The fourth agricultural revolution: technological developments in primary food production

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The Fourth Agricultural Revolution: past, present, and future

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Abstract

This chapter explores the past, present, and future of agricultural technology. It provides an overview of the evolution of agricultural technology over time and, the spectrum of technologies from the high-tech to the low-tech, as well as envisioning what farming of the future may look like. It discusses the possible benefits and drawbacks of the so-called fourth agricultural revolution, including who is most likely to win and lose from the increased use of sophisticated technology on-farm, and identifies key questions for the research community and others to consider as we move towards this so-called revolution.

1. Introduction

This chapter explores the past, present, and future of agricultural technology. It is difficult to define 'agricultural technology', or its more commonly used abbreviations 'agri-tech' or 'agtech'; a review of the literature will not give a definitive definition. Some papers have attempted definitions of the 'digital agricultural revolution' (Bertoglio *et al.*, 2021), 'agriculture 4.0' (Barrett and Rose, 2020; Klerkx and Rose, 2020), 'precision agriculture' (many definitions – see Miles, 2019), and other similar variants, such as 'precision livestock farming' (Berckmans, 2014). But, there is no consensus about what we mean by agricultural technology. For many, agricultural technology refers to the high-tech, including technologies such as artificial intelligence, robotics, remote sensing, and decision support systems. For others, the term refers to lower-tech items, such as milk bottles, string, a Swiss Army Knife, radio, or a set of scales. Some people speak of innovation, rather than technology, which can be defined as 'doing something differently' and thus is much broader than a tangible piece of technology. A key lesson from the literature is, therefore, that policy-makers, funders, and other actors who set the direction of agriculture, equate agricultural technology with 'high-tech' only at their peril – because it risks diverting attention away from existing technologies, which could be better implemented and for which evidence proves benefit (Klerkx and Rose, 2020).

For the purposes of this chapter, we do not make a tacit judgement of what agricultural technology specifically refers to. Rather, we attempt to provide an overview of the evolution of agricultural technology over time, the spectrum of technologies from the high-tech to the low-tech, and envision what agriculture of the future might look like. We explore the possible benefits and drawbacks of the so-called fourth agricultural revolution, including who is most likely to win and lose from the increased use of sophisticated technology on-farm, and we also identify key questions to consider as we move towards this so-called revolution.

2. 'The Past'

Agricultural change has been defined by long periods of stagnation and short periods of rapid change. Although demarcations of revolution events in agriculture vary, one school of thought is that there have been three previous agricultural revolutions - the first occurring when hunter-gatherer societies moved to settled agriculture, the second associated with new technologies developed before the Industrial Revolution in Britain, and the third coinciding with the post-Second World War 'Green Revolution' in the developing world as new technologies (e.g. seed varieties) were exported from developed countries overseas (Rose and Chilvers, 2018).

Research has shown, however, that this is a Western-centric and oversimplified view of agricultural change, focusing selectively on apparent headline moments, and ignoring the non-linear reality of technological development and uptake. As van der Veen (2010) argues, the term 'agricultural revolution' has often been used to describe the end point in which many different innovations have come together over a long period of time, adding up to a magnitude of change, worthy of a revolution. But, focusing on the moment of revolution ignores the slow, non-linear, incremental change that characterises technological change in agriculture. Development and uptake of technology can sometimes be quick (Lowenberg-DeBoer and Erickson, 2019), but this appears to be relatively rare. Two examples help to illustrate the non-linearity of change.

In 18/19th century England, traditional agricultural labourers earned a living by using a flail to manually harvest grains. In the first few decades of the 19th century, however, threshing machines were invented and became increasingly popular with farmers who could save money on labour. A simplified chronological narrative may suggest that threshing machines were a better technology than the simple flail and thus were adopted relatively quickly and without controversy. Yet, this would ignore the huge controversy created by the introduction of threshing machines, which were resisted by labourers. As people lost their jobs, a series of so-called 'Swing Riots' occurred across southern and eastern England with threshing machines smashed and burned. Though the impact of such resistance was relatively short-lived, there were examples of farmers returning to the old method of flailing, at least for a short time (MERL, 2021).

A more famous narrative of technological improvement in agriculture is the so-called 'third agricultural revolution' or the 'Green Revolution' as it is better known. Popular accounts of the Green Revolution tell a story of Western-led technological improvement across the Global South, particularly in Asia, which increased yields and saved hundreds of millions of people from starvation. On the face of it, therefore, the Green Revolution appears to be an example of linear technology uptake, which led to positive benefits for all. Yet, scholars have critiqued this 'political myth of the averted famine' (Pielke Jr and Linnér, 2019), arguing that improved yields came largely as a result of improved weather and changing agricultural policies, as well as labour-saving mechanisation and plant breeding advancements. There are accounts of long-term innovation by farming communities across Asia and South America which led to improvements masked by the claim that Western technology saved the day (Kumar *et al.*, 2017). Furthermore, there are many studies that explore the negative consequences of new technologies associated with the Green Revolution from labour displacement, to the seizing of more power from rural communities, and a rise in social inequality (Shiva, 2016). But, as Pielke Jr and Linnér (2019, 278-279) argue:

> *"[f]amine averted by the intervention of scientific genius is a much more straightforward narrative than a famine-free story of incremental, accumulating, multi-factor progress in local agricultural production due to a complex tapestry of societal and political actors."*

Change is thus rarely caused by the introduction of a radical, 'high-tech' product, but rather by the accumulation of low-tech and non-tech innovations. Farmers still use old equipment; a BBC Farming Today tweet[i] to ask for examples of old machinery still in use today saw farmers respond with working tractors from the 1940s.

