through broadly based investments in the sector, such as improving telecommunications and Internet infrastructure, and either extending the electricity grid or putting in place off-grid renewable energy in rural areas.
6. Introduce regulations on responsible lending by financial institutions to protect small-scale borrowers and establish financial literacy programs to reduce the risk of them becoming indebted.
7. Introduce clear laws and regulations around data access, privacy, and technology integration to provide certainty to both developers and adopters.
8. Work with effective government and non-government institutions to provide education, training, and extension services for farmers on the design and appropriateness of new technologies, including when and how to use the equipment and data.
9. Measure and monitor changes in employment levels and ensure adequate social safety nets are provided where mechanization and automation increase unemployment.
10. Strengthen institutions that test and license products and ensure adequate aftersales service standards and warranties.

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