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Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?

Laurens Klerkx[a,*], David Rose[b]

[a] Knowledge, Technology, and Innovation Group, Wageningen University, the Netherlands
[b] School of Agriculture, Policy and Development, University of Reading, United Kingdom

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ABSTRACT

Agriculture 4.0 is comprised of different already operational or developing technologies such as robotics, nanotechnology, synthetic protein, cellular agriculture, gene editing technology, artificial intelligence, blockchain, and machine learning, which may have pervasive effects on future agriculture and food systems and major transformative potential. These technologies underpin concepts such as vertical farming and food systems, digital agriculture, bioeconomy, circular agriculture, and aquaponics. In this perspective paper, we argue that more attention is needed for the inclusion and exclusion effects of Agriculture 4.0 technologies, and for reflection on how they relate to diverse transition pathways towards sustainable agricultural and food systems driven by mission-oriented innovation systems. This would require processes of responsible innovation, anticipating the potential impacts of Agriculture 4.0 through inclusive processes, and reflecting on and being responsive to emerging effects and where needed adjusting the direction and course of transition pathways.

1. Introduction

The agricultural sector is currently facing major challenges to feed a growing world population in a sustainable way, whilst dealing with major crises such as climate change and resource depletion (Firbank et al., 2018). At the same time there are major technological advances in the fields of robotics, nanotechnology, gene technology, artificial intelligence and machine learning, and energy generation, amongst many others (De Clercq et al., 2018; NFU, 2019). These new technologies will lead to what commentators have called the 'fourth agricultural revolution', or 'Agriculture 4.0' (Rose and Chilvers, 2018), and encompass a wide variety of potential 'future agricultures' or 'future food systems' which are characterized by high-tech, radical, and potentially game-changing technologies. Previous agricultural revolutions were, of course, radical at the time – the first seeing hunter-gatherers move towards settled agriculture (Agriculture 1.0), the second characterised by innovation as part of the British Agricultural Revolution which saw new machines such as Jethro Tull's seed drill (Agriculture 2.0), and the third involving production changes in the developing world with the Green Revolution (Agriculture 3.0) (Rose and Chilvers, 2018).

At present, 'Agriculture 4.0' is a vague and poorly defined term used to refer to a range of different concepts and technologies, and connected to ideas on the Fourth Industrial Revolution or Industry 4.0 (Zambon et al., 2019). Future agriculture and food systems under the new Agriculture 4.0, which in many cases are already being developed and operational but are yet to come to full scale, comprise concepts such as vertical farming, digital agriculture, bioeconomy, circular agriculture, and aquaponics (Hermans, 2018; Junge et al., 2017; Pigford et al., 2018; Pinstrup-Andersen, 2018; Herrero Acosta et al., 2019). We use the term here to indicate potentially game-changing technologies that can dramatically affect the way food is produced, processed, traded, and consumed. These include technologies such as gene editing, synthetic food production (e.g. synthetic protein), cultured meat or cellular agriculture nanotechnology, microalgae bioreactors, drones, internet of things (IoT), robotics and sensors connected to precision farming technology, 3D food printing, artificial intelligence and machine learning, and blockchain (De Wilde, 2016; Burton, 2018; Klerkx et al., 2019; De Clercq et al., 2018; NFU, 2019; Herrero Acosta et al., 2019; Stephens et al., 2019; Grieve et al., 2019).

It has been noted that Agriculture 4.0 has the potential to be disruptive and transformative in many ways. It may have biophysical, economic and social impacts on food and nutrition security, as well as on the ways in which agricultural production systems are designed and operated. It will also have implications for the way agriculture is embedded in ecosystems and landscapes. Furthermore, it is likely to change the way agricultural supply chains function, and the ways in which products are composed by food manufacturers, sold by retailers,

* Corresponding author.
E-mail address: laurens.klerkx@wur.nl (L. Klerkx).

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bought by end-consumers, and food waste is prevented (Brandt and Barrangou, 2019; Bronson, 2018; Burton, 2019; Creamer et al., 2002; Ezeomah and Duncombe, 2019; Lowry et al., 2019; Rotz et al., 2019; Watanabe et al., 2018). It will likely change the way agricultural innovation systems interact with innovation systems from other sectors (such as energy, building, fashion, digital technology) due to technologies being cross-cutting (Pigford et al., 2018). As Fielke et al. (2019) argue, it is likely to be a once-in-a-generation event that will drastically change production systems and agricultural values, although we note that despite the radicality of Agriculture 4.0 technologies transitions might be slow. Diffusion of new ideas and technologies, for example precision agricultural technologies, is not always quick (Eastwood et al., 2017; Griffin et al., 2017), and generally large scale transformations of sectors takes more than a decade or even several decades (Elzen et al., 2012).