There can be no doubt, however, that agricultural technology has been transformative over the whole period of settled agriculture, but such transformation often takes time. 'Diffusion of innovations' does occur, if not perhaps in the linear fashion implied by those who use Rogers' (1962) framework. Precision agricultural technologies, such as GPS-guided tractors and variable rate seeding and chemical application, are now relatively widespread in developed countries, but this did not happen overnight (Griffin *et al.*, 2017; Lowenberg-DeBoer and Erickson, 2019). In these countries and the developing world, farmers have started to use various technologies such as mobile phone apps and other decision support systems (FAO, 2019). But, equally new technologies have appeared by farmers 'tinkering'; retro-fitting new things to the old and shaping them to suit their farm (Klerkx and Rose, 2020). There are also examples of agricultural technologies that were never implemented at scale, such as the 'dungledozer'[ii] designed to spread manure, but these are readily forgotten from the annals of history.

Although this introduction to the history of technological change in agriculture is brief and simplifies the nuanced work of agricultural historians, its purpose is to show that 'evolution' is a better word to describe change in farming than 'revolution' (but we stick with 'revolution' for this chapter as this is currently the more commonly used phrase). Adoption of new technologies are often made possible by the convergence of a number of innovations in policy, society, and institutions, which have a much longer history. Sometimes technological change can be resisted, new technologies emerge through tinkering on the farm and not as a result of a scientific breakthrough attributed to a famous scientist or engineer, and old ideas return to the mainstream (e.g. traditional ideas of regenerative agriculture). Though the past can rarely be used to predict the future accurately, as the context is always different, it does suggest that the so-called 'fourth agricultural revolution' is unlikely to be rapid and that its benefits are unlikely to be spread evenly between actors and across different places in the world.

3. The promise of a fourth agricultural revolution

Digitalisation is occurring across the agricultural sector (Fielke *et al.,* 2020). Current trends in digitalisation are touching smallholder farmers in developing countries, although inequality and the digital divide is still prevalent here, and in many rural areas in the Global North. The penetration of mobile phones, improving network connectivity, affordable smartphone devices, inexpensive mobile data, widespread adoption of mobile money platforms and social media, availability of satellite imagery, enhanced weather forecasting, and remote sensing, are some of the drivers that are leading to the use of digital innovations across the agri-food value chain in the Global South, with some examples provided by the World Bank (Schroeder *et al.*, 2021) and the FAO (2019).

Moving beyond mere digitalisation of agriculture, we now may be in the midst of the so-called fourth agricultural revolution (Rose and Chilvers, 2018). Though the 'fourth agricultural revolution' is poorly defined, it tends to be associated with the use of particular technologies. These include, but are not limited to, gene editing, cultured meat, robotics, AI and machine learning, drones, blockchain, cameras and wearable tech to monitor animals, and the Internet of Things (IoT) (Klerkx and Rose, 2020). Robotic automated milking has been adopted to various degrees in different countries; on 30% of dairy farms in Iceland and Sweden, 20-25% in Denmark, The Netherlands, Norway, Belgium, and Switzerland, with less than 10% adoption in Canada, the UK and the USA (Eastwood and Renwick, 2020).

In the context of precision farming, Miles (2019, 2) describes how emergent agricultural technologies are talked about in the popular press and marketing literature as 'changing agriculture for the better from degrees ranging from the cautiously optimistic to the epochal' (see also Duncan *et al.*, 2021). This resonates with a study of how the fourth agricultural revolution is discussed in policy documents and media articles in the UK (Barrett and Rose, 2020). The language reminds us of how previous events of change were described, couched in an implicit or explicit lens of linearity of the 'technological sublime' (Matless, 2018).

Market research is predicting a significant increase in the value of the agri-tech market. Recent AgFunder investment reports found that investment in Farm Tech startups has grown 370% since 2013 and, in 2019, $19.8 billion has been invested in agri-food tech across the world. Birner *et al.* (2021) show that the supply side of digital agriculture is continuing to grow rapidly. They argue that rapid growth is being powered by a 'dramatic' decline in the cost of digital infrastructure, such as high-speed internet and smartphones, as well as the drive to save input costs. The agri-tech market thus has the potential to create jobs and boost productivity across the economy and thousands of agricultural start-ups have already entered the digital revolution (Birner *et al.*, 2021).

It is certainly the case that some of the technologies associated with the fourth agricultural revolution offer potential solutions to sustainability challenges facing farmers. Table 1 summarises some of the potential benefits of this revolution with a selective list of sources for further information.

Agricultural technology is being projected as the solution to many different 'missions' (Klerkx and Begemann, 2020). A recent report from the World Bank called ''What's Cooking: Digital Transformation of the Agrifood System' identifies new technologies as being key to address the Sustainable Development Goals, for example reducing poverty and famine (G1 'No poverty'; G2 'Zero Hunger'). De Clercq (2019, 11) argues that the world has to 'produce 70 percent more food by 2050, using less energy, fertilizer, and pesticide while lowering levels of Greenhouse Gas emissions and coping with climate change'. New technologies are seen as a way of achieving the sustainable intensification (creating more with less) of the food system (Dicks *et al.*, 2019).

