What are the Priority Research Questions for Digital Agriculture?

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1. Introduction

Digital agriculture, defined broadly as the application of big data and precision technology systems in agriculture (Rotz *et al.*, 2019, p1), comprises a range of practices which collectively herald a transformation in agri-food systems. Although this transformation emanates from multiple points in the system, the changes in agricultural production systems are thought to be profound. Technology-intensive, data-supported forms of precision agriculture and field specific data have been available for some time to help farmers make appropriate decisions on the production process (Kritikos, 2017; Finger *et al.*, 2019). A new era of smart farming, where smart devices and intelligent systems, supported by networks of interconnected things and facilitated by cloud computing (Wolfert *et al.*, 2017), now promises to supply farmers with "quick-witted intelligence" which can potentially transform traditional (process-driven) agricultural systems into smarter, data-driven systems (Lioutas *et al.*, 2019, p2).

Such developments are framed by some as 'the fourth agricultural revolution' and the accompanying narrative is one of improving agricultural efficiencies and productivity. Digital technologies and big data in this context bring benefits to both food production and ecosystems services (Weersink *et al.*, 2018; Rose and Chilvers, 2018) and set the foundations for the future of sustainable agriculture (Saiz-Rubio and Rovira-Más, 2020; Garske *et al.*, 2021). Ongoing developments and big data advances (e.g., Walter *et al.,* 2017; Wolfert *et al.,* 2017) continue to make precision technologies more accurate, more widely applicable, and more efficient (Weersink *et al.,* 2018), offering the prospect of a 'step change' in productivity and profitability across the value chain.

However, this 'agri-food tech solutionism' has been critiqued as hype and over-confident by a number of commentators (e.g., World Bank, 2016; Miles, 2019; Fairbairn and Guthman, 2020; Lajoie-O'Malley *et al.*, 2020). Evidence that digital agriculture can meet such expectations is arguably limited to a few innovative firms (Zambon *et al.*, 2019), while big data has yet to fulfil its promise (Huberty, 2015; Basso and Ante, 2020; Clapp and Ruder, 2020). Others point to the relatively low uptake of precision technologies, particularly the more complex applications (Barnes *et al*., 2019; Lowenberg-DeBoer and Erickson, 2019; Carolan, 2020; Spati *et al.,* 2021). More fundamentally, the assumptions and "normative desirability and expected benefits" (Fleming *et al.,* 2018, p19) of these technologies, articulated by science and policy (Defra, 2021) and embedded in high level policy and international agency discourse, are being questioned (Poppe *et al.,* 2015; Kuch *et al.,* 2020; Lajoie-O'Malley *et al.*, 2020; Schroeder *et al.,* 2021). Furthermore, it is increasingly understood that digital agriculture is rooted in economic, political, social and ethical relations with a range of issues being raised about data governance (Bronson and Knezevic, 2016; Carbonell, 2016; Capalbo *et al.*, 2017; Rotz *et al.*, 2019) and the threat of reinforcing existing economic, spatial, and social divides (Carolan, 2017a, 2020; FAO, 2019).

This multiplicity of issues results in research being dispersed, and addressed from a number of disciplines (Finger *et al.,* 2019), risking poor integration as multiple perspectives, with diverse and often contradictory arguments, are merged together (Lioutas *et al.,* 2019). Whilst we understand that digitalisation is a socio-technical process, formulating and enacting research from a systems perspective is still a challenge.

These concerns have prompted researchers to question future trajectories and potential impacts of digital transformation in food production and agri-food systems. Although there is an emerging body of work, our understanding, as researchers, industry practitioners and policy makers, of how to use digitalised agricultural technologies and big data is still at an embryonic stage (Lioutas *et al.,* 2019). As Lajoie O' Malley *et al.* (2020 p2) state, "it is still uncertain what the future of digital agriculture will look like, who will benefit from digital agriculture, and how it will affect agricultural production and food systems at large, including the delivery of ecosystem services". There is a need therefore to identify key existing and emerging issues relevant to digitalisation in agricultural production that would benefit from a stronger evidence/research base which can help steer policy formulation and associated research investment strategies.

This need is particularly relevant to the UK where the evidence base is still relatively small compared to more digitally advanced countries and regions (notably Australia, New Zealand and North America). Building on the more mature precision technologies (Barnes *et al.,* 2019; Houses of Parliament, 2015), digitalisation is now slowly permeating the UK's agri-food system, as the industry is starting to adopt and adapt technology, software, sensor and robotic innovations. Studies to date, however, have been disparate, from adoption of precision farming (Barnes *et al.,* 2019), experiences with dairy robotics (Holloway *et al.,* 2014; Bear and Holloway, 2019) and industry perceptions more generally (Barrett and Rose, 2020), and crucially none have envisaged a future research trajectory or agenda to steer policy.

As such, a research prioritisation exercise was undertaken in the UK. Technological innovations to boost productivity and enhance agri-businesses lie at the heart of the government's discussions about a renewed agricultural sector and thus embody a modernising technological discourse. This is illustrated by the positive language of UK policy documents (Barrett and Rose, 2020) and the level and direction of investment from the government's research funding body UK Research and Innovation through its Transforming Food Production Challenge, which announced in 2018 funding of £90m (HM Government, 2018). This is core to the UK's Industrial Strategy Challenge Fund, which aims to address the grand challenge of food system transformation. However, other perspectives are arguably not being given due attention at this critical time of post-brexit policy development and debate, as government and industry seek ways of achieving a sustainable agri-food system (Defra, 2020).

