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Implications of new technologies for future food supply systems

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Abstract

The combination of advances in knowledge, technology, changes in consumer preference and low cost of manufacturing is accelerating the next technology revolution in crop, livestock and fish production systems. This will have major implications for how, where and by whom food will be produced in the future. This next technology revolution could benefit the producer through substantial improvements in resource use and profitability, but also the environment through reduced externalities. The consumer will ultimately benefit through more nutritious, safe and affordable food diversity, which in turn will also contribute to the acceleration of the next technology. It will create new opportunities in achieving progress towards many of the Sustainable Development Goals, but it will require early recognition of trends and impact, public research and policy guidance to avoid negative trade-offs. Unfortunately, the quantitative predictability of future impacts will remain low and uncertain, while new chocks with unexpected consequences will continue to interrupt current and future outcomes. However, there is a continuing need for improving the predictability of shocks to future food systems especially for ex-ante assessment for policy and planning.

Shocks to global food systems

Throughout history, societies have contended with how to produce sufficient food. Currently, both economically developing and developed countries struggle to achieve and balance a wide range of food-related goals such as food and nutrition security and safety, environmental sustainability, wildland conservation, economic development and rural poverty alleviation (Godfray *et al.*, 2010). These challenges have become increasingly global in scale and in complexity with the growth in international food trade.

Food systems have always been subject to short-term regional shocks such as inclement weather, pests and diseases, and social conflicts, as well as longer-term stresses caused by climate change (Porter *et al.*, 2014), population growth (Roser and Ortiz-Ospina, 2017), environmental degradation (Ferber, 2001; Smith *et al.*, 2017) and political and economic development. The 2008 food price crisis that led to widespread food riots in many countries showed how regional shocks to food production and policies have global consequences not only for food supply and distribution, but also for social and political systems (Berazneva and Lee, 2013). There is an increasing concern about the impact of global climate change on food production and its associated environmental, economic, social and political impacts (Godfray *et al.*, 2010). More recently, trade disputes and the COVID-19 crisis further highlight the risks of massive disruptions in the globalized food supply chains, unveiling an underlying vulnerability of agricultural systems.

A new kind of emerging shocks to global food systems stems from advanced technologies that are transforming food production and agricultural systems at an unprecedented rate. Until now, the technological changes such as irrigation, mechanization and crop breeding have revolutionized food production, but these changes generally came gradually and at different times in different places, like the 'Green Revolution' during the last 60 years (Evenson and Gollin, 2003). These technological changes often focused on production (Evenson and Gollin, 2003), with harmful consequences for the environment (Ferber, 2001; Smith *et al*., 2017) and society (Ng *et al*., 2014). What will differentiate the coming technological revolution in food systems from previous developments will be its speed, breadth, reach and the corresponding opportunities as well as challenges it will pose in feeding the globe, as discussed in this Editorial.

Potential food system 'game-changers'

Simultaneous advances in knowledge, technology and changes in consumer preference have created a set of new food technologies. Herrero *et al*. (2020) listed many emerging single technologies with reference to their state in the 'pipeline' from research to initial implementation, but without considering the potential impact on the society at large. In addition, many of the advances in technology listed by Herrero *et al*. (2020) will unlikely achieve much widespread impact on food systems on their own, such as artificial intelligence or big data. Only when these are combined and linked to a specific domain and involved the stakeholders, they potentially become 'game-changers'. These 'game-changers' encompass crop, livestock, aquaculture and fisheries systems and include:

(1) Artificial intelligence linked with Big Data, sensors and food systems knowledge to increase productivity, optimize resource use and minimize externalities in food supply chains,
(2) Autonomous acting technologies including robots and drones throughout the food supply chain,
(3) Tailored genes for specific food production, nutritional and environmental outcomes,
(4) Large-scale aquaculture both on-land and in the ocean,
(5) Novel food and feed from farmed single-cell organisms, algae and insects, and designed food using synthetic biology, and
(6) Vertical farming with controlled-environment production of crops, livestock and seafood.

Components within these technologies have been developed for decades, but have reached or will reach soon a combined maturity and affordability that will warrant fast and widespread implementation. For example, sub-technologies have experienced recent breakthroughs in autonomous acting (like autonomous driving), on-time sensory and picture recognition, high-speed data transmission and processing, genetic manipulation, and energy (e.g. solar) and light production (e.g. LEDs) – all combined with much lower cost in manufacturing these technologies. As a consequence, each of these six major technologies will likely take off fast, disrupt the functioning of food production systems and related systems with both positive and negative implications. For example, the operation of crop, livestock and aquaculture systems will be substantially improved by artificial intelligence connecting remote, continuous, real-time and low-cost sensor monitoring through production systems with autonomous interventions (Carvajal-Yepes *et al*., 2019). These technologies can simultaneously improve resource use efficiency with reduced environmental externalities, thus increasing the sustainability of food and feed production and their acceptability by producers and consumers alike.

