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Review

A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda

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ABSTRACT

While there is a lot of literature from a natural or technical sciences perspective on different forms of digitalization in agriculture (big data, internet of things, augmented reality, robotics, sensors, 3D printing, system integration, ubiquitous connectivity, artificial intelligence, digital twins, and blockchain among others), social science researchers have recently started investigating different aspects of digital agriculture in relation to farm production systems, value chains and food systems. This has led to a burgeoning but scattered social science body of literature. There is hence lack of overview of how this field of study is developing, and what are established, emerging, and new themes and topics. This is where this article aims to make a contribution, beyond introducing this special issue which presents seventeen articles dealing with social, economic and institutional dynamics of precision farming, digital agriculture, smart farming or agriculture 4.0. An exploratory literature review shows that five thematic clusters of extant social science literature on digitalization in agriculture can be identified: 1) Adoption, uses and adaptation of digital technologies on farm; 2) Effects of digitalization on farmer identity, farmer skills, and farm work; 3) Power, ownership, privacy and ethics in digitalizing agricultural production systems and value chains; 4) Digitalization and agricultural knowledge and innovation systems (AKIS); and 5) Economics and management of digitalized agricultural production systems and value chains. The main contributions of the special issue articles are mapped against these thematic clusters, revealing new insights on the link between digital agriculture and farm diversity, new economic, business and institutional arrangements both on-farm, in the value chain and food system, and in the innovation system, and emerging ways to ethically govern digital agriculture. Emerging lines of social science enquiry within these thematic clusters are identified and new lines are suggested to create a future research agenda on digital agriculture, smart farming and agriculture 4.0. Also, four potential new thematic social science clusters are also identified, which so far seem weakly developed: 1) Digital agriculture socio-cyber-physical-ecological systems conceptualizations; 2) Digital agriculture policy processes; 3) Digitally enabled agricultural transition pathways; and 4) Global geography of digital agriculture development. This future research agenda provides ample scope for future interdisciplinary and transdisciplinary science on precision farming, digital agriculture, smart farming and agriculture 4.0.

1. Introduction

1.1. Digitalization as a transformative force in agricultural production systems, value chains and food systems

Digitalization, the socio-technical process of applying digital innovations, is an increasingly ubiquitous trend. Digitalization comprises phenomena and technologies such as big data, internet of things (IoT), augmented reality, robotics, sensors, 3D printing, system integration, ubiquitous connectivity, artificial intelligence, machine learning, digital twins, and blockchain among others (Alm et al., 2016; Smith, 2018; Tilson et al., 2010). Digitalization is expected to radically transform everyday life (Yoo, 2010) and productive processes in agriculture and associated food, fibre and bioenergy supply chains and systems (Poppe et al., 2013; Smith, 2018) and initial signs of transformation are already visible (Di Silvestre et al., 2018; Leviäkangas, 2016; Rotz et al., 2019a).[1] In the agricultural sector, several concepts have emerged to express different forms of digitalization in agricultural

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[1] At the same time, it should be recognised that digitalization in agriculture has been going for decades already, expressed for example through work on decision support systems (Leeuwis, 1993, 1999. McCown, 2002) and also precision agriculture has a long trajectory already (Wolf and Buttel, 1996; Wolf and Wood, 1997).

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production systems, value chains and more broadly food systems. These include *Smart Farming* (Blok and Gremmen, 2018; Wolfert et al., 2017), *Precision Agriculture* or *Precision Farming* (Wolf and Buttel, 1996; Eastwood et al., 2017b), *Decision Agriculture* (Leonard et al., 2017), *Digital Agriculture* (Keogh and Henry, 2016; Shepherd et al., 2018), *Agriculture 4.0* (Rose and Chilvers, 2018) or what is referred to in French as *Agriculture Numérique* (i.e. *Numerical Agriculture* - Bellon-Maurel and Huyghe, 2016).[2] Regardless of the exact term used, digitalization implies that management tasks on-farm and off-farm (in the broader value chain and food system) focus on different sorts of data (on location, weather, behaviour, phytosanitary status, consumption, energy use, prices and economic information, etc.), using sensors, machines, drones, and satellites to monitor animals, soil, water, plants and humans. The data obtained is used to interpret the past and predict the future, to make more timely or accurate decisions, through constant monitoring or specific big data science enquiries (Eastwood et al., 2017a; Janssen et al., 2017; Wolfert et al., 2017).

Digitalization in agriculture is thus expected to provide technical optimization of agricultural production systems, value chains and food systems. Furthermore, it has been argued that it may help address societal concerns around farming, including provenance and traceability of food (Dawkins, 2017), animal welfare in livestock industries (Yeates, 2017) and the environmental impact of different farming practices (Balafoutis et al., 2017; Busse et al., 2015). Digitalization is also expected to enhance knowledge exchange and learning, using ubiquitous data (Baumüller, 2017; Daum et al., 2018; Eichler Inwood and Dale, 2019) and improve monitoring of crises and controversies in agricultural chains and sectors (Stevens et al., 2016). The uptake internationally of digital technologies in the past two decades has been most prevalent in agricultural sectors such as cropping and viticulture through precision farming technologies (Bramley, 2009), and to a lesser extent in animal-based farming (Borchers and Bewley, 2015; Eastwood et al., 2017a), and there are high expectations as regards its further diffusion and transformative potential (Rose and Chilvers, 2018; Shepherd et al., 2018).

The scientific literature on digital agriculture has primarily focused on the technical aspects of applying these technologies for improving agricultural practices and productivity (Rutten et al., 2013; Wathes et al., 2008), as well as improving post-farmgate processes, such as postharvest quality monitoring in logistic process and real-time traceability (Wolfert et al., 2017). By now, there is a large body of predominantly natural and design science oriented literature on (potential) applications of digital technologies in agriculture. This is evidenced by an increasing number of review articles on topics such as precision farming, big data analysis, drones, artificial intelligence and robotics, 3D printing, artificial intelligence, IoT, and the transformative potential of these digital technologies for agricultural production systems, value chains and food systems (de Amorim et al., 2019; Dick et al., 2019; El Bilali and Allahyari, 2018a; Hunt and Daughtry, 2018; Kamilaris et al., 2017; Mogili and Deepak, 2018; Patrício and Rieder, 2018; Portanguen et al., 2019; Shamshiri et al., 2018; Skvortsov et al., 2018; Smith, 2018; Verdouw et al., 2013, 2016a,b; Voon et al., 2019; Weersink et al., 2018; Zhang and Wei, 2017; Zhao et al., 2019).

1.2. The importance of interdisciplinary social science on digital agriculture: aims of the special issue and this introductory review article

The body of social science literature on social, economic, and institutional approaches to investigating digital agriculture has also been growing in recent years. It has for example looked at management aspects of the digitalization of agriculture, the social dimensions of the innovation processes surrounding the digitalization of agriculture, but also critically scrutinizing its impact on people, institutions, animals and ecosystems. Whereas some of the early publications date from more than two decades ago (Wolf et al., 2001; Wolf and Buttel, 1996; Wolf and Wood, 1997), given the technological advances and the pervasiveness of digital technologies in all realms of society (Scholz et al., 2018), the last 5 years have seen an accelerated growth in social science publications on digital agriculture (as will also become clear in section 2). The topic of social, economic and institutional aspects of digital agriculture has also received increasing dedicated attention at scientific conferences, such as the 2018 International Farming Systems Association symposium, the 2019 European Society for Rural Sociology conference, and the upcoming 2020 International Rural Sociology Association conference, with numerous specific session, themes and workshops. Large science and innovation programmes also focus on digital agriculture and the social, economic and institutional aspects. These include the European Horizon 2020 project 'Internet of Farm & Food' (IoF2020), the Digiscape Future Science Platform from CSIRO in Australia, the #DigitAg programme in France, the NZBIDA project from AgResearch in New Zealand, the DESIRA, FAIRshare and Smart-AKIS projects and thematic networks in Europe, the Canada Digital Agri-Food programme and the Cornell Open Ag initiative in the United States.

There is also a growing interest in the topic of digital agriculture within policy circles, including the socio-economic elements of digitalization, and this has resulted in several policymaker and practitioner oriented publications. For instance, the Standing Committee on Agricultural Research from the EU, through its Agricultural Knowledge and Innovation Systems Strategic Workgroup, has a specific focus on Smart Farming/Digital Agriculture (Poppe et al., 2013; EU SCAR AKIS, 2019) and reviews commissioned by the EU have emerged on the topic (Soma et al., 2019). The World Bank has published a sourcebook and a future outlook (World Bank, 2019; World Bank, 2017), and the FAO has recently published a status report (Trendov et al., 2019), all of them presenting several experiences with and models of digital agriculture. The Australian Farm Institute has organized three policy oriented conferences on 'Digital Disruption' in recent years (2016–2018), while the OECD also organized a conference in 2018 on the topic and published a policy-oriented publication (Jouanjean, 2019).

