System Initiative on Shaping the Future of Food Security and Agriculture

Innovation with a Purpose:
The role of technology innovation in accelerating food systems transformation

Prepared in collaboration with McKinsey & Company

January 2018

Quotes

Innovations in technology – as well as policy, financing and business models – are essential to nourish the world in a safe, responsible and sustainable way. To improve global food security and nutrition, different players and stakeholders must come together to acknowledge gaps and share approaches for addressing them. We have an incredible opportunity to work together to use technology and innovation to create more inclusive and sustainable food systems.

David W. MacLennan
Chairman and Chief Executive Officer, Cargill

Technology has the potential to answer some of our biggest questions and help us better understand the world around us. In almost every industry, massive efforts are underway to connect our physical and digital worlds, unleashing the Fourth Industrial Revolution. We must work together to ensure that the food and agriculture sector is not left behind – and that these efforts contribute towards global food systems that benefit farmers, consumers and the planet.

Bernard Meyerson
Chief Innovation Officer, IBM Corporation

A new revolution in food has the potential to create healthy food systems that sustain our families and our planet. We have the tools and technology to create innovations that could expand dignity and justice to vulnerable populations. To this end, we must continue to build the shared capacity of businesses and philanthropies, faith institutions and state and local governments to come together to try to solve the world's toughest problems.

Rajiv Shah
President of the Rockefeller Foundation

Food today generates a heavy environmental footprint. A shift to sustainable food systems is essential and includes: sustainable production and harvest on land and at sea, integrated land-use planning, land and marine restoration, reducing food loss and waste, and shifting to low footprint diets. To achieve this we need progressive regulation, smart land-use governance, technology innovation, behavioural change and multi-stakeholder collaboration."

Marco Lambertini
Director General of WWF International

Smallholder farmers produce 80% of Africa's food supplies, but they have limited access to finance, inputs, markets, information and other services. Technology innovations can overcome all these challenges – but it won't happen automatically. We need to combine innovation, investment and policy to harness the power of the Fourth Industrial Revolution to benefit smallholder farmers.

Ishmael Sunga
Chief Executive Officer, Southern African Confederation of Agricultural Unions (SACAU)

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Preface

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By 2050, global food systems will need to sustainably and nutritiously feed more than 9 billion people while providing economic opportunities in both rural and urban communities. Yet our food systems are falling far short of these goals.

A systemic transformation is needed at an unprecedented speed and scale. At the same time, the Fourth Industrial Revolution is driving disruptive technology innovations across many sectors. Agriculture and food systems have been slow to benefit from these developments – the sector lags significantly behind in harnessing the power of technology and making it widely accessible.

This report aims to identify emerging technology innovations that have the potential to drive rapid progress in the sustainability, inclusivity, efficiency and health impacts of food systems to achieve the Sustainable Development Goals. It highlights the significant economic, environmental and health benefits that could be realized through the broad adoption of certain technologies and enabling actions that can support and scale them. It recognizes that technology is just one of a wide range of solutions that need to be applied in tandem to transform food systems and that a “systems leadership” approach is needed to engage all stakeholders towards that shared goal.

The “Innovation with a Purpose” project forms part of the World Economic Forum’s System Initiative on Shaping the Future of Food Security and Agriculture. The initiative is one of 14 major global programmes to drive systemic change in response to complex global challenges. The initiative engages over 650 organizations in shaping a common agenda for food systems transformation and mobilizing 21 countries through partnerships catalysed by the New Vision for Agriculture (NVA) initiative. The NVA is driven by ministers, CEOs, farmer leaders, civil society, international organization leaders and other key stakeholders collaborating on over 100 value-chain projects in Africa, Asia and Latin America. We hope that the technology applications explored in this report – and the “innovation ecosystems” that enable them – will prove useful to leaders seeking to drive accelerated progress and innovation on the ground.

This report was developed in partnership with McKinsey & Company, led by Sunil Sanghvi, Pradeep Prabhala, Marla Capozzi, Joshua Katz and Antonin Picou. At the Forum, the project was led by Lisa Dreier, Saswati Bora and Caitlin O’Donnell with input from Sean de Cleene, Tania Strauss, Jim Riordan, Maria Elena Varas and Christian Kaufholz. Members of the World Economic Forum’s Global Future Council on Food Security and Agriculture, as well as other leading experts and technology innovators (listed in the Annex) provided substantial input. We also gratefully acknowledge the support of the Government of the Netherlands, Global Affairs Canada, the Rockefeller Foundation and the Wellcome Trust in funding our System Initiative, including work on this report.

Executive summary

With the right enabling actions we can harness the power of technology innovation to help transform global food systems.

The need to transform food systems

Global food systems today are in need of transformation. Billions of people are poorly nourished, millions of farmers live at subsistence level, enormous amounts of food go to waste and poor farming practices are taking a toll on the environment. Achieving the Sustainable Development Goals (SDGs) by 2030 will require food systems that are inclusive, sustainable, efficient, nutritious and healthy.

Achieving a true transformation of food systems requires a holistic approach – one engaging all stakeholders and deploying a wide array of actions such as improved policy, increased investment, expanded infrastructure, farmer capacity-building, consumer behaviour change and improved resource management. Technology innovations, combined with other interventions, can play an important role in enabling and accelerating food systems transformation.

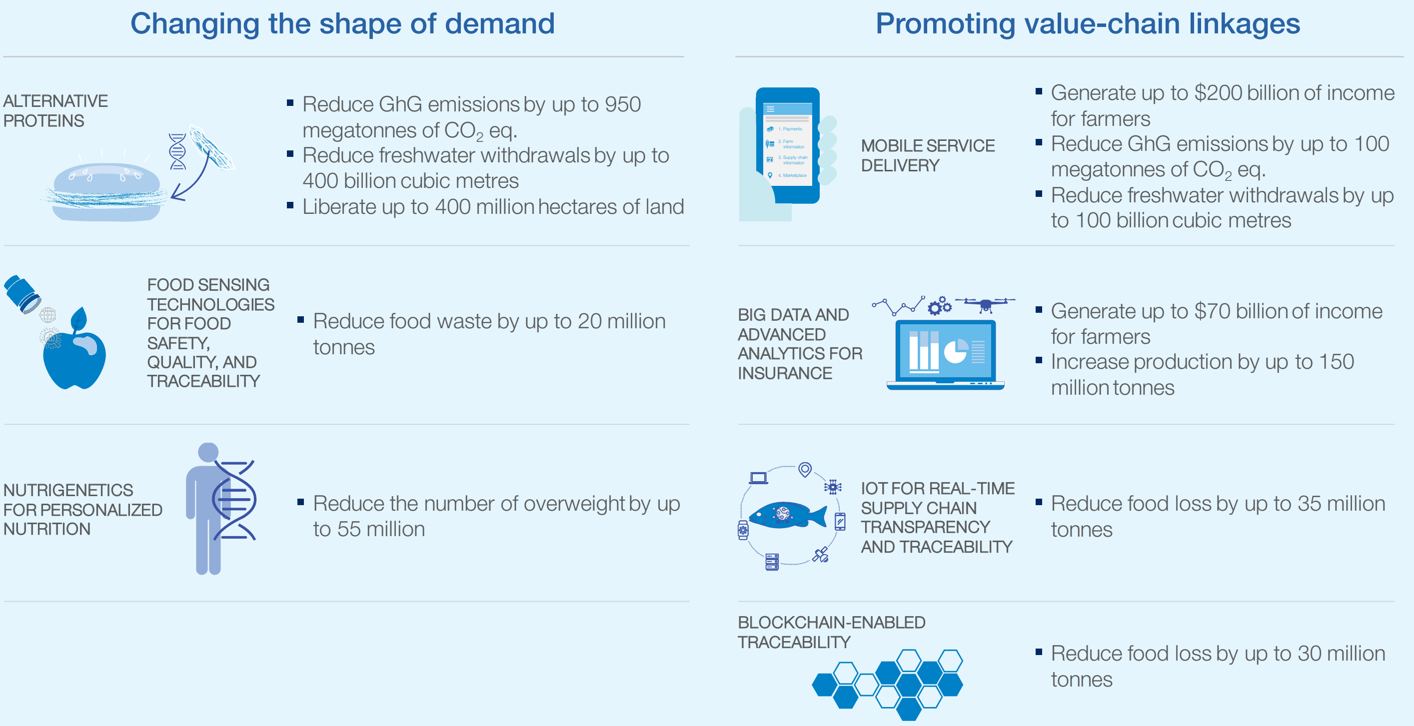
Technology innovation for food systems: emerging opportunities

Emerging technologies driven by the Fourth Industrial Revolution are disrupting many industries, bringing rapid and large-scale change. These include:

— **Digital building blocks** such as big data, the Internet of Things (IoT), artificial intelligence and machine learning and blockchain
— **New physical systems** such as autonomous vehicles, advanced robotics, additive manufacturing, advanced materials and nanotechnologies
— **Advances in science** such as next-generation biotechnologies and genomics, and new energy technologies

Until now, the food and agriculture sectors have been slow to harness the power of these technologies, attracting significantly lower levels of investment and inspiring fewer technology start-ups than other sectors. **Our research revealed $14 billion in investments in 1,000 food systems-focused start-ups since 2010, while healthcare attracted $145 billion in investment in 18,000 start-ups during the same time period.**[1]

Figure 1: The ‘Transformative Twelve’ could deliver significant impacts to food systems by 2030



The lower levels of investment in food systems are due in great part to the complexity of the sector. Fragmented rural markets, poor infrastructure, high regulatory burdens and other factors raise costs, while revenues are constrained by customers' limited ability and willingness to pay. In addition, much of the food systems' start-up activity is concentrated in developed countries and on improving the production landscape, indicating both the risk of unequal access to new solutions and the opportunities for scaling in developing countries and in demand-side innovations. Coordinated efforts by policy-makers, investors, educators and others to nurture and accelerate food systems enterprises in all regions can overcome those obstacles.

The 'Transformative Twelve': Innovations with much potential in food systems

We identified **12 technology applications** that illustrate the potential of emerging opportunities in food systems – including improving consumer nutrition, increasing supply-chain efficiency and transparency and boosting farmer productivity and profitability. While many are in the early stages, the 'Transformative Twelve' technologies could deliver significant positive impacts in food systems by 2030. Figure 1 illustrates the main impacts of each of the 12 applications of technology.

Achieving this potential is not a given – it will require key enablers including policy, investment, infrastructure and availability of complementary technologies. The broader impacts of these technologies, including the potential for unintended consequences, must also be considered.

Enabling continuous innovation

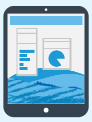
The activity taking place around the 'Transformative Twelve' technologies signals both growing momentum and rapid evolution in this area. Capitalizing upon and further developing the value of these and other technologies will require continuous innovation. By establishing "**innovation ecosystems**" designed to incentivize and accelerate technology innovation, communities can help develop a robust and competitive pipeline of solutions to future food systems challenges. Key elements such as **enabling policy, infrastructure, investment, business support services and access to academic and research institutions** are required to develop successful innovation ecosystems.

An agenda for action

New technologies present a **major opportunity to accelerate food systems transformation** – one that has been underused, particularly in developing-country regions.

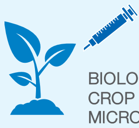
Every stakeholder can play a role in realizing this potential. Governments can deliver **infrastructure** and **innovative policy**. Companies can collaborate to open new markets through sharing **data and intellectual property**. Investors and donors can provide **growth capital** and enable entrepreneurs. Systems leaders can help bring these actors together to bridge gaps, align on common objectives and enable innovation. **Continuous dialogue and collaboration** is needed to understand the potential impacts of specific technologies and to harness them for positive effect in food system.

Creating effective production systems



PRECISION AGRICULTURE FOR INPUT AND WATER USE OPTIMIZATION

- Reduce farmers' costs by up to $100 billion
- Increase production by up to 300 million tonnes
- Reduce freshwater withdrawals by up to 180 billion cubic metres



BIOLOGICAL-BASED CROP PROTECTION AND MICRONUTRIENTS FOR SOIL MANAGEMENT

- Increase production by up to 50 million tonnes
- Reduce GhG emissions by up to 5 megatonnes of CO_2 eq.

GENE-EDITING FOR MULTI-TRAIT SEED IMPROVEMENTS

- Generate up to $100 billion in additional farmer income
- Increase production by up to 400 million tonnes
- Reduce the number of micronutrient deficient by up to $100 million

OFF-GRID RENEWABLE ENERGY GENERATION AND STORAGE FOR ACCESS TO ELECTRICITY

- Generate up to $100 billion in additional farmer income
- Increase production by up to 530 million tonnes
- Reduce freshwater withdrawals by up to 250 billion cubic metres

MICROBIOME TECHNOLOGIES TO ENHANCE CROP RESILIENCE

- Generate up to $100 billion in additional farmer income
- Increase production by up to 250 million tonnes
- Reduce GhG emissions by up to 30 megatonnes of CO_2 eq.

The need for global food systems transformation

Figure 2: Food systems are relevant to all of the Sustainable Development Goals

1 NO POVERTY	Nearly **80% of the world's poor** live in rural areas and work mainly in agriculture.[2]
2 ZERO HUNGER	There is enough food produced today to feed the global population yet **around 800 million people are chronically undernourished.**[3]
3 GOOD HEALTH AND WELL-BEING	**Malnutrition is the largest contributor to disease in the world.**[4] Over 4 billion people are either micronutrient deficient or overweight.
4 QUALITY EDUCATION	Malnutrition, which affects nearly one in four children under age 5 worldwide, is associated with **reduced school performance, and impaired brain development.**[5]
5 GENDER EQUALITY	Women represent 43% of agricultural labour yet have **unequal access to land, technology, markets and other resources.**[6]
6 CLEAN WATER AND SANITATION	Today, food systems account for **70% of freshwater withdrawals.**[7]
7 AFFORDABLE AND CLEAN ENERGY	Modern food systems consume around **30% of world's available energy** and are heavily dependent on fossil fuels.[8]
8 DECENT WORK AND ECONOMIC GROWTH	**Agriculture is the single largest employer in the world,** employing around 60% of workers in less developed countries.[9]
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Around 900 million people in rural communities, the majority of whom work in agriculture, **don't have access to electricity.**[10]
10 REDUCED INEQUALITIES	Seven out of 10 people live in a country that has seen a rise in inequality in the last 30 years.[11] **Inequality shapes who has access to healthy food.**[12]
11 SUSTAINABLE CITIES AND COMMUNITIES	By 2030, **nearly 60% of the world's population** will live in urban areas, changing the shape of consumer demand and increasing pressure on land and other resources.[13]
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	**Nearly one third of global food production –** 1.3 billion tons of food – is lost or wasted.[14]
13 CLIMATE ACTION	Food systems are currently **responsible for 20-30% of global greenhouse emissions.** Inversely, climate change threatens to cut crop yields by over 25%.[15]
14 LIFE BELOW WATER	Fish accounts for 17 percent of the global population's intake of animal proteins. However, **over 30% of the world's fish stocks are overexploited.**[16]
15 LIFE ON LAND	**Agriculture is the most significant driver of deforestation,** contributing to a record global tree cover loss of 30 million hectares in 2016, an increase of 51% from 2015.[17]
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Increased food insecurity – 815 million undernourished people, up from 777 million in 2015 – can be **both a cause and consequence of conflict.**[18]
17 PARTNERSHIPS FOR THE GOALS	**Partnerships are crucial to** transforming food systems. Unlocking opportunities in food systems could be worth $2.3 trillion annually for the private sector by 2030.[19]

Global food systems today are unsustainable for both people and the planet. They leave billions of people inadequately nourished, operate at a high environmental cost, waste large amounts of what is produced and leave many of their producers at or below the poverty level.