Technologies such as drones, artificial intelligence and machine learning, and remote sensing offer the potential to drive better evidence-based decision-making by giving farmers an extra level of precision. If new technologies can collect data at the scale of individual animals or individual plants, rather than more generalised assessments of fields and herds, farmers can undertake more targeted interventions - for example, asking a robot to spray an individual plant, rather than a whole field, reducing inputs and thereby offering financial and environmental benefits (Lowenberg-

DeBoer and Erickson, 2019). Or, allowing the farmer to adjust nutrition of an individual animal to suit its needs, which can again lead to financial and environmental benefits, but also improvements to animal welfare.

As well as this precision of monitoring, technologies have the potential to make resulting data more interpretable by farmers. As the World Bank (Schroeder *et al.*, 2021) predict, the fact that we will move from a scenario where 190,000 data points are produced on-farm each day (2014 figure) to 4.1 million data points daily by 2050, means that new technologies are needed to allow simple decisions to be made from it.

Technologies may be able to replace dull, dangerous, and dirty jobs, which is particularly valuable if specific regions are suffering from a shortage of labour (Christiansen *et al.*, 2020). Indeed, the increasing use of technology in agriculture may drive the recruitment of a younger, more skilled workforce who can design, operate, and repair machines, and occupy jobs in farming which have better defined career prospects (NFU, 2020). We know that many parts of the world, particularly in developed countries such as Japan, Korean, NW Europe, USA, Canada, Australia and New Zealand, struggle to recruit their citizens to do jobs in agriculture because of the stigma of long hours, poor pay, and bad career prospects. Farming lifestyles could be improved if difficult, laborious jobs can be done by technology and there is some evidence that this is driving the uptake of robotic milking. The fourth agricultural revolution could change notions of what farming is and open up the sector to innovative new ideas from outside, as is already being seen with controlled environment agriculture and the development of cultured meat (Sexton, 2020). It has been claimed that vertical farming boosts productivity and uses 95% less water, fertilizer, and nutritional supplements, whilst using no pesticides (de Clercq *et al.*, 2018).

Social media is also allowing farmers to connect better with consumers and can be used for marketing (Phillips *et al.*, 2018), and blockchain may increase data transparency (Yiannas, 2018). In a briefing paper on digital technology, the FAO (2019) use the example of a mobile phone application used by farmers in Kenya to reduce market distortions and plan better, which in some cases led to them receiving higher prices. Some innovators and companies are also exploring the use of the IoT and computer vision to solve the problem of manual grading and assaying, as well as food quality issues.

Technologies, such as gene editing and genetic modification, have the potential to increase productivity further by creating higher-yielding varieties of crops or animals and reducing the susceptibility of crops to pests and diseases (Hickey *et al.*, 2019). Also, drones may be used to identify crops in need of treatment before a human agronomist could with their naked eye.

Electrification of farm vehicles could also play a major role in reducing the carbon emissions associated with agriculture. Furthermore, new technologies, such as small robots, offer the potential for farmers to adopt new production systems that are more environmentally friendly, including agroforestry and strip-cropping (since the robot can navigate in tight spaces) (Rose *et al.*, 2021b).

Table 1: Potential benefits of the fourth agricultural revolution

Theme heading	**Theme description**	**Sources for further information**
Opportunities for SMEs	Development of new technologies can create business opportunities	AgFunder (2019)
Contribution to economy	Agri-tech development can make a contribution to the wider economy	AgFunder (2019)
Monitoring and data collection	Facilitating fine-scale data collection from an individual plant or animal (e.g. wearable animal tech, sensors, decision support)	NFU (2020)
Higher yields and profitability	As a result of evidence-based decision-making, lower input costs, and the development of higher-yielding, more tolerant varieties (e.g. gene editing)	Hickey et al (2019) Lowenberg-DeBoer and Erickson (2019)
Addresses some of the	Potential to address goals such as reducing poverty and hunger	Schroeder *et al.* (2021)

Sustainable Development Goals		Herrero *et al.* (2020)
Replaces dull, dangerous and dirty jobs. Improve lifestyles	Automation (e.g. AI/robotics) can replace manual jobs and free up time for the farmer	Rose *et al.* (2021b)
Addresses labour shortages	Automation could address labour shortages in parts of the world	Christiaensen *et al.* (2021)
Attracts new workers	Attract younger, high-skilled workers. Farming suffers from low formal skills, and an ageing workforce	Bock *et al.* (2020) RBC (2019)
Improved gender equality	Technology could change gender-based, false stereotypes of the industry	NFU (2020)
Improved eco-efficiency	Facilitating less chemical inputs, enabling land sparing, aiding agroecological system change. (e.g. variable rate application, higher yielding varieties, using non-traditional land through vertical farming or cultured meat)	Dicks *et al.* (2019) De Clercq *et al.* (2018)
Contributes to net zero	Reducing animal emissions (methane capture), smaller robots plus electrification	NFU (2020) Rose *et al.* (2021b)
Connects with consumers	Social media, blockchain etc. may increase transparency and consumer trust in food	Phillips *et al.* (2019) Yiannas (2018)

4. The ethics of the fourth agricultural revolution

While the potential promises of technology are exciting, we should not forget to also consider their potential drawbacks. In recent years, an increasing number of researchers are warning that we need to be more wary of the potential (unanticipated) negative consequences that technological development might bring with it; especially in relation to social aspects. They highlight that once new technologies are implemented, it becomes highly difficult to counteract their negative consequences and that, therefore, we need to carefully consider them throughout the entire innovation process and not address them as an afterthought (Eastwood *et al.*, 2019; Klerkx and Rose, 2020; Stilgoe *et al.*, 2013; Sveiby *et al.*, 2009). When it comes to potential social consequences of new technologies, we need to be aware of the disruptive, normative, and political nature of technological innovation (de Boon *et al.*, 2021).