The aim of the prioritisation exercise reported here was to identify priority research questions concerning digital agriculture in the UK through consultation with a wide range of stakeholders across a number of sectors and disciplines. Through this exercise, we determined key questions by providing a space for both discussion between researchers and stakeholders and finding a common understanding of knowledge needs in this important and emerging area of research enquiry and policy interest. This paper aims to report these outcomes and in turn opens up new perspectives that can guide agricultural research and policy in this area in the future. These are immediately applicable to the UK but equally inform research agendas in wider international contexts. With respect to the priority research questions informing policy, there are two related aims: firstly, to identify and prioritise existing and emerging issues that would benefit from a stronger evidence/research base and that if addressed could increase the effectiveness of policies; and secondly, to influence the way policy makers think, which is a necessary precursor to direct and longer-term policy changes arising from research (Weiss 1997; Sutherland *et al.,* 2011). These aims are commensurate with research published in this journal which has called both for a stronger evidence base and for policy makers promoting digital agriculture to pay more attention to different 'agricultures' and the contexts in which it is delivered (Vecchio *et al.,* 2020; Lioutas and Charatsari, 2021).

2. Research themes and priorities

Questions about the future of digital transformation of agriculture have prompted a series of reviews which identify technical and social research themes and agendas. With respect to data, these cover: big data applications in smart farming (Wolfert *et al.,* 2017); big data analysis (Kamilaris *et al.*, 2017; Lioutas et al., 2019); and data and decision-making (Evans et al., 2017). Collectively, these review-based exercises propose giving research precedence to governance issues, which can enable equal exchange of value from big data and identify suitable business models for data sharing in different supply chain scenarios. From a science perspective, Shepherd *et al.* (2020) reported on priorities for scientists and institutions to enable the potential benefit of digitalisation of science to be captured.

These reflect some emerging lines of social science enquiry clustered thematically by Klerkx *et al.* (2019) (and updated here) in another literature review, which include: i. Adoption, barriers, uses and adaptation of precision and digital technologies on farms (Pierpaoli *et al.*, 2013; Finger *et al.,* 2019; Knierim *et al.*, 2019; Balafoutis, et al., 2020; da Silveira *et al.,* 2021); ii. Impacts on farm identity, farmer skills and farm work (Lioutas *et al.,* 2019); iii. Power, ownership, privacy and ethical issues (farm and value chain) (Bronson and Knezevic, 2016; Jakku *et al.*, 2019; Wiseman *et al.*, 2019); iv. Implications for agricultural knowledge and innovation systems (AKIS) (Eastwood *et al.*, 2019; Rijswijk *et al.*, 2019; Fielke *et al.*, 2020); and v. The economics, management of digitalised agricultural production systems and value chains and impact on input industries (Phillips *et al.*, 2019; Birner *et al.,* 2021).

While this is an expanding and topical area of interest, to date these research themes and priority questions have largely emerged from literature reviews and not through a process of dialogue and deliberation between researchers and digital technology and agri-industry practitioners. A number of deliberative methods (e.g. the Delphi, Q methodology) are available to elicit stakeholder and expert views on important topics, while specifically for digitalisation, scenario and foresighting approaches have been used to explore possible futures and their implications for research practice and for farming communities (Fleming et al., 2021). However, the prioritisation method expounded by Sutherland *et al.* (2011) provides an established and effective participatory methodology for consultation on research questions, and as such addresses the aims of this paper.

3. Methodology - a priority research question exercise for digital agriculture

The method for identifying priority research questions for digital agriculture in the UK followed an iterative process previously applied in agricultural, conservation, food systems and related fields of research, often to deliberate societal grand challenges (see Pretty *et al.,* 2010; Sutherland *et al.,* 2013; Ingram *et al.,* 2013; Morris *et al.,* 2021). We applied the principles and lessons on methods as set out by Sutherland *et al.* (2011). The method places emphasis on making the process to identify the most important questions rigorous, inclusive and democratic. The process involves identifying a large number of participants (50-100) and eliciting an initial long list of research questions which is reduced and refined in subsequent voting stages to select the top priorities by theme.

The method starts with a clear vision about the aim and audience of the exercise. The aim in this case was to solicit questions about digital agriculture that could be addressed by a range of research methods. The parameters for the study were primary production, using the definition "Digital Agriculture refers to farm management systems where decisions are taken using an increasing amount of digital information in order to increase productivity and sustainability"; however, there was some flexibility to allow for any overlap of questions with other parts of the agri-food system.

The exercise was organised into a series of incremental steps. In Step 1, representatives from different stakeholder groups from across UK agriculture were selected (see selection details below) and invited to propose questions (up to 10) on aspects of digital agriculture that, from their perspective, should be a priority for research. The criteria for the questions was that they should be limited to key existing and emerging issues that would benefit specifically from a stronger evidence and research base; and could be addressed within a 3-5 year research project. The scope was defined as the use of digital information in farm management systems, including any impacts on and off farm.

This first step generated 200 questions. After removal of some which were unclear or not questions per se, the list was refined to 195. Preliminary analysis and clustering of the 195 questions was then undertaken. An inductive approach was employed since the analysis was not guided by theory or pre-defined framework, and this underpinned a thematic analysis. Themes (topic summary themes) were identified following data familiarisation (reading and re-reading data), and then a coding framework was created using NVivo 12. This was done iteratively by a team of three researchers to allow a shared approach to clustering of the questions. This required several iterations due to the large number, scope and interrelated nature of the questions. Crosschecks were made between researchers when coding the questions to the themes and topics to ensure a consistent and robust process was followed throughout. Seven main themes were identified, as follows: data governance; data management; enabling use of data and technologies; understanding benefits and uptake of data and technologies; optimising data and technologies for performance; impacts of digital agriculture; and new collaborative arrangements (Figure 1). Each theme had a number of constituent topics. Figure 2 presents a visualisation of the analysis for questions in one topic in Theme 1 by way of an example.