As such, stakeholders from all sectors and regions have recognized the need for a fundamental transformation of food systems – a transformation that will address the significant challenges across food systems and advance all of the Sustainable Development Goals (SDGs) as illustrated in figure 2.

Such a transformation would create not only social value, but economic value as well. New business opportunities generated in the course of addressing Sustainable Development Goals in the food and agriculture sector could reach $2.3 trillion annually by 2030, according to the Business and Sustainable Development Commission.[20]

A vision for transformation

To feed almost 10 billion people by 2050[21], while meeting the Sustainable Development Goals (SDGs), food systems will need to be:

- **Inclusive** – ensuring economic and social inclusion for all food systems actors, including smallholder farms, women and youth
- **Sustainable** – minimizing negative environmental impacts, conserving scarce natural resources, saving biodiversity loss and strengthening resiliency against future shocks
- **Efficient** – producing adequate quantities of nutritious and healthy foods for global needs while minimizing loss and waste
- **Nutritious and healthy** – providing and promoting the consumption of diverse nutritious and safe foods for a healthy diet

Achieving this vision requires considering the environmental, economic, and health-related dimensions of food systems. It requires continued investments[22] in crop improvement technologies, management practices, policy and governance, business model innovation and other strategies that have been proven over the last decade. And it requires substantial innovation and departures from the status quo.

Food systems are ripe for technology disruption

Global food systems today are riddled with inefficiency and ineffectiveness. Consider a few examples:

— Approximately 500 million smallholder farmers produce 80% of the food consumed in the developing world[23]. However, farming as an occupation is on the decline. Developing viable and attractive jobs for growing numbers of young people will be crucial to both economic and political stability.

— Food systems are currently responsible for 20–30%[24] of global greenhouse gas emissions, 70% of freshwater withdrawals and 70% of biodiversity loss. Twice as much water will be required for food production in 2050 but nearly one-third of agricultural production today takes place in water-stressed regions. Dramatically reducing the environmental footprint of food production is essential for sustainably meeting the needs of a growing population.

— Nearly one-third of global food production – 1.3 billion tonnes of food – is lost along the supply chain or wasted by consumers and retailers. Reducing this waste could cut costs, improve incomes and alleviate negative impacts on the environment.

— Nearly 800 million people are chronically undernourished and 2 billion are micronutrient deficient. Approximately 155 million children under the age of five suffer from stunted growth[25], while 2 billion people are overweight or obese. Improving access to affordable nutritious food is essential for reducing poor nutrition and the associated health costs.[26]

There are significant barriers to addressing these challenges. Constraints in changing consumer behavior, together with the limited innovation in food product development and distribution and a lack of proper incentives and access, limit our ability to shift consumer demand towards more nutritious and sustainable diets. Inadequate infrastructure, information, and financial inclusion make it difficult for farmers to gain access to cost-effective products, services, and information that could boost their productivity and profitability. The lack of transparency along supply chains has resulted in a loss of consumer trust. The high cost of developing crop technologies has reduced crop diversity, generating both dietary and environmental consequences. On a systemic level, the lack of a holistic approach across relevant sectors (including agriculture, health, and environment) prevents both policymakers and investors from making the right decisions to improve food systems.

Although these barriers are considerable, Fourth Industrial Revolution (4IR) technologies are making it easier to dismantle some of them. Taken together, these innovative technologies lower cost to scale, accelerate innovation, increase transparency in food systems, enable consumers to make informed choices, and allow policy makers to engage in evidence-based policy making.

Fourth Industrial Revolution technologies

Technologies are transforming the world around us. Improvements in the performance and cost of computing power, storage and bandwidth have led to the growth of digital technologies. Together, with advances in science and technologies that are altering the physical world, Fourth Industrial Revolution technologies are driving significant innovations. A wide array of industries – telecommunications media, transportation, life sciences and more – are experiencing the disruptive effects of emerging technologies.

Figure 3 illustrates the underlying technologies that are driving these rapid innovations.

Figure 3: Combinations of 4IR technologies can enable innovation to solve challenges faced in food systems

Digital building blocks

- New computing technologies
- Big data and advanced analytics
- The Internet of Things (IoT)
- Artificial intelligence and machine learning
- Blockchain
- Virtual reality and augmented reality

Advances in science

- Next-generation biotechnologies and genomics
- Energy creation, capture, storage and transmission

Reforming the physical

- Autonomous and near-autonomous vehicles
- Advanced, smart robotics
- Additive manufacturing and multidimensional printing
- Advanced materials and nanotechnologies

These technologies are also transforming how innovations are being conceptualized, designed and commercialized and, more generally, how businesses operate. For example, companies such as Kickstarter, Innocentive, Crowd Spring, Amazon, Google, and Salesforce have created online platforms that reduce the barriers to entry and transaction costs for innovators developing and commercializing new products of their own.

Opportunities for disruption in food systems

In 2017, the World Economic Forum developed a set of scenarios for the future of global food systems, outlining four distinct possible futures shaped by changes in consumer demand and market connectivity.[27] This work identified technological innovations as one of the elements that will help to shape global food systems.

The potential impacts of such disruptive technologies are wide ranging. Fourth Industrial Revolution technologies have the potential to help revolutionize food systems, dramatically changing the shape of demand, improving value-chain linkages and creating more effective production systems. At the same time, however, they are likely to introduce new challenges. They raise concerns pertaining to health and safety, the environment, privacy and ethics. They can create unintended consequences, which must be considered and explored in advance. In addition, their positive effects may be unevenly distributed, potentially deepening the divide between rich and poor. Harnessing the positive impacts of technology innovation and avoiding potential downfalls will require deliberate and coordinated efforts by investors, innovators and policy-makers.

While food systems have been slow to benefit from innovative technologies[28], especially in developing countries, a recent acceleration of innovation efforts make the future adoption of technology feasible. This report provides a glimpse of the novel technology applications companies are developing to address food systems challenges. These innovations have attracted more than $14 billion in investments in 1,000 start-ups since 2010, mostly in developed countries. To compare, healthcare has attracted $145 billion in investments in 18,000 start-ups over the same period of time.

This report aims to identify emerging technologies with the potential for achieving global aspirations for food systems and to start a discussion about enabling their use for constructive outcomes, while underlining the challenges and unintended consequences they may bring. The report focuses on technological innovation in food systems – recognizing that it is also essential to continue investments in low-tech interventions, create new and bold policies, move towards full-cost accounting, improve resource efficiency, influence consumer behaviours, build trust and transparency, align towards common objectives and collaborate across independent working groups. These additional interventions may also be enabled by the underlying Fourth Industrial Revolution technologies.

The power of technologies in transforming food systems

A vision for global food systems in 2030 that will meet will both human and planetary needs will be:

Inclusive – Smallholder farmers, including women and young people, are fully integrated into food systems with access to financing, insurance, transport, education, mechanization leasing and storage. Businesses, governments, international organizations and other food systems stakeholders effectively provide farmers with the infrastructure, policies, regulations and services they need to thrive.

Sustainable – With the knowledge, desire and means to make eco-friendly decisions, consumers focus on purchasing food with the minimum environmental impact. Sustainably grown foods are universally affordable. Retailers are incentivized to stock eco-friendly foods. Companies and farmers share more information than ever about their sustainable practices, and their reputations benefit. Conscious of their land's value, farmers deploy practices that reduce environmental damage, while countries meticulously monitor their food systems environmental impact, land rights and plan for land use.

Efficient – Food is produced in the right variety and in the required amounts to nutritiously feed the world. Little is lost or goes to waste: any food that is not consumed is delivered to those in need, reused to create other products or recycled into other uses, such as compost. Farmers have access to inputs and information tailored to their specific agro-environmental conditions. Government policies positively influence the decision-making of all actors towards common objectives. Land and other resources are used to their full potential. Price volatility is no longer an issue.

Nutritious and healthy – The triple burden of malnutrition – undernourishment, micronutrient deficiencies and over-nutrition – is reduced as everyone has access to nutritious food and follows a healthy diet. Enjoying better nutrition, adults are living longer, healthier lives and children are growing up to reach their full potential. Moreover, food is safe. People have better visibility of the sources and ingredients of the food they buy.

Such a future will not be possible without policy and regulation reform, accounting for externalities, new business model innovation, infrastructure development, massive consumer behaviour changes and technology innovation.

Point technology solutions focused on a specific aspect of food systems might result in imbalances in other areas of food systems. For example, technologies that improve productivity could result in increased post-harvest losses. As such, there is a need for technology innovations that have an impact across the four aspirations mentioned above by changing the shape of demand, promoting value-chain linkages, and creating effective production systems both simultaneously and in a mutually reinforcing manner.

Changing the shape of demand

Several emerging technologies have the potential to shape consumer diets and consumption behaviours in ways that could significantly impact food systems.

Smart appliances and **indoor or urban farming** can enable consumers to eat healthy and affordable home-cooked meals with the convenience of processed ready-prepared foods. Embedded microscopic electronic devices such as **radio-frequency identification** tags and **genetic markers**, as well as **hyperspectral imaging**, could be the barcodes of tomorrow. Used in combination with **mobile phones**, they could put information regarding the authenticity, freshness, ripeness, shelf life and nutritional content of food at people's fingertips. **Advanced analytics**, along with **nutrigenetics**, could allow people to get nutritional advice tailored to their ability to digest certain foods, dietary and health needs, and taste preferences. Connectivity technologies such as **social networks**, **peer-to-peer networks** and **online e-commerce** could provide platforms to significantly influence consumption patterns and increase access to nutritious foods. Aware of the environmental and nutritional implications of the production and consumption of certain foods, consumers may demand that their food meet minimum sustainability and health requirements, information which can be made available to them by **blockchain**. Consumers may switch their diets to **plant-based** or **cell-grown alternatives** or demand that the animals they eat be fed **insect-based proteins**.

Big data and analytics can inform policy decisions and facilitate total-cost accounting that can significantly alter consumer consumption. Additionally, **mobile payments** enabled by **blockchain** could efficiently deliver targeted health and nutrition subsidies, and **social networks** can enable public health campaigns.

Promoting value-chain linkages

Value-chains also stand to benefit – improved collaboration, simplified efficient supply chains and transparency could dramatically improve food systems outcomes.

Farmers could use **mobile services** to obtain valuable pricing information and gain access to markets on both the supply and distribution sides. Combined with **big data and analytics** and **blockchain**, improvements could be seen in financial inclusion for farmers by reducing adjudication costs and lowering cost to serve.

The **Internet of Things** (IoT), in combination with **blockchain**, could enable real-time product tracking to improve food safety and shelf life, dramatically reduce food loss, reduce adulteration and shed light on supply and demand imbalances. **Mobile applications** have the potential to connect consumers with an overabundance of food to those in need while companies could use **advances in science** to reuse food to nourish soil. **Online marketplaces** could link consumers directly to farmers, dramatically simplifying supply chains. Additionally, governments can leverage **big data and advanced analytics** to better understand supply and demand imbalances, forecast the impact of policies on neighbouring countries, and better understand the environmental burden of value-chains.

Creating effective production systems

Sustainably producing the right quantity and quality of food to meet the nutrition demands of the world can be enabled by technologies.

Advanced **precision agriculture** technologies that deploy **machine vision**, **big data analytics** and **advanced robotics** could allow farmers to apply the optimal amount of inputs for each crop and assist with the management of livestock and aquaculture, thereby boosting yields and reducing water use and greenhouse gas emissions.

Gene-editing technologies such as **CRISPR-Cas** could provide a way to achieve multi-trait improvements, producing a step change in productivity while improving the drought resistance and nutritional content of food. **Biological-based crop additives** and **micronutrients** could help reduce and possibly replace chemicals while improving soil quality. And **renewable energy** and energy storage could significantly reduce post-harvest losses and water usage though the electrification of cold-storage and irrigation pumps and allow farmers to improve price realization by being able to store foods.

Interventions beyond technology

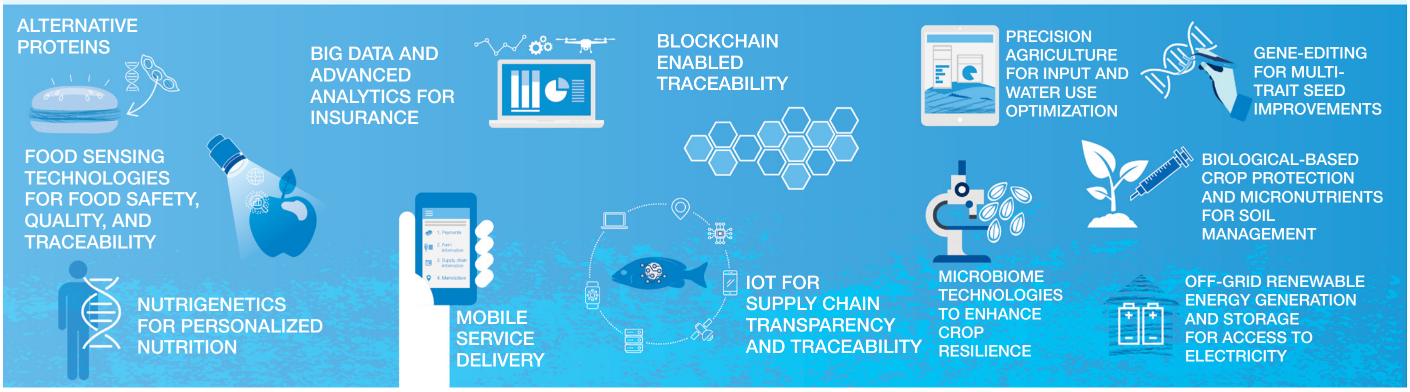
These examples illustrate the impact that innovative technologies could have on food systems. However, transforming food systems requires interventions that go beyond technology innovation. For example, creating new and bold policies that address the true costs of food systems, establishing the infrastructure and investment that allows technology innovations to thrive, influencing consumer behaviours, building trust and transparency, aligning towards common objectives and collaborating across siloes are all required to create the future we want.