Considering the growing attention to digital agriculture in both natural and social sciences, as well as policy discourse, the authors of this introductory review article, as guest editors of this special issue, thought it would be timely to bring together global experiences of social and institutional responses to digital agriculture. The idea was that with digital agriculture applications becoming more established, it was a good moment to bring together a collection of conceptual and empirical social science articles on this topic. Therefore, the special issue originally aimed to answer the following question as formulated in the call for articlespublished in 2018: *what reconfigurations of practices and institutions are emerging to embed and enact digital agriculture technologies and counteract possible negative consequences?* The call indeed yielded some articles showing reconfigurations of practices and institutions, showing for example new digital agriculture business models, new advisory practices, as well as showing practical and institutional difficulties and challenges in dealing with digital agriculture. Additionally, the call has also yielded conceptual reflections on ethics, digital social system concepts, and digital innovation concepts (see section 3). Given the recent surge of social science literature on digital agriculture noted above, of which many articles were actually published during the development of this special issue, the contributions of the 17 articles in this special issue do not fall into a vacuum but add to a rapidly growing body of social science literature.

However, while there has been growing interest in digital agriculture from different social science disciplines (such as sociology, geography, innovation studies and economics), as well as humanities

[2] While being cognizant of the diversity of terms employed in the literature, and also by the articles in the special issue, for the sake of clarity this article henceforth mainly employs the term 'digital agriculture'.

disciplines (such as ethics, law and philosophy)[3], the extant social science literature on digital agriculture is rather scattered. Despite the existence of some review articles on particular issues, such as the political economy of digital agriculture (Rotz et al., 2019a) and perspective articles on ethics (Carbonell, 2016), most review articles focus on technical issues or aim to provide an overview of the state of the art within a certain subfield (Aker, 2011; Banhazi et al., 2012; Protopop and Shanoyan, 2016; Baumüller, 2017; Eichler Inwood and Dale, 2019; Kamilaris et al., 2017; Mogili and Deepak, 2018; Patrício and Rieder, 2018; Salemink et al., 2017; Verdouw et al., 2013; Wolfert et al., 2017; Zhao et al., 2019).

This introductory review article therefore aims to provide an overview and thematic clustering of different, yet related, disciplines of social science literature on digital agriculture, show what the special issue articles add to this body of work and provide an agenda for future research. The three specific questions it seeks to answer are: 1) what are the main thematic clusters of social science literature on digitalization in agriculture, based on an explorative review; 2) what are the main insights from the articles in this special issue and how do they connect to these thematic clusters and/or open new lines of enquiry?; and 3) what are some possible future questions still to be explored by social sciences in this field?

In answering these questions, this introductory review article and the special issue as a whole demonstrate an interdisciplinary perspective at two levels. The first level of interdisciplinarity is between social science disciplines. The special issue brings together contributions from sociology, science and technology studies, economics, design thinking and policy studies, showing the diversity and complementarity of angles on the topic of digital agriculture. These angles highlight both the positive and negative effects that digitalisation might have on a sustainable development of agriculture, food systems and rural areas. It also stresses the need to support the reflexivity of actors (farmers, advisors, policy makers, researchers) contributing to the development of digital agriculture.

The critical social science perspective on digitalization and digital agriculture taken in this special issue has important implications for a second level of interdisciplinarity, between social sciences and natural, technical or life sciences, which is a key aim of NJAS-Wageningen Journal of Life Sciences. Outlining a future research agenda and new questions for social sciences on digitalisation could help researchers from other disciplines shed a new light on the direction and conditions they take into account when developing, testing, implementing and scaling new digital technologies. The article proceeds as follows. In section 2 we outline five major current thematic clusters in the social science literature, and in section 3 we map the special issue article contributions against these thematic clusters. Then, in section 4 we raise several emerging questions in the five existing thematic clusters, but also present four potential thematic clusters with sets of new questions. Section 5 presents some concluding remarks and a call for both social and natural sciences to engage with this future research agenda on social, economic, legal, organizational and ethical aspects of digital agriculture through interdisciplinary and transdisciplinary approaches.

2. Major current thematic clusters in the social science literature on digitalization in agriculture

The overview of thematic clusters of social science literature presented in this section is based on an exploratory review[4], achieved by searching with keywords such as 'digital agriculture', 'smart farming' in the comprehensive scientific database Scopus, with a focus on social science or interdisciplinary journals focused on agriculture (such as the Journal of Rural Studies, the Journal of Peasant Studies, Sociologia Ruralis, Agricultural Systems, NJAS-Wageningen Journal of Life Sciences, Land Use Policy, and the Journal of Agricultural Education and Extension). Furthermore, snowball methods were employed, such as using references in articles found, or screening articles citing pioneer work on digitalization. This led to over 100 social science articles on digital agriculture, and allowed for the identification of five major thematic clusters of social science literature related to digitalization in agriculture, some established and others emerging. The different thematic clusters draw on different social science disciplines (such as sociology, geography, economics, communication science, management science and innovation science) and humanities (philosophy, ethics), hence supporting interdisciplinary debates rather than a juxtaposition of disciplinary standpoints on digitalization. Table 1 provides an overview of articles reviewed per thematic cluster, social science disciplines, the theoretical and methodological perspectives and what articles in the special issue pertain to the different thematic clusters (detailed in section 3). Note that we focus here on agriculture, and not on how digitalization affects rural areas, which is a broader topic going beyond agriculture alone (see e.g. Roberts et al., 2017; Salemink et al., 2017).

2.1. Adoption, uses and adaptation of digital technologies on farm

This first thematic cluster is well established, with one line of enquiry focused on different aspects of precision technology adoption on farm[5], examining both economic and behavioural aspects. This literature concentrates on individual adoption determinants (Barnes et al., 2019; Hansen, 2015; Jensen et al., 2012; Kernecker et al., 2019; Leonard et al., 2017; Tey and Brindal, 2012), as well as extension and communicative interventions to stimulate adoption (Kutter et al., 2011). Another line of enquiry examines precision agriculture use on farm and how it affects farming practices (Fountas et al., 2005; Hansen, 2015; Hay and Pearce, 2014) and post-adoption processes of adaptation (Higgins et al., 2017; Schewe and Stuart, 2015), through concepts such as 'tinkering' and 'assemblages'. The latter topic has also been analysed from a beyond-farm level perspective, looking at the broader networks and innovation systems in which technology is shaped and where co-evolution between the technology and broader social and institutional environments takes place (Eastwood et al., 2017, 2012). This cluster builds on a variety of methods, ranging from modelling approaches of the costs and benefits of precision farming (Schimmelpfennig and Ebel, 2016), quantitative or econometric approaches testing the effects of different variables on adoption (such as farm size and specialisation, farmers' age, education, etc., see Annosi et al., 2019; Barnes et al., 2019; Lowenberg-DeBoer and Erickson, 2019), to more qualitative work, highlighting the situation of both adopters and non-adopters, and accounting for less measurable aspects, such as material contingencies and cultural dimensions of knowledge (Higgins et al., 2017). It should also be noted that while most research in industrial contexts focuses on the adoption of precision farming technologies, research in Africa rather focuses on the adoption (or non-adoption) of market information systems (Wyche and Steinfield, 2016). The literature on the African context looks at agriculture specific decision support tools as well as the

[3] While we recognize that humanities comprise different disciplines than those considered part of the social sciences, in the remainder of the paper we will use the term social science as an umbrella term. So when we talk about social science, we sometimes also refer to humanities in this article.

[4] This review was not a systematic review, as that would go beyond the scope of this introductory article. Nonetheless the authors feel the search results were quite comprehensive and allow for the clustering presented.

[5] While precision agriculture is a form of digital agriculture, and is also connected with broader value chain structures (e.g. Carolan, 2018b), some commentators argue that concepts such as Smart Farming and Agriculture 4.0 are 'larger' concepts, since as Smart Farming includes digitalization of supply chains and food systems as a whole and Agriculture 4.0 may also comprise other technologies such as gene editing (Wolfert et al., 2017; Rose and Chilvers, 2018).

Table 1
Overview of thematic clusters in terms of social science disciplines, theoretical and methodological perspectives, and how they link to special issue articles.