If we consider innovation to mean a change from an old to a new state, or a change in behaviour (Duru *et al.*, 2015; McKenzie, 2013; Spielman *et al.*, 2008), then technological innovation is disruptive as it requires the destruction of the old state or old behaviour. This disruptive nature can come forward on a small scale, but it also has the potential to change entire societal structures (Blok, 2020; Loorbach *et al.*, 2017; Voss and Bornemann, 2011).

This disruptive nature of technological innovation does not always have to be negative, and when used carefully, can help us to move away from unsustainable agricultural practices. However, whether or not a certain disruption will be seen as positive or negative is a highly normative question. Potential changes brought by a new technology will be experienced and valued differently by different people. In addition, people will have different perceptions on the acceptability of potential (negative) consequences and the potential kinds of farming futures that the innovation will contribute to (Köhler *et al.*, 2019; Leach *et al.*, 2007; Markard *et al.*, 2012). For example, some people might prefer a technology driven farming sector where farmers do not have to work in the field, others might prefer the agricultural sector to be dominated by vertical farming or by agroforestry, while others might want the sector to become completely organic, etc. Underlying all of this is the normative question of whether technological fixes to our problems are the right way to go, or if instead we need structural changes to the way we organise our society and treat the earth (Scott, 2011).

Because of the disruptive and normative nature of technological innovation, it is a political process. It is political because it forms a battleground for different interests who all compete over the power to influence how the agricultural sector will develop, which normative views are taken into account and which ones are neglected. These processes ultimately shape how resources, life chances, and well-being are distributed in society (de Boon *et al.*, 2021).

Thus, for the many promises offered by new agricultural technologies in section 3, there is the potential for negative social, environmental, and ethical consequences. These are being increasingly investigated by social scientists, with much of this work brought together in reviews by Klerkx *et al.* (2019) and Fielke *et al.* (2020). New technologies are unlikely to be desirable for everyone (Fleming *et al.*, 2018). Table 2 highlights some of the potential negative impacts of the fourth agricultural revolution with a selective list of sources for further information.

Whilst the collection of more data at a finer scale brings many potential benefits, there are concerns over who benefits from data collection and who owns it. In a survey of 1000 Australian farmers, Wiseman *et al.* (2019) found that only 9% had a good understanding of the terms and conditions of data collection by service providers and 67% would not feel comfortable if it was used to make profits for these providers. We have recently seen protests across India, partially driven by the perception that smallholder farmers were losing power over their farms, and there is widespread concern about the dilution of farmer expertise and autonomy. Brooks (2021) worries about the creation of so-called 'cyborg farmers' as they are configured to act with less autonomy in a world where 'algorithmic rationality' rules (Miles, 2019; Carolan, 2020). If we see the fourth agricultural revolution as a 'progressive transfer of autonomy to other human agents' (Higgins, 2007, 268), such as already powerful technology companies (and large ones rather than Small and Medium Enterprises), the power to decide and to shape the means of production moves further away from the farmer. Practical knowledge may be diluted and different stresses caused by new technology (Barrett and Rose, 2020). In parts of the world where corruption is rife, including in government, the use of technology to reduce the autonomy of smallholder farmers has an even greater potential to do harm.

Lack of data interoperability is a significant concern (Kalatzis *et al.*, 2019). Different technologies used on-farm designed by different companies may not speak to one another, presenting a huge challenge to farmers trying to interpret the collected data. Furthermore, some farmers find it easier to adopt new technologies than others; for example, those with higher cashflows, more skilled staff, higher skills, better rural infrastructure, and better social capital to network (Rose and Chivers, 2020). We have seen, for example, with the development and implementation of automatic milking systems that the existing societal structure of the industry has changed because smaller farms were not as capable to adapt to this innovation as larger farms. This resulted in the industry being left with fewer but larger farms (Tse *et al.*, 2017; Vik *et al.*, 2019). Benefits of the fourth agricultural revolution will, therefore, not be spread evenly across farming populations. Some of these adoption issues, such as poverty, low skills, and poor rural infrastructure, may be more pronounced in some parts of the world than others (Schroeder *et al.*, 2021). Furthermore, there is the potential for digitalisation to benefit larger companies more than the thousands of SMEs that have recently entered the sector (Birner *et al.*, 2021).

Whilst automation offers the potential to fill labour gaps and reduce dangerous jobs, there is a chance of displacement; displacement of these dangerous jobs to other industries to mine materials for these new technologies, and of traditionally-skilled agricultural labourers who find it difficult to re-train to suit a changed workplace (Rotz *et al.*, 2019). It is important to note that many parts of the world are not suffering from a shortage of labour. Whilst COVID-19 undoubtedly presents a short-term threat to safe working conditions on-farm, there is the potential for automation to exacerbate unemployment in parts of the world where traditional farm work is a major employer. Improving working conditions and pay may be an alternative to draw more workers towards farming rather than replacing them with technology.

Health and safety concerns, as well as cybersecurity issues, have been raised with new technologies, such as autonomous robots (see section 2.4). Although existing technologies can cause many injuries and deaths to farm workers, new autonomous technologies have the potential to injure or kill workers or members of the public accessing farmland (Sparrow and Howard, 2020). Determining the responsibility for injuries caused by autonomous machines is more challenging to navigate (Basu *et al.*, 2020). Such technologies are also open to hacking and data theft (NCC, 2020).