The following chapter highlights 12 technologies that hold significant promise for transforming food systems during the next decade and the actions needed to bring them to scale. This selection of technologies illustrates the potential of emerging technologies in food systems.

Exploring the power of the 'Transformative Twelve'

Figure 4: Combinations of 4IR technologies can enable innovation to solve challenges faced in food systems

Changing the shape of demand | Promoting value chain linkages | Creating effective production systems



At scale, technology holds extraordinary potential for solving today's food challenges. At the same time, however, scaling poses challenges and risks that need to be addressed if the technologies are to achieve their full impact. Twelve promising technologies that could significantly impact food systems over the next decade are identified as part of this work and are presented in this section.

These 12 technologies have the potential to:

— Materially impact food systems outcomes across various countries/regions, promoting inclusivity, efficiency, sustainability and nutrition and health
— Deliver impact to stakeholders across food systems, including input manufacturers, farmers, consumers, distributors, processors and the enabling environment (e.g. policy, financing, physical infrastructure and delivery mechanisms)
— Be developed and scaled in both developing and developed countries

These technologies were identified by means of an analytical process that included:

— Systematic scanning and mapping of the landscape to identify the technologies with the greatest potential to disrupt food systems. By combing querying databases, such as PitchBook, as well as industry journals and investment reports, the research team uncovered more than 1,000 unique enterprises working with these technologies in developed and developing countries. These companies have collectively attracted more than $14 billion in investment over the past five years
— Identification of technology applications. The research team identified 140 individual applications of technology across food systems
— Reviewing historic investment data, conducting expert interviews, facilitating various workshops and fielding a survey. These sources helped identify the technology applications that have attracted substantial investment. Some applications are already seeing significant interest from stakeholders across food systems

This is not a definitive, static or comprehensive list, and efforts to scale both supply- and demand-focused solutions are necessary. However, this list is representative of new and exciting market activity. It is evident that many of the technologies are production-focused, which underlines a gap in demand-focused technologies, especially in developing countries. Activity and investment in demand-side innovation should be encouraged to change consumption patterns in both the developed and developing world.

In the following section, we provide a brief overview of the 12 technologies, their estimated impact and what would it take to scale them.

The 'Transformative Twelve' explained

How do these technologies work? What challenges can they solve? How much impact can they have on food systems? What needs to happen for them to scale? What are the potential risks and trade-offs and how can they be addressed or anticipated?

Also important to note, sizing the potential impact of individual technologies is a directional exercise – it is meant to illustrate the possibilities these technologies could hold in transforming food systems. As such, realizing this impact would require significant changes to the status quo and substantive action from all stakeholders. Some of these changes and actions are outlined in the following section. For all details on the impact sizing methodology, please refer to the appendix.

Changing the shape of demand

Alternative proteins

Protein delivery is an important component of a healthy diet. As population growth heads towards 9 billion, we also see a shift in individual diets resulting from affluence and urbanization, resulting in growth in the global demand for animal protein.

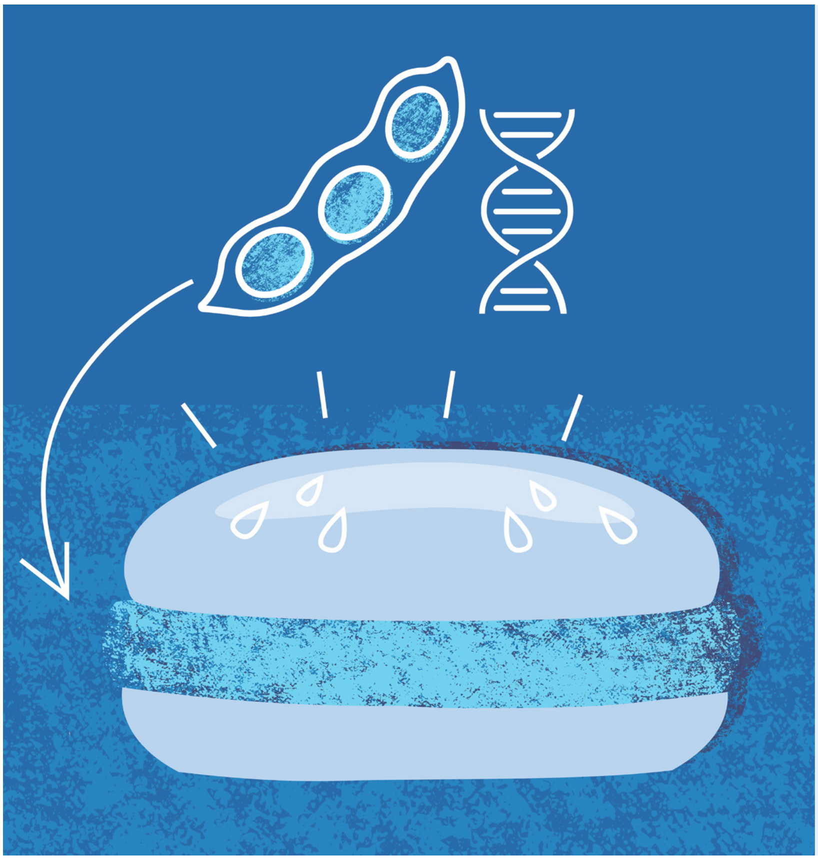
While growth in protein consumption for the malnourished can have positive health outcomes, the increased demand presents pressing environmental challenges: livestock today account for 15% of greenhouse gas emissions,[29] consume 10% of the world's fresh water and use more than one-quarter of the planet's ice-free surface.

In the future, the delivery of safe, affordable and sustainable protein will be critical. Alternative proteins are derived from sources with a smaller environmental footprint such as insects, plants, aquacultures and cell cultures, and offer promising alternatives to traditional proteins used in human, animal, fish and pet consumption.

Estimates suggest that if 10–15% of the global animal protein consumption were replaced with these alternative proteins by 2030, we could see CO_2-equivalent emissions reduced by 550-950 megatonnes and water use reduced by 225–400 billion cubic metres. Moreover, 250–400 million hectares of land would be spared.

To achieve this level of impact, consumer acceptance will be vital in certain food applications. Alternative proteins will need to become commercially available at prices equal to or lower than other proteins and with equal or better nutritional content, taste and texture. Consumer behaviour change will also be a factor; national media campaigns and outreach (e.g. meatless Mondays) could be useful in this regard. Regulations and incentives will be integral to ensure that feed and food are safe for consumption and to promote alternative protein adoption (e.g. regulations could include the full cost of animal protein in product pricing). Finally, alternative proteins should seek to complement more sustainable methods of livestock cultivation (e.g. alternative feeds, sustainable intensification, and new breeds).

Alternative proteins are still in an early stage of adoption and understanding and may come with ancillary implications that require a systems perspective: if they prove popular, they could negatively affect the livelihood of livestock farmers and the economies of countries dependent on livestock highlighting the need to account for trade-offs and externalities associated with this demand shift. Finally, the health implications of the novel processes and ingredients used in some of these products are not yet well understood.



Protix has invented a string of technologies to produce insect-based proteins on an industrial scale. Insect-based proteins are a promising new category of ingredients that can be used in a broad range of applications such as fish feed, livestock feed and food. Insect-based proteins can be produced with a very low carbon footprint and can be produced anywhere in the world due to the innovative and highly controlled production systems using big data, robotics and artificial intelligence.

Impossible Foods has invented a burger that is made entirely of plant-based ingredients but tastes and smells like meat. Technicians insert genes that code for the soy leghaemoglobin protein, which resembles animal protein, into a species of yeast. Feeding the modified yeast sugar and minerals prompts it to replicate and manufacture heme with a fraction of the footprint of field-grown soy. Impossible Foods' fake burger uses a twentieth of the land needed for livestock/cattle, a quarter of the water, and produces only an eighth of the greenhouse gases.

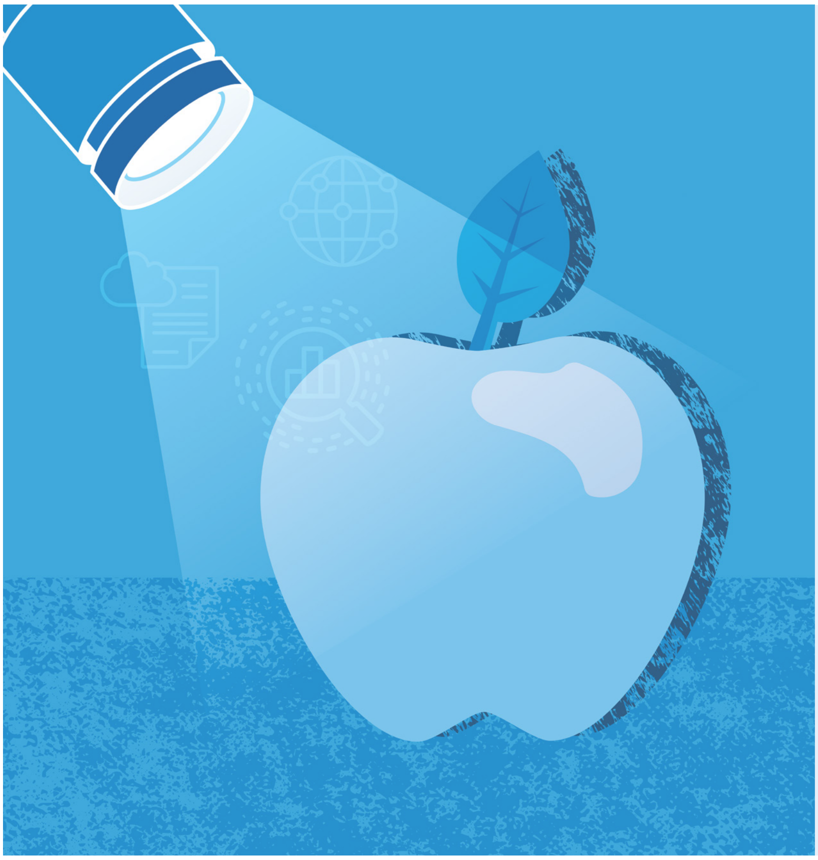
Food sensing technologies for food safety, quality, and traceability

Sensors, such as near-infrared spectrometers and hyperspectral imaging, are increasingly being used to conduct non-destructive analysis of food. This emerging application of technology combines spectroscopy with computer vision. Images are analysed via the cloud using machine learning and imaging-processing algorithms to interpret the data, resulting in actionable information such as quality, safety and authenticity of food. The information generated from scanning technologies can determine the freshness of food and could replace the need for sell-by and use-by dates. The perishability of individual items could be determined, dramatically reducing domestic food waste. If sensing technologies could reach 30-50% of the consumers in developed markets, domestic food waste could decline by 10–20 million tonnes.

Additionally, with incidents of food fraud rising (e.g. 2013's horsemeat scandal in Europe, melamine contamination in milk powders, inter-species fish substitution), these technologies provide an accurate picture of a food item's composition that can determine authenticity. Finally, some believe that the technologies will also be able to identify pathogens, such as listeria, thereby improving food safety and preventing expensive product recalls. These imaging capabilities are not currently available on smartphones. But significant developments in miniaturization of these sensors, and imaging and mobile computing advances, may one day provide consumers with the visibility into the supply chain to understand what it is they are buying, when it will go bad and whether it is contaminated, in real time.

In order to scale sensing technologies, applications will need to first be integrated into industrial and retail environments to drive the mass production of sensors, thereby reducing costs for consumer applications in the longer term. Second, anti-food waste regulations (such as those put into effect in France and Italy in 2016), anti-fraud policies and food safety legislation could provide a rationale for businesses and consumers to adopt this technology. Education and public awareness campaigns could also help in this regard (e.g. improving consumer acceptance with regards to the appearance of food). Large-scale adoption could lead to the emergence of innovative retail models, such as charging for food by nutritional content instead of by weight or quantity.

There are risks associated with the large-scale adoption of sensing technologies, particularly when they are used to screen for pathogens. Thorough testing and validation will be critical for certifying the ability of these technologies to detect the presence of these disease-bearing microorganisms.



ImpactVision aims to build more transparent and secure global food systems using hyperspectral technology. It has developed a software platform that provides real-time insights into the quality and characteristics of different foods non-invasively, using image recognition and predictive learning. The start-up uses third-party hyperspectral sensors to image foods and develops classification software and algorithms to determine characteristics such as the tenderness of meat, the freshness of fish or the presence of foreign objects. This enables the optimization of a product's end use and dynamic pricing. Another application it is developing is for determining avocado ripeness, allowing the fruit to be ripened in select bands and sent to food-service companies much closer to the "ready-to-eat" specification desired. All of these parameters are measured non-invasively and in real time.

Nutrigenetics for personalized nutrition

Nutrigenetics technology identifies how genetic variations affect people's responses to nutrients. Quick and cost-effective DNA analysis is possible because of advances in the understanding of the human genome as well as enhancements in computing and data analytics. The ultimate objective is personalized nutrition – the ability to optimize a person's nutritional intake based on their genetic make-up. Using this technology, nutritionists and doctors will be able to individualize health and diet recommendations, potentially improving the health of consumers.

By 2030, nutrigenetics is likely to affect the dietary choices of consumers in higher-income countries, resulting in those consumers living longer and healthier lives. Additionally, the technology could have a material impact on the overweight population. If it was adopted by 10-15% of the overweight population in higher- and upper middle-income countries, it could reduce the number of overweight people by 25–55 million.

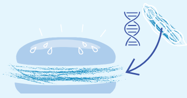
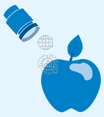
For nutrigenetics to be scaled up, considerable numbers of nutritionists and doctors, and insurers will have to advocate for it. Some consumers may adopt the technology on their own because they are interested in knowing more about their ability to process nutrients. Most consumers, however, will do so only if their healthcare professionals encourage them and if their healthcare insurance plans cover the cost. Additionally, additional uptake could be driven by reduced life-insurance premiums if consumers follow personalized nutrition programmes.

Providing dietary information only provides one part of the solution, however. Expansion also depends on consumers being adequately educated on healthy dietary practices and in food selection and preparation.

Nutrigenetics is still in the early phases of development. The impact of certain genes on absorbing, transporting, storing or metabolizing nutrients is not yet sufficiently understood.

Habit, a personalized nutrition start-up based in San Francisco, provides consumers with personalized food recommendations tailored to their unique DNA. Consumers collect bio-samples and send them to a processing facility. Habit uses the data to provide biology reports and a personalized eating plan via a mobile application. The company also provides one-on-one nutrition coaching.