In Step 2, an online voting stage was then conducted, which sought to rank and prioritise the questions. This used a JISC online survey structure. Each respondent was contacted with a survey link and asked to score all the questions within each theme. In total, 28 participants responded. Voting numbers for each theme are shown in Table 1 and preferences by different stakeholder type were spread evenly across the seven research themes. From this, we ranked the questions according to their scores and identified the top 10 questions in each theme. Questions remained unedited in Steps 1 and 2.

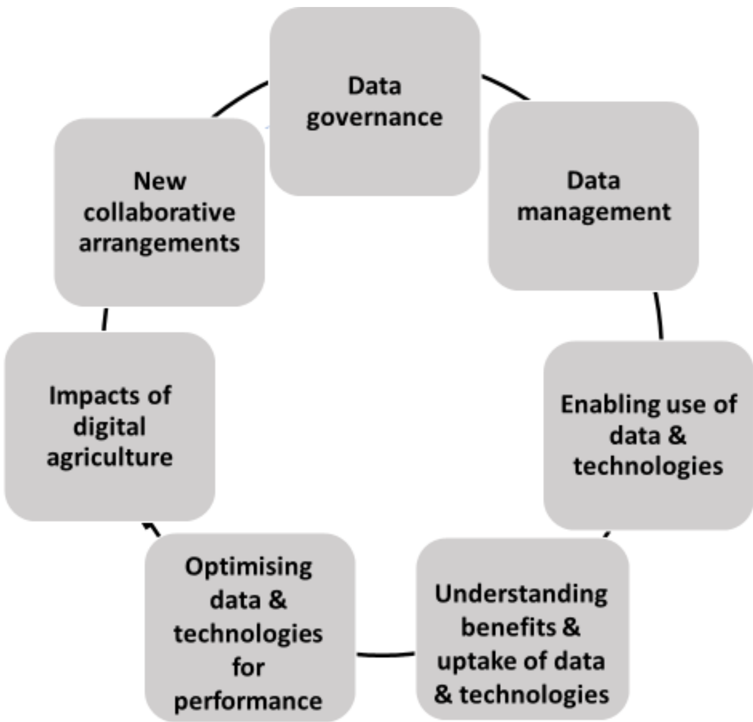

Figure 1. Key themes identified in the prioritisation exercise

In Step 3, an online workshop was held in order to further unpack and explore the questions and associated narratives for each theme. All participants who had responded to the ranking exercise were invited to the workshop and 25 attended. The workshop was interactive, with four facilitated break-out groups each addressing two of the seven themes (bar one group, which addressed one theme). In the breakout sessions, participants were asked first to review the top five ranked questions in their respective theme and to address the following questions: What is the scope of these questions? What has framed them? The second task was to then: prioritise the questions; remove duplicates and unpack multiple questions; improve question wording and clarify meanings if needed; and identify gaps. A qualitative scale of gold, silver or bronze was used for question prioritisation, whereby gold questions are the highest priority, in terms of significance and being most in need of a stronger evidence and research base, with silver and bronze being of relatively lower priority. This scale was discussed prior to the break out group activities to ensure all groups followed the same ranking process. A plenary session provided opportunity for discussions that cut across the themes.

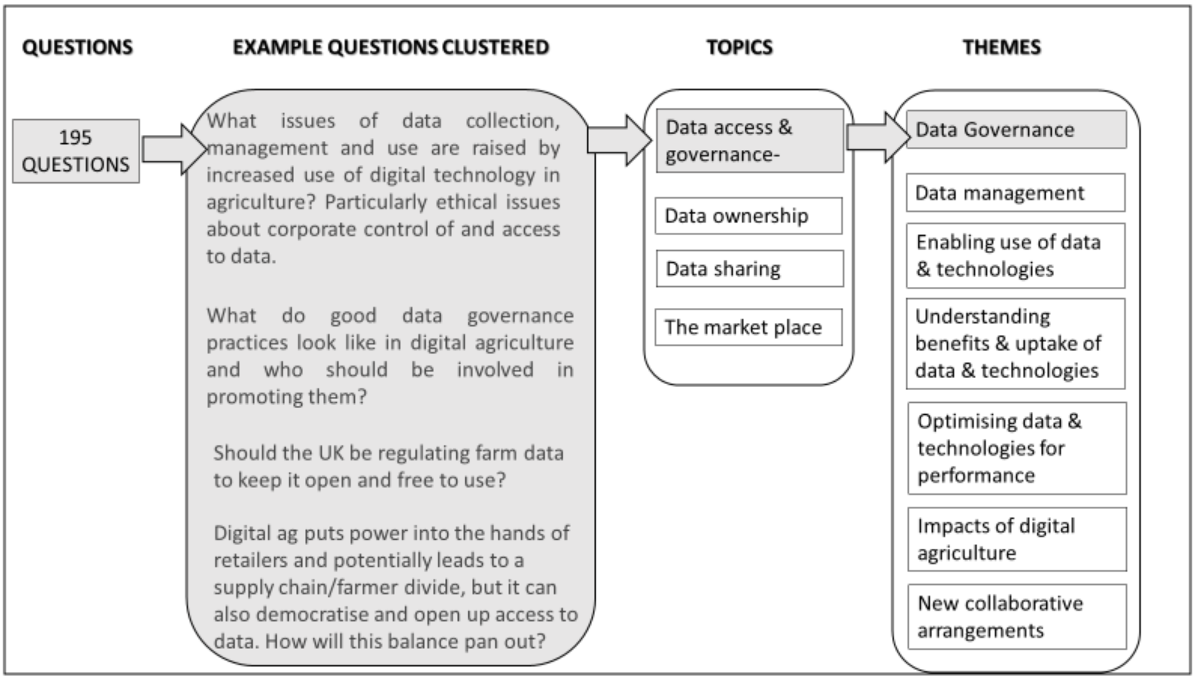

Figure 2. A visualisation to show analysis of priority questions for one topic in Theme 1 (grey shading)

All participants were sent the top 10 ranked questions for all themes before the workshop. The workshop, including the breakout sessions, was recorded, transcribed and analysed and summary notes and final rankings were updated and shared with participants via Microsoft Teams for a final round of edits, prioritisation and comments. This paper was co-authored by a self-selected group of participants.