As well as the possibility that new technologies will not deliver their promised benefits in practice, some unintended consequences of trying to make environmental gains may occur. Whilst cultured meat, for example, attempts to reduce the burden of traditional meat production, sparing this land from being used by greenhouse gas-emitting livestock, research has suggested that alternative systems can have higher energy costs (Mattick *et al.*, 2015; Lynch and Pierrehumbert 2019). We also do not know whether consumers will have concerns about new methods of producing food

(Regan, 2019; Specht *et al.*, 2019); for example cultured meat, or from controlled environment agriculture or systems using wearable livestock technologies (Schillings *et al.*, 2021a).

Table 2: Potential drawbacks of the fourth agricultural revolution

Theme heading	Theme description	Sources for further information
Data ownership	Concerns over who owns and benefits from data collection	Wiseman *et al.* (2019) Lioutas *et al.* (2019)
Lack of interoperability	Technologies do not work together on the farm (e.g. made by different companies)	Kalatzis *et al.* (2019) Phillips *et al.* (2019)
More power to big companies/lack of benefits to individual farmers	Tech companies benefit most. Farmers locked into repairs and upgrades from the same manufacturer.	Klerkx *et al.* (2019) Bronson (2019) Duncan *et al.* (2021)
Lack of innovative capacity	Smaller farms, with less staff, lower cash flow, fewer skills, and lower social capital find it harder to adapt	Rose and Chivers (2020) Vik *et al.* (2019)
Greater intensification of the food system	New technologies could facilitate more intensive monoculture	Miles (2019) Thomson *et al.* (2019)
Consumer backlash	Consumers might not like how food is being produced	Regan (2019) Specht *et al.* (2019)
Labour displacement	Loss of jobs for traditional agricultural workers who cannot re-train plus potential disruption to advisor roles	Rotz *et al.* (2019)
Increased energy use	Non-traditional systems (e.g. cultured meat, vertical farming) may have a high energy input	Mattick *et al.* (2015) Lynch and Pierrehumbert (2019)
	New technologies can create an	

Increased stress on farmers	‘always on’ culture and data can be difficult to deal with	Barrett and Rose (2020)
Loss of practical knowledge	More sophisticated technologies can reduce farmer autonomy and erode practical knowledge creating a ‘cyborg farmer’	Brooks (2021) Carolan (2020) Higgins (2007) Miles (2019)
Health and safety	New technologies may not work within current regulations and may cause danger to workers or the public	Basu *et al.* (2020) Lowenberg-DeBoer *et al.* (2021) Sparrow and Howard (2020)
Cybersecurity	New technologies could be open to hacking and data theft	NCC (2020)

Two cases of precision livestock technology and autonomous robotics help to show how a single piece of technology can both offer great potential to drive sustainability, helping people, production, and the planet (Rose *et al.* 2021a), but also simultaneously cause negative impacts, whether intended or unintended (figures 1 and 2).

Precision Livestock Farming (PLF) technologies are designed to help farmers monitor their animals and assist them in making effective management decisions which could result in improved productivity, better animal health and welfare, and reduction of costs (Berckmans., 2014). PLF technologies can monitor a variety of parameters in a real-time, automatic and continuous way. These can, for example, detect diseases at an early stage and alert farmers through notifications on digital devices such as computers or smartphones, indicating which specific animal may require particular attention. However, there are potential drawbacks depending on how these technologies are used and how they may influence management decisions. Some of the potential benefits and challenges of using PLF technologies are described in figure 1 below (see also Schillings *et al.*, 2021a; 2021b).

Figure 1: The potential benefits and risks of Precision Livestock Farming technologies

Likewise, autonomous robotics in farming offer great potential to address labour shortages, reduce chemical use, switch to agroecological systems, create new jobs, and reduce input costs (Rose *et al.*, 2021b). However, there are concerns over their role in labour displacement in parts of the world where rural unemployment is high, as well as safety and cybersecurity threats, reliability and cost issues, and that they could facilitate greater intensification (Sparrow and Howard, 2021). Figure 2 summarises these points.

Figure 2: The potential benefits and risks of autonomous robotics in farming

5. The future of agricultural technology

If we are on the cusp of a so-called fourth agricultural revolution, the future of agriculture may be very different from the past and present. Various reports, including 'Farmers of the Future' from the EU Commission (Bock *et al.*, 2021) and 'Farmer 4.0' (RBC, 2019), project a digitalised future where farmers will need new skills and will perform non-traditional roles. However, there are different potential futures for agriculture including agroecology, the introduction of new technologies, or the combination of both. Agroecology is the application of ecological concepts and principles in agriculture. Technologies include nutrient cycling, soil biological activity, organic matter accumulation, resource conservation and regeneration (soil and water), and natural control mechanisms including the biological control of weeds and insects along with disease suppression (Lang and Heasman, 2015). Agroecology is often presented as a 'bottom-up approach' providing an alternative set of principles and practices for organising the food system (Anderson *et al.*, 2019; Lang and Heasman, 2015). Some people see high-tech futures as different from agroecological futures, but this often results from a misconception of how technologies can be used (Miles, 2019; Castell *et al.*, 2021; Little, 2019).

