Robots in Agriculture: Prospects, impacts, ethics, and policy.

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Abstract

Agriculture is both the site of development of important new technologies and a key area of application of technologies developed elsewhere. It is little wonder, then, that many thinkers believe that progress in the science and engineering of robotics may soon change the face of farming. This paper surveys the prospects for agricultural robotics, discusses its likely impacts, and examines the ethical and policy questions it may raise. Along with the environmental and economic impacts of robots, political, social, cultural, and security implications of the introduction of robots that have received little attention in the larger literature on agricultural robotics are considered. Key policy choices necessary to meet the ethical challenges likely to arise as agricultural robots start to become used more widely, and to maximise the social, environmental, and economic benefits of robots in agriculture, are highlighted.

Keywords: Agricultural robotics; precision farming; ethics; automation/autonomy; sustainability

Robots in Agriculture: Prospects, impacts, ethics, and policy.

Agriculture is both the site of development of important new technologies and a key area of application of technologies developed elsewhere. It is little wonder, then, that many thinkers believe that progress in the science and engineering of robotics may soon change the face of farming. This paper surveys the prospects for agricultural robotics, discusses its likely impacts, and examines the ethical and policy questions it may raise.

The first section of the paper highlights existing and proposed uses of robots in agriculture based on a review of the recent literature and discusses the prospects for robots going forward. The second section provides an account of the impacts and implications of the use of robots in agriculture that should be expected across a number of different domains. A novel feature of this section of the discussion is that, along with the environmental and economic impacts of robots, it includes political, social, cultural, and security implications of the introduction of robots that have received little attention in the larger literature on agricultural robotics. The third section examines the ethical questions that are likely to arise as agricultural robots start to become used more widely. The fourth section of the manuscript highlights key policy choices necessary to meet these ethical challenges and to maximise the social, environmental, and economic benefits of robotics in agriculture.

Prospects

Any discussion of the prospects for robots in any domain must grapple with the problem that there is no universally agreed upon definition of what counts as a robot. A plausible definition is that robot are programmable machines, with sensors and actuators, that can move and/or move things in the world (Sparrow 2020. Compare the 1979 Robot Institute of America definition according to Xie (2003) at p.8). However, as with most definitions of robots, given the extent to which modern devices contain microelectronics, this definition risks including some machines, such as dishwashers and washing machines, that people would not typically identify as robots. It also risks excluding some devices, such as drones, which people *do* often think of as robots despite usually being remote-controlled rather than "programmable". Inevitably, then, any classification of machines as robots or not either involves some reference to "folk" attitudes or be willing to stray widely from the ordinary language use of the term: this paper adopts the former approach here and classifies as a robot those machines identified in the literature as such.

The recent literature reveals the following applications – and proposed applications – for robots in agriculture:

- GPS-enabled, teleoperated, and autonomous tractors and harvesters (De-An *et al.* 2011; Reid *et al.* 2016; Kayacan *et al.* 2015)
- Precision farming systems for the measured application of pesticides and fertilisers (King 2017; Belforte *et al.* 2006)
- Automated and precision irrigation systems (Bergerman *et al.* 2016)
- The use of automation in food handling, processing, and packaging (Caldwell 2012)
- The use of automation in slaughterhouses (Nielsen *et al.* 2014)
- Automatic and robotic feeding stations for livestock (Bergerman *et al.* 2016)
- Robots for meatpacking (Barbut 2014)
- Robotics and automation in textile production (Fantoni *et al.* 2014)

- Robotic milking stations and dairies (Holloway *et al.* 2013; Schewe and Stuart 2015; Hansen 2015; Bergman and Rabinowicz 2013)
- Drones for remote inspection of agricultural infrastructure, especially fences and irrigation systems (Puri *et al.* 2017)
- The use of automation in intensive livestock production (Bergerman *et al.* 2016)
- Drones for rounding up livestock and crop-dusting (Hair 2016)
- Driverless trains (Weichselbaum *et al*. 2013)
- Robots for weeding (Slaughter *et al.* 2008)
- Robotic shearing (Bergerman *et al.* 2016)
- Robotic fruit and vegetable pickers (Bac *et al.* 2014)
- Autonomous trucks for haulage (Meech and Parreira 2011)