Figure 5: Summary of impacts by 2030: Changing the shape of demand

	WHAT IF...	THE IMPACT COULD BE...		WHICH IS THE EQUIVALENT OF...	DRIVEN BY...
ALTERNATIVE PROTEINS 	Consumers chose to replace 10-15% of meat (40-60 million tonnes of meat) with alternative proteins by 2030	Reduced GhG emissions Megatonnes of CO_2 Eq.	550-950	5-8% of total agricultural GhG emissions[31]	Reduced emissions from the production of livestock and feed
		Reduced water use Billion cubic metres	225-400	7-12% of total fresh water withdrawn for agriculture[32]	Reduced water from the production of livestock and feed
		Freed land Million hectares	250-400	5-10% of total land use for agriculture[30]	Reduced number of livestock driving increased availability of land
FOOD SENSING TECHNOLOGIES FOR FOOD SAFETY, QUALITY, AND TRACEABILITY 	30-50% of the consumers in developed countries used food scanning to determine expiration dates by 2030	Reduced food waste Millions of tonnes	10-20	5-7% of total food wasted[33]	Reduced domestic food waste from individualized and real-time expiration dates
NUTRIGENETICS FOR PERSONALIZED NUTRITION 	10-15% of the overweight population (250-370 million people) followed personalized nutrition plans by 2030	Reduced overweight population Millions of people	25-55	1-2% of the total global overweight population[34]	Reduced number of overweight from tailored and individualized nutrition and diets

Promoting value-chain linkages

Mobile service delivery

The expansion of digital infrastructure and mobile technologies is vital for reaching agricultural development goals. Digital tools and services delivered on mobile phones include:

- Access to improved financial services – mobile payments and financing
- Provisioning of agricultural information – farm-level information and helplines
- Improved visibility into supply-chain efficiency – traceability and tracking, supplier and distribution management
- Enhanced access to markets – trading, tendering and bartering platforms

For example, mobile technologies allow farmers to make and receive payments, access loans, obtain tailored information on seed and input selection and availability, better receive weather forecasts, gain optimum farming practices through information and hotlines and improve negotiation leverage at the time of sale. Mobile payments can also enable governments to provide targeted subsidies to farmers.

If approximately 275-350 million farms gain access to mobile-based services by 2030, 250–500 million more tonnes of food could be produced and 20–65 million fewer tonnes of food lost. The total additional income would be $100-200 billion, an increase of 3–6% of the total production value. The environmental impacts would also be considerable: 50-100 fewer megatonnes of CO_2-equivalent and 40–100 billion cubic metres less water use.

Achieving results of this magnitude requires basic agricultural infrastructure, farmer education and trainning and low-cost solution. Access to inputs, mobile phones, broadband connectivity, post-harvest storage and transport infrastructure is necessary to ensure that farmers can make use of the insights and information available. Farmers also need training and ongoing support to maximize their ability to use the services as well as increase retention rates. To expand quickly, services would need to be affordable or free.

If mobile delivery is not scaled comprehensively, illiterate farmers – that is, those in greatest need – could be excluded. Areas lacking basic agricultural infrastructure and data availability could be left out as well – an area in which governments could help.

Reuters Market Light's (RML) decision-support technology uses a mobile app to provide farmers with personalized agricultural data analytics for the entire growing cycle, from pre-sowing to post-harvest. RML's solution provides information on more than 450 crop varieties and more than 1,300 markets. Farmers can receive support in their local language from call centers and remote intervention by SMS, voice and mobile applications. Farmers using this mobile service have seen income improvements estimated at between 8 and 25%.

Big data and advanced analytics for insurance

Data-collection technologies, computing power and algorithms are lowering the costs of collecting and processing data. Harnessing the power of big data and analytics, financial institutions can lower transaction costs (through reduced need for field inspections) and mitigate agriculture-specific risks. For both index and conventional insurance applications, big data derived from current and new sources (e.g. crowdsourcing, cellphone apps, satellite and radar-based imaging and drone-based imaging) can be used to improve modelling and reduce the risks of providing insurance products to farmers. Studies show that, in addition to providing a safety net, farmers' adoption of insurance products has a positive impact on investments, efficiency, nutrition and income.

By 2030, insurance solutions could be provided to approximately 200–300 million farmers worldwide. This could generate 40–150 million tonnes of additional food and $15–70 billion in additional farming income. Indirectly, farmers would benefit from improved nutrition and health. In fact, studies show that households facing severe environmental conditions will not refrain from having proper meals when income is guaranteed by some form of insurance.[35]

Low-cost methods for aggregating and collecting data will be essential for scaling insurance solutions quickly. Improved access to information and education will be important factors in enabling farmers to make better decisions about what products are available to them and how payments work. However, access to insurance on its own is not enough. Farmers will also need access to inputs, infrastructure and services to take full advantage of these products. One potential benefit is the increased willingness of farmers to take risks, whether that means increasing farm investments, trying new inputs or implementing innovative farming practices.

Scaling insurance products, however, has associated risks. Index insurance relies on accurate agronomic models to determine the payouts to farmers; if the data they are based on is inaccurate, insurers' costs can soar. In addition, if farmers use inputs without the proper training, it may potentially lead to negative impacts. Typical insurance programmes are aimed at specific crops, livestock or fisheries that can act to influence farmers in producing those insured items, reducing the incentive to diversify. Finally, insurance may discourage investments in vital on-farm infrastructure. For example, insurance products aimed at rain-fed regions may reduce the investments in irrigation infrastructure.

Launched in 2014, Mobbisurance offers crop insurance and market access to smallholder farmers. The South African start-up gives farmers the ability to sign up through their mobile phones. Mobbisurance then monitors their crops and the weather using satellites owned by NASA and the European Space Agency, to which it has access via a partnership with the South African National Space Agency.

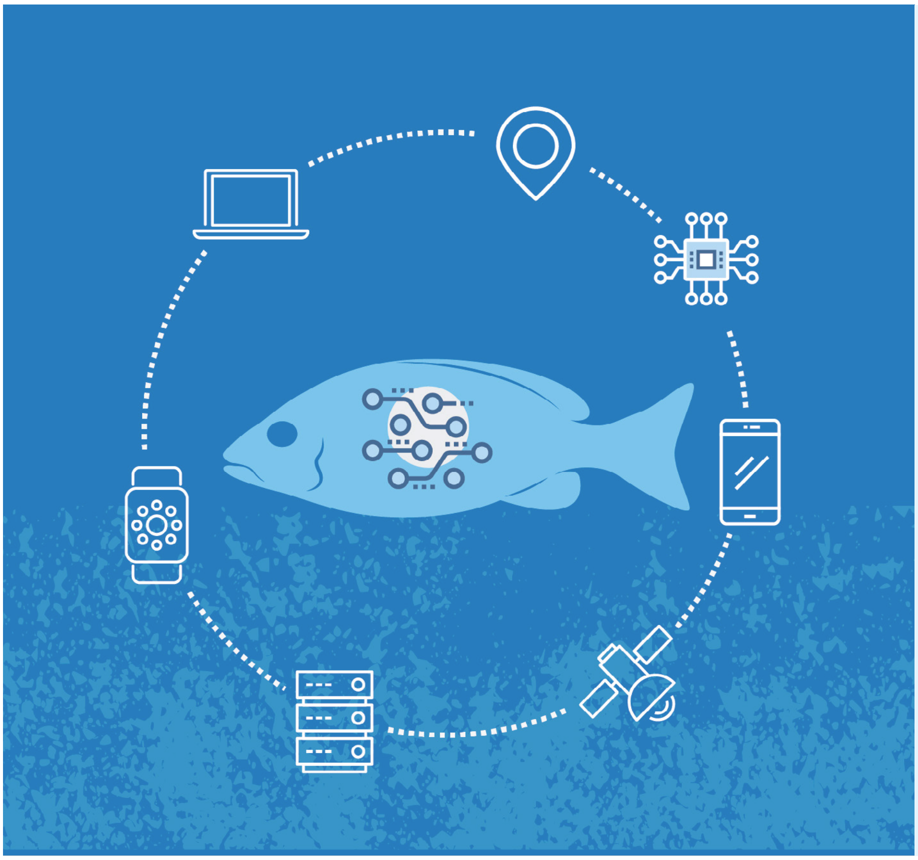
Internet of Things for real-time supply-chain transparency and traceability

Transparent and traceable supply chains are critical for advancing the world's food systems. The Internet of Things, which relies on sensors and actuators connected by networks to computing systems, makes it possible to track the trajectory of products through supply chains and control the transportation and storage environments (e.g. temperature, humidity, gas) in real time. Thus, companies can optimize the environmental conditions of food transportation. The data generated could also provide an opportunity to better match supply and demand while ensuring that sourcing is ethical and sustainable. At the same time, the Internet of Things can provide consumers with nutritional and environmental information about the food they purchase. From farm to fork, details about a product's provenance, environmental impact and more will become available, not only at the generic level but also for specific items.[36]

If the internet of things was implemented in 50-75% of developed countries' supply chains by 2030, 10–50 million fewer tonnes of food will be lost in distribution.

To unlock this potential, all members of the supply chain need to be persuaded to help improve transparency and traceability. Ensuring such traceability starts at the farm will require sensors that are affordable for farmers. To get corporations to participate, it will be important to define the type and amount of information to be shared. Additionally, consumers can use social media to launch major transparency and traceability campaigns, which will likely influence other parts of the supply chain in adopting these technologies.

Transparency and traceability also have risks. In a world where consumers demand transparency, companies that fail to make this a priority could see their reputations damaged. Over-reliance on automated, data-driven systems could also lead to large losses in the case of a technological glitch.



Verigo offers food-monitoring hardware devices, a cloud-based platform and a mobile app to customers across the value-chain. The system provides actionable information that is needed to minimize losses in the supply chain and maximize the final quality of products. A range of sensors are available that can track temperature, humidity, product life and more. The information is sent to the cloud and can be seen in real time from any location, allowing customers to track their products in the value-chain.

Blockchain enabled traceability

Blockchain, a type of distributed ledger technology, can serve a multitude of roles in food systems such as reducing transaction costs and the time needed to process payments, and tracking land tenure.[37] Most pertinent for this discussion, blockchain can be used to monitor information about food moving through the supply chain. This is important because the technology makes it impossible for the information to be censored or tampered with by supply-chain participants. As a result, farmers, manufacturers and retailers can justify premiums for certain products and consumers can be more confident about the source and quality of their food.

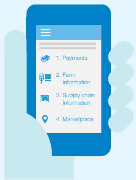
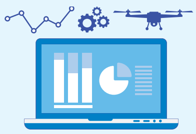
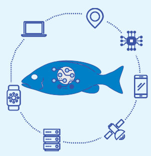
It is difficult to estimate the impact of blockchain on food systems. However, for the supply chains it reaches, it is likely to reduce food fraud, stop illegal production such as production on deforested lands, reduce food-borne illness through quicker response times, and reduce recalls and losses by tracking individual items as opposed to batches. In a similar way to food-sensing technologies, blockchain could affect domestic food waste by providing consumers with individualized perishability dates. If blockchain were to monitor the information in half of the world's supply chains, efficiency gain could lead to a reduction in food loss by 10-30 million tonnes.

To achieve blockchain's potential, more computing power needs to be unleashed. One main concern about blockchain is its ability to scale while remaining secure. In fact, all nodes (computers) in the blockchain network must process transactions one at a time – the more transactions in a blockchain, the more computing is required at every single node. Therefore, as blockchains grow, fewer and fewer nodes have the computing power required to process the volumes of transactions, driving centralization of computing and potentially compromising the network's trust. Additionally, adopting blockchain solutions requires investment in basic infrastructure such as reliable electricity and high bandwidth communications. Otherwise, a power outage could cause them to stall in the middle of the verification process.

Although standard blockchain protocols for the agriculture industry may be premature, it is important to keep an eye on them. Knowing what these standards will look like may prevent different organizations from developing incompatible systems. Additionally, given the tremendous computing power required to run blockchain systems, there may be negative environmental effects of its use.[38]

Since October 2016, IBM and Walmart have worked together on a pilot study to demonstrate the benefits of tracing food products on blockchain. It was demonstrated that tracking information using blockchain could be done in 2.2 seconds – a process that would take almost seven days using previous methods. This process will help reduce response times when contaminated foods are discovered as well as make it possible to perform selective recalls.

Figure 6: Summary of impacts by 2030: Promoting value-chain linkages

	WHAT IF...	THE IMPACT COULD BE...		WHICH IS THE EQUIVALENT OF...	DRIVEN BY...
MOBILE SERVICE DELIVERY 	**70-90% of farms in developing countries (275-350 million)** used mobile applications by 2030	Increased income Billions of dollars	100-200	3-6% of the total agricultural production value[39]	Access to financial payments, agricultural information, increased price from enhanced market access
		Increased yields Millions of tonnes	250-500	3-6% of the total agricultural production[40]	Access to information to improve farming practices, resource management, and choice of inputs and seeds
		Reduced food loss Millions of tonnes	20-65	2-5% of total food losses[41]	Better farmer-trader coordination and access to information (e.g. farmer helplines)
		Reduced GhG emissions Megatonnes CO_2 eq.	50-100	0-1% of total agricultural GhG emissions[42]	Increased access to agricultural information for better decision making
		Reduced water use Billions of cubic metres	40-100	1-3% of total fresh water withdrawn for agriculture[43]	
BIG DATA AND ADVANCED ANALYTICS FOR INSURANCE 	**50-75% of all farm holdings** without insurance opted into insurance (200-300 million holdings) by 2030	Increased income Billions of dollars	15-70	0-2% of the total agricultural production value[39]	Increased willingness to take risk, experiment with new methods and technologies and diversify crops
		Increased yields Millions of tonnes	40-150	1-2% of the total agricultural production[40]	
IOT FOR REAL-TIME SUPPLY CHAIN TRANSPARENCY AND TRACEABILITY 	**50-75% of supply chains in developed countries** were controlled by IoT	Reduced food loss Millions of tonnes	10-50	1-4% of total food losses[41]	Improved ability to manage environmental conditions of transportation in real-time (e.g. temperature, humidity, gas) and better shelf-life management
BLOCKCHAIN ENABLED TRACEABILITY 	**Half of the world's supply chains were tracked** by blockchain	Reduced food loss Millions of tonnes	10-30	1-2% of total food losses[41]	Improved value-chain efficiency driven by improved collaboration and data visibility

Creating effective production systems

Precision agriculture for input and water use optimization

Farmers are constantly forced to make crucial decisions based on countless variables. All too often, they don't make the best decisions, and this leads to suboptimal results. Precision agriculture offers a way to address this challenge. Deploying information technology, automation, robotics and decision-support technologies, precision agriculture takes the guesswork out of input use, irrigation, livestock management and fishery operations, making farming more efficient, profitable and sustainable.