To ensure that we can make use of the positive potential of technological innovation whilst simultaneously mitigating the potential negative consequences and being wary of its normative and political implications, it is essential that we do our best to anticipate potential consequences early on. Understanding governance of technologies means taking a step back and examining governance of the whole food system. Technologies add to the complex entanglement of challenges associated with the food system such as health, the environment, social values and trust, culture, jobs, and the wider economy (Lang, 2021). A clear example of this is the introduction of genetically modified maize in Mexico. For Mexicans, maize is culturally important as a crop and as food, and is a fundamental component of both urban and rural people's diets (Carro-Ripalda *et al.*, 2015; Fitting, 2014; Fitting 2006). The introduction of genetically modified maize was seen as a form of imposed globalisation with traditional practices of seed saving threatened (Carro-Ripalda *et al.*, 2015). Just as with other areas of the world, corporations were benefiting from the introduction of GM maize as opposed to Mexican farmers and smallholders (Little, 2019).

If large corporations are seen as driving change without wider input, this can be problematic. They can dominate global and regional food systems, leading to the concentration of power (Howard, 2016; Lang and Heasman, 2015). For farmers, using agricultural technologies may mean they become tied to an organisation such as for servicing and repairs as has happened with John Deere (Dauvergne, 2020). Also, companies such as Bayer-Monsanto, BASF, and DowDuPont have long dominated the global market for seeds, fertilisers and agri-chemicals (Dauvergne, 2020; Howard, 2016; Lang and Heasman, 2015). Rather than challenging the underlying social, political and economic structures of the global food system, technologies may reinforce existing structures.

For more responsible futures, therefore, all types of actors need to be involved in decision making processes, not least because building socio-technical networks is vital to the success of technology systems (Higgins, 2007). The main approach in the agricultural literature, and which is also endorsed by the European Union to help support these efforts, is Responsible Research and Innovation (RRI). It consists of four components that all address ways to improve our capacity to anticipate consequences and also highlight the importance of reacting to the new insights that we gain (Eastwood *et al.*, 2019; Rose and Chilvers, 2018).

The first component is *anticipation*. Within this component the approach stresses the need to explore 'what if' questions, to systematically examine what we already know, consequences that may be likely, plausible, or possible, both in the short and in the long term and across all societal scales (Stilgoe *et al.*, 2013). Examples of methods that can be used for these kinds of explorations include scenario studies (van de Poel *et al.*, 2017) and foresighting (e.g. Fleming *et al.*, 2021).

The second component, *reflexivity*, invites innovators to critically assess their own assumptions, perceptions, value system, actions, and the limits of knowledge, and to recognize that these might block or steer their imagination of potential consequences (Eastwood *et al.*, 2019). Developing and using critical codes of conduct or standards could be helpful to support these reflections (Rose *et al.*, 2021b). In addition, these conversations need to be opened up to the public so that conflicting views can be brought together and steps taken to reach compromise (Stilgoe *et al.*, 2013).

Inclusion is the third component of the RRI approach. It relates to the inclusion of stakeholders throughout the innovation process. Potential methods that can be used for this purpose include workshops, user-centred design, and citizen panels (Eastwood *et al.*, 2019). When including stakeholders into the innovation process it is important that the process is not dominated by the 'usual suspects' and that attention is given to power inequalities between the stakeholders. Including a wide range of stakeholders in the innovation process can help support anticipatory efforts as it broadens and diversifies the knowledge that can be taken into account in anticipatory exercises (Rose and Chilvers, 2018; Rose *et al.*, 2021b).

The final dimension, *responsiveness*, highlights that none of the aforementioned components matter if we do not act on the insights that we gain through them. It stresses the importance to act upon newly gained insights, to adapt our innovations accordingly, and in some instances withdrawing the innovation altogether if it is not considered desirable by society. Potential methods to increase responsiveness include value-sensitive design and stage-gating (Eastwood *et al.*, 2019; Stilgoe *et al.*, 2013).

A recent perspective by Rose *et al.* (2021b) argued that a relatively small number of methods had been used to-date for the purpose of engaging publics on the issue of autonomous robotics in farming; mainly surveys or demonstration events. It is argued that more substantive methods of public engagement, such as citizen juries and deliberative workshops should be used, alongside innovative methods such as science-fiction movie nights, in order to stimulate the question of what future different people would like to see. One possibility to govern more responsible approaches is an observatory or coordinating body, and this has been proposed for gene editing (Burrall, 2018). An observatory or coordinating body enables different types of actors to ask questions and could stimulate conversations about an agreed set of standards, regulations, and codes of practice for the development and use of technology on-farm (see draft Australian code of practice for use of autonomous vehicles[1]). With gene editing, we should be asking what 'new beings, for whom, and out of whom' (Haraway, 2018: 58) are being produced? This question is important for agriculture, social and environmental justice, democracy, and the environment, because plants, animals, and seeds are becoming part of the bio-genetic economy, with companies profiting from life itself (Braidotti, 2019). Answering questions like this about technological futures in agriculture, means taking into account both science and the concerns associated with values and beliefs. However, deliberation activities only work if the background issues of who gets to ask a question, and which questions and concerns are excluded, are also addressed (Jasanoff and Hurlbut, 2018).

6. Conclusion

Though the fourth agricultural revolution and the technologies associated with it promise much, it is not the first time in history that farming has been on the cusp of change. We have shown how farmers have always innovated and that technological change does occur, but often in a non-linear way, punctuated by controversy, mis-steps, and the resurrection of old ideas. Technological change is disruptive and decisions over desirable trajectories are always normative. It would be unrealistic to think that the fourth agricultural revolution is going to see the rapid uptake of technologies without negative and unintended consequences. New technologies promise much to people, production, and the planet, and many of the innovations being heralded may well make a significant contribution to sustainability. But, there will also be inevitable disruption. There will be winners and losers and the voices of the potential losers, those already with less power such as smallholder farmers and their families, are likely to be unheard unless decision-makers embrace methods of responsible innovation. Unchecked techno-optimism has the potential to sideline these important issues and put faith in high-tech silver bullets at the expense of low-tech or non-tech innovation, or socio-political change, that could make an equal or bigger contribution to achieving sustainability. The progress of the so-called revolution is most likely to be halted by the inadequate inclusion of citizens in determining desirable futures, leading to an unsatisfactory consideration of

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[1] https://www.harper-adams.ac.uk/news/203570/code-of-practice-for-autonomous-crop-equipment-planned

social, ethical, political, and legal issues. In setting futures, therefore, decision-makers should be mindful of the tinkerer, as well as the radical technologist.