For this study, a wide range of perspectives were sought by inviting representatives selected from different stakeholder groups across UK agriculture. An initial list of relevant stakeholder groups was drawn up by the lead researchers using personal contacts, Google and Google Scholar searches to scope out participants' interests and expertise. The criteria for inclusion was firstly, stakeholder areas of operation, namely: academia, agricultural research institutes, farmer representatives, agricultural suppliers, agri-tech businesses, NGOs, government bodies and consultants (technical, business, legal), and secondly, relevant experience or interest in digitalisation of agriculture. These criteria were used to reflect the technical, social, legal and ethical dimensions of digital agriculture, shown in the literature to be significant, and to capture a range of views, including conflicting or alternative views. Potential participants (148 in total, see Table 1) were sent an invitation explaining the research and were invited by email to propose questions. This was enhanced by a snowballing method in which we asked those selected to suggest contacts or colleagues. In addition, a link to the invitation was circulated via the host institution's Twitter account (2462 followers) and website (2000 visit per month) which reaches a wider range of people in the agri-food and agri-environment community. In total, 40 respondents sent in questions. Some of these respondents (4) shared the task with colleagues (4-6) and agreed a set of questions together. Table 1 shows the distribution of respondents compared to the original invitations. Approximately half of respondents in Steps 1 and 2 were from the research community (this included university departments and research institutes concerned with agriculture and technologies, data analytics, agri-food systems and humanities) and research funders; and half from a range of practitioner or commercial stakeholder groups. There was a good representation across the range of targeted stakeholders. Although responses from technology and data services were lower than hoped for, those who responded represented some of the larger actors in this sector. No responses from agricultural suppliers suggest that this sector does not consider this topic relevant. The aim was to include participants from across the UK, and although the majority of respondents were from England, some representation from Wales (4) and Scotland (2) was also achieved.

Stakeholder groups	Invitation to participate	Step 1 Questions	Step 2 Voting	Step 3 Workshop
Researchers (academics- technical, natural resources, agri-food systems, social sciences, humanities), research institutes (e.g. Rothamsted Research), research funders (e.g. BBSRC)	48	19	12	14
Agricultural research & consultancy (commercial/ private) (e.g. RSK ADAS)	8	3	2	2
Agritech - digital technologies & data services (e.g. Agri-EPI Centres, precision technologies, mapping and software services)	45	8	5	3
Farmer representatives (e.g. AHDB, NFU, Farming Connect, I4Ag)	8	3	3	4
Government depts & agencies (policy, research) (e.g. Defra, Natural England, FERA)	7	3	2	1
Agricultural suppliers of inputs & machinery (e.g. John Deere, YARA)	20	0	0	0
Other (NGOs e.g. LEAF, Food Ethics Council)	12	2	4	1
Total	148	40	28	25

Table 1. Participant numbers and types at each stage in the prioritisation exercise

4. Results and discussion: Prioritised themes and research questions

The themes and constituent questions cover a plurality of ideas and topics and indicate a range of evidence needs. They interconnect with respect to issues of institutional governance, the ability to utilise digital agriculture effectively, equitably and collaboratively, and the impacts and restructuring of different relationships and power structures across agriculture and the wider agri-food system.

For each theme, the gold, silver and bronze questions as refined in the workshop, are presented together with an analysis of the accompanying discussion. A brief list of the original question topics (step 1) are provided, the refined top 5 questions per theme from the voting (step 2) are available as supplementary material. In total 27 priority research questions were identified: 15 gold, 7 silver and 5 bronze, across the 7 themes.

4.1 Theme 1: Data governance

Theme 1 questions collectively identify challenges of data ownership, sharing and ethical issues about corporate control of data. The original questions (30) focused on: data access and governance; data ownership; data sharing; and the market place. These were ranked in the voting stage, and further prioritised and rephrased in the workshop to the following questions:

1. Gold: How can data sharing be underpinned by a governance system which takes account of ethical concerns?
2. Gold: How can the value proposition inherent in data sharing be underpinned by a governance system that gives people the confidence to enter into that proposition?
3. Silver: How to create the ecosystem / community that is needed to develop a transparent shared system of data which is attractive for farmers and commercial developers alike?
4. Bronze: How can farmers work together to benefit from the data that they provide (knowingly/ unknowingly) to big global suppliers?

Governing data ethically and responsibly was the priority issue for this theme in the workshop. The two gold questions (Q1 and Q2) thus address respectively how to create systems whereby people feel confident in entering and sharing data and in turn how to create systems to govern the data for the benefit of all. These two questions are seen to be interlinked, as “the way you make people trust and share the data, is to demonstrate that you've got good governance”, as summed up by one workshop participant.

This strong focus on governance systems for sharing and managing data, and social and ethical concerns about privacy and ownership, chimes with issues raised in the social science literature. The need for transparent governance systems is not disputed (Stilgoe *et al.*, 2013; Jakku *et al.*, 2019), because, as Hajer (2003) notes, emerging technologies often fall into an ‘institutional void’. However, governance is often discussed as an abstract concept. Although a range of governance mechanisms and models have been advocated with responsibilities potentially distributed across private and public sectors (Linkov *et al.*, 2018; Rotz *et al.*, 2019), our understanding of how these might be defined and operationalised is still limited, and emerges here as a clear and important future research priority. In particular the coordinating and monitoring activities (data processing, reporting, analysis and usage) and support that enables the maintenance and operation of institutions, which is at the core of governance arrangements (Bryson *et al.,* 2006), are only now receiving research attention in the digital agriculture sphere (Newton *et al.,* 2020).