Thematic cluster	Number of reviewed articles in this thematic cluster (some are present in several clusters)	Principal social science disciplines involved	Examples of theoretical and methodological perspectives used in this thematic cluster	Articles in the special issue pertaining to this thematic cluster
Adoption, uses and adaptation of digital technologies on farm	16	Economics, sociology, innovation studies, science and technology studies	Adoption and diffusion theory Behavioral psychology Practice theory Assemblage theory Cost and benefit modelling Econometrics Evolutionary economics Innovation systems	Janc et al., 2019 Knierim et al, 2019
Effects of digitalization on farmer identity, farmer skills, and farm work	16	Sociology, social geography, anthropology	Political economy Practice and identity theory Studies of discourse, power, politics and social transformation (e.g. Foucault, Bourdieu, Durkheim, Giddens) Actor-network theory Assemblage theory Gender studies Ethnography Farming styles Cultural scripts	Vik et al., 2019 Lioutas et al., 2019
Power, ownership, privacy and ethics in digitalizing agricultural production systems and value chains	28	Sociology, political science, philosophy and ethics, science and technology studies	Political economy Institutional economics Animal ethics Human ethics Responsible Research and Innovation Activity theory	Van der Burg et al., 2019 Lioutas et al., 2019 Jakku et al., 2019 Bronson, 2019 Wiseman et al., 2019 Regan, 2019
Digitalization and agricultural knowledge and innovation systems	27	Innovation studies, science and technology studies, communication science, economics	Knowledge and Innovation systems Social media analysis Learning theories Evolutionary economics Socio-technical transitions	Fielke et al., 2019 Ingram and Gaskell, 2019 Relf-Eckstein et al., 2019 Rijswijk et al., 2019 Eastwood et al., 2019 Ayre et al., 2019
Economics and management of digitalized agricultural production systems and value chains	21	Economics, management science, sociology	Value chain theories Business model theories Risk analysis Institutional economics Service economics	Phillips et al., 2019 Rojo Gimeno et al., 2019

role of generic technologies, such as cell phones, in access to information on input and commodities prices (Baumüller, 2017).

2.2. Effects of digitalization on farmer identity, farmer skills, and farm work

This thematic cluster, which is also well established, focuses on how digital technologies impact on the method of farming, demanding different knowledge, skills and labour management among farmers. One strand of enquiry is rooted in systems design and focuses on the practical issues of human-robot interaction in farming, such as ergonomics and health and safety, as a review article by Vasconez et al. (2019) shows. Another strand of research within the field of rural sociology looks at broader socio-cultural implications, drawing on a range of theorists (e.g. Foucault, Latour, Durkheim, Giddens) and perspectives, such as political economy and assemblage theory. Digitalization can have major impacts on the cultural fabric of rural areas and farmer identities as it affects what it means to be a farmer (Burton et al., 2012; Carolan, 2017b). Digitalization may change the culture of farming from 'hands-on' and experience driven management to a data-driven approach (Butler and Holloway, 2016; Carolan, 2017b, 2019a; Eastwood et al., 2012) and may 'discipline' farmers' work routines in certain ways (Carolan, 2019), conditioned by 'algorithmic rationality' (Miles, 2019). As a consequence, the compatibility of digitalization with approaches such as agro-ecology is a matter of debate (Plumecocq et al., 2018; Van Hulst et al., 2020), as it has been argued that agro-ecology would specifically require hands-on farming as opposed to digitally-mediated farming.

Questions have also been raised about the effect of digitalization on farmers' autonomy, including concerns about farmers becoming 'data labourers' (Rotz et al., 2019b). Digitalization has also been found to affect gendered identities on farms (Bear and Holloway, 2015; Hay and Pearce, 2014). Furthermore, technology aimed at automating tasks and increasing efficiency may deskill or displace farmers and farm workers and exclude or discriminate against those not digitally literate. This may have negative effects on demand for rural labour and hence affect marginalized groups such as migrants, in a context of growing separation between labour and capital in agriculture (Carolan, 2019; Rotz et al., 2019b; Smith, 2018). However, other authors argue that digital technologies may also be merged into existing practices to create combinations of 'digital' and 'analogue' skills (Burton and Riley, 2018), or give rise to a new sort of 'responsible professionalism' (Blok, 2018).

2.3. Power, ownership, privacy and ethics in digitalizing agricultural production systems and value chains

This established cluster of work applies critical social science perspectives on digitalization in agriculture, focusing on the political economies and political ecologies of digital agriculture. Key issues in this thematic cluster include issues of power, data ownership, inclusion and exclusion, privacy, and how to deal with these issues ethically. One strand of enquiry uses the lens of corporate structures in relation to production systems and supply chains, often with political economy or science and technology studies perspectives. This literature examines how digitalization changes or reproduces the rules, institutions and balances of power governing these systems, how that affects different actors and what responses or resistances emerge and how ethical issues such as those around privacy and data ownership emerge and are addressed (Sykuta, 2016; Bronson, 2018; Carbonell, 2016; Carolan, 2017a, 2018a,b,c, 2019; Eastwood et al., 2017a; Fleming et al., 2018; Fraser, 2019a, b; Freidberg, 2019; Rose and Chilvers, 2018; Rotz et al., 2019a; Schuster, 2017; Miles, 2019). This research includes critiques of the lack of policy interventions tackling the digital divides produced by rapid, unregulated technological change and the power imbalances that could constrain the integration of societal issues (Bronson and Knezevic, 2019). Other research identifies how risks such as cyber-attacks may destabilize precision agricultural systems and digitalized food systems (Barreto and Amaral, 2018; Trendov et al., 2019; West, 2018).

Besides digital agriculture having implications for humans, animals are also affected by digital agriculture. This happens for example in dairy farming, where this is operationalized through approaches such as robotic milking systems (Driessen and Heutinck, 2015) and use of technologies to replace animal husbandry tasks (Butler and Holloway, 2016). Robotic milking adoption has been shown to involve a varied range of factors, and therefore equally varied outcomes for animals, people, and the environment (Schewe and Stuart, 2015). This has given rise to philosophical and ethical perspectives, in which ethical challenges affecting animal autonomy and human-animal relationships of farms have been analysed (Bear and Holloway, 2019; Driessen and Heutinck, 2015; Bos and Munnichs, 2016).

2.4. Digitalization and agricultural knowledge and innovation systems

Digitalization has also been observed to be a driving force of the evolution of agricultural knowledge and innovation systems (AKIS). In this thematic cluster, which has emerged recently but is increasingly becoming established, different lines of enquiry can be discerned with either a macro, meso or micro perspective on knowledge and innovation systems. From a macro perspective, some research that uses innovation systems perspectives looks at how innovation support structures enable digitalization, but also change themselves under the influence of digitalization, e.g. by incorporating big data analysis (Kamilaris et al., 2017). Some research also looks at how AKIS for digital agriculture are shaped through a diversity of existing and new actors in these systems: high-tech firms (e.g. drones or satellite manufacturers, etc.), service industries, and multinationals producing farming equipment, such as self-driving tractors and automated milking machines (Eastwood et al., 2017b). Given the ethical concerns raised in cluster 3 (section 2.3), there is an emerging literature that explores how innovation systems can apply principles of Responsible Research and Innovation (RRI) (Owen et al., 2012) to the digitalization of agricultural production systems, value chains and food systems (Bronson, 2018; Eastwood et al., 2017a; Jirotka et al., 2017; Rose and Chilvers, 2018). This literature also explores the role that transdisciplinary science can play in supporting integrative solutions that look at a combination of technological, ethical, social, economic and business challenges (Shepherd et al., 2018). At a meso perspective, some research, drawing on theories of learning and communication, looks at how networks of learning are formed to enable digital agriculture innovation (Eastwood et al., 2012; Kelly et al., 2017; Van Der Vorst et al., 2015). For example, some studies examine how digital platforms and social media enable local and global information sharing and peer learning (Aker, 2011; Baumüller, 2016; Burton and Riley, 2018; Chowdhury and Hambly Odame, 2013; Jespersen et al., 2014; Kaushik et al., 2018; Kelly et al., 2017; Munthali et al., 2018). Other studies have also looked at how user generated data, through social media analysis and citizen science approaches, feeds into real-time decision making and informs policy decisions (Cieslik et al., 2018; Leeuwis et al., 2018; Stevens et al., 2016). At the micro-level of knowledge systems, using theories of learning and user centred-design, other research looks at the continuous processes of how digital decision support systems are better attuned to users (O'Donoghue et al., 2016; Antle et al., 2017; Rose et al., 2018; Driessen and Heutinck, 2015; Rose et al., 2016; Lindblom et al., 2017) and how advisors interact with farmers to connect 'digital knowledge systems' to 'farmers knowledge systems' (Tsouvalis et al., 2000; Lundström and Lindblom, 2018; Bechtet, 2019).