Similarly, multiple, small autonomous robots and drones will replace repetitive and hard labour, similar to past trends in other manufacturing industries, e.g. car production, revolutionizing efficiency and challenge traditional food production, harvesting, processing, packaging and distribution. Replacing farm labour, which is the most expensive cost in many farm operations (Mundlak, 2005), with such autonomous machines could change the historic trend of increasing farm size. The prior approach of increasing farm size required expensive and heavy machinery that caused soil degradation, reducing crop growth and yield (Unger and Kaspar, 1994), large mono-culture field units with low biodiversity (Green *et al*., 2005), and increasing concentration of livestock with local nutrient surplus and eutrophication of the environment (Ferber, 2001; Smith *et al*., 2017). In the future, with the introduction of autonomous-acting field technologies, larger farms will not necessarily be more profitable or successful than smaller farms (Asseng and Asche, 2019). Less dependency on labour could also mitigate major food supply disruptions resulting from recent events such as the COVID-19 pandemic and drastic changes in immigration policies.

Increased productivity through tailored genes for crops and fish is now possible, e.g. a genetically modified Atlantic salmon was the first GMO animal, to be approved for sale in the USA. The breeders of this new salmon claim that it has an increased growth and improved feed conversion enabling a more efficient food supply. There is a growing consumer interest in 'plant-based meat' that consists of extracted plant protein, spices and binding ingredients. Technological advances in synthetic biology and precision fermentation could lead to mass production of engineered protein in factory fermentation facilities and cultivation of meat cells for food and feed (Tubb and Seba, 2021). If widely accepted, such technology could challenge traditional livestock production systems, but not necessarily reducing greenhouse gas (GHG) emissions while also increasing the demand for starch crops such as maize (Lynch and Pierrehumbert, 2019). New technologies for large-scale production of seafood on land and in ocean cages could increase seafood accessibility for consumers and possibly reduce pressure on wild fish stocks (Diana, 2009). Linking new developments in aquaculture and livestock by producing feed from algae could significantly reduce GHG emissions in livestock, the largest GHG emitter in agriculture (Roque *et al*., 2019). Tailored genes can also enhance nutrient composition and value of food and eventually lead to substantial improvements in nutrition and ultimately human health (Glass and Fanzo, 2017), in addition to increasing the food supply volume. Growing crops in vertical farm factories with many stacked layers of crop production under controlled conditions with artificial lighting have the potential to produce large amounts of food with minimal land requirement, independent of weather, climate change, soil and location. In addition, there are strong environmental benefits through the reuse of most of the water, no application of pesticides and no fertilizer loss to the environment (Pinstrup-Andersen, 2018). This technology could free agricultural land and reduce the pressure on deforestation of rainforests due to the expansion of land required for agricultural production. It could also minimize transport and thus the carbon footprint by producing food closer to the consumer. For example, the average global wheat yield could theoretically increase by 6000 times per area per year in a 100 layer vertical farm (Asseng *et al*., 2020).