Research questions about the relationship between data ownership, access and security and related concerns about increasingly disproportionate investment, power and control of agri-food corporations have been widely discussed by other scholars (Bronson and Knezevic, 2016; Carbonell *et al.,* 2016). However, the perspective in the questions here shifts towards the notion of value proposition inherent in data sharing and how governance systems can give people the confidence to enter into these propositions and access the inherent value. Some workshop participants suggested that the prominence given to data governance and ownership in debates actually undermines the confidence in the value. As one practitioner participant remarked, rather than emphasise governance, "it's better to demonstrate the value of the sharing, this reassures people of the integrity, through transparency. If you can't give people confidence to join that value proposition in the first place, it's never going to fly". However, other participants argued that if data is not governed properly, it is unlikely that this (potential) value will materialise and data providers should find ways to diminish the perceived risk of sharing by clarifying ethics and ownership. As Carolan (2017a, p. 20) noted, opening up data sources without applying checks and balances is not always the solution, remarking that "free access isn't necessarily fair access". In this respect, all participants agreed that answers to most of these questions lie in transparency (and its many facets, including accessibility and explainability). Regarding what might lead to a transparent shared system of data which is attractive for farmers and commercial developers alike (silver Q3), there were different views.

These discussions about data ownership and transparency resonate with Lioutas *et al.* (2019), who argue that the focus on the rules of ownership, access and control of the *data itself* should be shifted *to value* (see also Rotz *et al.,* 2019, Bronson and Knezevic, 2016)*,* because "what creates the power imbalance within a community is the uneven access not to big data but to the value emerging from them" (Lioutas *et al.,* 2019 p 6). In line with other commentators, they note that the distribution of value from big data is unequally allocated across agri-food systems, with farmers enjoying only a limited share of it (Haire, 2014). In our workshop deliberations it was deemed essential to shift the central question in the discussion from 'who owns the data?' to' who owns or has the rights to extract the value underpinning those data?', as articulated by Stubb (2016).

Regarding Q4, the need to involve farmers themselves as co-creators and co-curators in collaborative governing has been recognised by other scholars too (Carolan, 2017b; Jakku *et al.,* 2019). However, Newton *et al.* (2020) highlight the need for appropriate analytical tools and frameworks to represent and assess the role of farmers. Their framework to understand farmers as the key governance actors in strategic and operational domains of a herd recording system in Australia was developed to fill gaps in this area of study, but the need for further research is evident.

4.2 Theme 2: Data management

Theme 2 questions concern issues of data management and is closely linked to Theme 1. The original questions (21) covered the following: data storage; data security; standardising and analysing data (interoperability to lessen the burden on farmers); software and algorithms; licencing and patents, legal responsibilities; data requirements. These were ranked in the voting stage to topics focused on common standards and interoperability and further distilled and prioritised in the workshop as follows:

1. Gold: How can we create data standards to allow data to effectively be interoperable between systems and solutions?
2. Silver: How can the industry create systems for adopting common security standards?
3. Bronze: What measures is the industry taking to mitigate cyber-security threats connected to farming technology?
4. Bronze: What are the regulatory powers necessary to ensure that the technology and data used can be trusted?

The questions in this theme have interoperability and 'the need for a common standard' as a consistent priority, and agreement was reached to merge them into the gold Q1 and Q2. Different understandings of standardisation were unpacked in the discussions. In one scenario, a common standard was regarded as allowing different datasets of farm metrics from different manufacturers and software packages to be used alongside farmers' anonymised data for precompetitive research into crop production, protection and environmental impacts. In another scenario standardisation was seen as a means of improving farmers' ability to collect and collate their own data and to make data entry easy for them. However, some participants working in the private sector questioned whether a standardised system was the best approach, arguing that farmers have the right to be able to move their data from one system to another and that creating a 'single platform for everything' idea would stifle privately built solutions which are the way to 'unlock genuine innovation for the sector'. In line with this, Q2 asks how can industry create systems for adopting common security standards, which hitherto has not received much attention in the literature.

The responsibility for security and the risk of cyber security (Q3) was thought to be with industry rather than individual farmers. Regulation and legality were also key concerns (Q4), as one practitioner participant described the day to day need for this: "the biggest challenge we have for data management is making sure that the right person can see the data they're legally allowed to [….] that's what we spend most of our time battling with, when we're handling data management".

For Themes 1 (Data governance) and 2 (Data management) the questions arise because of the dominance of private corporations in creating platforms to aggregate data, enable data exchange between systems and offer decision support (Finger *et al.,* 2019; Weersink *et al.*, 2018). High levels of investment in platforms and vertical integration by such firms (Birner *et al.,* 2021) not only raises issues of data ownership and power but also of so-called 'platformisation', which risks closing down options for smallholders (Brooks, 2021; Chiles *et al.,* 2021). Different models are already in operation representing networks of competitors and collaborators and the degrees of interoperability of their digital applications (Antle *et al.*, 2017; Kritikos 2017; Philips *et al.,* 2019; Rotz *et al.,* 2019; Finger *et al.*, 2019; Kenney *et al.,* 2020). How these are embedded institutionally will play a crucial role in determining the outcome between closed, proprietary systems and open, collaborative systems (Wolfert *et al.,* 2017; Carolan, 2017a/b). Prioritising research to understand how this unfolds is emphasised in both Theme 1 and 2. An emerging area of research and policy interest is the development of trust frameworks which offer new mechanisms to manage decentralised and distributed collections of data, and enable secure information sharing for the benefit of all stakeholders in the food system (Pearson *et al.,* 2021), although their deficiencies re recognised (Van Der Burg *et al.* 2020). Interestingly, questions about technology ownership and the proprietary nature of many commercial systems (Carolan, 2017b, 2020) were not specifically raised.