The research community has a key role to play in ensuring that transitions towards new forms of agriculture are fair and just for all stakeholders and this will require a major trans-disciplinary effort. Several papers have identified key questions that need to be considered, including reviews by Klerkx *et al.* (2019) and Fielke *et al.* (2020), and a forward-thinking piece by de Boon *et al.* (2021), who specifically set questions for researchers, innovators, and society at large to examine collaboratively, aimed at exploring the normative, disruptive, and political dimensions of transitions alongside a list of possible methods to support these efforts. De Boon *et al.* (2021) argued that there are six partially overlapping stages of agricultural innovation processes at which various questions should be posed, such as for example:

Stage 1: Problem and goal formulation – exploring perceptions on the underlying drivers of problems that need addressing and values that are strived for in the aimed for goals, as well as potential alternative problem and goal formulations.

Stage 2: Idea generation – investigating the values underpinning suggested ideas, for example specific technological solutions, and the consequences of different futures, closed-down alternative visions, trade-offs, and who these affect.

Stage 3: Concept/prototype development – articulating who the technological solution is for and benefits, the resources needed to develop it, and its consequences for farmers with differing capacities to adapt and innovate.

Stage 4: Concept/prototype testing – interrogating the criteria used to measure whether a tested technology is beneficial or not, and for whom, and whether they take into account the views of all stakeholders.

Stage 5: Implementation – exploring the trade-offs involved in implementation, whether the solution is beneficial for all, which farmers can adapt easier than others, and the consequences of implementation at scale for the structure of the farm industry.

Stage 6: Monitoring and evaluation – considering the criteria used for monitoring and evaluation, their underlying values, and whether lessons are learned to alter the technological solution or process.

Across all stages – exploring which stakeholders are involved, how they are involved, which types of knowledge are influential, and whether there are mechanisms in place to allow technology trajectories to be set by all actors equally (not just the most powerful).

Thus, there is considerable work to be done to explore the process and consequences of transitions towards a so-called fourth agricultural revolution and such research is likely to involve a range of participatory methodologies suggested by de Boon *et al.* (2021). Ultimately, we should be motivated to investigate not only the 'exciting' parts of the fourth agricultural revolution, but also the 'scary' aspects (Rose and Chivers, 2020), and this will require us to employ a range of critical social science approaches from across multiple disciplines (de Boon *et al.*, 2021).

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Figure 1: The potential benefits and risks of Precision Livestock Farming technologies