By 2030, precision agriculture could benefit 80–150 million farmers, mostly on large and midsize farms (see "Mobile service delivery" for more on small farm decision support). The production and environmental results would be substantial: 100-300 million tonnes more crops produced and 5-20 less megatonnes of CO_2-equivalent emitted. Farmers could see costs drop by \$40–100 billion. At the same time, water use could decrease by 50-180 billion cubic metres.[44]

These results depend on farmers having access to precise remote sensing data (e.g. satellite or drone imagery) as well as machine vision and advanced robotics technologies. At the same time, regulations that protect data privacy need to be in place. For this technology to benefit small farmers, companies and governments will have to deploy versions of precision agriculture which are appropriate for their conditions – sharing economy models could provide a viable solution to reducing the costs of accessing this technology.

Although precision agriculture offers considerable benefits, it has some attendant risks. Automating decision-making could lead to farms not requiring human labour. Moreover, data ownership could provide unfair advantages in a market that is extremely fragmented.

Farmers Edge is one of a growing number of big data players in the agriculture sector, offering farmers precision agriculture tools to help them make daily farm management decisions, such as when to apply inputs. They use data sources that include weather stations, satellite imaging and tractor GPS to provide manageable field-level insights to farmers in real time.

Gene editing for multi-trait seed improvements

Historically, there have been three ways to improve seeds: open pollination, hybridity and genetic modification. There is now a fourth: genome editing (or gene editing). Modern biotechnologies involving the modification of genetic materials are controversial, however.

Like open pollinated and hybrid breeding, gene editing manipulates genes, though more efficiently and precisely. It typically exploits the vast diversity of genes that exist within a plant species. In this sense, it differs from gene modification that can introduce traits from other species. This results in crops that are less vulnerable to drought, pests and disease, and food that is more nutritious, with substantially lowered costs and development time.

Gene editing offers the opportunity for substantial improvements in yield, environmental and nutritional outcomes. If gene-edited seeds were adopted by 60-100 million farms by 2030, there could be 100–400 million tonnes more crops produced and 5–20 million fewer tonnes of production lost annually. Farmers' incomes would grow by $40–100 billion and nutrition would improve for 20–100 million people that are micronutrient deficient.

To realize this potential, there are still scientific hurdles to achieve the anticipated multi-trait modifications at low costs and development time. An effective regulatory and registration process for new seeds is also needed. To have broad product development across many crops and meeting the needs of smallholder farmers as well as commercial farmers, decentralized ownership of the enabling technologies is needed. Innovative governance models and technology transfer mechanisms should be explored. And, equally important, farmers would need to have both access to the genetically edited seeds and proper training on how to use them.

That said, gene editing has its attendant risks. First, given the transaction costs of serving small-scale farms, seed innovation is likely to be geared first towards developed countries and small farms run the risk of being left out. Second, the concentration of intellectual property in relatively few hands could create economic oligopolies or monopolies that would limit the technology's use to only a few types of seeds. This could result in less biodiversity. Third, if used irresponsibly, gene editing could present risks to human health and environmental biodiversity. Greater research and public dialogue is crucial for managing all of these risks and ensuring fair distribution and accessibility for smallholders to such innovations.

CRISPR-Cas is a molecular defence mechanism found in bacteria. Scientists have found a way to use this mechanism to direct enzymes to cut DNA.

This gene-editing technology has enabled companies such as Caribou Biosciences to develop crops that are resistant to drought and disease and food that is healthier and more nutritious.

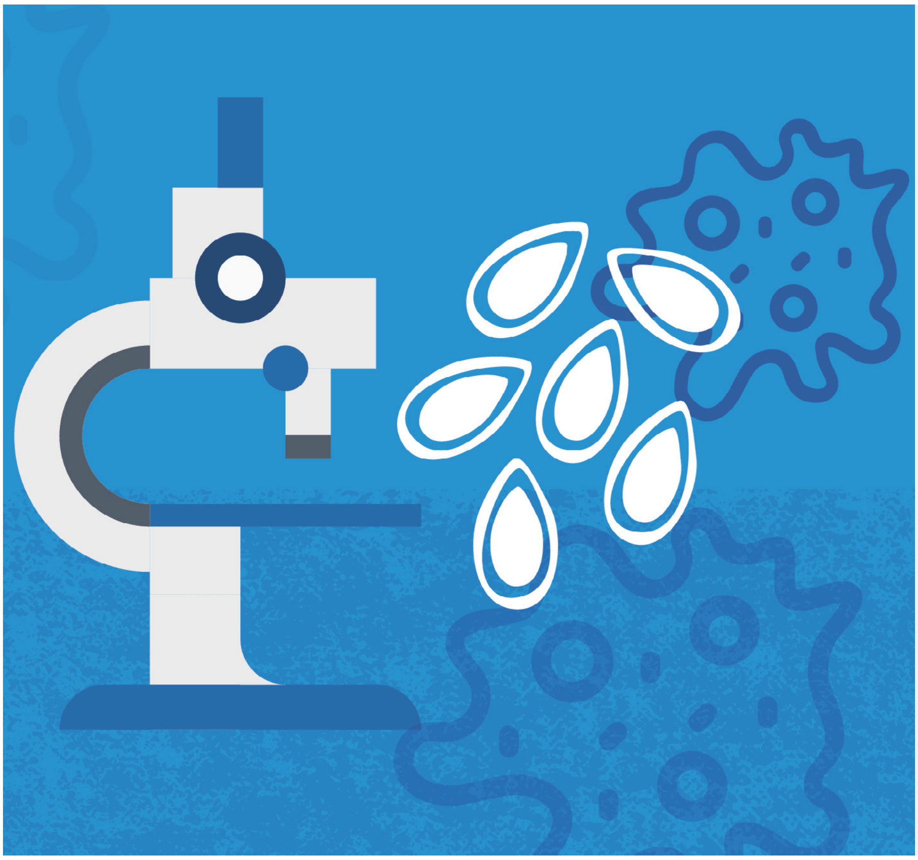
Microbiome technologies to enhance crop resilience

The human microbiome has opened new frontiers in human medicine. Likewise, the plant microbiome – the environment of microorganisms in and around the roots, in the soil, on the leaves and within the plant itself – has the potential to change modern agriculture. When applied directly to the surface of seeds and to plants themselves, microbiome technologies can complement or replace chemical agriculture products. The results are impressive: abundant, healthier crops that are more resistant to droughts, low nitrogen, high temperatures, salty soils and harmful insects.

Companies are now trying to identify the organisms that are most beneficial in different environments and to create products based on them. If 120–150 million farmers were to purchase seeds coated with microbes by 2030, 130–250 million more tonnes of crops could be produced and 5-20 million fewer tonnes of food lost. At the same time, reducing the use of fertilizer could result in reduced emissions of 15-30 megatonnes of CO_2-equivalent and farmers' could see their income rise by $60-100 billion.

To realize this potential, continued advancement will be needed in the methods for analysing agro-ecological conditions and in creating products for specific contexts. Moreover, the regulatory and registration process for agricultural inputs will require streamlining. And last-mile supply-chain operations for the production and distribution of coated seeds and live cultures will need to become more efficient. A mechanism to share intellectual property more broadly, so that more organisations are doing research and developing products, would promote the development of applications for the needs of smallholder farmers. And, again, farmers would need to have access to the seeds and proper training on how to use them.

More research is needed to better understand the effects of microbiomes on the environment as well as on nutrition and health. However, it is worth noting that microbes are already present everywhere in the environment and in the food supply.



Indigo's work focuses on beneficial microbes – the bacteria, viruses and fungi that naturally coexist with plants. Some of these microbes work with plants, helping them overcome typical stresses during the growing season. Indigo's technology screens samples to identify beneficial microbes, which it then develops into a seed coating. Indigo launched its first product, a treatment for cotton plants, last year. Since then, it has brought to the market microbial products for corn, wheat, soybeans and rice.

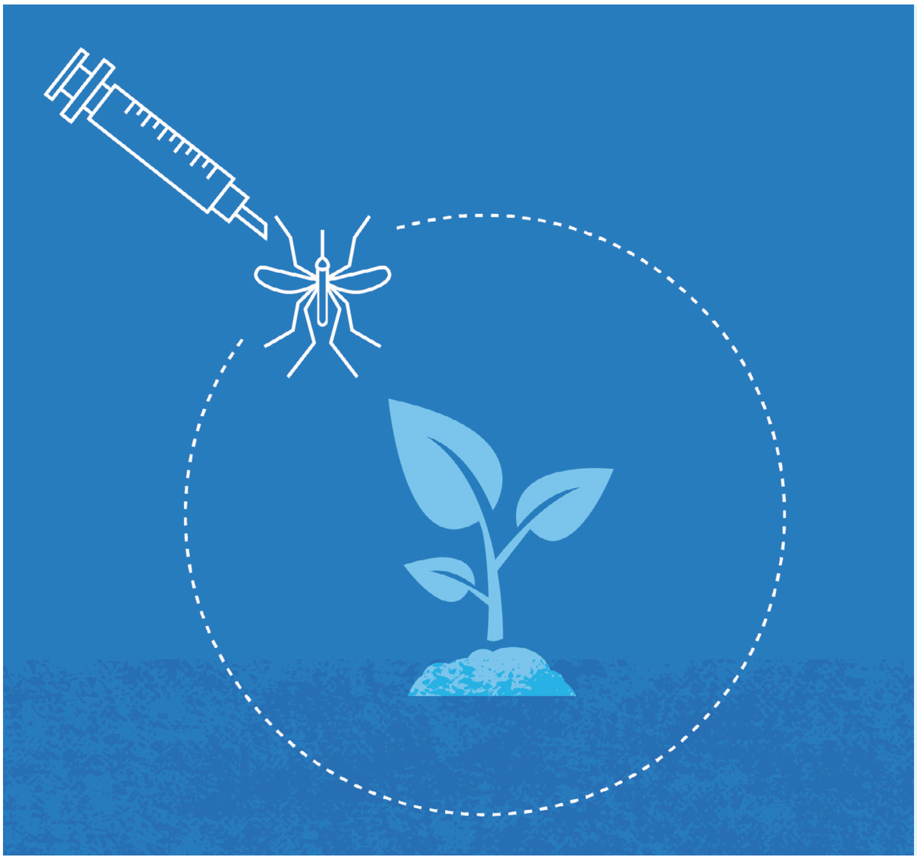
Biological-based crop protection and micronutrients for soil management

Biological-based crop protection and micronutrients address the environmental challenges of using chemicals and of growing plants in soils degraded by poor agricultural practices. They include: bio-pesticides (including pheromones), crop-enhancement inputs and micronutrient soil additives. Bio-pesticides actively eliminate pests such as weeds, mildew and insects, and prevent diseases. They are derived from microbials and biochemicals. Crop-enhancement inputs improve a plant's ability to assimilate nutrients by evoking physiological benefits. Micronutrients are soil additives designed to increase soil fertility.

If 15–50 million farmers used biologicals and micronutrients by 2030, 10–50 million more tonnes of crops could be produced and emission could reduce by 1-5 megatonnes of CO_2-equivalent, mostly driven by improved soil nutrients. The use of biological products could significantly improve the health of farmers and the safety of food by reducing their exposure to pesticides and herbicides.

This level of impact would require more start-up activity and greater investment in R&D. In addition, consumer preferences would need to shift to biologics. Equally important, biological crop protection applications would have to be developed to meet the specific agro-environmental needs of the developing world. Farmers would require proper training to use these products safely. Innovative regulation and disease-response methods, such as crowdsourced surveillance systems, would be helpful for tracking pest or disease outbreaks. Combined with on-farm data analytics (e.g. mobile-phone image recognition), they could further prevent outbreaks.

Biologicals, like other technologies, have their risks. The manipulation of bacteria and viruses could lead to health scares. Additionally, a thorough understanding of biologicals' spillover effects (e.g. their impact on bees) is essential for limiting the loss of biodiversity.



AgBiTech produces a naturally occurring nucleopolyhedrovirus (NPV) that targets Helicoverpa armigera caterpillars (aka cotton bollworm) on an industrial scale. As one of the most serious agricultural pests, the caterpillars affect a wide range of crops including soybeans, corn, cotton, tomatoes, sweetcorn and sorghum. To produce NPV, AgBiTech develops insect viruses in vivo. This involves the mass rearing of insects and infecting larvae to produce the virus. AgBiTech then uses the larvae as an ingredient in its bio-pesticide.

Off-grid renewable energy generation and storage for access to electricity

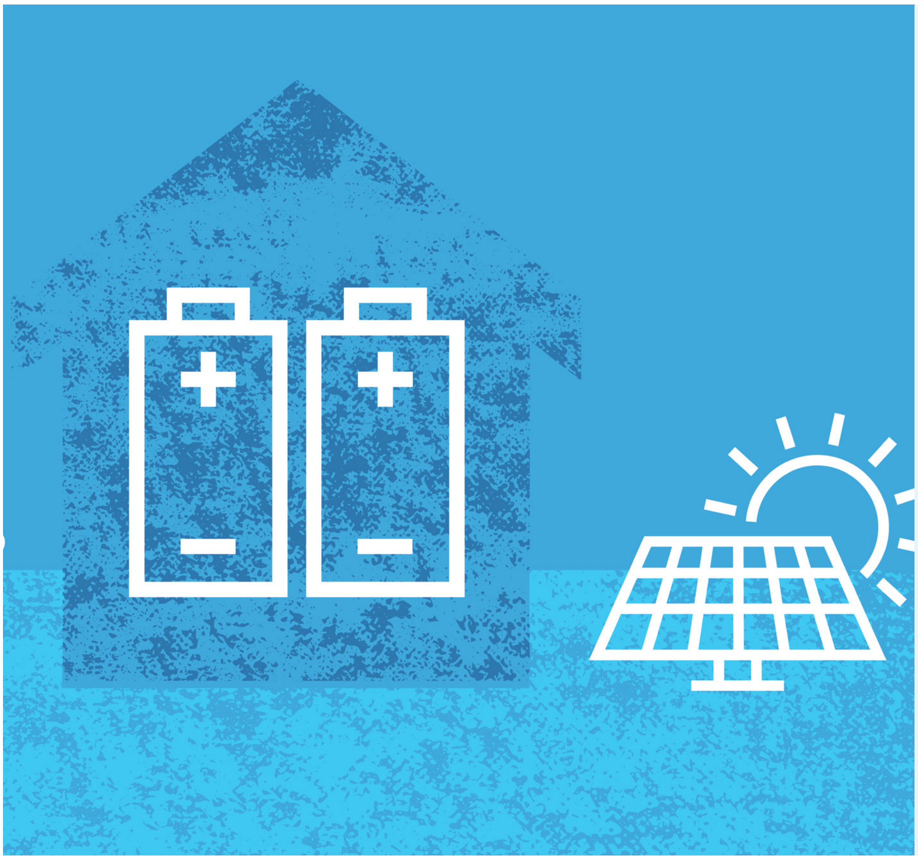
Energy is needed across food systems in the production of crops, fish, livestock and forestry products; in post-harvest operations; in food storage and processing; in food transport and distribution; and in food preparation. Off-grid renewable electrification that uses solar energy provides a sustainable alternative for diesel- and gasoline/petrol-fuelled mini-grid and off-grid generation systems.