Several authors see in Agriculture 4.0 technologies a possibility to create a new 'Green Revolution' and refer in this sense to 'Green Revolution 2.0' (Llewellyn, 2018; Lowry et al., 2019; Martin-Guay et al., 2018; Marvin, 2018; Pingali, 2012; Pradhan and Deo, 2019; Schurman, 2018; Armanda et al., 2019). Some comentators see Agriculture 4.0 as part of a Digital Agriculture Revolution which may eventually lead to 'Agriculture 5.0' (Fraser and Campbell, 2019). Influential international organisations in the sphere of food and nutrition security such as World Bank, FAO and OECD allude to the potential of Agriculture 4.0 technologies and describe the global state of play in recently published reports (Jouanjean, 2019; Trendov et al., 2019; World Bank, 2019). Thus far, significant amounts of money are being spent in the design and application of Agriculture 4.0 technologies worldwide. For example, there are investments worldwide in large research and innovation programmes on digitalization such as the DigiScape Platform and Food Agility Hub in Australia, the #DigitAg programme in France, and the Internet of Food and Farming programme and Digital Innovation Hubs or SmartAgriHubs in the European Union (Klerkx et al., 2019). Research institutes such as Wageningen University and Research in The Netherlands and AgResearch in New Zealand have strategic investment programmes in 'Protein Transitions' and 'New Zealand Bioeconomy in the Digital Age', respectively (Pyett et al., 2019; Shepherd et al., 2018). CGIAR and CSIRO collaborate in initiatives such as 'Wild Futures', focused on technologies for accelerating food systems innovation towards the Sustainable Development Goals (Herrero Acosta et al., 2019). Giving an example of the amount of investment involved, the UK government have pledged £90 million of public money to transform food production through Agriculture 4.0 technologies, following an earlier £160 million investment (UK-RAS, 2018).

Amidst the clamour to invest in Agriculture 4.0 or Green Revolution 2.0, little attention has been placed on a number of important questions relating to inclusion and exclusion, the impact of Agriculture 4.0 technologies and how agricultural innovation systems can deal with Agriculture 4.0 (Rose and Chilvers, 2018). Little emphasis is being placed on organising the innovation systems that develop and bring them to scale in a responsible fashion, meaning that they contemplate and take into account potentially undesirable consequences ex-ante (Bronson, 2018; Fielke et al., 2019). It has been argued that innovation systems are not neutral, and they can support transition pathways including only certain technologies and food system futures, while excluding others (Schlaile et al., 2017; Pigford et al., 2018). In order to initiate a debate, this perspective starts to address some issues and questions associated with the advancement of Agriculture 4.0, what Agriculture 4.0 narratives mean in terms of inclusion and exclusion and the potential impacts of this (section 2). Then, we reflect on how transitions pathways towards sustainable Agriculture 4.0 can be responsibly organised by mission oriented agricultural innovation systems (section 3). Our intention is not to predict how Agriculture 4.0 technologies will be further developed by agricultural innovation systems, but to give ideas for reflection on how to organise such a process responsibly.

2. Reflections on the current state and emerging and potential impacts of Agriculture 4.0

2.1. *Agriculture 4.0: how far has it actually advanced?*

It is yet to be seen which of the vast array of technologies associated with Agriculture 4.0, such as artificial intelligence and machine learning, robotics, and gene editing will move beyond a niche stage and become implemented at scale.[1] Perhaps some technologies are already at the 'peak of inflated expectations' in the hype cycles that drive expectations as regards to technology developments (van Lente et al., 2013) and they may eventually never materialize. Horizon scanning exercises, using the technology readiness level indicator (NASA, 2012), could begin to ask when some of these technologies will be ready for market and how feasible implementation at scale would be (see also De Wilde, 2016). Initially tacitly, but increasingly explicitly (Trendov et al., 2019; World Bank, 2019), narratives of Agriculture 4.0 have thus identified a number of technologies, some listed above in section 1, that are placed on a pedestal as the game-changing, emergent innovations that will transform food production. However, they seem not all to be currently in a position to improve means of food production at scale (Herrero Acosta et al., 2019), in line with arguments by Zambon et al. (2019) who state that Agriculture 4.0 is still limited to a few innovative firms.