This list includes a number of technologies that are already widely used, some that are just coming online, and some that remain mostly theoretical. It deliberately casts the net widely and includes applications of robotics outside of "farming" that will impact on the agricultural sector. The scope of the discussion here is, however, confined to robots and robotics, as opposed to artificial intelligence (AI), despite the fact that it is sometimes difficult to maintain a strict distinction between robotics and AI, given the reliance of many robots on machine vision and machine learning systems. The authors intend to discuss the prospects, impacts, ethics, and policy of AI in another setting.

Despite substantial investments in research and development over a number of decades (Bechar and Vigneault 2016), mobile or "field" robots, capable of autonomous operations, currently have little presence in farming. Field uses of robots in agricultural settings are demanding and ensuring that systems are robust enough for extended use in real-world conditions is difficult (Bac *et al.* 2014; Bechar and Vigneault 2016). Some, if not all, forms of agriculture require tasks to be performed in unstructured environments, which remain challenging for autonomous systems (Bechar and Vigneault 2016; Bergerman *et al.* 2016). Moreover, while some applications and enabling technologies are advancing rapidly, the widespread adoption of robots in many of the applications listed above awaits technological breakthroughs, or at least significant progress, in the areas of battery technology, machine vision in cluttered environments, autonomous navigation, and dexterous handling (Bechar and Vigneault 2016).

For these reasons, further applications of agricultural robotics will most likely emerge gradually as an extension of precision farming technologies in agriculture and the use of automation in food processing and packaging. Many applications are likely to be pioneered in hydroponics, greenhouses, and/or food handling before being rolled out to table-vegetable crops, and orchards. Other systems will develop, relatively independently, in the context of broadacre agriculture and the livestock industry, where automatic milking machines (Schewe and Stuart 2015; Hansen 2015; Bergman and Rabinowicz 2013) already have a significant presence. The vision of a "fully automated" farm is unlikely to be realised for some time, if ever, except perhaps in the form of highly specialised hydroponic operations (Pala *et al.* 2014). For the foreseeable future, most applications of robotics in agriculture will require human supervision of systems with more or less autonomy (Bac *et al.* 2014; Clarke 2017).

Impacts

Should robots come into more widespread use in agriculture they may be expected to have a number of important impacts and implications, which are highlighted in this section. To aid analysis these potential impacts are placed under six headings: environmental; economic; political; cultural; social; and security. Inevitably, the placing of particular issues under each heading is potentially tendentious as the distinction between each set of issues is somewhat arbitrary. Economic relations are themselves political; social and cultural changes may have political import; economic, political, and cultural changes often have implications for the environment. Nevertheless, it is important to at least begin a conversation about how these implications interact by attempting an initial, somewhat tentative, categorisation.

Both potential benefits *and* risks arising from the use of robots in agriculture are identified here. However, it is important to emphasise that very few, if any, of the potential benefits identified below can be guaranteed simply by replacing human beings with a robot. Conversely, many of the risks mentioned are not unique to robots and are also associated with the use of industrial techniques in agriculture more generally. Moreover, while technologies have "affordances" (Norman 1988) – they make it easier, and more tempting, to do some things rather than others (Davis and Chouinard 2016) – and thus politics (Winner 1980), they do not determine the circumstances and the manner of their use: "technological determinism" (Marx and Smith 1994) should be abjured. The ultimate balance of risks and benefits will be a matter of how robots are used rather than that they are used: it is human beings who are responsible for the results of technological deployment (De George 2003; Johnson 2015). As is discussed further below, realising the potential of agricultural robotics will require confronting ethical questions and developing sound policy to minimise the risks and maximise the benefits.