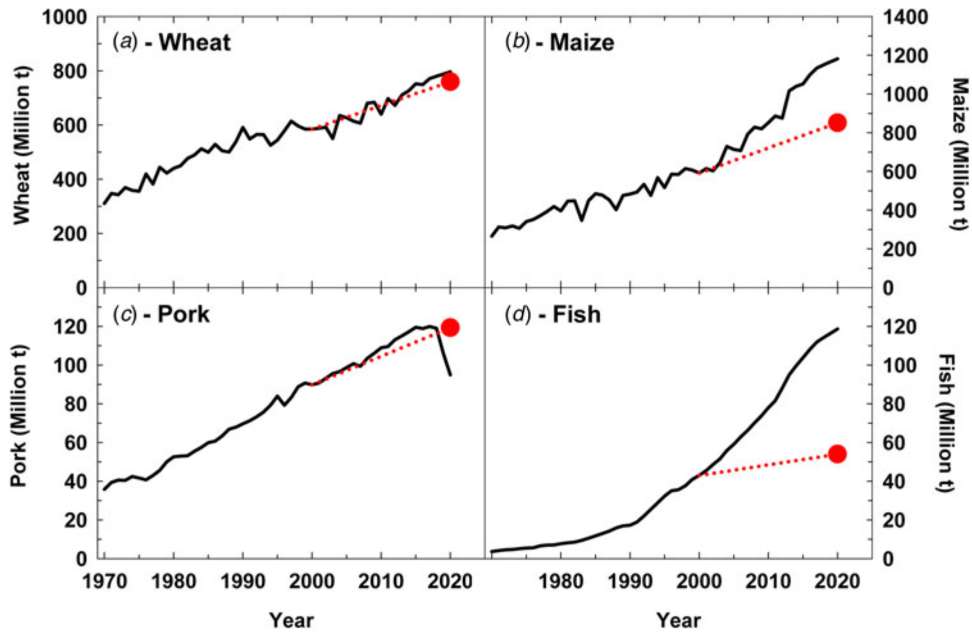

Fig. 1. Global reported production (black line) and IFPRI projections (red dotted line and red symbol). Projections made by IFPRI in 2000 for the year 2020. (a) Wheat, (b) maize, (c) pork and (d) farmed fish (including shellfish). Source (Rosegrant *et al*., 2001; Delgado *et al*., 2003; FAO, 2019; United States Department of Agriculture (USDA), 2019).

However, this is unlikely to be economically viable for broad-acre crops due to the high energy costs for light and air-conditioning (Asseng *et al*., 2020), but could well be viable for other more valuable crops, like vegetables (Eaves and Eaves, 2018).

Many unanswered questions

The outcomes, and whether these 'game-changing' technological innovations are beneficial to society, will depend on consumer preferences as well as policy regulation and economic factors. Substantial uncertainty about the technology revolution relates to whether or not new technologies will be considered ethical, socially acceptable and equitable. New technologies are embraced as major advancements for societies but may perpetuate societal divides in agricultural workforces as well as between countries. Policy regulation and economic factors will determine how these new technologies are adopted and by whom.

A critical issue is whether Africa, Asia and Latin America that are currently the major regions for food insecurity, poverty and rapid demographic change will advance from technological solutions for the required productivity increases, and if so, if they can leapfrog technologies similar to the rapid adoption of cell phones for telecommunication and the associated digital payment evolution. Public and private actors will play defining roles in smallholder farmers' access to 'game-changing' food technologies and enabling factors such as effective infrastructure for feed delivery and market access, maintaining new technologies (on the inputs side), processing and marketing (on the output side), and access to financing. Future governance at all levels, including local, regional, national and international, will be important for a socially responsible revolution in food and agricultural systems.

Predictability of food production

One of the key questions is if future food production will be able to meet the demand of a growing world population given resource and environmental constraints? More than two centuries ago, Malthus famously predicted that it could not, thus limiting both population growth and living standards (Malthus, 1798). The failure to date of Malthus is a reminder of our historical inability to anticipate how food production can change and increase in response to technology and institutions, and how the potential for future shortages creates incentives for such technological and institutional changes.

At the turn of the century, the International Food Policy Research Institute (IFPRI) used a sophisticated model of food supply to project global production in 2020 for wheat, maize, pork and aquaculture (farmed fish and shellfish) (Rosegrant *et al*., 2001; Delgado *et al*., 2003). The wheat projections were quite consistent with actual production (Fig. 1(a)), because the essential elements of the global wheat supply and demand system were captured by the IFPRI model while there were also no large exogenous shocks nor large changes in the underlying drivers.

In contrast, maize production was 39% larger than projected (Fig. 1(b)), largely because the US and EU government requirements to add ethanol gasoline – an institutional change not anticipated in the model assumptions – created a large increase in demand for maize. The pork projections over-estimated production by 20% (Fig. 1(c)), mostly due to another exogenous shock, i.e. African Swine Fever, that decimated China's pork production in 2019. However, the greatest difference between the projected and actual production was for aquaculture for which actual production exceeded the projections by 64% (Fig. 1(d)). Models for this relatively new industry did not capture the impact of unanticipated new technologies, the role of globalization and international trade and policy on aquaculture and fisheries, despite access to large amounts of data and broad food systems knowledge.

The next technological revolution in food production systems suggests that all future food production will continue to be difficult to predict quantitatively, with all types of foods potentially subject to as dramatic changes as occurred for aquaculture over the past two decades. However, more accessible global data and new AI tools to analyse these might improve the prediction of some of these trends in the future.