2.2. *What inclusion and exclusion issues does Agriculture 4.0 raise?*

We see a number of problems created by an over-emphasis on emergent, high-tech solutions to our food system challenges, and this has potential inclusion and exclusion effects. Firstly, narratives associated with food security may become even more technocentric. The discourse surrounding food security is currently dominated by neo-Malthusian justifications which see a rapidly growing population as the central problem and technology as the solution (see e.g. Royal Society, 2009; FAO, 2019; Hickey et al., 2019). The rise of Agriculture 4.0 thinking is only likely to extend this narrative towards the high-tech end of the innovation spectrum, further side-lining other responses to food security challenges which are not technology-based. These include social responses to food security challenges, built on the work of scholars such as Sen (1999) and Nally (2016), who have shown that lack of access to food is rarely caused by a lack of food production, but by unequal distribution and entitlement to the food being produced due to societal inequalities. Increasing food production using technology, particularly in the developing world, is not a solution to this problem in and of itself. While technology is important to boost productivity and has indeed contributed to enhancing food security and prosperity, merely generating more food does not guarantee improved food security for marginalised groups (Nally, 2016; Sen, 1999), and Agriculture 4.0 technologies should not be considered a panacea (Fraser and Campbell, 2019). Furthermore, authors such as Nally (2016) speculate that a mere focus on technology would reinforce unequal modes of capitalist production and further take power away from marginalised communities. For example, both for developed countries (Bronson and Knezevic, 2019; Fraser, 2019; Rotz et al., 2019a) and developing countries (Mann, 2018; Trendov et al., 2019; World Bank, 2019) it has been argued that digital technologies may concentrate (already more than currently) power in hands of a few corporate or state players.

[1] We note that there are a variety of technologies associated with Agriculture 4.0, but this has largely occurred tacitly. There appear to be no formal rules through which to determine what an 'Agriculture 4.0 technology' is, but oft-mentioned technologies seem to be emergent, high-tech, and not currently widely implemented on-farm.

Here, in relation to debates on financialization of agriculture (Anseeuw et al., 2017), it has also been noted that there are a lot of acquisitions by existing and new players seeking to find the next 'unicorn' agri-tech company. Though it has been argued that innovation in (conventional) agriculture has traditionally been driven by supplier companies (of seeds, machinery, for example – see Pavitt, 1984; Fuglie, 2016), these new models with a 'winner-takes-it-all approach' or 'platform model' run the risk of further concentrating ownership and control over food systems (i.e. both the production, trade and sales, consumption and waste subsystems) and threatening food sovereignty (Trendov et al., 2019; Klerkx et al., 2019). This reinforces concerns over investments in agriculture having private return on investment as a primary motive instead of serving broader public goods (Clapp, 2014) Furthermore, a technocentric narrative diverts attention away from other ideas such as the degrowth paradigm, which would see existing economic structures as the primary reason for food insecurity and environmental degradation (Feola, 2019). There is thus a consequence of placing certain ideas, such as Agriculture 4.0, on a pedestal without adequate challenge about whether high-tech innovations are the best way of solving some of our most serious food security issues.

Secondly, we argue that the dominance of emergent innovations associated with Agriculture 4.0 could divert money and attention away from currently implementable technologies (or the design of such technologies) that could make a difference now. Rose and Chilvers (2018) argue that there is an 'ecology' or spectrum of innovations in agriculture ranging from the emergent high-tech (e.g. robotics, synthetic protein) to more mundane low-tech products (e.g. a set of scales to weigh cattle).Would it be currently more productive, for example, to encourage beef farmers to weigh their cattle more regularly, which is a proven method for making gains (Tucker, 2017), or to spend time and money trying to use wearable diagnostic technology for which the value is largely still unproven and the human impacts and animal welfare implications unconsidered? Though wearable technology may yield data for analytical purposes, will farmers be able to make full use of this or will benefits mainly accrue to the tech companies selling them and their investors (see also Wiseman et al., 2019)? The most tangible gains on-farm could well result from the better implementation of simple ideas that we already know to work. We note, however, that the potential benefits of such diagnostic technology in terms of data analysis could be significant and that many novel technologies initially meet some scepticism, but in the pursuit of potential future gains, we could risk forgetting to encourage the use of already proven technology.