2.5. Economics and management of digitalized agricultural production systems and value chains

While there is some generic (i.e. non-agriculture specific) literature looking at economic and business model aspects of digital technologies and big data (see e.g. Koch and Windsperger, 2017; Teece, 2018; Teece and Linden, 2017), in agriculture the body of work with this focus seems to be more modest. There is some research reflecting on costs and benefits of unmanned aircraft systems, for example (Hunt and Daughtry, 2018), or of other precision farming technologies (Schimmelpfennig and Ebel, 2016). Related to the literature on precision technology adoption, one strand of enquiry in this emerging thematic cluster looks at investment decisions (Rutten et al., 2018). Some research has tried to assess the effect of precision farming technologies on productivity in the agricultural sector. Lio and Liu (2006) for instance show a positive effect of these technologies, but also potential divergences and inequalities across countries. Some pieces reflect, beyond the farm level, on the (potential) economic impacts of digitalized supply chains (Jouanjean, 2019; Smith, 2018), and big data services and analysis (Boehlje, 2016; Sykuta, 2016).

Another important stream of research deals with the economic impact of digital technologies on markets, mostly using theoretical and methodological approaches embedded in micro-economics, modelling and econometrics of the relation between demand, supply and patterns of use of information. In the context of developing countries, many studies have assessed the impacts of market information systems to compensate for asymmetries of information and enhance access to markets (David-Benz et al., 2017; Aker, 2011; Islam and Grönlund, 2010; Agyekumhene et al., 2018). In the context of industrialised agriculture, there are discussions about actors developing information systems to support farmers in risk management, be they climatic or financial risks (Fraisse et al., 2006). The business models associated with these services are often related to new forms of insurance for farmers, such as index-based climate insurance systems. Nevertheless, empirical research about business models of digital agriculture remains rare, and typologies are often limited to new direct marketing solutions between farmers and consumers (Andreopoulou et al., 2008). Connected to the issue of power, as mentioned in section 2.3, some studies taking a political or institutional economy or value chain perspective, highlight potential downsides of vertically integrated systems and new business models. In such models, multinational corporations offer large 'digital package deals' to farmers (Bronson, 2018; Bronson and Knezevic, 2016; Carolan, 2017b, 2018b). These package deals tend to maintain balances of power to the benefit of models of agriculture based on the intensive use of chemical input, as hypothesised by Wolf and Buttel (1996) already in the 1990s. However, innovative business models may provide new opportunities for reshaping value chains. For example, the idea of the 'circular economy' aims to find ways for traditional streams of 'waste' to be converted into diverse value-added products through on-farm processing (Galliano et al., 2017;

Geissdoerfer et al., 2017), or start-ups launching platform technologies aimed at preventing food waste at the consumer end of (urban) food systems (Miles and Smith, 2015).

3. Contributions of the articles in this special issue

The seventeen articles in this special issue advance our understanding of the thematic research clusters presented in the previous section. The articles explore social responses to smart farming across different empirical and geographical contexts, ranging from Canada and the United States (Bronson, 2019; Phillips et al., 2019; Relf-Eckstein et al., 2019), to Australia and New Zealand (Ayre et al., 2019; Eastwood et al., 2019; Fielke et al., 2019; Jakku et al., 2019; Rijswijk et al., 2019; Wiseman et al., 2019) and Europe (Janc et al., 2019; Knierim et al., 2019; Regan, 2019; Vik et al., 2019). Some articles are not bound to a certain geographical location but present conceptual reflections on issues such as ethics (van der Burg et al., 2019), digital knowledge and activity systems (Ingram and Gaskell, 2019; Lioutas et al., 2019) or the value of digital information (Rojo Gimeno et al., 2019). A variety of theoretical frameworks are presented, including activity theory, innovation opportunity space, the multi-level perspective on socio-technical transitions, the responsible research and innovation framework, as well as the perspective of agricultural knowledge and innovation systems, affordances, and the ontological framework of syntactic, semantic and pragmatic capacities.

3.1. Contributions to the thematic cluster adoption, uses and adaptation of digital technologies

Despite many promises and cases studies about the development of digital technologies in agriculture, there are still many uncertainties about their actual use by farmers. Two articles of this special issue contribute to filling this knowledge gap, using quantitative methodologies. The article by Janc et al.(2019) on internet use among Polish farmers gives insights into some of the basic elements needed to enable farmers to digitalize their practices. Janc et al. (2019) find that there is still a large ‘digital divide’ in terms of access and capabilities to use the internet. Underlying reasons that Janc et al. (2019) found include the way in which the social fabric of Polish agriculture may have a disabling role, whereby digital technology is seen as individualistic and seen to erode the previous feelings and institutions associated with common knowledge acquisition, based on local ties of blood and neighbourliness. The authors conclude that Polish farming still finds itself at the preliminary phase of entry into smart agriculture, a situation which may also be found elsewhere and presents a challenge in the development of a new and locally embedded digital knowledge. Hence, beyond giving insights on technology adoption, this article also hints at changes in farmer identity, as discussed in section 2.1 and the development of digital agricultural knowledge and innovation systems, as discussed in section 2.4.

The article by Knierim et al.(2019) provides a better understanding of the various profiles of farmers using digital technologies in diverse European contexts. Based on interviews with farmers and experts in Germany and insights from six other countries (the UK, the Netherlands, France, Spain, Greece, and Serbia), they enrich previous findings (Barnes et al., 2019) about the effects of farms’ socio-economic characteristics and orientation in terms of production systems on the adoption of precision farming technologies. An original contribution of the article is that it assesses the perceptions of actors regarding the impacts of such technologies on societal issues, including environmental protection. Their multi-actor approach reveals contrasting expectations. While positive expectations are widely expressed by experts and stakeholders from the AKIS, German farmers have more reservations about the performance of precision farming in moderating farms’ externalities on the environment. This result is interpreted as a realistic assessment of technological pros and cons, which is however not effectively supported by empirical evidence, due to a lack of information, training, and access to advice on precision farming.

3.2. Contributions to the thematic cluster on effects of digitalization on farmer identity, farmer skills, and farm work

Two articles in this special issue make contributions to the thematic cluster on the effects of digitalization on farmer identity, farmer skills and farm work. In their article on the use and expansion of automatic milking systems (AMS) in dairy farming in Norway, Vik et al.(2019) explore how this form of smart farming technology is changing the nature of farm work, farmer skills and farmer identity in this context. Their analysis uncovers the broader networks and systems in which this technology is shaped and the social aspects and political implications of its development, and hence the performative aspects of robots. They find that the primary motives for investing in milking robots relate to quality of life, including a more flexible workday, reduced physical work, as well as a desire to achieve what is regarded as the future standard of dairy farming. The domestic political framework has not pushed the observed structural developments, rather policy has adapted to them. Vik et al. (2019) conclude that structural developments resulting from the introduction of robotic milking in Norwegian agriculture are a series of unplanned consequences of farm level strategies, political adaptations, technological characteristics, and milking robot capacities. This conclusion is echoed by the work of Lioutas et al. (2019), who take an activity theory approach and see the farm as a cyber-physical-social system. Based on an analysis of pertinent literature, Lioutas et al. (2019) examine how big data may affect farmers, both as users and co-producers of big data, and how it may guide their decision making, as well as how this affects and is affected by the wider community and institutional setting that farmers operate within.

3.3. Contributions to the thematic cluster on power, ownership, privacy and ethics in digitalizing agricultural production systems and value chains

A strength of this special issue is that it gathers together a unique set of studies in various sectors and supply chains to illustrate how digital technologies impact on power relationships and highlight a range of data ownership and privacy issues related to digital technologies. Five articles explore this issue in various contexts, across Europe, North America and Australia. Altogether, these articles extend to new technologies the debate opened 20 years ago by Wolf and Buttel (1996), which has resurged in recent years (see section 2.3): does digitalization of agriculture transform supply chains or does it reinforce the position of dominant actors and industries? Firstly, van der Burg et al. (2019) review the literature on ethical challenges associated with smart farming and identify three key themes: (i) data ownership and access; (ii) distribution of power; and (iii) impacts on human life and society. However, despite increasing attention in research, policy and practice for ethics of smart farming/digital agriculture, they conclude that there seems to be different yet implicit ideas regarding the purpose and function of digital farms in society, which are not made explicit in research and societal debates.

The article by Lioutas et al. (2019), besides looking at farm level effects (see section 3.2), also reflects on how power dynamics and institutional factors shape the use of big data, including issues surrounding data ownership and privacy and power imbalances in access to the value derived from the use of big data. Similar issues are explored by Jakku et al. (2019) through their case study of perceptions of big data applications in the Australian grains industry, which combines a multi-level perspective on transitions with social practice theory. Their analysis demonstrates how concerns about transparency, data ownership and access and the distribution of risks and benefits are driving social responses to smart farming.