4.3 Theme 3: Enabling use of data and technologies

This theme collates questions on how to enable farmers to analyse and effectively utilise and exploit new forms of data and technology, as well as understand the risks entailed in inappropriate interpretation and poor decision making. The original questions (18) were clustered as: decision making and using data effectively; real-time data, monitoring and modelling; knowledge and skills. These were filtered in the voting stage down to questions that focused on analytics, interpretation, skills and effective use of data, and further refined in the workshop to:

1. Gold: How can data be collated, combined, and analysed to be useful to and therefore valuable for farmers?
2. Gold: What is the value that farmers get out of using these data compared with more traditional datasets and intuitive forms of decision making?
3. Silver: How to support farmers in using digital technologies and do they need new skills, or just better solutions?

The first gold question (Q1) arose because, as one participant explained: “the ability to collect data is […] burgeoning, and it is understanding what data is actually useful to help make a better decision that is important… the farmer has to be able to understand which bit of all this morass of data is actually of a value to him or her”. The quality and accuracy of data and availability at a high resolution was also seen to be important. The question reflects the fact that, to date, the interpretation and use of data from smart technologies is not matching expectations (Leonard *et al.*, 2017; Weersink *et al.*, 2018). It also underscores the fact that understanding how data can be collated, combined and analysed to be useful and valuable for farmers compared to current decision making has received relatively little research attention (Sonka, 2015; Evans *et al.*, 2017; Ingram and Maye, 2020).

The participants agreed that the questions under this theme fundamentally come down to understanding contexts and situations where being data rich is actually going to make a substantive difference. Value is again emphasised in the gold questions (Q1 and Q2), resonating with discussions of 'big data analysis' where practices are designed to enable farmers (and related organisations) to extract economic value from very large volumes of data (Sonka, 2016; Lioutas *et al.,* 2019). However, if big data analytics is to produce new forms of value, it needs to support actors in making smarter, faster and impactful decisions (Lioutas *et al.,* 2019). Understanding how to achieve this through building capabilities, skills or better solutions and investing in analytical service support for data analysis remains a significant research gap, as captured in silver Q3 (see also Jakku *et al.,* 2019). This is important because the on-farm capability to transform data into actionable knowledge to achieve the promised benefits is limited (Capalbo *et al.*, 2017; Evans *et al.,* 2017; Lioutas *et al.* 2019). Here, there are implications for actors who support farmers who themselves need help to exploit data and technologies, a point picked up in Themes 4 and 7 and by other scholars (Ayre *et al.,* 2019; Lioutas *et al.,* 2019; Fielke *et al.,* 2021; Higgins and Bryant, 2021). As with other themes, this emphasis on value reorients how researchers need to understand data usage.

In comparing digital data with traditional knowledge for decision making (gold Q2), there was agreement that: "you're basically moving from intuitive decision making, based on experience, to database decision making", as one participant commented. When exploring this further, there were a number of shared experiences between practitioner participants demonstrating that data on its own does not necessarily provide the solution and in some cases can be disruptive. This is commensurate with observations of disruption of 'hands-on' and experience-driven management and embedded knowledge by digitalisation (Eastwood *et al.*, 2012; Butler and Holloway, 2016; Carolan, 2020). The risk of accelerating agricultural deskilling by transferring decision making authority to machines and algorithms has been raised (Rotz *et al.,* 2019; Miles, 2019; Brooks, 2021), with the prospect of unskilled farmer cyborgs who have lost all intuitive knowledge, as suggested by Brooks (2021).

However, participants suggested that research should understand how to achieve successful data-driven agricultural systems through integrating all types of agricultural knowledge (e.g. from farmers, agronomists and plant scientists) with remote digital data, rather than looking at the tension between them. This view concurs with that of commentators who seek to understand how data-driven decision making and processing in real-time interacts with highly intuitive and experiential decision making to optimise the best of both worlds (Xin and Zazueta, 2016; Shepherd *et al.*, 2018}. Without being able to integrate contextually specific information, many farmers may struggle to trust or see value in the outputs from digital analytical tools and it may also preclude certain agro-ecological trajectories based on sustainable value creation as opposed to purely extracting economic value (Wittman *et al.,* 2020; Huang *et al.,* 2021). This question prioritisation and critical analysis on enabling and optimising use of digital technologies and data emphasises an area of research which has previously received limited attention, and highlights the need for interdisciplinary studies in particular which can cross epistemological boundaries.

4.4 Theme 4: Understanding benefits and uptake of data and technologies

The questions clustered in this theme included reference to factors that determine and support adoption and benefit or hamper farmers' capacity to adopt digital technologies. The original questions (38) focused on: understanding uptake; factors affecting uptake; how practices are being implemented; digital infrastructure; potential benefits; and enabling uptake through support and engagement. These were refined in the survey to benefits, value that technology generates on-farm and how to enable and empower farmers, and further distilled and ranked in the workshop as follows:

1. Gold: What are the benefits of new digital technologies and for whom (including farmers and other food chain actors) and how are those benefits evidenced?
2. Gold: What support might be needed to help disadvantaged farms and farmers to take advantage of digitalisation?

3. Gold: What are the day-to-day experiences of implementing new digital technologies on farms and do the practices and outcomes match expectations?
4. Silver: What factors influence the uptake of new digital technologies on farms?

These questions recognise that ultimately the potential of digital agriculture technologies and data can only be materialised when applied to derive improvements in management practices (Finger *et al.,* 2019). Rather than a focus on how to encourage adoption of digital technologies per se, the issue is reframed in this exercise by asking, what are the benefits and how can (and which) farmers derive value? This acknowledges that farmers can have rational reasons for not using digital technologies and can be wary of investing in an expensive set of technologies of potentially questionable value (Defra, 2018; Lowenberg-DeBoer and Erickson, 2019). As well as asking what are the benefits, Q1 also asks for whom, but the participants did not elaborate on this. Although benefits derived by those who support adoption have been questioned (see Bryant and Higgins, 2021; Lioutas *et al.,* 2019), and disruption to their professional practice and relations noted (Rijswijk et al., 2019), further empirical data is needed on this topic.