Environmental

Global and local food security are currently facing profound challenges, including climate change, soil depletion, loss of biodiversity, water scarcity, and population growth (Chappell and LaValle 2011). As several authorities have argued, robots may help farmers confront these challenges by improving yield and productivity, while reducing levels of fertiliser and pesticide use, as well as water wastage (Duckett *et al.* 2018; King 2017; Pederson *et al.* 2006). Replacing heavy machinery with lighter teleoperated or autonomous machines may reduce problems associated with compaction of topsoil in agriculture (Clarke 2017; King 2017).

Robots clearly have significant potential here but it is worth emphasising that whether or not this potential is realised will depend upon economic and political choices. It is for instance possible that application of pesticides might actually increase as the costs are of applying them are lowered or that more powerful — and perhaps dangerous — pesticides might be used once human beings were no longer involved in their application. If human workers are replaced by heavier robots this might compound existing problems arising from soil compaction due to the use of heavy machinery in farming. As a result of the standardisation of food items necessary to facilitate the early applications of robots (of which, more below) consumers may come to have an even stronger expectation that all food will be "perfect" (Yue *et al.* 2009), resulting in more food wastage as fewer items are judged suitable for sale.

The implications of robots for environmental sustainability will also depend on the political and economic context of their application. As is the case with precision agriculture more generally, economies of scale are highly important when it comes to robots (Schimmelpfennig 2016; Sheng *et al* 2015; Sheng and Chancellor 2019; Key 2019), which in the short term at least may offer only marginal improvements relative to the agricultural methods they replace. As robots currently perform poorly in unstructured environments, a standard means of improving their performance is to impose more structure on the environments in which they are used. This favours enterprises that have access to sufficient capital to modify the landscapes of, and plantings on, their farms or to modify or rebuild milking, shearing, or food handling facilities to take advantage of automation (Bergman and Rabinowicz 2013). It is possible that the invention of smaller, more sophisticated, mobile robots might change this calculus, if they can be manufactured and sold cheaply enough to be available to smaller farms (Lowenberg-DeBoer *et al.* 2019). For the moment, however, the main manufacturers of farm equipment are, for the most part, concentrating on automating their largest and most expensive products. If larger agricultural producers are able to undercut the prices of small producers by virtue of being able to better realise the cost savings and/or productivity benefits made available by robots, this may lead to smaller enterprises going under and ultimately to further consolidation of, and concentration of ownership in, agriculture (Key 2019; Sheng and Chancellor 2019).

Many of the proposed applications of robots for weeding, fruit picking, food handling also currently founder on the range of variation in the foliage, height, structure, fruit, or edible portion of plants, and the size, shape, and behaviour of animals (Bechar and Vigneault 2016; King 2017). The desire to use robots in these roles is therefore likely to encourage, and their application may even depend upon, further standardisation of the outputs of agricultural production, including the breeding, or creation via genetic modification, of crops and livestock that are better suited to robotic harvest or manipulations (Bechar and Vigneault 2016).

Importantly, the combination of more large-scale industrialised farming and more monoculture is the antithesis of what the United Nations (FAO, IFAD, & WFP 2015) and other experts argue is required to ensure food security, relieve poverty, protect biodiversity, and meet the challenges of climate change (Foley *et al* 2011; Horrigan *et al.* 2002; Thrupp 2000; Diaz *et al.* 2006; Tilman 2002). That is to say, there is a risk that further consolidation of, and concentration of ownership in, agriculture will impact negatively on biodiversity and on the environmental sustainability of agriculture more generally. As is discussed further below, then, realising the benefits of robots for environmental sustainability will require strong policy to encourage the development of robots that can contribute to small-scale, local, and biodiverse agriculture and do not just promote existing unsustainable agricultural practices.