The article by Bronson (2019) sheds light on the norms and values embedded in digital agriculture concept, tool and artefact design and how this relates to the distribution of roles and balances of power in various North American supply chains. Bronson argues that decisions made by scientists and designers can impact on the directions innovation take and thus influence the resultant agri-food systems. She found that social actors working in private and public contexts to shape these innovations hold a narrow set of values that characterise a 'good farmer', 'good farming' and 'good technology' in such a way that their data practices privilege large scale and commodity crop farmers. This reinforces existing power structures and (im)balances. The article concludes by suggesting, similar to Van der Burg et al. (2019), a responsible research and innovation approach. The principles of responsible research and innovation proposed by Bronson (2019) includes engaging engineers and designers, paying particular attention to social innovations in an emerging socio-technical system, which has had a rather technological innovation focus. Such an approach also identifies the need for necessary legal measures to regulate control over data and distribution of power connected to streamlined and standardized interoperable data systems.

The article by Wiseman et al. (2019) reveals a lack of transparency and clarity around issues such as data ownership, portability, privacy, trust and liability in the commercial relationships governing digital agriculture. They find that these are contributing to farmers' reluctance to engage in the widespread sharing of their farm data. At the heart of farmers' concerns is the lack of trust between the farmers as data contributors, and those third parties who collect, aggregate and share their data. Wiseman et al. (2019) find that farmers currently feel that they bear too much of the risk and vulnerability and argue that broader legal and regulatory issues must not be ignored. Current complex data licences presented to farmers are on a 'take it or leave it' basis. However, Wiseman et al. (2019) argue that it is essential to ensure that the terms and conditions of data licences are understandable and transparent, in terms of who has access to the data, who derives the benefits of data sharing as well as how privacy concerns are addressed.

The article by Regan (2019) identifies a range of risks perceived by agricultural sector stakeholders in Ireland. These include consumer rejection of technologies, inequitable distribution of risks and benefits within the farming community, adverse socio-economic impacts of increased farmer-technology interactions, and ethical threats presented by the collection and sharing of farmers' data. Her research demonstrates how ambiguity can surround the discussion. Based on this assessment, Regan (2019) calls for a reflexive and transdisciplinary perspective to anticipate, with key governance actors, the risks of 'Smart Farming' in Ireland, through a responsible innovation approach. This call for responsible innovation approaches is also echoed by other articles within the special issue (e.g. Bronson, 2019; van der Burg et al., 2019), which in turn has implications for how programmes within the meso level of AKIS (see section 2.4) organize digital agriculture innovation.

3.4. Contributions to the thematic cluster on digitalization and agricultural knowledge and innovation systems

Another major contribution of this special issue is that it provides a better conceptual understanding of the digitalization of agricultural knowledge and innovation systems, in terms of epistemological, ontological and organisational changes and challenges. Here we introduce the six articles in this thematic cluster, following the distinction between macro, meso, and micro levels in AKIS as outlined in section 2.4.

At a macro level, Fielke et al. (2019) propose the concept of Digital Agricultural Innovation Systems (DAIS) to explicitly consider the element of digital innovation within innovation systems. They discuss how this may alter the way innovation is supported by offering new affordances for organizing innovation, both as a generative force and goal of innovation, and as a transformative force (Nambisan et al., 2019). They position the concept to support the reflexivity of actors who are developing digital technologies for farmers through R&D activities. They argue that the future development of digital technologies will reshape production, values and understanding in agriculture. Thus, there is a need to have spaces for reflection on how digitalization will affect innovation systems, for example on the acceptability of human-machine interaction as machines begin to think, learn and make decisions from their own data-driven experiences through unsupervised machine learning. In this, the concept of DAIS can also serve as a boundary object (Tisenkopfs et al., 2015).

The article by Ingram and Gaskell (2019) examines the organisation of digital knowledge systems and the process of digital co-design, and reflects on how languages and ontologies matter in terms of accessibility and use of search engines. The article asks the question: 'How effective is the process of co-constructing an ontology with experts, practitioners and other stakeholders in enabling the search for useful and meaningful knowledge?' Their analysis shows how involving users in the design of the user-centred ontology moves the search engine from an information processing synaptic capacity to a semantic capacity (beyond current web semantic abilities), where common meaning concerning specific agricultural domains can be represented and shared. It proposes that the remaining interpretative differences can be overcome by building pragmatic capacity and managing knowledge at a pragmatic boundary through further multiple iterations with users.

Relf-Eckstein et al. (2019) apply the Innovation Opportunity Space framework to map in detail the innovation pathway taken by an agricultural equipment innovation within the Canadian broadacre farming system. Their case study details the development of an autonomous farm equipment innovation named DOT™ by an agriculture equipment manufacturing firm based in Saskatchewan, Canada. The article explores three main questions: (i) How are smart farming innovations enabled or limited by public policy and governance; (ii) How might smart farming address problems at the farm level, while also reducing environmental impacts of crop production; and (iii) What are the potential risks associated with smart farming innovations? Their case study reveals some of the many opportunities and challenges that are involved in the smart farming innovation space. For instance, opportunities and benefits include reducing farm input costs (equipment, fuel, labour) and potential improvements to farmer health, welfare and safety and improved soil health. Numerous challenges remain though, including limited regulatory frameworks, both in relation to autonomous vehicles as well as the ownership, security and third-party use of agricultural data and control of the product life cycle of agriculture equipment. They conclude by observing the need for a reflexive, systems-level approach to the future of smart farming.

Taking a meso-level perspective, Rijswijk et al. (2019) look at how agricultural knowledge providers (e.g. research organizations and advisors) in New Zealand perceive and respond to digital agriculture and digitalization as a whole. Using the concept of organizational identity, Rijswijk et al. (2019) find digitalization actions in response to digital agriculture were often ad-hoc, starting with adapting capabilities, practices and services as their clients and partners require (i.e. focused on tangible organizational identity). This contrasts with a more strategic approach, which would involve fundamentally changing organizational values (intangible identity), allowing for more flexibility of roles and processes and changing business models in order to deal with uncertainty. Hence, Rijswijk et al. (2019) conclude that knowledge providers in New Zealand are at early stages of what has been dubbed 'digi-grasping' (Dufva and Dufva, 2019). Echoing earlier findings (e.g. Shepherd et al., 2018), they recommend that AKIS should better support the development of a digitalization strategy for agricultural knowledge providers. This improved approach would involve anticipating possible futures and reflecting on the consequences of these for value propositions, business models and organisational identities of agricultural knowledge providers. This again resonates with calls for the application of responsible innovation principles, through developing the reflexivity of AKIS actors about the consequences of digitalization of innovation processes.

Looking both at meso-level and micro-level interactions in AKIS, Ayre et al. (2019) and Eastwood et al. (2019) address more specifically the consequences of digitalization for one key actor of Agricultural Knowledge and Innovation Systems: agricultural advisory services. Following the metaphor introduced to agricultural advisory services by Labarthe (Labarthe, 2009; Prager et al., 2016), Both Ayre et al. (2019) and Eastwood et al. (2019) show how digital technologies can impact on both the front-office activities (new interfaces between farmers and advisors) and the back-office activities (use of ICTs in R&D). Eastwood et al. (2019) find that, in relation to front-office activities, advisory capabilities evolve to include skills related to determining the value propositions of new technologies. This results in new skills for farmers and advisors in terms of linking data to better decision-making on farm. In other words, the advisor becomes a sense-maker of digital data. Back-office advisory roles may also change, moving from information gathering and implementation of field experiments to remote data computation and interpretation.

The article by Ayre et al. (2019) demonstrates that creating and adapting to these new advisory roles is not easy. Digital innovation presents challenges for both farmers and advisors, due to the new relationships, skills, arrangements, techniques and devices required to realise value for farm production and profitability from digital tools and services. Ayre et al. (2019) analyse how a co-design process supported farm advisers to adapt their routine advisory practices and identify the value proposition of digital farming tools and services for their and their clients' businesses. This co-design process supported an adaptation of advisory services in both their front-office and back-office dimensions. This process involves finding ways to harness and mobilise diverse skills, knowledge, materials and representations for translating digital data, digital infrastructure and digital capacities into better decisions for farm management. Ayre et al. (2019) use the term 'digiware' to capture these unique practices of digital innovation. For instance, 'digiware' includes demonstrating digital data quality and digital data compatibility as well as managing outputs of digital data manipulation and analysis such as yield maps. 'Digiware' also involves: implementing interpretative frameworks and digital data infrastructures to combine disparate digital datasets (i.e. spatial and temporal) for integrated analyses; negotiating new written agreements to enshrine digital data ownership, controlling and distributing benefits from the use of digital data; and, capturing and curating satellite and aerial (digital) imagery and formats (i.e. Global Positioning Systems) of farm attributes such as weeds and soil.