That is not to say, of course, that the value proposition of Agriculture 4.0 technologies will not improve, but then further problems of implementation are likely to occur. Research in a number of different contexts, including decision support tool use (Rose et al., 2018; Rose et al., 2016), has shown that there are a number of barriers to the adoption of new technologies on-farm, and ingrained habits and lack of operating skills might be more pronounced in relation to new high-tech innovations. Also, farmers indicate that costs of Agriculture 4.0 technologies can be prohibitive (Barnes et al., 2019), and expectations between experts and farmers of benefits of Agriculture 4.0 technologies diverge (Kernecker et al., 2019). This begs the question, therefore, of whether farmers will be able to invest in and use innovations at the high-tech end of the spectrum. Furthermore, it raises the question of how many different types of Agriculture 4.0 technologies farmers will be able to purchase and use. Is it practical to think that our farmers of the future will use robots, drones, artificial intelligence, sensors, all at the same time, or will they have to make a prioritised choice about which technology they can economically afford to use?

Thirdly, it is yet to be seen what connections will be made between the different Agriculture 4.0 technologies (e.g. how does synthetic food production interact with robotics?), and how they will interact with other types of technologies which are not seen as part of Agriculture 4.0 (Grieve et al., 2019). Thus, how are Agriculture 4.0 technologies to be positioned within diverse agricultural and food systems concepts which are being forwarded as solutions to current problems in agricultural and food systems? Agriculture 4.0 is often associated with and seen to benefit large scale, technology intensive and specialized farms (Bronson, 2019) following a conventional agricultural and food system concept, but there are alternative agricultural and food system concepts less associated with 'high-tech', but rather considered to be 'retro-innovation' (Stuiver, 2006). In other words, reconsidering sometimes ancient technologies and practices in new ways, such as commercial mixed crop-livestock systems, as opposed to monocultures, and forms of ecological intensification (Garrett et al., 2017; Tittonell et al., 2016). Examples of these concepts include different strands of agroecology, such as permaculture, regenerative agriculture, and ecological intensification, which may themselves demand the use of various technologies and often incorporate indigenous knowledge (Clay et al., 2019; Ferguson and Lovell, 2014; Gallardo-López et al., 2018; Plumecocq et al., 2018; Wezel et al., 2009). In a standalone way, given their potentially disruptive value proposition, these could be conceived of as 'Agriculture 4.0' and may also connect and integrate with digital technologies (Bellon-Maurel and Huyghe, 2017). Indeed, agroecology and Agriculture 4.0 may be complementary in many ways; research has indicated that farmers are more likely to see them as working together, whereas scientists view the two concepts to be incompatible (Van Hulst et al., 2019).

Research has illustrated another associated problem caused by different agricultural and food system concepts competing in a crowded space, particularly if they are not differentiated from each other and if they try confusingly to pull actors in agricultural and food systems in different directions. Garibaldi et al. (2017), for example, pulled together a list of concepts associated with sustainable agriculture and Rose et al. (2019) used it to assess how the concept of 'integrated farm management' fit alongside them. They found that it was poorly differentiated from similar terms such as integrated pest management which caused confusion amongst the farming community. Such confusion matters because knowledge exchange activities aimed at promoting more sustainable farming practices need to deliver simple, actionable messages to farmers, without leaving them feeling bombarded by a range of different ideas which may be competing. Whilst many of the technologies associated with Agriculture 4.0, such as precision farming, may compliment some of the aims of alternative agricultural and food system concepts concepts such as agroecology, there is also likely to be competition. Thus, communities of agricultural policy and practice need to have clear conversations about how Agriculture 4.0 technologies fit into the already crowded conceptual landscape of sustainable agriculture.