In recent years, the renewable energy technologies and battery storage systems that power off-grid systems have advanced rapidly, with quality rising and costs declining. If renewable energy and energy storage were accessible for 50–75% of farms who lack access to electricity (approximately 100-150 million farms), access to cold storage could spare 10-15 million tonnes of food lost and increase farmer incomes by $20-100 billion. Moreover, irrigation systems could reduce water use by 150-250 cubic metres and increase food production by 300-530 million tonnes.

Several factors will be critical for realizing this level of impact. Renewable energy and battery storage technologies must continue to advance and their associated costs must continue to decline. For end-users and companies, the upfront costs of off-grid clean energy technologies are often larger than fossil fuel alternatives even when there are long term economic benefits. Pay-as-you-go mechanisms, made feasible by mobile technologies, make renewables more affordable. Since energy systems tend to be expensive, quality assured products and standards are essential.

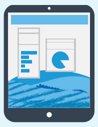
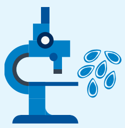
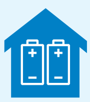
Additionally, it is important to have a good understanding of the total life cycle costs of each renewable application because there are cases where the environmental costs of producing these systems may be greater than the gains from using them on-field.

Renewable energy and storage technologies have tremendous potential, especially for developing countries in Africa and Asia. If the cost issues can be addressed, both people and the environment will benefit.



Cold storage is in short supply for small farmers in India. Because some 10 million tonnes of cold storage capacity is lacking, more than 30% of perishable produce goes to waste each year. Existing facilities are accessible only to large-scale farmers and intermediaries. They hoard when supplies of produce peak, which leads to huge price fluctuations. Meanwhile, the bottom of the pyramid, i.e. small farmers, lose out because they are forced to sell their produce at very low prices immediately after the harvest. To remedy this situation, Ecozen developed micro cold storage, a solar-powered cold storage system. After two years of use, small-scale farmers can see an increase in profits of more than 40%. This innovative product can be adapted for local conditions across the world.

Figure 7: Summary of impacts by 2030: Creating effective production systems

	WHAT IF...	THE IMPACT COULD BE...		WHICH IS THE EQUIVALENT OF...	DRIVEN BY...
PRECISION AGRICULTURE FOR INPUT AND WATER USE OPTIMIZATION 	15-25% of all farms (80-150 million farms) adopted precision agriculture by 2030	Reduced costs Billions of dollars	40-100	1-4% of total costs incurred by farmers[45]	Input use optimization and machinery use optimization
		Increased yields Millions of tonnes	100-300	1-4% of the total agricultural production[46]	Improved seeding and optimized use of inputs
		Reduced GhG emissions Megatonnes of CO_2 eq.	5-20	0-1% total agricultural GhG emissions[47]	Optimized use of inputs reduces the amount applied and runoffs
		Reduced water use Billions of cubic metres	50-180	2-5% of the total fresh water withdrawn for agriculture[48]	Optimized water use from improved irrigation systems and field visibility
GENE-EDITING FOR MULTI-TRAIT SEED IMPROVEMENTS 	10-15% of farms (60-100 million farms) chose to use gene-edited seeds by 2030	Increased income Billions of dollars	40-100	1-2% of the total agricultural production value[49]	Increased yield, and reduced loss from drought, pest and disease
		Increased yields Millions of tonnes	100-400	1-5% of the total agricultural production[46]	Increased yield from improved seed genotype
		Reduced food loss Millions of tonnes	5-20	1-2% of total food losses[50]	Increased crop resilience to pest, disease and drought
		Reduced micronutrient def. Million people	20-100	1-5% of total people in a state of malnutrition[51]	Ability to biofortify seeds and crops
MICROBIOME TECHNOLOGIES TO ENHANCE CROP RESILIENCE 	20-25% of farms (120-150 million farms) chose to use microbiome technologies by 2030	Increased income Billions of dollars	60-100	2-3% of the total agricultural production value[49]	Increased yield and reduced loss due from drought, pest and disease
		Increased yields Millions of tonnes	130-250	2-3% of the total agricultural production[46]	Improved plant ability to assimilate nutrients
		Reduced food loss Millions of tonnes	5-20	1-2% of total food losses[50]	Increased crop resilience to pest, disease and drought
		Reduced GhG emissions Megatonnes of CO_2 eq.	15-30	0-1% of total agricultural GhG emissions[47]	Improved crop ability to assimilate nutrients
BIOLOGICAL-BASED CROP PROTECTION AND MICRO-NUTRIENTS FOR SOIL MANAGEMENT 	5-10% of farms (15-50 million farms) used biologicals and micronutrients by 2030	Increased yields Millions of tonnes	10-50	0-1% of the total agricultural production[46]	Improved crop health leading to increased yields from the use of micronutrients
		Reduced GhG emissions Megatonnes of CO_2 eq.	1-5	0-1% of total agricultural GhG emissions[47]	Reduced use of fertilizers from the use of micronutrients
OFF-GRID RENEWABLE ENERGY GENERATION AND STORAGE FOR ACCESS TO ELECTRICITY 	50-75% of farms currently unable to access electricity (100-150 million farms) gained access to off-grid renewable electricity by 2030	Increased income Billions of dollars	20-100	1-3% of total agricultural production value[49]	Increased access to cold storage allowing farmers to improve price realization at time of sale
		Increased yields Millions of tonnes	300-530	4-7% of the total agricultural production[46]	Access to efficient irrigation systems reducing the amount of water wasted
		Reduced food loss Millions of tonnes	10-15	0-1% of total food losses[50]	Access to cold storage increasing product shelf-life
		Reduced water use Billions of cubic metres	150-250	4-8% of the total fresh water withdrawn for agriculture[48]	Access to efficient irrigation systems reducing the amount of water wasted (e.g. drip irrigation)

Scaling technology innovations

The challenge of scaling technology solutions in food systems

Food and agriculture systems, particularly in emerging markets, are decades behind several other industries on the technology adoption curve. It is extremely difficult to scale innovations because of the fragmented nature of the production landscape in emerging markets, customers' ability and willingness to pay, operational complexities and government interventions in markets to address the food security imperative.

In the case of technologies, the challenges are even greater because development and commercialization can be long, complicated and risky. It requires translating technology innovations into offerings that meet the needs of different types of customers, creating consumer and grower demand, navigating intellectual property regulations, finding upstream and downstream supply-chain partners and acquiring retailing talent with the right technological and managerial skills. Lack of incubation support and barriers to financing across the growth phases (from early-stage seed funding to patient growth capital) make it challenging to meet these imperatives.

Even if these challenges are resolved, it is hard to make these technology innovations ubiquitous. Very few companies developing innovative technologies can single-handedly have a material impact on the desired outcome – inclusive, sustainable, efficient, and nutritious and healthy food systems. More likely, a multitude of organizations from the public and social sectors are needed to replicate the success of the technology innovators in other regions and value-chains.

Not surprisingly, many food systems technology innovations either fail to see the light of the day or reach any meaningful scale. According to the Kaufmann Foundation, only 1.1% of technology innovations across all sectors expand[52]. Our research suggests that food systems-focused technology innovations are experiencing a similar trend. Many innovative technology companies that started five years ago no longer exist.

Given these realities, all stakeholders – private sector, public sector, international organizations, non-profits, and donor and investment funds – need to make a concerted effort to scale innovative technologies with the potential to have a positive impact on food systems.

Innovation ecosystems support the development and scale of technologies

Crucial to scaling food systems technology innovations is the "innovation ecosystem" – an environment that enables innovators to engage in iterative processes with the goal of generating solutions for local challenges and scaling them up.

Key enablers to creating such an environment include:

- Access to flexible forms of capital from start-up to scale
- Technology and economic infrastructure
- Managerial and technical talent
- Assistance on technology and business model development
- Business support services
- Enabling policies and regulations
- A diverse mix of institutions – academic institutions, business incubators, governments, philanthropic actors, private enterprises

The key to developing an innovation ecosystem is to determine the most pressing development and commercialization challenges in any given market and the conditions that need to be met to resolve them.

Technology innovators, on their own, are often unable to navigate these complexities. The public and social sectors can play a significant role in this regard. Universities, public research centers, government agencies, philanthropic foundations, and bilateral and multilateral agencies can all contribute the necessary knowledge and resources.

When it comes to creating innovation ecosystems, developed countries are generally at an advantage because they tend to have deeper banks of scientific knowledge, stronger enablers of high-growth entrepreneurship, larger pools of capital and more extensive support networks than developing countries. Technology innovation ecosystems, therefore, should be set up so that developed and developing countries can share assets. North-South and South-South exchanges will be crucial.

Scaling technologies, however, requires more than just providing support to individual innovators. Support structures need to be put in place to enable smallholder farmers to adopt the new technologies. Investments in basic agricultural and technology infrastructure (roads and bridges, storage and broadband or connectivity, respectively) as well as last-mile infrastructure are essential. Tax and regulatory policies are also critically important. Policies that curb harmful practices could spark major shifts in the way food is produced, handled, purchased and consumed and, subsequently, drive innovation.

An innovation ecosystem should be able to provide support in three key areas:

— **Encouraging technology and business model innovation:** Important to overcoming the challenges of creating and bringing products to market, technology innovators need to be nurtured in the early ideation and prototyping stages. More patient capital and blended financing models are essential, as is tailored support in a range of areas – from technical expertise to help in navigating intellectual property protection.

  Numerous actions are needed to promote technology and business model innovation. It is important to build deep internal expertise and tailored networks of advisers and mentors. It is also important to establish innovation labs and/or market spaces to support product development, business models, financing and networking all under one roof. Similarly, innovation labs and experimental farms can be set up to provide entrepreneurs with a safe and confined space to test and learn in real conditions. Innovators that need to test their solutions in the field should be linked to organizations with strong community connections. Financing in the form of patient seed capital and loan guarantees is crucial, as is support in navigating the regulatory environment.

— **Scaling ideas in markets:** The types of support needed to achieve scale will evolve over time. It may begin with just one firm that can provide access to financing and grow to include networks that can help address broader bottlenecks. Such networks can help with commercialization, consumer education, infrastructure development, and policy and regulatory changes. Designing space for pre-competitive models that combine core competencies of diverse institutions to scale impact, as well as support the growth of business models that share benefits and economic inclusion across agricultural value-chains, will be equally important.

  More specifically, providing technical assistance and management support tailored to the needs of emerging markets is essential. Also important is supporting the growth of organizations that provide distribution, sales, marketing and after-sales service. Supporting innovative grower financing vehicles for large-ticket technologies will be crucial in addressing financing challenges. The adoption of quality standards should also be encouraged.

— **Expanding into multiple markets:** Replication of technology solutions outside the original market requires transferring technology and business model expertise from successful innovators to established businesses and/or to other innovators. It also requires building up the supply chain. Equally important, it requires the creation of supporting infrastructure, policies and regulatory environment.

  To make such expansion possible, technology innovators will require help in identifying the right path to bring forward their breakthrough technologies. They will also need platforms and networks to facilitate productive connections with other entrepreneurs and established enterprises. Support in navigating issues ranging from patenting technology to negotiating transfer agreements will also be crucial.

In 2016, the United Nations World Food Programme (WFP) launched the WFP Innovation Accelerator. Based in Munich, Germany, the Accelerator identifies, nurtures and scales bold solutions to hunger globally. It helps WFP intrapreneurs and external start-ups and companies by providing financial support, access to a network of experts and a global field reach.

The Accelerator believes that the way forward in the fight against hunger lies in identifying and testing solutions in an agile way. It is a space where the world can find out what works and what doesn't in addressing hunger – a place where bold ideas can be tested.

Accelerating the pace of change by promoting complementary and aligned innovations

Technological interventions introduced in isolation run the risks of failing or having little systemic impact. By contrast, multiple complementary and aligned technological interventions can have a bigger impact while solving various challenges simultaneously. For example, mobile service delivery can provide farmers with access to bank accounts. But when combined with big data and analytics for insurance, as well as blockchain, it can provide farmers with a solution for payments, insurance and financing simultaneously. Similarly, mobile service delivery to provide farmers with agricultural information can on its own incrementally impact the system. Combined with access to gene-edited seeds or biological-based crop protection, it can generate much more meaningful impact. Put all four of the applications together and farmers are now able to finance the purchase of seeds and inputs, selected on the basis of accurate agro-environmental information – all while enjoying the benefits of insurance.

In addition, aligning complementary innovations with other sectors such as health, environment and education can be mutually beneficial to food and adjacent systems. For example, innovations in education to improve consumer awareness plus innovations in health that incentivize consumers to eat healthier diets, thereby changing demand, can be combined with food-sensing technologies to provide consumers with nutrition and environmental information about the foods they purchase. Mobile applications that provide tailored information on these demand changes, using forecasting algorithms, can help farmers make more informed decisions.

Technologies are at different stages of development and countries are at different stages of adoption readiness. This makes it important to determine the requirements at each layer of the technology stack – the set of components or layers that provide both broad functionality and the scope to sequence different interventions.

To illustrate, consider Uber-like social economy platforms that provide farmers with mechanization or leasing services such as Hello Tractor, EM3 Agri Services or Trringo. At the bottom of the stack is the infrastructure and hardware required to enable GPS-capable tractors. From this, mapping capabilities were developed, which created the ability to link virtual and physical locations. Finally, applications such as EM3 Agri or Hello Tractor can layer onto these capabilities to bring mechanization services to smallholder farmers. In the same way, organizations need to think about sequential interventions in a way that creates base layers that are scalable and which players may layer onto in order to develop new solutions.

Global networks can play a significant role

Food systems have a unique set of needs that vary from market to market, and even by value-chain. It is relevant to develop new innovations in response to local needs and context and have a level of confidence and support to test those models for market application. More established systems offer substantive investments in scientific knowledge, a culture of entrepreneurship, significant pools of capital and strong support networks. Increasingly, the interconnectedness of markets across the globe require networks covering countries and regions. Likewise, stakeholders should consider where the talent, knowledge and ideas needed to build successful ventures are coming from, as well as the target markets in which these need to be deployed.