3.5. Contributions to the thematic cluster on economics and management of digitalized agricultural production systems and value chains

There are two articles in the thematic cluster on the economics and management of digitalised agricultural production systems and value chains. The article by Rojo Gimeno et al. (2019) deals with the assessment of the value of information for precision livestock farming and thus shares some common themes with the articles by Ayre et al. (2019) and Eastwood et al. (2019) presented above. Rojo Gimeno et al. (2019) provide a framework to critically address a key question: does more precise information derived from using digital technologies result in improved economic value? The framework proposed in this study identifies the different steps that occur from data collection until a decision is taken and effective action yields outcomes with impact on various criteria. The framework outlines the factors that influence these different steps. The originality of the article is that it shows how the value of information can be assessed using economic measures but also expressed in terms of environmental performance, animal welfare and health, and social well-being of the decision maker. This study also highlights that there is no standard value of information: it remains highly farm specific. As a result, advisory services might still have a key role to play. New business models could emerge, where advisors' main contribution would be to help farmers to interpret whether and how acquiring more precise information may enhance the value of information in their specific circumstances.

Phillips et al. (2019) contribute to the literature on what digital agriculture means in terms of multinational agribusiness firms and value chain management, by exploring the range of business models that are emerging in Western Canadian agriculture. Using a typology that contrasts top-down vs. bottom-up innovation and closed vs. open platforms, they identify four potential business models: (i) the corporate model; (ii) strategic networks; (iii) primordial systems; and (iv) perfect competition or the hacking universe. They find that the first top-down, corporate model is not widespread, despite being adopted by multinationals such as John Deere, with vertical coordination and an integrated business model. Also, they did not find what they call 'networked activity' in Canada – open standards systems. They did however find substantial evidence of local investment, development, adaptation and adoption of bottom-up efforts, both through entrepreneurial start-up companies and through platform technologies (in the style of Uber and AirBnB), which for example connect buyers and sellers of produce then transact independently of the service. Based on their identification of these business models, they also point at issues requiring policy attention, such as ownership and control of data, but also identify risks such as cyberattacks, which may especially affect business models based on concentrated structures.

4. Future outlook: emerging and new research themes and questions

In this section we propose a series of topics for future research that emerge across the five thematic clusters identified in section 2 (with often multiple cross-relationships). We also offer a wider reflection and present four potential (new) thematic areas of work, which form an agenda for future social science research on socio-economic and ethical aspects of digitalization in agriculture. For each thematic cluster, we suggest possible research questions to provide inspiration and guide future studies on these topics, but we realize there may be several other questions.

4.1. A research agenda to advance the identified thematic clusters

4.1.1. Emerging topics and questions in the thematic cluster of adoption, uses and adaptation of digital technologies

The special issue articles in the thematic cluster of adoption, uses and adaptation of digital technologies (Janc et al., 2019; Knierim et al., 2019) urge us to look deeper into the role of the diversity of farm types, farming styles, and producer characteristics, in terms of adoption and adaptation of digital agriculture technologies. This is also related to the thematic cluster on power, ownership, privacy and ethics in digitalizing agricultural production systems and value chains and would be needed to better assess distribution effects. Also building on earlier studies (Eastwood et al., 2017b; Higgins et al., 2017; Schewe and Stuart, 2015), an area that could be further explored would deal with adaptation and learning dynamics after adoption. Furthermore, it could study what co-evolutionary processes are triggered between digital agricultural technologies and the context they are embedded in (the farm, the supply chain, the knowledge system, the policy environment, for example). In relation to the thematic cluster of digitalizing agricultural knowledge and innovation systems, this could also assess what type of service providers assist in what phase and what their contribution is (following Eastwood et al., 2017b). Possible sets of future research questions include:

- Who are the beneficiaries and losers following the adoption of digital agriculture technologies in agriculture, and why? How are the benefits and risks distributed among different actors in the agricultural sector?
- What are the effects of farming scale on the uptake and application

of digital agriculture technologies? Reciprocally, is digitalization one of the drivers of farm enlargement and capital concentration in agriculture, allowing for further standardisation and remote monitoring of farm practices? What are the relationships with broader value chains and food systems?
- How does digital agriculture affect the process of farm innovation, in terms of the feedback it provides, and the learning and experimentation processes it triggers? What are the implications for farmers' learning and experiential knowledge production following wide scale adoption of digital agriculture technologies?
- How do human and animal systems respond to digital agriculture artefacts such a sensors and drones and how do they co-evolve?

To explore these questions, well-known theories and models for assessing individual adoption behaviour, such as diffusion and adoption theory (Rogers, 1995) or behavioural models (Mills et al., 2017), could be used. Adoption and adaptation processes could also be explored with approaches looking at the broader 'assemblages' of both human and non-human actors involved in farm performance and change (Higgins et al., 2017) as well as the support networks and social capital affecting adoption and adaptation of digital technologies (Cofré-Bravo et al., 2019; Oreszczyn et al., 2010).

4.1.2. Emerging topics and questions in the thematic cluster of farmer identity, farmer skills, and farm work

Considering the thematic cluster on the effects of digitalization on farmer identity, farmer skills, and farm work, the articles in this special issue by Vik et al. (2019) and Lioutas et al. (2019) raise several questions for future empirical analysis. Their articles investigate how big data may not only facilitate the transformation of the farm, but also mediate within communities of farmers, between farmers and communities, and between communities and farms, and prompt the development of new rules, which in turn may lead to a reorientation of the division of labour in the agri-food system. Hence, digital agriculture could be more deeply analysed as one component of the major structural changes facing the distribution of labour and capital in agriculture. This relates to structural changes both within farms (increase in farm size, in the share of employees in farm labour, etc.), and between farms (joint corporate farming, etc.), or between farms and other actors of the supply chain, which could build on and advance earlier critical analysis mentioned in section 2.2 (e.g. Carolan, 2017b, 2019; Rotz et al., 2019a). In line with questions on how diversity impacts digital agriculture technology adoption, Lioutas et al. (2019) suggest this may play out differently for different types of farms (i.e. horticulture, arable farms, dairy farms) as they may have different activity systems, and this would require further research. Other relevant questions in this thematic cluster may include:

- What is the performativity of the concepts of Smart Farming, Digital Agriculture and Agriculture 4.0, for example in terms of implied dichotomies of 'Smart Farming' versus 'Dumb Farming', 'Digital Agriculture' versus 'Analogue Agriculture', and 'Farmer 4.0' versus 'Farmer 3.0'?
- How do interactions between digital farmer worlds and analogue farmer worlds lead to development of new farmer identities and farming style types, e.g. 'youtubers', 'cyborg farmers', 'geek farmers', 'joystick farmers' or 'drone farmers'?
- What is the influence of social media on farmer identity? How do farmers perform identity work through social media? How does social media affect their autonomy, in view of public scrutiny and policy and supply chain surveillance? How does it change farmers' communities and the role of leaders within these communities?
- What is the effect of interactions between digital technologies, plants and animals on farm work? How do plants and animals become 'digital agents' and how do they prompt human responses? What are the affordances of digital technologies towards several human and non-human actors on farms?
- How is farm work affected by digitalization in terms of farmer skills, in terms of quality and joy? What deskilling and reskilling processes are triggered? What is the balance between reliance on digital knowledge, and on experiential knowledge and intuition? What is the extent of trust of farmers in information generated by machines?
- What are the implications of digitalization for farm succession, how does it affect choices of coming generations of farmers and succession parameters such as investment and future perspectives?
- How does digitalization affect male and female farmers in different ways? How does it affect gender relationships on farms and in rural communities?

Topics such as farmer identity and farm work are often investigated by qualitative methods, consisting of interviews and participant observation. The new realities of digital agriculture and the abundance of data they afford enable web and mobile analytics, visualization of large data sets, machine learning, sentiment analysis and opinion mining, computer-assisted content analysis, natural language processing, automated data aggregation and mining, and large social media networks (Mills, 2018). These new data sources and methods could offer possibilities for doing new sorts of ethnographies or technographies (Jansen and Vellema, 2011), such as 'netnography' (Kozinets, 2010). However, such analysis is obviously subject to accessibility and personal data issues, and similar ethical concerns related to power, privacy and data ownership as those noted by works described under section 2.3, and would require dedicated research ethics (Glenna et al., 2019).