Finally, it has been suggested that robots (in combination with AI) might be used to improve the wellbeing of animals in intensive livestock facilities, by allowing the adoption of feeding and watering regimes that are tailored to individual animals, swifter identification of sick animals, more rapid and individualised administration of medication, more humane veterinary procedures, and more humane and efficient means of slaughter (Jukan *et al.* 2017). Again, it seems possible that robots have something to contribute here, although it should also be acknowledged that, by their very nature, intensive farming practices pose significant challenges to animal welfare, especially once the social and psychological needs of livestock are taken into account. It is possible that some critics might argue that ameliorating the worst consequences of these practices would only work to render them superficially politically palatable to the ultimate detriment of the welfare of animals. Moreover, perversely, the fact that there will sometimes be few human witnesses to the activities of robots may facilitate a higher organisational tolerance for harms to animals and thus actually exacerbate the threats to animal welfare in practice. Again, then, ethical and policy choices will be crucial here.

Economic

Although the environmental benefits of robots feature heavily in accounts of their potential, the reality is that robots are unlikely to have significant environmental impacts unless there is a compelling economic case for their adoption.

An important economic argument for the use of robots in agriculture highlights their potential to increase the productivity and also the profitability of agriculture by allowing more efficient uses of inputs. Precision farming already allows farmers to sow more accurately, harvest more efficiently, and use less water, pesticide, and fertiliser to achieve the same — or even increase – farm yields (Yahya 2018). Improvements in precision farming technology through increased applications of robotics and, especially, autonomous robots may further extend these productivity gains (King 2017). Similarly, the use of automation in food processing, packaging and handling has (for the most part) reduced wastage and enabled products to be shipped to new markets more distant in both time and space: increased use of robots may realise further gains of this sort (Dai and Caldwell 2010). Improvements in textile manufacturing, including more sophisticated automation and the use of robots, have the potential to add value to wool and fibre production (Nayak and Padhye 2018; Saggiomo *et al*. 2018). While outcomes vary widely internationally and between different scales of operation, automated milking systems (AMS) can add value to milk production by increasing milk yield and decreasing labour costs (Tse *et al* 2018). Should autonomous transport technologies come to fruition, producers and consumers may benefit from lower shipping costs due to the adoption of driverless trains and autonomous truck haulage.

The backbreaking nature of much agricultural labour, as well as its intermittent and seasonal nature, means that labour shortages stand as a significant barrier to productivity in the sector (Millar and Roots 2012). If robots can be developed to carry out weeding, fruit and vegetable picking, and (more) food handling and packaging tasks, this would allow farmers to realise dramatic productivity gains by bringing produce to market that is currently wasted by virtue of being uneconomic, or impossible to harvest before it spoils. It may also allow them to farm crops, including heirloom crops, or adopt methods of farming, such as organic farming, which would not otherwise be economically viable due to the high cost of labour. More generally, as is discussed further below, robots may reduce labour costs, by reducing the number of employees required to generate a given level of agricultural outputs.

Inevitably, the pursuit of these benefits of robots will be accompanied by economic risks. For instance, there is a risk that higher capital costs associated with the need to employ robots to compete with other producers might become another barrier to entry into farming and/or food production. The fact that robots will have been designed with existing crops and livestock animals in mind may work to hinder development of new crops and markets for novel animal products (UK-RAS Network 2018). This would be especially unfortunate in Africa, Latin America, and Asia where there is significant potential in this area (Price Waterhouse Coopers 2017). Another possibility is that farmers in some nations, especially in the global South, will be out-competed in particular markets as a consequence of successful adoption of robotics technology by agricultural producers in wealthier countries (Fleming *et al.* 2018). Management of these risks will require good policy.