Towards 2050

Herrero *et al.* (2021) suggested combining the list of food systems innovations in Herrero *et al.* (2020) with multiple Sustainable Development Goals (SDGs) through well-planned transition pathways, carefully monitoring key indicators and through an implementation of transparent science targets at local levels. While a noble goal, achieving this in many situations might be difficult, as policy has often been lacking behind technology advancements, such as computing and the Internet, and might even hinder future innovations. Future food production systems and technology innovations will also happen regardless of SDGs and the question will remain how to eventually guide these through policies that lead to broad positive outcomes. The next technology revolution needs to be considered in the context of multiple food-related challenges, shocks and risks. These include changing demographics, climate change, inequitable food distribution, declining quality and adequacy of diets, accessibility of healthy foods, food waste, food safety and zoonotic disease transmission, antimicrobial resistance and the paradoxical growing 'triple burden' of malnutrition (hunger, insufficient nutrients, and overweight and obesity) (Gomez *et al.*, 2013). When combined, this complex challenge requires a paradigm shift in which we rethink how, where and what food is produced in the future. How can the new 'game-changing' food system technologies be employed to address the existing challenges and minimize potential negative outcomes? Some of the new food technologies create an opportunity to consider food systems as an ecological system, with transitions to circular agriculture from local to global scale. They have the potential to increase and diversify production systems and minimize environmental degradation with food production becoming carbon neutral, recycling water and minimizing externalities. If successfully implemented, these technologies can enable societies to produce healthy, nutritional and environmentally friendly food for all. However, while the technology revolution by itself will disrupt many aspects of life, coupling technology innovations with sociocultural and policy changes will be necessary to make progress towards multiple SDGs (Barrett *et al.*, 2020).

Policy implications

Technological innovation will undoubtedly transform the global food system, but which technologies have the greatest influence will hinge on economics and business models, challenges on scaling up technologies, consumer preferences and the decisions of governments and international bodies about regulation and international agreements. A transformation of food systems through technology innovations will require changes in the components of food systems and values, regulations, policies, markets and governments surrounding it (Herrero *et al.*, 2020). Herrero *et al.* (2020) identified a number of policies to accelerate technology change including trust building among actors, transforming mindsets, enabling social license and stakeholder dialogue, guaranteeing changes in policies and regulations, designing market incentives, safeguarding against indirect, undesirable effect, ensuring stable finance and developing transition pathways. In addition, we see that the challenge for governance is to identify market failures where private incentives for innovation fall short or do not discourage innovation in technologies that are harmful. Governance systems can respond by providing incentives for new technologies that generate the greatest net benefits to society. They can also assist with incentives for bundling of technologies with positive social outcomes (Barrett *et al.*, 2020). We suggest four key questions and their potential solutions for food technology policy.

Firstly, when do private market incentives lead to underinvestment in basic science and technology that supports nutritional security? There are many private incentives to develop premium products for high-income consumers in niche markets and high-volume, low-cost products for large numbers of medium and low-income consumers in wealthier countries. However, it is less clear that private firms are incentivized to pack nutritional content into low-cost, high-volume products when breeding new crop varieties, genetically modifying crops and fish, or when experimenting with new processed foods, much less incentivized to developing products accessible to the poorest segments of society. Private incentives to innovate for nutritional and healthy foods and against hunger are inadequate, making the role of publicly-funded national and international food and agricultural centres even more crucial.

Secondly, which innovations are likely to produce desirable co-benefits for the environment and society and thus warrant more support from the public sector? Global policy agendas are diverse, with various nations attaching different weights to food safety, nutritional security, ecological sustainability and economic development. Identifying technologies with co-benefits in these domains can help overcome disagreements about policy priorities in negotiating trade agreements, technology transfer or international aid.

Thirdly, to what extent does delaying a needed climate policy in some countries weaken private incentives for green innovation in the food system? For example, carbon pricing would change the relative values of different food technology innovations by increasing the relative costs of GHG-producing technologies. This delay forces private investment to not only bet on the success of developing new technologies but also on the timing and stringency of new policies.

Fourthly, how will societies engage and lead the technology revolution in food production systems? Policymakers must prioritize future investments in human capacity-building. Countries without the capacity to engage in technological advances will have limited ability to realize technologies' potential benefits. A set of essential skills in each country will be vital to create or maintain each country's global integration. An educated public is needed to weigh both the economic, environmental and ethical implications and to help guide the next revolution in food supply systems.

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