4.1.3. Emerging topics and questions in the thematic cluster of power, ownership, privacy and ethics in agricultural production systems and value chains

The articles from the special issue connected to the thematic cluster of power, ownership, privacy and ethics in agricultural production systems and value chains clearly point out the need for reflection on power, values and ethics. For example, on the basis of their extensive review, Van der Burg et al. (2019) raise four important areas of future research: 1) investigating the societal role of farms, thus broadening the imagination of stakeholders about the possible other goals that smart farming could serve, and enhancing their reflection about their relative value; 2) reflection on the epistemological choices that are made in the selection of data, the ways in which meaningful connections are made between them and how they are interpreted (echoing suggestions by Bronson, 2019); 3) understanding the preconditions for trust between stakeholders who have a role in smart farming and who engage in a relationship together when they become members in a data sharing network (an issue also raised by Jakku et al., 2019; Wiseman et al., 2019); and 4) scrutiny of codes of conduct, as it is unclear how current regulation could satisfactorily combine the private and societal goals that smart farming is intended to serve. Regan (2019) adds to this the importance of looking at issues such as perceived uncertainty and risk. Most of the authors in this thematic cluster point to the need for responsible research and innovation. Based on the insights from articles in this special issue, as well as a wider reflection by the authors of this article, future research could explore topics such as the role of values in digital agriculture design, the organisation and governance of data and the application of responsible innovation principles. For instance, examples of specific questions could include:

- How do the values of different stakeholders in the digital agriculture design processes differ?
- What are the broader societal or public interests that digital agriculture should fulfil, and what are potential trade-offs with private interests? The issue of digitalization may be integrated into the current debates over the effects of new institutional arrangements, such as the Public-Private-Partnerships (PPP), on the integration of societal issues and empowerment or further privatisation of public

goods (Wettenhall, 2003; Sclar, 2015).

- What sort of governance responses emerge, for example in relation to surveillance through digital technologies?
- What are the forms of resistance within or against digitalization? Furthering earlier work by Carolan (2018c), how do novel grassroots and corporate organisational responses emerge around Big Data and the Internet of Things, such as Right to Repair, Farm Hack and Data Cooperatives, and how do they function? How localised or global are such grassroots and corporate organisational arrangements and how do they influence decision making in value chains?
- How do different policy or governance models either hinder or enable the development of trust between actors? How do digital technologies increase or decrease power and information asymmetries?
- How can principles of responsible innovation help different actors deal with the 'unknowns' and 'unseens' related to digital agriculture? What are the uncertainties and risks perceived by different actors? How are these contemplated in actual RRI processes? What are considered the 'digital game changers' (following Brunori et al., 2019)?

In terms of research approaches and theories, following the earlier work by scholars in the fields of rural sociology and science and technology studies, discussed in section 2.3, there is ample scope here for political economy and political ecology approaches, as well as practice theory and social movement theory, to unravel the 'digital food regimes' (as per the term introduced by Burch and Lawrence, 2009; McMichael, 2005). Feminist and post-structuralist Foucauldian theory and Latourian actor-network theory can also contribute to identifying power relations. Critical discourse studies could also help with unravelling the values and tacit assumptions of different stakeholders and how these are negotiated in interaction. The emerging field of digital sociology (Lupton, 2014) brings together a variety of analytical lenses from contemporary social and cultural theory, which can help investigate the kinds of assemblages that are configured through digital technology use and encourage reflection on the implications and consequences of such use, including social dynamics relating to the increasing pervasiveness of digital surveillance in everyday life.

4.1.4. Emerging topics and questions in the thematic cluster of digital knowledge and innovation systems

Regarding the thematic cluster of digital knowledge and innovation systems, several articles in the special issue (Ayre et al., 2019; Fielke et al., 2019 and Rijswijk et al., 2019) introduce new and perhaps tentative concepts to better understand digitalizing AKIS, such as 'digiware' (Ayre et al., 2019), 'Digital Agricultural Innovation Systems' (Fielke et al., 2019) and 'digi-grasping' (Dufva and Dufva, 2019; Rijswijk et al., 2019. Further developing these concepts will be a major task for future conceptual and empirical work. Future work should look at both macro, meso and micro levels in AKIS, and questions may include:

- In view of ideas coined around 'agriculture 4.0', which encompasses several other technologies in connection with digital technologies (e.g. nanotechnologies, gene editing, 'omics', synthetic foods), and what that implies for organizing cross-sectoral innovation (Pigford et al., 2018; Rose and Chilvers, 2018), how do traditional and non-traditional players (e.g. silicon valley style tech companies) in the agri-food sectors collaborate? What is the role of new AKIS players (e.g. tech firms) on local and global innovation dynamics? What does this mean for the inclusion of different sorts of knowledges in agri-food innovation?
- What models of future agricultural production (e.g. agro-ecology, sustainable intensification, circular agriculture, vertical agriculture) are supported by digital AKIS and what models are not? How does digitalization change the functioning of agricultural R&D, its routine for experimenting and assessing the potential of new technologies for farmers? Can virtual models or digital twins, and Big Data replace field experimentation?
- How does digitalization affect the sector specificity of AKIS? How is it transformed by and integrated in the development of more generic technologies, ranging from social media through to block chains?
- In relation to new modes of governance, including interactive digital innovation, what new forms of digital learning and innovation spaces emerge (e.g. public-private partnerships through Digital Innovation Hubs, Digital Living Labs, Data Cooperatives, Hacker Spaces and open source innovation, rural FabLabs and Makerspaces)? What goals do they have, what methodologies do they use, and what is their effect on innovation processes? How do citizen science-based and social network-based exchanges of data and information shape farm innovation?
- In relation to digital agriculture adoption and adaptation, how are new roles, functions, and identities of agricultural researchers and advisors shaped? What roles do they take in (big) data gathering, aggregation, curation, sensemaking, and application? How are processes of analogue and digital unlearning/deskilling – learning/reskilling managed by advisory services? What new advisory and research organizational structures and business models emerge as a result and how does this affect advisor and research capabilities and training? What autonomous innovation forces do machines exercise?

In order to empirically research digital AKIS, existing frameworks such as functional-structural innovation systems analysis could be used to map digital AKIS within countries, but also across borders (Turner et al., 2016; Wieczorek and Hekkert, 2012). Certain technologies have now been developed for long enough to trace back their technological innovation systems and provide historical insights on how they impacted agricultural R&D (in line with Eastwood et al., 2017b). Methods for researching online activity could also be used to map information exchange and learning dynamics, as well as other data science methods mentioned already above. Following Nambisan et al. (2019), this could enable a different sort of social science capable of better grasping the potentially different innovation dynamics afforded by digital agriculture.

4.1.5. Emerging topics and questions in the thematic cluster of economics and management of digitalized agricultural production systems and value chains

In terms of the last thematic cluster identified, economics and management of digitalized agricultural production systems and value chains, the article in this special issue by Phillips et al. (2019) has made evident that we need more systematic mapping of emerging business models, to help see how local or global these are, and identify what advantages and risks come with each model. Furthermore, following the review by Rojo Gimeno et al. (2019), we need new sets of questions to assess:

- What are some of the emerging models for value-adding and brokering of data and what opportunities do these create for different actors?
- What are the effects on distribution or labour and capital in agriculture, both within farms (e.g. increase in farm size, in the share of employees in farm labour, etc.), between farms (joint corporate farming, etc.) or between farms and other actors of the supply chain?
- How does digitalization affect interactions between value chain players (e.g. input suppliers, intermediaries, traders, retailers) in terms of contracts, trust and transaction costs, through for instance implementation of platform technologies, Internet of Things and Artifical Intelligence?

Economics and management sciences can make many analytical contributions to policy, farm management, supply chain, consumer demand and sustainability issues (Coble et al., 2018), using the variety of methods they employ. Approaches from economics and marketing of innovation (Desmarchelier et al., 2013) and production organisation specific to services (and more precisely to Knowledge Intensive Business Services - Lusch et al., 2007) might usefully be applied to agriculture (as done earlier by Klerkx and Proctor, 2013)). This could involve applying the case studies approach to new business models, to understand how actors create value out of agricultural data. Another useful avenue of enquiry would be to develop more quantitative approaches in this context, which have proven their value in other sectors, such as statistical analysis of systematic surveys on firm innovation (Cainelli et al., 2004).

4.2. A research agenda in potential future clusters of research

We have outlined, following the established and emerging thematic clusters of research, several questions for future research. However, there seems to be areas that are underdeveloped and could form new thematic clusters of social science research on digitalization in agriculture.