There is also some danger that, even if such robots can be developed, reliance on robots might lead to increased vulnerability of agricultural systems to climate change. Droughts, fires and floods make it difficult for robots to operate effectively. The emergence of new weeds and pests may require robots to be adjusted or redesigned. Changes in environmental conditions elsewhere in the country and, indeed, the world can radically alter the economics of farming and thus the tasks that need to be performed at any given time. All of these are more likely as the climate changes and global warming accelerates. Even if robots are more productive than human workers, they may be significantly less robust, and production methodologies based around robotics may be less able to adapt to new realities established by climate change within the timescale required (UK-RAS Network 2018).

Political

As this last possible implication makes clear, the economic impacts discussed above are also political insofar as they lead to some groups (for instance, farmers in wealthy Northern nations) being empowered relative to others (farmers in the Global South). There are a number of other ways in which the introduction of robots into agriculture may be expected to alter relations between different social and interest groups and thus the distribution of political power.

In particular, the use of robots is likely to empower capital at the expense of labour. The impact of technology, and especially automation, on agriculture over the last century has been to radically reduce the number of people employed in the sector (Autor 2014; United States Department of Agriculture 2020; Schmitz and Moss 2015). There is little reason to think that robotics will be an exception to this trend. Indeed, as many of the benefits of robots derive from their potential to replace human beings in key roles, it is highly unlikely that robots will be adopted in agriculture unless they do reduce labour costs, by reducing the number of employees required. Thus, the introduction of more robotics into agriculture should be expected to lead to widespread job losses as robots replace people in fruit picking, food handling, food packing, and rounding-up livestock (Werkheiser 2018). These impacts should be expected even though, as noted above, for the foreseeable future most agricultural robots are likely to be semi-autonomous or require human oversight even when operating in an autonomous mode (Bechar and Vigneault 2016), because one person will typically be able to supervise multiple robots. Even if new jobs emerge building and servicing robots, it is unlikely that these jobs will exist in the same locations as the jobs robots eliminate. Moreover, the introduction of robots is often associated with significant deskilling of labour. Increases in the autonomy of machines are often at the expense of the autonomy of those who must supervise them (Carr 2015). In addition, robots often place employees under greater surveillance due to the data gathering capacities of the robot and its associated systems (De Stefano 2018). Higher levels of unemployment in rural areas generated by robots, a decline in the level expertise or experience required to perform the jobs that do remain, and any increase in workplace surveillance will mean a corresponding increase in the power of employers to dictate the wages and conditions of those who are able to find work in the agricultural sector.

Should robots lead to significant job losses in farming and in rural communities and/or further concentrate wealth within the agricultural sector this may also lead to shifts in the social and political relationship between rural and urban populations. Political appeals to the needs of the “man on the land” may fall on deaf ears if the man on the land is perceived to be a robot. If fewer of the people living in rural areas are farm owners or farmworkers in the future, and/or farming comes to be identified with big business, it may become more difficult to mobilise electoral support for policies that address the needs of the agricultural sector. Reduction in the size of the agricultural labour force as a result of the introduction of robotics may have also political impacts in some nations due to the fact that agricultural labour is historically migrant, and occasionally indigenous (First Nations), labour.

Increased use of robots may also impact on the political relationship between farmers and agricultural services providers. By virtue of needing access to high-tech equipment, farmers must already enter into contractual arrangements with agricultural services providers, which severely restrict their freedom to determine how they use these services (Shah 2018). There is a real danger that increased use of robots in agriculture will exacerbate this trend, especially given that robots are likely to be even more complex, contain more proprietary software, and be further integrated into corporate IT ecosystems, than the machines they replace (Carbonell 2016). Control over the data produced by robots is likely to be especially contested (Carbonell 2016; Fleming *et al*. 2018; Wolfert *et al*. 2017).

Social

What about the social and cultural implications of agricultural robotics? The division between social and cultural impacts is somewhat artificial: those impacts that mostly affect how people think and feel as here treated as “cultural” and those with more definite implications for social practice on a daily basis are identified as “social”.

Increased use of robots in agriculture is likely to impact on the social fabric of rural communities, over the longer term, in at least two ways.