Inspiring stakeholders to act

Given the complexities in scaling technologies in food systems, there is a real need for all stakeholders to play a part in leveraging technologies to transform food systems. Some interventions can be done individually; others require collaboration among multiple stakeholders.

Governments

Governments play a vital role in creating business-enabling environments. They are responsible for adapting policy and regulations that support and promote technology innovations. In some instances, governments fund high-impact technology innovations as well as data collection and aggregation. They also have a critical role to play in raising consumer awareness.

Successful technology scaling requires investment in the digital and physical infrastructure required to reach rural areas. Digital infrastructure design can support technological scale (e.g. high throughput communications); physical infrastructure can target rural communities while also catering to emerging technologies. Technical assistance can accelerate the pace of technological adoption, especially at the farm level. Governments are uniquely positioned to promote farmer and consumer education that can help shift mindsets, improve technological savviness and promote the adoption of new technologies.

A systems approach to supportive policies can enable contributions to the Sustainable Development Goals, promoting more inclusive, sustainable, efficient, and nutritious and healthy food systems. Government policies aimed at increasing the impact of innovations need to promote a systems-level holistic agenda that can evaluate need, connect and incentivize innovations across many sectors and scale those with the highest impact.

Governments can adopt total-cost frameworks that consider a technology's full impact and can implement Pigouvian tax legislation to offset negative externalities.

Companies and start-ups

The private sector can form new types of partnerships, promote start-up activity through intrapreneurship and investments and share data whenever possible.

Public-private partnerships have historically been effective at bringing together diverse stakeholders with common objectives. New types of partnerships could be used to accelerate technology transfers, encourage trust and accountability, and promote pre-competitive models that combine the core competencies of different institutions. For example, seed innovations so far have concentrated on developed countries. Making the seed intellectual property available to developing countries may lead to better seeds being developed for countries in need.

Promoting start-up activity can be done in many ways. Intrapreneurship is a proven model that can be beneficial to both corporations and start-ups. Corporate venture capital can provide start-ups with the necessary funding and mentorship required to successfully create and bring products to market.

Sharing data, too, is something the private sector can do to promote expansion. Aggregating data that companies have collected and putting it on open platforms while ensuring no competitive advantage is lost could prove immensely helpful to other organizations looking to scale their technologies.

Investors

Technologies offer promising opportunities to transform food systems. While instances of sizeable returns from greater opportunities exist, many commercial investors seeking to invest in technology innovations appear to have a more definite (and higher) expectation of financial returns than what innovations can offer. In addition, many innovative enterprises are still small, with total operating budgets of less than $5 million. Their needs for capital can range from equity to debt, to working capital or even grants, depending on the task required to scale up or reach commercial viability. And the amounts required are likely to be substantially lower than the floor of most commercial investors. Investors will need generous amounts of patience, a willingness to tolerate some unpredictability in returns and, perhaps, some new vehicles for both finding and making relatively small commitments efficiently.

Donors

Donors are the only source of reliable and consistent long-term patient capital that tolerates lower-than-market returns and cushions sub-scale enterprises as they develop their business models.

Successful technology scaling may require donors to reorient some traditional models of promoting enterprises. They will need, for example, the ability to invest in and encourage large corporations to take a role. For many philanthropies, however, this raises justifiable qualms and legal issues and most aid donors are not equipped to make these kinds of investments.

The donors must use their capital in three important areas. First, they can help address the crucial capacity-building challenges that many technology innovators have. Innovation labs are an excellent way to provide such assistance. In addition, donors can provide flexible growth capital, especially in the early stages of technology development. This could be in the form of direct capital, or developing facilities that can either make direct investments or provide risk-mitigation mechanisms. Third, donors can drive a data and analytics effort to define impact metrics that will clarify which innovations work and to develop compelling cost and impact dimensions for the externalities of today's food systems. In addition, donors can also offer "sandboxes" of data for start-ups to test their innovations; such open-data platforms help accelerate experimentation and prototyping.

Without the right support, some technologies will not be used to improve the state of the world. The pace of technology deployment could be accelerated if non-competitive actors in food systems shared intellectual property. North-South or South-South technology transfers or distribution partnerships could move mature tech solutions across geographies effectively. Technologies, such as microbiome and mobile pricing algorithms, could be deployed to benefit countries where they are currently unavailable. Different types of agreements could significantly shorten the discovery and development cycle of fundamental and applied research. Such agreements include university partnerships, intellectual property transfers, formal organizations and both private-private and public-private partnerships.

Systems Leaders

Individual actions from stakeholders are necessary but insufficient in supporting food systems transformation. The complexities of transforming food systems will require unprecedented cooperation among stakeholders and commitment towards common goals which can be accomplished by a special form of leadership: systems leadership. Systems leadership can play a catalytic role in bringing together a diverse set of stakeholders to align around a shared vision for change, empowering widespread innovation and action, and enabling mutual accountability.[53]

Individual leaders and institutions across business, government and civil society can pursue their specific institutional interests in ways that also benefit the broader systems in which they operate, recognizing that, in the long term, the two are inextricably linked. Encouraging widespread adoption of this approach will require active facilitation, brokering and capacity-building to encourage systems leadership and systems thinking.

Multistakeholder partnerships are examples of systems leadership in practice that can help promote innovation ecosystems at the country and regional levels by engaging diverse stakeholders around a common vision, encouraging transparent and inclusive dialogue and facilitating collaboration and coordinated action.

There may be an opportunity to leverage such multistakeholder initiatives and platforms to foster innovation ecosystems for the 'Transformative Twelve' and other relevant, highly impactful technologies. These platforms will need to develop targeted action plans, outlining how they will incorporate and promote innovations in a way that supports a shared agenda to transform food systems.

Through its New Vision for Agriculture (NVA) initiative, the World Economic Forum is already playing a facilitating role in the effort to transform food systems. Engaging over 650 organizations, the NVA supports country-led multistakeholder collaborations in 21 countries worldwide. Together these efforts have catalyzed over 100 value-chain partnerships. The country-led partnerships are locally owned, aligned with country goals, and drive integrated value-chain activities in viable business cases to benefit all actors.

Conclusion

This report represents an initial effort to understand and illustrate how technologies can affect food systems. Although much more work remains to be done, several insights can be drawn from the effort to date. These include:

— **Food systems are decades behind many other sectors in adopting technology innovation, particularly in developing countries.** The fragmented nature of the production landscape in emerging markets, consumers' ability and willingness to pay, operational complexities throughout food systems and government interventions create significant barriers to the adoption and scale of technologies.

— **The recent advancements in Fourth Industrial Revolution technologies present a major opportunity to accelerate food systems transformation.** These technologies could fundamentally shape the demand landscape, enhance value-chain linkages and increase the effectiveness of the production landscape. While many of these technological innovations are in the early stages of development, these technologies could deliver significant positive impacts in food systems by 2030, if scaled properly.

— **Current trends in global investments do not yet reflect the potential for disruption in demand-side innovations and in developing countries.** Most investments in innovative technology applications are currently concentrated in developed countries, highlighting both the risk of unequal access to new solutions and the opportunities for developing countries if they can be effectively scaled. Also, many of today's technologies and innovations are focused on improving the production landscape, highlighting a gap and opportunity for demand-side innovations.

— **Emerging technologies can have unintended consequences.** The trade-offs and risks of scaling these technologies on health, the environment and biodiversity should be well understood and mitigated. Concerns over privacy and intellectual property rights also need to be addressed. Innovative governance models, greater research and public dialogue will be crucial in shaping and scaling these new technologies in ways that improve the state of the world.

— **Technological interventions introduced in isolation run many risks.** Innovations will have greater impact if complemented with innovations within and across other systems. Innovations introduced in isolation in food systems are likely to fail, so active participation from all stakeholders is essential. At the same time, complementary and aligned innovations in neighbouring systems such as health, education and the environment can accelerate the impact of innovations in food systems.

— **Scaling emerging technologies could have a major impact on food systems.** This will require a vibrant innovation ecosystem in which stakeholders including, governments, companies, investors, donors and systems leaders can collaborate to provide support to technology innovations across their life cycles. There is also a need to encourage global networks that could enable the cross-pollination of ideas and learnings across markets and geographies.

— **The role of systems leaders in enabling an innovation ecosystem cannot be overstated.** It is essential to coordinate interventions among the diverse set of stakeholders within food systems towards solving common objectives. Systems leaders can do just that.

— **Transforming food systems requires interventions beyond the disruptive technological innovations.** Continued investments in low-tech interventions, creating new and bold policies, moving towards full-cost accounting, improving resource efficiency, influencing consumer behaviours, building trust and transparency, aligning towards common objectives and collaborating across siloes are all required to create the future we want.

As a next step, stakeholders will need to engage in a dialogue on how best to accelerate this agenda, including identifying technologies to be scaled, enabling innovations in policy and business models and determining geographies and markets where pilots can be designed and implemented. It will also be important to identify existing initiatives that can provide experimental platforms for these technology innovations.

The World Economic Forum's System Initiative on Shaping the Future of Food Security and Agriculture explores the potential to apply the opportunities and actions highlighted in this report through multistakeholder partnerships inspired and supported by the New Vision for Agriculture (NVA) initiative in Africa, Asia and Latin America. This will provide an opportunity to explore which technologies can contribute to country-led priorities and support the scaling of new and existing activities on the ground to advance impact.

We encourage and invite other initiatives and stakeholders to join in exploring the potential to strengthen food systems through technology innovation.

Annex: Methodology notes

Impact of technologies on food systems

It is important to note that the exercise of sizing the potential impact of individual technologies is at best a directional exercise. First, estimations of the adoption of technologies by 2030 depend on the maturity of the technology as well as other factors such as consumer acceptance, government regulation and efforts on behalf of the stakeholders to scale the technologies – all of which are difficult to predict accurately. Second, the impact generated by the technologies individually is also difficult to estimate. In fact, given how nascent some of these technologies are, impact estimations are often unavailable and were assessed based on publicly available information and closest comparable estimates. When literature was available, impact estimates ranged significantly – often driven by the specific agro-environmental conditions and circumstances of the local context. This exercise attempts to generalize at a global level and should be considered as directional and illustrative.

That being understood, it is easier to discuss implications if there is some quantification of impact, so we have made assumptions to provide a starting measure of potential impact with an optimistic mindset. These values should be seen as directional so that the conversation might be progressed.

To illustrate the potential effect of the highlighted technologies on food systems, the impact that could be realized by 2030 was evaluated. In all cases, the impact was calculated as a function of a baseline dataset, an estimated reach and an estimated impact.

Impact by 2030=(Baseline- Unadressable Value [Unit])*Est. Reach [%]*Est.impact [%]

Where,

- The "baseline" is the total value of the unit as it relates to food systems. This value was projected into 2030 proportionate to population growth unless otherwise stated in the assumptions.
- The "unaddressable value" is the portion of the baseline that already has access to the technology or that has access to a technology with similar attributes and benefits.
- The "estimated reach" is the portion of the addressable value that could adopt the technology by 2030. Given the uncertainty of predicting the reach of the technologies by 2030, a range was used to determine the overall adoption. Assumptions were made on a country's income level as defined by the World Bank (high income, upper middle income, lower middle income, and low income).
- The "estimated impact" is the improvement that can be expected from those adopting the technology. Most of the impact estimations are based on literature and case studies and generalized to meet the global context. In cases where no literature was available, expert opinion and closest comparable estimations were used.

All assumptions follow – please note that any discrepancies in the calculations are due to the rounding and averaging of values.

Changing the shape of demand

	Alternative proteins			Food sensing technologies for food safety, quality, and traceability	Nutrigenetics for personalized nutrition
What if…	**Consumers chose to replace 10-15% of meat (40-60 million tonnes of meat)** with alternative proteins by 2030			**30-50% of the consumers** in developed countries used food scanning to determine expiration dates by 2030	**10-15% of the overweight population (250-370 million people)** followed personalized nutrition plans by 2030
Lever	Reduced GhG Emissions Megatonnes of CO_2 Eq.	Reduced water use Billion cubic metres	Freed land Million Hectares	Reduced food waste Million of tonnes	Reduced overweight population Millions of people
Baseline value	7,700	2,900[3]	2,800[4]	270[6]	2,500[8]
Un-addressable	0	0	0	200-220[7]	0
Addressable value[13]	7,700	2,900	2,800	50-70	2,500
Reach %		10-15[11]		30-50[12]	10-15[9]
Impact baseline[14]	600-1,000	270-400	250-400	15-35	250-375
Impact, %	90-95[2]	80-90[10]	90-100[10]	80-90[10]	10-15[10]
Total impact[15]	**550-950**	**225-400**	**250-400**	**10-20**	**25-55**
Drivers of impact	▪ Reduced emissions from the production of livestock and feed	▪ Reduced water from the production of livestock and feed	▪ Reduced number of livestock driving increased availability of land	▪ Reduced domestic food waste from individualized and real-time expiration dates	▪ Reduced number of overweight from tailored and individualized nutrition and diets
Other impacts	▪ Improved health from reduced consumption of meat			▪ Reduced food fraud from the ability to identify food composition and authenticity ▪ Improved food safety from ability to identify pathogens	▪ Improved health and longer lives ▪ Improved performance for athletes

1 Total emissions driven from livestock in 2030 calculated based on total population in 2030 (World Bank Database), average meat consumption per capita (OECD-FAO Agricultural Outlook 2016-2025), and average emissions per kg of meat (Environmental Working Group, Meat Eaters Guide: Methodology 2011); 2 Assumes the emissions from the production of alternative proteins is equivalent to the production of 3-5 kg of soybeans per kg produced; 3 Calculated based on the average consumption of water per kg of meat (Institute of Mechanical Engineering); 4 Calculated as total pastures and meadows (World Bank Database); 5 Assumes application in high income and upper middle income countries only; 6 Total global food waste, McKinsey, 2013; 7 Assumes total food waste from low income and lower middle income countries is not addressable (50 million tonnes), assumes 20-30% of food waste is driven by "use-by" or "sell-by" dates in developed countries (i.e., 70-80% of waste is un-addressable), sources include: http://www.refed.com/download, http://www.wrap.org.uk/sites/files/wrap/ES%20Technical%20 report%20dates_0.pdf; 8 Overweight values based on the Global Burden of Disease Study, 2015 (http://ghdx.healthdata.org/gbd-2015), estimations assume proportion of overweight stays the same over time; total number of overweigh in 2030 estimated using 2030 forecasted global population (World Bank Database); 9 Reach estimated to be 20-25% in high income countries, 10-15% in upper middle income counties, 5-10% in lower middle income countries, and 0% in low income countries; 10 Estimated based on expert opinion; 11 Assumes that 15-20% of high incomes countries, 10-15% of upper middle income countries, 5-10% of lower middle income countries, and 0-5% of low income countries substitute meat for alternative proteins; 12 Assumes reach of 30-50% in high income and upper middle income countries; 13 Addressable value = Baseline value – un-addressable value; 14 Impact baseline = addressable value * reach; 15 Total impact = impact baseline * impact