It was considered important to provide better evidence and to clearly demonstrate to farmers the benefits of digital agriculture. On this point, participants' remarks included: "Farmers are being told a lot at the moment that, you know, your data is valuable. But I think the question that they will have is "Yeah, valuable to who at the moment?", it feels like it's probably more valuable to suppliers, and maybe government agencies, than actually the farmer"; and "The benefits seem to lie elsewhere". Such unclear or ambiguous value propositions explaining why producers should change to digital agriculture are often noted as the main reason farmers do not adopt digital technologies (Keogh *et al.*, 2016; Leonard *et al.,* 2017; Spati *et al.,* 2021).

Workshop participants felt that this notion of value, and its distribution, in terms of economic benefits, needed to be unpacked by researchers; furthermore, that all the dimensions and dynamics of sustainable value (economic, environmental and social value) should be considered, moving beyond the locus of the farm to shareholders, stakeholders in a supply chain and society (Huang *et al.,* 2021). This emphasises the need to devise frameworks that allow the value of information to be expressed not only by economic measures but also in terms of environmental performance, animal welfare and health, and social well-being of the decision maker (Rojo Gimeno *et al.,* 2019; Wittman *et al.,* 2020). With respect to how benefits are evidenced, Relf-Eckstein et al. (2019) ask ’what evidence’ is being used to advance smart farming innovation in Canada arguing that industry survey data is not representative of the population of farm operators, and that the industry lack the expertise, research skills, and scale of resources to conduct rigorous scientific studies. They propose that governments need to facilitate coordination among multiple groups of actors to gather valid evidence of benefits, through experimentation.

Regarding who will be (dis)advantaged (gold Q2), the general agreement was that larger commercial farms would benefit most from digitalisation, and that this would characterise future trends, as production systems becomes more specialised. One participant argued, however, that: “there's a constant kind of assumption that only the larger more business-like agri-business, large-type farms can benefit from this data and this technology […] I don't see it like this, I see this thing more as something that levels, that closes, that could potentially close that gap … I think it could actually help the small farms”. In recognition that some farms and farmers have less adaptive capacity, participants agreed that support is needed in terms of skills training, capital investment, infrastructure, and advice to improve uptake. Accordingly, a role for advice to plug the knowledge gap between data collection and interpretation was highlighted, as noted for Theme 3.

This discussion reflects a range of common concerns: that digital agriculture will perpetuate the trend driven by larger firms of: concentrating markets (Birner *et al.,* 2021), increasing inequality in the agricultural sector (Walter *et al.*, 2017), potentially locking out some groups, or further benefiting those who are already privileged (Van der Burg *et al.*, 2019). However, by re-orientating the question towards what support is needed to allow all farms to derive benefits and value from digitalisation, this avoids debates which open up a potentially false dichotomy of benefits for the few or the many (Fleming *et al.,* 2018). It also goes some way in resolving the more fundamental concerns of some participants about the assumptions and language behind the questions, such as 'benefits' and 'advantaged' and 'disadvantaged', which suggest a normative view that digital agriculture is universally beneficial and desirable.

Commentators argue that a range of technologies need to be available for a diverse set of agricultural systems, across systems and across scales (Walter *et al.,* 2017), and need to be scale-neutral so that they can be utilised by both small- and large-scale operations (Basso and Antle, 2020). The potential for smart technologies to accelerate an agroecological transition for smallholders, for example, has been explored (Wittman *et al.,* 2020; Cumulus Consultants, 2021) and their compatibility with short food supply chains assessed (Lioutas and Charatsari, 2020). Other forms of support such as opening up access across different scales, however, can be problematic as inequalities persist. However, the ability to access something is not the same as having the capabilities to do so in ways that generate benefits, and it is unclear how disempowered farmers, who do not have the requisite skills and competencies, can exercise their access rights so as to independently exploit the potential of big data (Mittelstadt and Floridi, 2016; Carolan, 2017a; Finger *et al.,* 2019). This highlights a clear connection between questions concerning benefits, capability and fairness and suggests that this intersection deserves more focus in future research.

Questions about how technologies are experienced on a day-to-day basis, how farming practices develop and change, and farmer experiences and impressions in terms of values and benefits were also discussed and clarified in gold Q3. This was felt to be inextricably linked to the other questions and important because there is a significant knowledge gap in terms of what happens when farmers buy and start to use (or indeed stop using) data and new digital technologies on their farms (Kernecker *et al.,* 2020), and adapt and experiment with it (Carolan, 2018). This concurs with Phillips *et al's* (2019) critique of current research which, they argue, tends to speculate about the future but lacks analysis of what is happening at present in terms of changes or not to socio-material practices. This gold question emphasises the importance of this hitherto neglected topic for future empirical study.

With respect to uptake of technologies (silver, Q4), the workshop participants acknowledged that this question should be seen as integral to the other questions in this theme about benefits and changing social practices. They agreed that, although demographic and farm factors are influential determinants, there are many other critical factors, such as trust, habits, skills and infrastructure, which deserve urgent research attention. These questions intend to widen the scope of the existing evidence on farmers' uptake which tends to centre on: determinants and drivers of adoption of precision farming (Pierpaoli *et al.,* 2013; Knierim *et al.,* 2019; da Silveira et al., 2021), context-related factors (Vecchio *et al.,* 2020), decision making processes (Higgins *et al.,* 2017), and farmers' communication and co-operation strategies (Kutter *et al.,* 2011). A more critical perspective on the enabling conditions in the Agricultural Knowledge and Innovation System and the relations of the constituent actors was also felt to be missing by some participants. This echoes studies showing the importance of agricultural knowledge and advice network in increasing the utility of digital agricultural technologies (e.g. Vecchio *et al.,* 2020; Fielke *et al.,* 2021; Newton *et al.,* 2021), and the need to consider the role of so called meso-scale actors (Higgins and Bryant, 2021). The requirement for a more networked and collaborative understanding of adoption is also expressed in Theme 7 (New collaborative arrangements).