First, if robots eliminate the need for significant amounts of agricultural labour, in the future there may be fewer economic opportunities for those who live in rural areas. While it should be anticipated that use of robots will create jobs as well as eliminate jobs (for instance by creating opportunities to farm crops that might previously been uneconomic due to the cost of labour) the skill sets required to build and maintain robots are likely to be very different to those typically possessed by residents of rural areas and thus many of the jobs created by progress in robotics are likely to be located elsewhere (Rotz *et al*. 2019). For example, while the adoption of AMS in the dairy industry has reduced the demand for labourers to milk cattle, it has created a need for farmers to manage increasingly complex IT systems (Tse *et al* 2018; Jacobs and Siegford 2012). If tele-operation of agricultural robots becomes feasible, it may be the case that some jobs on farms will come to be filled by people living hundreds, if not thousands, of kilometres away (Cheein and Carelli 2013). Thus, over the longer term, use of robots in agriculture might lead to significant demographic changes.

Second, if robots lead to further consolidation in the agricultural sector, this may exacerbate inequalities in the distribution of wealth in rural areas. This change in class relations might interact with the social decay associated with underemployment (Howard 2017; see also Fineman 1987; Kates *et al.* 1990) to significantly corrode the quality of life of those who live in rural areas. This might counter the potential lifestyle benefits of the applications of robots, which include increased family time, flexibility of work, and reduced labour intensity (Schewe and Stuart 2015; Stræte *et al.* 2017; Mathjis 2004)

Cultural

Robots are also likely to have implications for the way people think about the natural world, food, and farming.

Modern agriculture has been accused of conceptualising plants and animals solely as inputs into an industrial process (Francione 2010; Franklin 1999; Twine 2010). However, for the most part, it is arguably still the case that people working on farms must, on a daily basis, confront the reality — and the distinctive, non-human, nature — of the organisms that are being farmed as well as the other living creatures that share their environment. There is some danger that robots would further attenuate, perhaps even sever, this relationship. Robotic handling of livestock seems especially problematic and risks treating living animals solely as parts of a larger machine to the detriment of both humans and animals (Franklin 1999; Holloway *et al.* 2013; 2014; Woods 2012).

The vast majority of consumers are already a long way from the farms and the processes whereby the food they consume is produced, with most being notoriously ignorant about what is required to place it on their tables (Brom 2000). A vague cultural sense that food is produced by “robots” might further alienate owners from the realities of food production and facilitate patterns of consumption, such as excessive consumption of red meat, that are now widely recognised to be environmentally destructive (Horrigan *et al.* 2002). Conversely, the rise of robots in agriculture may play into the hands of critics of the way modern farming has improved productivity at the expense of animal welfare (Franklin 1999; Rollin 1990) and may shift the preferences of at least some consumers towards local and organic produce.

Many societies valorise the idea of a “connection to the land”. Those who are thought to have a connection to the land, including indigenous persons and farmers, are thought to possess a special wisdom and are – in theory at least — accorded special respect (Thompson 2017). Some farmers seem to draw comfort in hard times from a self-image that emphasises the value of their struggle to draw a living from the soil (Stock and Forney 2014). If farming ever comes to be mostly a matter of deploying and supervising robots these cultural narratives may be impossible to sustain (Butler and Holloway 2015), which in turn might impact negatively on the social and psychological well-being of rural communities as well as on their relations with the larger society (Bell *et al.* 2015; Klerkx *et al.* 2019, p. 4; Werkheiser 2018, p.186).

Robots may also be anticipated to have significant – if difficult to predict — implications for the (already complex — see Bock and Shortall 2006; Sachs 1996) “gendering” of agricultural labour and farm management (Liepins 2009; Pini 2017). The more work that can be done by robots, the less need there is for farmworkers to be “strong” or to have whatever other virtues are traditionally supposed to be the sole province of men, which may make it easier for women to participate in the formal agricultural workforce. Yet an increased demand for STEM skills in the agricultural sector, as farming comes to require more expertise in the applications of robots and computers (for example as seen with the implementation of AMS: see, Tse 2018; Stræte *et al.* 2017), might work to further exclude women from farming given the historically low rates of participation of women in engineering and other STEM disciplines (Smith 2011).