4.2.1. Digital agriculture social systems conceptualizations: towards cyber-physical-socio-ecological systems?

Whereas some authors reflect on the need for inclusion of social systems in conceptualizations of digital agriculture, such as cyber physical systems (Wolfert et al., 2017), or the 'socio-cyber-physical systems' that Lioutas et al. (2019) refer to in their article for the special issue, this seems an underdeveloped area. As digital agriculture enables multiple new material, spatial and temporal flows, this area could benefit from conceptual reflection and empirical studies. It could draw on bodies of work looking at socio-technical systems (Bijker, 1995), or as mentioned earlier use assemblage theory, as Carolan and Higgins and colleagues have already applied or suggested (Carolan, 2017a; Higgins et al., 2017), or activity systems theory (Lioutas et al., 2019). Other related concepts that could be useful include 'socio-technological-ecological systems' (McPhearson et al., 2016), or connecting digital transformation with ideas on 'innovation ecosystems' (Pigford et al., 2018) or 'nature based innovation systems' (Van der Jagt et al., 2019). Another relevant concept could be 'telecoupling' between geographically distant but nonetheless connected human and ecological worlds (Hull and Liu, 2018; Liu et al., 2013), or what has been called a 'sociology of flows' (Oosterveer, 2015). Empirical but also philosophical questions could include:

- What kinds of new socio-cyber-physical connections are made through digital agriculture and smart value chains and food systems, and what kind of feedback mechanisms do they engender? How do new modes of information exchange between farmers and their environment influence structural change, for example, in terms of how fields are set up and agricultural landscapes are shaped?
- How do digital agricultural systems create new links between humans and the farming environment, and how does this feed back into human systems (motorial, cognitive). For example, what is the effect of new spatial dimensions provided by drones and augmented reality, new tactile and motorial dimensions provided by automation/robots, and what cognitive dimensions are triggered by artificial intelligence?
- How do digital twins foster learning and experimentation with new sorts of human- technology-natural environment interactions?
- What are the limits of digital technologies in terms of human values and willingness to integrated with machines, following concepts such as the 'quantified self' and 'digitally enhanced humans'? Also, following Holy-Luczaj and Blok (2019), what are the moral and ethical consequences of hybrid entities combining digital farming technologies and natural ecosystem elements, crossing the ontological binarism of naturalness and artificiality?

4.2.2. Digitally enabled agricultural transition pathways

While digital technologies have become pervasive, their role in transitions towards sustainability remain understudied. Digital agricultural technologies have often been suggested as potentially contributing to realizing more sustainable practices (El Bilali and Allahyari, 2018a), but have hardly been studied as part of transition dynamics. Following Köhler et al. (2019), we think that digitalization as a transformative force needs much more attention. Also, so far, the literature does not often focus on how digital agriculture links to diverse future models of agriculture, which tend to co-exist (Gaitán-Cremaschi et al., 2019; Pigford et al., 2018; Plumecocq et al., 2018). Most authors doing critical analysis see digital agriculture as reinforcing neoliberal industrialized agricultural production systems and food systems (e.g. Bronson and Knezevic, 2016, 2019; Carolan, 2017b, 2018a,c, 2019a). However, some authors consider it a possible way to enhance agroecological models (Bellon-Maurel and Huyghe, 2017; Dumont et al., 2018; Leveau et al., 2019; Van Hulst et al., 2020). Empirical questions include:

- What are the roles of digital technology as a change agent? How does it enable actors in the agri-food sector to foster change? How does it support alternative 'sustainable niches', how does it disturb or reinforce incumbent 'food regimes'?
- How do digital technologies relate to different paradigms in agriculture that coexist or compete, such as organic farming, agroecology, bio-economy, regenerative agriculture, urban agriculture, vertical agriculture?

4.2.3. Digital agricultural policy making

Some research has been done with the intention to inform agricultural policies (Jouanjean, 2019; Soma et al., 2019; World Bank, 2017; World Bank, 2019; EU SCAR AKIS, 2019), and is the focus of many reflections and recommendations in earlier work (Lele and Goswami, 2017; Bronson, 2018; Bronson and Knezevic, 2019; Carbonell, 2016;). However, there are still limited accounts of policy and law-making processes, for example in relation to data ownership regulations, with some exceptions (Sanderson et al., 2018; Trendov et al., 2019). This is an area that could receive more attention, for example from the disciplines of political science and law. Here empirical questions could include:

- How does digital agriculture feed data into real-time policy making? What distributive effects does such data and algorithm-informed agricultural policy have?
- How is the notion of segmentation of target audiences of policies affected by digitalization (small vs. big farms, young farmers, gender issues, etc.)? How do policy makers respond to counteract negative impacts of digital agriculture, such as concentration of power and risk of cyber-attacks on the food system?
- How do agricultural public policy makers and politicians operate in political arenas with large information technology companies and agri-tech firms? How does digital agriculture relate to the financialization and corporatization of agriculture, and what policy responses can be witnessed to counteract potential negative effects?
- What policy discourses around digital agriculture emerge, and how are they used in food policy and innovation policy debates?
- How is the nature of policy instruments itself framed or restricted by technologies? For instance, is there a risk that farmers' subsidies are restricted to support practices that can be monitored using remote methods (satellites images, censors, etc.), to the detriment of more systemic practices?

4.2.4. The global geography of digital agriculture development: social dynamics related to digital agriculture in developing and emerging countries

Digital agriculture is also heavily promoted in the global south, and multiple studies have documented experiences and lessons so far, in relation to market information systems and advisory provisioning through mobile phone apps for example, as well as agricultural citizen science (Aker, 2011; Barreto and Amaral, 2018; Baumüller, 2016, 2017; Lele and Goswami, 2017; Cieslik et al., 2018; Ezeomah and Duncombe, 2019; Munthali et al., 2018; World Bank, 2017; Trendov et al., 2019; Jouanjean, 2019). However, critical social science studies seem to be empirically biased towards the Global North (North America, Europe) and developed countries in the Global South (Australia, New Zealand). It has therefore been suggested that a critical approach towards the pervasive application of digital technologies in developing and emerging country agriculture is much needed (Cieslik et al., 2018; Mann, 2018; Sulaiman V. et al., 2012). This is because digital agricultural technology is not context neutral (Eastwood et al., 2017b), but needs to be unpacked, situated, reconfigured, and supported by a local, context-sensitive support infrastructure (Glover et al., 2019, 2017; Marin et al., 2015). As agriculture is a sector where both the organisation of production, the innovation dynamics and policy have been often developed within national trajectories, but also have global dimensions through interconnected value chains, it is critical to assess the development of digital agriculture around the globe through the lenses provided by the different thematic clusters (established, emerging, and potential). This could help answering questions such as:

- How do digital agricultural technologies travel and how are they translated to different contexts? What is the role of national digital agriculture technological innovation systems in relation to global digital agriculture technological innovation systems in processes of technology generation and diffusion, and adoption and adaptation?
- What is the role of global technology providers, local technology firms and public-private partnerships? What types of frugal digital innovations emerge? What is the role of upcoming nations, such as China, India, Brazil and Chile, in terms of digital agricultural technology, and how does this influence digital agriculture technology markets?
- What is the role of donor discourse in digitalization of agriculture? How does this discourse include or exclude local values towards agriculture?
- How do ethical values regarding digital agriculture (e.g. data ownership, privacy, farmer and animal autonomy) come to expression in different contexts? How is digital agriculture regulated in different contexts?

5. Conclusion

This review and introductory article to the special issue has provided an overview of thematic clusters of social science research on digital agriculture, thereby showing this is a burgeoning field that provides important insights for the policy and practice of digital agriculture. Being an exploratory review, while summarizing earlier strands of work, this article has not systemically analysed, compared, and synthesized the evidence in the different thematic clusters of social science on digital agriculture. This calls for future studies taking a systematic review approach.

The studies in this special issue add to the five thematic clusters, by showing recent responses in terms of policies, practices, and institutional arrangements to embed digital agriculture in different sectors and countries, such as new AKIS arrangements and changing organizational identities, and new business models and policy responses. Beyond summarizing the findings from the studies in the special issue, this article has drawn out an agenda for future research by suggesting new questions in the five thematic clusters identified. Furthermore, we have articulated four new thematic fields: 1) digital agriculture social systems conceptualizations; 2) digital agriculture policy processes; 3) digitally enabled agricultural transition pathways; and 4) global geography of digital agriculture development.

While we have shown the diversity of social science perspectives employed so far, and their complementarity, we believe there is more scope for interdisciplinary as well as transdisciplinary work. Interdisciplinarity as well as transdisciplinarity can help enrich our understanding of the specific institutional contexts and stakeholder dynamics in which digital innovations are developed and what they might impact (Taebi et al., 2014). There is also scope for methodological innovation, moving from an analogue social science to digital social science or social data science, because as Roth et al (2019) argue quite strongly, computer illiterate social scientists produce analogue theories of digital societies.

The diversity of new questions presented in this article shows that there are many possible lines of enquiry across and between different social science and natural and technical science disciplines. As digital agriculture increasingly moves beyond prototype and hype stages, there will be ample opportunity to empirically address these questions and identify many others. In doing so, social science research in conjunction with natural or technical sciences can help to guide the development of digital agriculture in ways that consider and respond to social dynamics, thus trying to enhance the benefits and mitigate the potential negative consequences of these emerging technologies.

Conflict of interest

The authors state they have no conflict of interest.

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