2.3. Inclusion and exclusion: what's the impact?

Agriculture 4.0 thus can generate inclusions and exclusions in terms of who can partake in it and who benefits from it (Rose and Chilvers, 2018; Rotz et al., 2019a, Rotz et al., 2019). This is not necessarily problematic, as from the viewpoint of diversity, co-existence of different agriculture and food systems may occur (Gaitán-Cremaschi et al., 2019; Pigford et al., 2018; Plumecocq et al., 2018). However, when there is no space for diversity and some systems become dominant and hegemonic, this may generate inequalities and injustices which are nondesirable from a human welfare point of view, an animal ethics viewpoint, or an ecosystem integrity and sustainability standpoint (Fraser, 2019; Rotz et al., 2019). The different Agriculture 4.0 technologies and the agriculture and food system concepts they underpin and include (and exclude) have different directionalities; in other words, they steer agriculture and food systems in terms of the set of technologies, markets, institutional arrangements, and values they embody and the transformative outcomes they envision (Kanger and Schot, 2018; Schot and Kanger, 2018; Stirling, 2011), with potentially unknown and unseen outcomes once going to scale (Hartswood and Jirotka, 2016; Scholz et al., 2018; Wigboldus et al., 2016). They may also have different outcomes in different contexts; for example, in developed countries as opposed to developing countries. This is because technology is not context neutral and is also connected to certain configurations of political and economic power, as has been noted for Green Revolution technologies (Eddens, 2019; Gengenbach et al., 2018; Vanloqueren and Baret, 2009) and also for Agriculture 4.0 technologies such as robotics and sensor driven agriculture (Bronson, 2019; Carolan, 2018; Carolan, 2019; Rotz et al., 2019a, 2019b; van der Burg et al., 2019; Wolf and Buttel, 1996). Ultimately, pursuing Agriculture 4.0 is a choice; a choice which makes specific futures more or less likely to occur.

There has been lots of work on the potential for Agriculture 4.0 technologies to transform means of food production, increasing yields and improving eco-efficiency, but only an emerging body of work investigates potential social and ethical impacts (Rose and Chilvers, 2018; Rotz et al., 2019a, Rotz et al., 2019; van der Burg et al., 2019), similar to other work for example scrutinizing ethical aspects of nutrition (Fanzo, 2015). Research is now beginning to explore what Agriculture 4.0 means for farmers with issues relating to where data ownership lies (Wiseman et al., 2019), connection with the land when their farm operation is moving to a sort of control centre (Rose et al., 2018 ; Carolan, 2019). Addicott (2019), for example, explores an advert by John Deere which depicts a vision of a farmer managing their land purely from the office, and describes it as a disturbing, dystopian future. Disruption may occur to farm workers and advisors as the nature of rural employment changes and there is a decrease in demand for these jobs or they require considerable reskilling (Rotz et al., 2019a, Rotz et al., 2019; Eastwood et al., 2019), and the welfare implications for animals are important to understand (Bear and Holloway, 2019). Research has begun to investigate how consumers feel about food being produced and consumed in radically different ways indicating that this will require different views towards food production and attitudes towards choice and consumption of food and disposal of food waste (Borrello et al., 2017; Shew et al., 2018; Gómez-Luciano et al., 2019; Fraser and Campbell, 2019) and how rural communities will change if small family farms are replaced by fewer, larger, more commercial landholdings (Nuthall and Old, 2017) a process which has already been going on for decades the world, but may receive an additional push in view of new concentrations of ownership and new business models (see also Phillips et al., 2019). There are many trade-offs to be considered here. While resolving some issues such as resource inefficiency by offering more precise management options, an efficiency push may also have undesirable side effects. For example, how will the premise of digital technologies reducing need for human labour affect rural employment and rural-urban migration, an issue which affects many developing countries and may have large social consequences (Rotz et al., 2019)? Or, a shift to synthetic foods may reduce the size of land-based sectors (Burton, 2019), which on the one hand could have positive effects (reducing livestock emissions), but on the other hand may have a negative impact on the social and economic fabric of rural areas. Although these potential social and ethical impacts have initially not been part of dominant narratives about Agriculture 4.0, they are likely to become more important as many of the technologies move towards market readiness and hence also have seen emerging policy responses (Jouanjean, 2019; Trendov et al., 2019; World Bank, 2019). In light of the fact that different technologies will be implemented alongside one another, and within a congested space filled with sustainable agricultural ideas and concepts, we argue that more joined-up evaluations of (potential) impact are required. We should not just anticipate the potential implications of specific innovations in isolation, but consider how the use of one innovation alongside another may produce very different outcomes. This leads us to suggest ways for agricultural innovation systems to deal with this.