Security

Finally, the use of robots will generate security concerns. Farms and production facilities that are highly reliant on automation and robotics will become correspondingly more vulnerable to hacking, sabotage, and corporate espionage. While this may seem far-fetched, so-called ransomware attacks targeted at industry have become increasingly common and in some cases have been spectacularly destructive (Greenberg 2018). At a risk of sounding even more paranoid, it would be negligent not to mention the possibility that agricultural systems that rely heavily on robotics and automation might become vulnerable to, and the target of, enemy cyber operations in the lead up to war, or perhaps even simply in pursuit of economic advantage (Clarke and Knake 2010). While it is unlikely that an attacker could succeed in “crashing” a target’s food production in the long-term, the short-term consequences of deliberate disruptions to key technologies at the time of sowing or harvesting, for instance, might be large, and even disruptive in the medium term if over reliance on robotics had led to significant deskilling of the agricultural labour force.

Ethics

Throughout, this discussion has tried to emphasise the diversity of possible outcomes from introducing (more) robots to agriculture as well as the various ways in which these might be shaped by policy choices (Duckett *et al.* 2018). Many of the likely impacts of the use of robots in agriculture may be seen either as “bugs” or as “features”, depending upon the interests of the critic. Choosing between policies that might bring about particular outcomes, or alternatively frustrate them, therefore involves confronting questions of value — which is to say ethical questions.

The range of possible environmental impacts of robots means that their application raises a correspondingly large range of questions in environmental ethics. In particular, by raising the prospect of a profound alienation between farmers and consumers, and the natural world, it raises questions about the implications of such alienation for environmental sustainability and also for the welfare of human beings. Balancing the competing demands of increased yields and environmental sustainability also involves an ethical negotiation. Finally, the robotisation of livestock production highlights questions about the proper extent of human domination over non-human animals.

Economic decisions always implicate ethics, especially in relation to what is left up to the market, regulation and enforcement of contracts, and the definition and distribution of externalities (Satz 2012). Of particular importance, when it comes to agricultural robotics, is the choice between robots that might further encourage industrial farming and consolidation of ownership in the agricultural sector versus robots that might assist smaller enterprises and facilitate the development of more diverse forms of agriculture. Judgements about the appropriate trade-offs between competing ethical concerns (for instance, equity versus efficiency), as well as intuitions about social justice and the distribution of wealth will have a crucial role to play here. Similarly, when it comes to the impacts of robots on levels of employment in the agricultural sector, ethical questions about the extent of society's obligation to provide people with the opportunity for meaningful labour will come to the fore, as well as (again) about social justice. It must also be observed that there is a significant ethical case "for" the elimination of jobs that are "dull, dirty, and dangerous" and that some forms of agricultural labour are all of these (Byard 2017).

Changes in the distribution of political power are always ethically inflected, as are shifts in social relations and cultural understandings. Given that there is a significant risk that robots will contribute to the concentration of political power in the hands of large corporations, designers, and employers, exacerbate inequalities between urban and rural areas, and further alienate human beings from the natural world, there are *prima facie* grounds for ethical concerns here (See Klerkx *et al.* 2019). Nevertheless, the urgent need to move towards more sustainable agricultural practices while, at the same time, meeting an increased demand for agricultural produce globally means that there is a strong ethical imperative to explore how robots might be used to advance these goals.