Promoting value-chain linkages

	Mobile service delivery					Big data and advanced analytics for insurance		IoT for real-time supply chain transparency and traceability	Blockchain-enabled traceability
What if…	**70-90% of farms in developing countries (275-350 million)** used mobile applications by 2030					**50-75% of all farm holdings** without insurance opted into insurance (200-300 million holdings) by 2030		**50-75% of supply chains in developed countries** were controlled by IoT	**Half of the world's supply chains were tracked** by blockchain
Lever	**Increased income** Billions of dollars	**Increased yields** Millions of metric tonnes	**Reduced food loss** Million metric tonnes	**Reduced GhG emi-ssions** Mega-tonnes CO_2 eq.	**Reduced water use** Billions of cubic metres	**Increased income** Billions of dollars	**Increased yields** Millions of metric tonnes of food	**Reduced food loss** Million metric tonnes of food	**Reduced food loss** Million metric tonnes of food
Baseline value	3,500[1]	7,900[4]	350[5]	12,000[6]	3,500[7]	3,500[1]	7,900[4]	360[9]	360[9]
Un-addressable	1,900[2]	4,200[2]	150[2]	6,000[2]	1,500[2]	1,900[2]	4,200[2]	160[10]	0
Addressable value[16]	1,600	3,700	200	6,000	2,000	1,600	3,700	200	360
Reach %	70-90					50-75		50-75	40-50
Impact baseline[17]	1,100-1,400	2,600-3,300	140-180	4,000-5,500	1,300-1,700	800-1,200	1,900-2,800	100-150	150-180
Impact, %	10-15[13]	10-15[14]	15-35[13]	1-2[15]	3-6[12]	2-6[8]	2-6[8]	10-30[11]	5-15[15]
Total impact[18]	100-200	250-500	20-65	50-100	40-100	15-70	40-150	10-50	10-30
Drivers of impact	Access to financial pay-ments, agri-cultural infor-mation, increased price from en-hanced market access	Access to infor-mation to improve farming practices, resource manage-ment, and choice of inputs and seeds	Better farmer-trader coordi-nation and access to infor-mation (e.g., farmer helpline)	Increased access to agri-cultural infor-mation for better decision making	Increased access to agri-cultural infor-mation for better decision making	Increased willingness to take risk, experiment with new methods and technologies, and diversify crops		Improved ability to manage environmental conditions of transportation in real-time (e.g. temperature, humidity, gas) and better shelf-life management	Improved value-chain efficiency driven by improved collaboration and data visibility
Other impacts	▪ Improved financial inclusion					▪ Income smoothing over time allowing farmers to maintain livelihoods in severe circumstances		▪ Ability to provide nutritional and environmental impacts of food ▪ Improved food quality ▪ Reduced wastage from accurate expiration dates	▪ Reduced food fraud from ability to determine food authenticity ▪ Reduced food losses and impro-ved food safety driven by recalls ▪ Improved supply and demand matching leading to optimized food production and distribution ▪ Ability to provide nutritional and environmental impacts of food

1 Based on total agricultural production value from FAO, 2030 projection estimated based on population growth (World Bank Database); 2 Assumes that 100% of farmers in high income countries and 50% of farmers in upper middle income countries, 30% of lower middle income countries, and 10% of low income countries already have access to similar services – based on the proxy of the percentage of the rural population with an account at a financial institution, % age 15+, (World Bank Database); 3 Assumes average margin of 15% compared to total agricultural production value, FAO (i.e. costs are 85% of the total agricultural production value); 4 Total agricultural output includes crop, meat, milk, and eggs, FAO, 2030 projection estimated based on population growth (World Bank Database); 5 Includes only post-harvest losses; 6 2030 total agricultural greenhouse gas emissions forecasted to 2030 using linear regression - base data from FAO and World Bank Database; 7 Total agricultural freshwater withdrawals, 2030 estimates forecasted based on population growth, World Bank Database; 8 Driven by increased farmer willingness to take risks and change practices, https://www.ifama.org/resources/Documents/v19ia/520150132.pdf; 9 Total processing, packaging, and distribution losses, estimated by McKinsey; 10 Excludes food waste from lower middle income and low income countries; 11 Large reduction in food loss during production, packaging, and transportation driven by the ability to control environmental conditions (temperature, humidity, and gas) in real-time, https://docs.wixstatic.com/ugd/e4f595_aef7d3c7e8794c06b8f67f586f6d3a7c.pdf; 12 Based on: http://www.vodafone.com/content/dam/vodafone/about/sustainability/2011/pdf/connected_agriculture.pdf; 13 Based on: https://www.weforum.org/agenda/2014/12/how-mobile-phones-benefit-farmers/;14 Based on: https://ageconsearch.umn.edu/bitstream/155478/2/2_Mittal.pdf; 15 Based on expert opinion; 16 Addressable value = Baseline value – un-addressable value; 17 Impact baseline = addressable value * reach; 18 Total impact = impact baseline * impact

Creating effective production systems

	Precision agriculture for input and water use optimization			
What if…	15-25% of all farms **(80-150 million farms)** adopted precision agriculture by 2030			
Lever	**Reduced costs** Billions of dollars	**Increased yields** Millions of tonnes	**Reduced GhG emissions** Megatonnes of CO_2 eq.	**Reduced water use** Billions of cubic metres
Baseline value	2,400[1]	6,600[4]	750[5]	3,500[6]
Un-addressable	750[2]	1,950[2]	150[2]	1000[2]
Addressable value[33]	1,650	6,000	500	2,500
Reach %	15-30[3]			
Impact baseline[34]	450-750	1,000-2,000	125-220	500-1000
Impact, %	10-15[8]	10-15[9]	5-10[10]	10-20[7]
Total impact[35]	**40-100**	**100-300**	**5-20**	**50-180**
Drivers of impact	Input use optimization and machinery use optimization	Improved seeding, and optimized use of inputs	Optimized use of inputs reduces the amount applied and runoffs	Optimal water use from improved irrigation systems and field visibility
Other impacts	▪ Increased income depending on costs of services and sensors			

	Gene-editing for multi-trait seed improve-ments			
What if…	10-15% of farms **(60-100 million farms)** chose to use gene-edited seeds by 2030			
Lever	**Increased income** Billions of dollars	**Increased yields** Millions of tonnes	**Reduced food loss** Millions of tonnes	**Reduced micro-nutrient def.** Millions people
Baseline value	2,800[11]	6,600[4]	450[13]	1,400[14]
Un-addressable	0	0	0	0
Addressable value[33]	2,800	6,600	450	1,400
Reach %	10-15[17]			
Impact baseline[34]	400-550	900-1,300	60-90	100-180
Impact, %	10-15[12]	10-30[19]	5-25[16]	20-50[15]
Total impact[35]	**40-100**	**100-400**	**5-20**	**20-100**
Drivers of impact	Increased yield, and reduced loss from drought, pest and disease	Increased yield from improved seed genotype	Increased crop resilience to pest, disease and drought	Ability to biofortify seeds and crops
Other impacts	▪ Reduced use of pesticide and herbicide ▪ Improved quality and aesthetic of foods leading to reduced waste			

	Microbiome technologies to enhance crop resilience			
What if…	20-25% of farms **(120-150 million farms)** chose to use microbiome technologies by 2030			
Lever	**Increased income** Billions of dollars	**Increased yields** Millions of tonnes	**Reduced food loss** Millions of tonnes	**Reduced GhG emissions** Megatonnes of CO_2 eq.
Baseline value	2,800[11]	6,600[4]	450[13]	750[5]
Un-addressable	0	0	0	0
Addressable value[33]	2,800	6,600	450	750
Reach %	20-25			
Impact baseline[34]	550-700	1,300-1,650	90-120	150-200
Impact, %	10-15[18]	10-15[18]	5-15[20]	10-15[20]
Total impact[35]	**60-100**	**130-250**	**5-20**	**15-30**
Drivers of impact	Increased yield and reduced loss due from drought, pest and disease	Improved plant ability to assimilate nutrients	Increased crop resilience to pest, disease and drought	Improved crop ability to assimilate nutrients
Other impacts	▪ Reduced use of pesticide and herbicide			

	Biological-based crop protection and micronutrients for soil manage-ment	
What if…	5-10% of farms **(15-50 million farms)** used biologicals and micronutrients by 2030	
Lever	**Increased yields** Millions of tonnes	**Reduced GhG emissions** Megatonnes of CO_2 eq.
Baseline value	6,600[27]	750[28]
Un-addressable	0	0
Addressable value[33]	6,600	750
Reach %	5-10[30]	
Impact baseline[34]	200-550	25-50
Impact, %	5-10[29]	5-10[32]
Total impact[35]	**10-50**	**1-5**
Drivers of impact	Improved crop health leading to increased yields from the use of micronutrients	Reduced use of fertilizers from the use of micronutrients
Other impacts	▪ Improved farmer health due to reduce exposure to toxins ▪ Replacement of traditional pesticides and herbicides could have beneficial effects on consumer health	

	Off-grid renewable energy generation and storage for access to electricity			
What if…	50-75% of farmers currently **unable to access electricity (100-150 million farms)** gained access to off-grid renewable electricity by 2030			
Lever	**Increased income** Billions of dollars	**Increased yields** Millions of tonnes	**Reduced food loss** Millions of tonnes	**Reduced water use** Billions of cubic metres
Baseline value	2,500[21]	6,600[27]	350[24]	3,500[26]
Un-addressable	2,150[22]	5,200[22]	250[22]	2500[22]
Addressable value[33]	350	1,400	100	1000
Reach %	50-75[31]			
Impact baseline[34]	150-300	700-1000	50-75	500-750
Impact, %	10-40[23]	40-50[23]	15-20[25]	30-40[23]
Total impact[35]	**20-100**	**300-530**	**10-15**	**150-250**
Drivers of impact	Increased access to cold storage allowing farmers to improve price realization at time of sale	Access to efficient irrigation systems reducing the amount of water wasted	Access to cold storage increasing product shelf life	Access to efficient irrigation systems reducing the amount of water wasted (e.g., drip irrigation)
Other impacts	▪ Reduced GhG emissions from replacement of fossil fuel powered pumps and electricity generation			

1 Based on total crop production value from FAO multiplied by a margin of 15%, 2030 projection estimated based on population growth (World Bank Database); 2 Assumes 50% of farms in high income countries (http://www.ustrust.com/ust/pages/agriculture-tech.aspx), 30% of farms in upper middle income, 20% of farms in lower middle income, and 10% of farms in low income countries already have access to some variation of precision agriculture applications; 3 Assumes 50-75% of farms in high income countries, 30-50% of farms in upper middle income countries, 10-25% of farms in lower middle income countries, and 5-10% of farms in low income countries will adopt precision agriculture; 4 Total crop production forecasted to 2030 proportionally to population growth, FAO, World Bank Database; 5 Based on emissions generated from fertilizer use, FAO; 6 Total agricultural freshwater withdrawals (World Bank Database), 2030 estimates forecasted based on population growth 7 Impact estimates vary widely, conservative estimates selected (http://www.ustrust.com/ust/pages/agriculture-tech.aspx, http://www.sciencedirect.com/science/article/pii/S037837741400211X, http://www.mdpi.com/2071-1050/9/8/1339/htm); 8 Derived from multiple sources including: https://www.reacchpna.org/precision-agriculture-offers-conservation-opportunities; 9 Derived from multiple sources including: https://www.reacchpna.org/precision-agriculture-offers-conservation-opportunities; 10 Derived from multiple sources including: http://www.mdpi.com/2071-1050/9/8/1339/htm and https://www.reacchpna.org/precision-agriculture-offers-conservation-opportunities; 11 Based on total crop production value from FAO, 2030 projected based on population growth; 12 Based on multiple sources including: http://www.weeklytimesnow.com.au/agribusiness/decisionag/genetic-modification-science-suggests-its-not-evil-or-unhealthy/news-story/4565c866f004bb8c0398cd0a0408014e and expert opinion; 13 Includes production/on-farm losses; 14 Assumes that each farm holding can reach 4 people, assumes that it only applies to low income and lower middle income countries; 15 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.864.2952&rep=rep1&type=pdf; 16 Assumes that gene editing can reach improvements that are at least as good as gene modification http://12.000.scripts.mit.edu/mission2017/genetically-modified-crops/; 17 Assumes that 20-30% of high income countries, 15-20% of higher middle income countries, 10-15% of lower middle income countries, and 0-10% of low income countries are using gene edited seeds; 18 https://www.indigoag.com/pages/news/2017/from-the-ground-up-on-kbtx; 19 Based on historical maize improvements seen in the US - low bound represents average yield improvements in the past decade, high bound represents the yield improvements realized in the 1960s (high uptake of seeds with improved genotype), USDA Foreign Agricultural Service, PSDOnline; 20 Based on expert opinion; 21 Total value of perishable production (milk, eggs, meat, fruits, and vegetables) from FAO stat, 2030 forecast based on population growth, World Bank Database; 22 Assumes that benefits will be attributed to farmers without access to electricity; based on rural access to electricity (% of rural population), 2014, World Bank Database; 23 Derived from multiple sources including https://www.innovationpolicyplatform.org/system/files/8-Storage%20Solutions_Agri_Profile%20Ecozen.pdf, https://www.ifc.org/wps/wcm/connect/2a54040046a86bc6989db99916182e35/Impact+of+Efficient+Irrigation+Technology+on+Small+Farmers+-+IFC+Brochure.pdf?MOD=AJPERES; 24 Post harvest losses only; 25 Based on estimated losses of milk driven by lack of cold storage - http://naturalleader.com/wp-content/uploads/2016/04/UTC-Nottingham-Report_3-30_FINAL.pdf; 26 Total agricultural freshwater withdrawals, 2030 estimates forecasted based on population growth (World Bank Database); 27 Total crop production forecasted to 2030 proportionally to population growth, FAO, World Bank Database; 28 Based on emissions generated from fertilizer use, FAO, 2030 est. projected based on increased population (World Bank Database); 29 Increased micronutrients in soil can lead to increased yields, see yield calculator here: http://www.microessentials.com/performance; 30 Assumes that 5-10% of high income and upper middle income countries and 0-5% of lower middle income and low income countries adopt this technology; 31 Assumes that 50-75% of all farmers without access to electricity gain access to electricity; 32 Based on expert opinion; 33 Addressable value = Baseline value – un-addressable value; 34 Impact baseline = addressable value * reach; 35 Total impact = impact baseline * impact

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