3. Organising transition pathways responsibly in mission-oriented agricultural innovation systems

It has been widely acknowledged that in transition pathways, the transformative processes leading to new technological and economic systems, processes of co-evolution (technologies evolve with societal structures and have cross-connections with each other), selection (some technologies will not become dominant) and retention (some technologies will evolve into new dominant designs and corresponding social, market and policy structures) occur (El Bilali, 2018; Geels and Schot, 2007; Loorbach et al., 2017). This implies that in the current processes of establishing and scaling Agriculture 4.0 technologies there is likely a lot of interaction between different technologies and the agricultural and food system concepts they underpin. Such interaction may be 'passive' via competitive dynamics through global markets or 'active' through processes of active collaboration, competition or co-opetition between innovators (Planko et al., 2019). These co-evolutionary dynamics take place in the self-organising interaction between multiple actors, and are affected by economic, biophysical and social forces which are not under the control of one actor (Ekboir, 2003; Kash and Rycroft, 2002; Klerkx et al., 2010).

Despite the fact that these transition pathways are only partially steerable, it does not mean they cannot be influenced. This would however require a different approach to how agricultural innovation systems are considered in terms of the directions they pursue and how inclusive they are. Often agricultural innovation systems foster a particular set of technologies, but remain unclear about what values underpin these. Also, it remains unclear how these contribute to shaping certain transition pathways towards sustainability and either underpin current technological and economic paradigms or foster 'deep transitions' (Pigford et al., 2018; Schot and Kanger, 2018; Schot and Steinmueller, 2018). Despite embracing sustainable development and paying attention to key policy issues such as food and nutrition security, in many countries the main goal of dominant and powerful groups within agricultural innovation systems (i.e. the complex of actors from business, science, government, civil society that creates and diffuses innovations) is enhancing agricultural productivity and growth through a modernization pathway continuing the current ways of producing, trading, and consuming food (Pigford et al., 2018; Plumecocq et al., 2018; Gaitan-Cremaschi et al., 2018). Such a modernization focus has come under increasing critical scrutiny (Horlings and Marsden, 2011; Poole et al., 2013). Hence, arguments have been made that agricultural innovation systems and the innovation policies that support them should:

(a) become more explicit about the diversity of transition pathways they contemplate, what is potentially game changing about them, and what inclusion and exclusion choices are made, and what cross fertilizations may exist in seemingly very different agriculture and food system futures (Pigford et al., 2018),
b) become much more 'mission oriented' in the sense that they actively seek to stimulate those directions deemed desirable, and also actively 'destabilize' incumbent systems not considered sustainable (Kivimaa and Kern, 2016; Schot and Steinmueller, 2018;),
c) be sensitive to context and acknowledge that technologies are not universal (a lesson already learned from the first Green Revolution), but evolve with, and are embedded in, different contexts in terms of socio-economic, cultural, and political contexts (Eastwood et al., 2017; Glover et al., 2017; Glover et al., 2019). This may also imply seeking where Agriculture 4.0 and retro-innovation, frugal types of transition pathways meet.

What would the recognition of diversity of transition pathways, imply for Agriculture 4.0 technologies and associated agricultural and food system futures and transition pathways, in view of the opportunities, risks, 'unforeseens' and unknowns, and trade-offs alluded to before? It seems important that governments and other innovation system stakeholders seek transitions that are responsible in order to ensure that it creates more winners than losers, and contemplate this in formulating mission oriented innovation policies and creating mission oriented agricultural innovation systems (following Wanzenböck et al., 2019). In relation to Agriculture 4.0, there is a growing interest in understanding how innovation processes can be made more responsible (Eastwood et al., 2019; Bronson, 2018; Brunori et al., 2019; Regan, 2019; Fraser and Campbell, 2019). There are four key components (Stilgoe et al., 2013) and we outline them with regards to their role in creating responsible transitions: inclusion, anticipation, reflexivity and responsiveness.