Policy

Good policy to guide the application of robots in agriculture will be determined by answers to these ethical questions as well as by pragmatic considerations that are mostly beyond the scope of this discussion. Insofar as there is room for reasonable disagreement on the ethical questions it is not appropriate for the authors to try to pre-empt the policy debate here. Indeed, given the potentially large impacts of agricultural robotics, it is vitally important that, as the "responsible innovation" literature has argued, the broadest possible community be included in this discussion (Eastwood *et al* 2019; Rose and Chilvers 2018). Nevertheless, the following proposals are advanced in the hope that they might usefully inform this larger debate.

The scale of the current global environmental crisis, and the challenge it poses to food security, suggests that every option to try to improve the sustainability of agriculture should be considered. In order to reduce the risk that robots will further centralise ownership in the agricultural sector and further encourage monocultures at the expense of biodiversity governments and researchers might prioritise the development of sophisticated robots which are sufficiently flexible to allow their use on small properties and with a wider range of crops and livestock. Investment in research into the applications of agricultural robotics, and perhaps subsidies for their early adoption, could also reduce the risk that small farms would miss out on the benefits of robots (Fleming *et al.* 2018; Lowenberg-DeBoer *et al.* 2019).

In the longer term it seems highly likely that robots will displace many jobs and put significant numbers of people out of work in rural areas. Thus, a key question is what will replace paid employment in the agricultural sector for those whose jobs have been taken by robots (Srnicek and Williams 2015). A Universal Basic Income (UBI) is often touted as a solution to technology driven unemployment. However, it is doubtful that loss of income is the only negative consequence of unemployment; nor is it clear that a UBI would address the social and political impacts of inequality. Whether or not a UBI is ultimately adopted, then, it will also be necessary to develop policies to reduce the risk that technological displacement of agricultural labour will exacerbate social or economic injustice, including, especially, extremes of inequality. In the shorter term, it will be important for governments to engage with key stakeholders, including farmers, peak bodies, and trade unions, to negotiate and manage the transition to a more automated agriculture. In order to ensure that such discussions are adequately informed, research to quantify the likely impacts of the use of robots in agriculture is urgently required (Lowenberg-DeBoer *et al*. 2020).

As robots come to possess more and more capacity for autonomous operations a number of legal questions will arise (Basu *et al*. 2020). One confronting possibility is that robots will eventually prove to be better than human beings at important tasks, with the consequence that governments come to be subject to ethical and political pressure to make it illegal for human beings to perform that task (Sparrow and Howard 2017). Given the potential for such legal uncertainties to delay the uptake of highly autonomous robots until they can be resolved, legislators and policy makers would be well advised to address these sooner rather than later.

In order to facilitate the adoption of robots it will also be important to address the impact of automation on farmers' relations with agricultural service providers. The extent and nature of the contractual obligations incurred by farmers when they use robots are clearly susceptible to modification by regulation. For instance, while this would undoubtedly prove unpopular with manufacturers, governments might require that all agricultural robots run "open source" software and, perhaps more plausibly, that farmers should be allowed to retain and control the data they produce (Keogh and Henry 2016; Jakku *et al*. 2019). Policy makers will also need to be conscious of the impacts of regulation on the incentives for manufacturers to develop robots.

The vulnerability of robots to hacking is hardly unique to this technology and represents a familiar challenge to be addressed by cyber security researchers and engineers. Nevertheless, the threat to national security posed by cyber-attacks targeting agricultural technologies should be seriously considered and may constitute a reason for states to resist monopolisation of agricultural robotics in order to reduce the risk that an attack on one system or class of systems might have too large an effect.

Conclusion

Public fears and stakeholder anxieties often stand as significant barriers to the development and adoption of new technologies. Failure to address public concerns and redress social and political impacts may undermine the development and deployment of agricultural robots, having a flow on effect on the economy, environment and society. Only by directly confronting the ethical and policy questions can researchers, government, and industry hope to bring the public along with them to embrace the potential of robots in agriculture. This initial survey and discussion of the prospects for, and impacts of agricultural robots, as well as the ethical and policy issues they raise, is intended to serve as a strong foundation for this larger project.

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