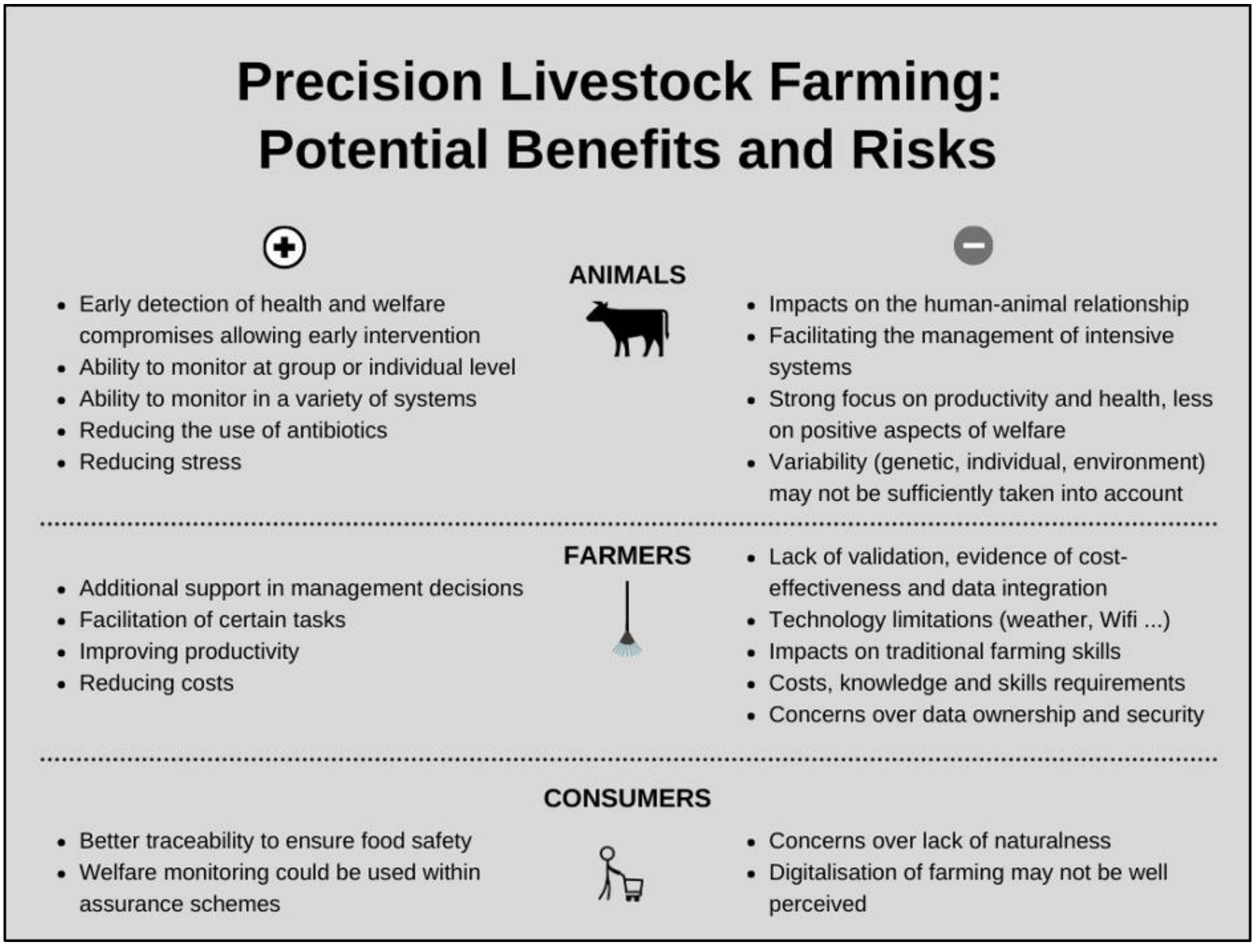
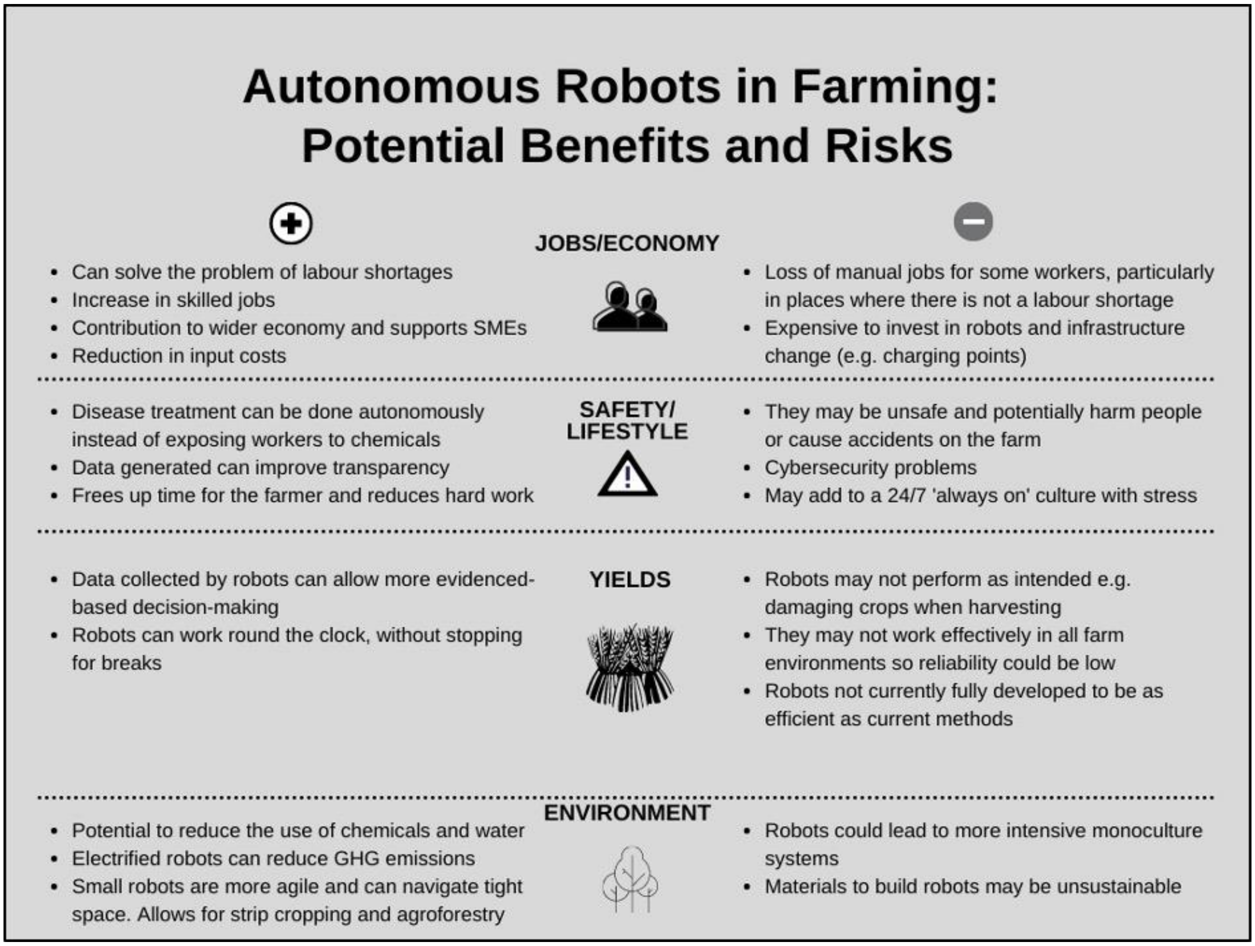


Figure 2: The potential benefits and risks of autonomous robotics in farming



[i] https://twitter.com/BBCFarmingToday/status/1390530582023655424

[ii] https://www.i-bidder.com/en-us/auction-catalogues/cheffins/catalogue-id-cheffi10019/lot-f421f74c-ed39-4398-ad0d-a2e0013ab3f1