We can only achieve a responsible transition to more sustainable agricultural and food systems by working together (Schot and Steinmuller, 2018) and good methods of inclusion underpin efforts to innovate responsibly (Rose and Chilvers, 2018). In order to be responsible, transition pathways should evidently reflect a range of social and environmental needs. Inclusion of a range of actors in determining what the trajectory should be is crucial because existing actors (the 'usual suspects') may have a vested interest in maintaining the status quo (Schot and Steinmuller, 2018). These actors should include farmers and other land managers, landowners, advisors, retailers, consumers, technology companies, membership organisations, NGOs (e.g. agricultural and environmental), policy-makers. Dedicated spaces of forward oriented thinking and practice in agricultural innovation systems, such as policy communities, think tanks, or what have been referred to as 'systemic intermediaries' that can convene innovation system actors (Kivimaa et al., 2019) These spaces can help create an open dialogue in which different stakeholders can have their say, need to articulate what the purpose of Agriculture 4.0 is, what problems technologies will solve, and what the future of agricultural production systems should look like. Inclusion methodologies should seek to open up conversations at an upstream stage, for example through interactive design (Elzen and Bos, 2019), and make participation easy to all types of stakeholders (Chilvers and Kearnes, 2016). In the context of responsible innovation of agri-tech, Rose and Chilvers (2018) questioned whether existing methods of inclusion, for example government online consultations or public forums, actually exclude certain sections of the public and prevent stakeholders beyond the usual suspects from sharing their visions of the future. For example, in the list of actors presented above, quite often policy-makers consult the same few innovative farmers, select membership organisations, and powerful technology companies, rather than a broad list of stakeholders (Rose and Chilvers, 2019). Alternative inclusion processes could seek to speak with people not usually included, for example as practised by the RSA in the UK for their recent consultation exercise on food and farming. In doing their study, they travelled across the whole of the UK "so that [they] could meet people in their homes, in businesses, schools and community groups." They specifically "wanted to hear from people who would not ordinarily get a chance to contribute … and talk with them about their experiences" (RSA, 2019, 7). Alternative visions of food and farming articulated by different actors may not involve Agriculture 4.0 technologies in the future of farming, or seek to utilise them alongside other concepts such as agroecological systems. Until we articulate inclusive visions of the future, it is difficult to start to anticipate what the impacts of the transition will be, and how they can be made more responsible. Certainly, the pursuit of visions determined by only a select group of people (policy-makers or other powerful actors) is unlikely to be fit-for-purpose.

In articulating visions, we will need to consider how Agriculture 4.0 technologies interact with one another and with other ideas in sustainable agriculture like agroecology or regenerative farming and what that will mean for future agricultural and food systems. It is, of course, difficult to anticipate fully what the consequences of implementing new technologies at scale will be (Wigboldus et al., 2016). Anticipation is by definition a process of learning and experimentation (Schot and Steinmuller, 2018), but responsible transitions are far more likely to occur if we proactively consider consequences rather than reactively doing so (as now often happens). Those that formulate and are tasked to enact mission-oriented innovation policies (e.g. to increase yields, alleviate poverty, make food systems circular and climate smart) should proactively contemplate how these missions are realized and through what types of technologies and social innovation, anticipate the consequences of those missions, and continuously reflect on how these missions evolve. This includes a reflection on whether Agriculture 4.0 is a mission in itself, or rather is supportive to other missions? Also, it would include a reflection on what issues Agriculture 4.0 aims to address (in terms of their complexity, contestation and uncertainty), or what issues Agriculture 4.0 technologies provoke and what this implies for organizing mission oriented innovation policies and innovation systems (following Wanzenböck et al., 2019). We should also seek to anticipate the consequences of alternative scenarios, for example if we chose not to implement Agriculture 4.0 technologies at scales – would this create more losers than winners, and if so why and how? The degree of reflexivity in strategies designed to create socio-technical transitions is crucial. If proponents of projects, for example, are not amenable to listening to diverse views, to learning that negative impacts are being caused by the transition pathway, and to understanding that a trajectory change is needed towards a different pathway, then innovation cannot be responsible. There will then not be an articulation of what trade-offs (e.g. social outcomes versus productivity outcomes) are equitable and acceptable. When Agriculture 4.0 transitions unfold, this implies being responsive to emerging consequences and adjust the direction of transitions, also in view of unpredictable events and changes in broader systems agriculture is embedded in which impact transition pathways.

It can be noted that several countries are adopting mission-oriented approaches in their agricultural innovation systems in view of future food systems and how these contemplate issues such as food and nutrition security and environmental integrity. For example, The Netherlands has adopted a paradigm of 'circular agriculture' (Ministry of Agriculture et al., 2019) and invests in a 'protein transition' (Pyett et al., 2019), Nicaragua has a strong focus on agro-ecology, and New Zealand has a recent orientation towards 'digital bioeconomies' (Schiller et al., 2019; Shepherd et al., 2018; Tziva et al., 2019). We hope that this perspective paper spurs thinking of decision makers in agricultural innovation systems around the world about how open they are to diverse agriculture and food system futures, where and if Agriculture 4.0 fits in, choices and trade-offs to be considered in prioritizing certain transition pathways, and how they may responsibly manage these transition pathways.

Declaration of competing interest

The authors declare to have no conflict of interests.

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