4.5 Theme 5: Optimising data and technologies for performance

These questions explore how technologies, monitoring and benchmarking can lead to improvements in on-farm productivity and efficiency, and sustainability. The original questions (32) focused on the following topics: livestock health and welfare; livestock productivity through monitoring and benchmarking; public value; supply chain value, efficiencies and resilience; knowledge (researcher and farmer). These were filtered down in the voting stage and further refined in the workshop as follows:

1. Gold: How can data be used to monitor farms' sustainability performance and bring about behaviour change?
2. Gold: How does digitisation of livestock farming affect the day-to-day treatment of animals? How are such impacts perceived by different groups (farmers, welfarists etc)?
3. Silver: How can data and associated digital technologies be used to predict sustainability performance to inform supply chain and policy actors?
4. Bronze: How can we monitor progress towards sustainability in different agricultural systems to help steer future trajectories for the food system?

The priority questions selected are about monitoring and predicting sustainability performance with a view to bringing about beneficial changes in agricultural practices and the food system. The gold question (Q1) asks not only about using data to monitor farms' sustainability performance, but also how this will bring about behaviour change, with its many nuances. Although the sustainability concept itself was not unpacked, the use of defined metrics at a range of scales (farm and supply chain) was implicit. Possibilities of creating a sensor network allowing for almost continuous monitoring of the farm to minimise site-specific application of inputs, such as fertilizers and pesticides and measure impacts have been explored (Walter et al., 2017). According to Rebound et al. (2022), networks of passive sensors could be used to evolve biomonitoring for environmental and biodiversity conservation subsidies in agriculture, and, by including farmers and citizens, could encourage farmer uptake. However, despite this potential, there still appears to be few appropriate methods for evaluating the sustainability performance of data-driven farming, and a gap in empirical evidence (Relf-Eckstein et al., 2019; Lioutas and Charatsari 2020). Furthermore, Knierim et al. (2019) found that some farmers themselves have reservations about the performance of precision farming in moderating farms' externalities on the environment.

The second gold question (Q2) collates questions asking how digitally enabled monitoring impacts day-to-day treatment of animals and how this is perceived by different actors. This reflects the specific interests of certain participants, the emerging literature on ethical challenges and human-animal relationships of autonomous systems (Bear and Holloway, 2019, and the policy attention animal welfare receives in the UK.

The silver question (Q3) asks how can we use data to run scenarios and analyses to predict what might happen, and inform policy makers and supply chain actors accordingly. This complements the bronze question (Q4) which asks how we can monitor progress towards sustainability in different agricultural systems. Participants agreed that modelling the outcomes of different production systems is important in order to compare sustainability (according to a range of metrics) will help steer future food system trajectories.

These questions highlight the connection between using fine-grained, real-time data to allow better monitoring of environmental effects and public policy and private food system drivers.

In line with previous scholarship, the participants identified the need for research to understand how such monitoring can open up new markets for environmental goods in consumer markets and supply chain revenue models based on certifications, as well as enable refinement of many policy mechanisms, a call echoed by others (Weersink *et al.,* 2018; Philips *et al., 2019*; Basso and Antle, 2020). The role for digital technologies to support self-monitoring and verification of public goods is another area being explored (Gosal *et al.,* 2020), and this has particular resonance to the UK where policy is looking for ways of monitoring the delivery of public goods for public money.

Although studies have identified opportunities for using digitalisation and AI to measure the ecological footprint along the entire food chain, they also identify constraints (such as governance instruments) which need to be further understood (Garske *et al.,* 2021). Similarly, a recent UK study identified the potential of remote sensing of environmental impact, big data analysis for environmental footprint accounting, and dynamic food procurement for creating a food system supportive of agroecology, although noted that sensitivity to context, farmer involvement and new governance processes are critical to achieving this (Cumulus Consultants, 2021). The potential of Procurement 4.0, and smart traceability as part of digital transformation in agriculture is equally gaining attention (Yu *et al.,* 2020). However, overall the empirical evidence on the environmental gains achieved by digitalisation in agriculture, and the necessary governance arrangements needed to best support this transition, is still highly heterogeneous (Garske *et al.,* 2021) and confirms that this is an important area for future research.

4.6 Theme 6: Impacts of digital agriculture

These questions explore anticipated impacts on farm level work practices and the nature of employment; and on relationships with supply chain stakeholders and the wider public. The original questions (34) focused on: interactions with other solutions and farming systems; farmer relationships with food consumers, with each other; with livestock, with other actors (advisers, agri-tech and policy makers); culture and farmer identity; employment and labour; and power relations. These were filtered down in the voting process and further prioritised in the workshops as follows:

1. Gold: What are the possibilities for using digital data for informing and empowering citizens within a more democratic food system?

2. Gold: What are the possibilities for using digital tools for more effective communications between farmers and publics?
3. Gold: What are the likely effects of digital technologies in agriculture for the nature and experience of agricultural work?
4. Silver: What are the likely effects of digital technologies in agriculture on farming identities and on the power and knowledge relationships between farmers and other food system actors?

These questions span different levels of impact and relations from farm level, to farmer-stakeholder relationships, to society. They are underpinned by broader questions related to democracy and power relations and in this sense are closely linked to all themes.

The gold questions (Q1 and Q2) ask what role digital data and tools might play in creating a more democratic food system. The possibilities for using digital data for establishing better relationships between farmers and publics (referring here to food consumers and citizens) was recognised as an under-researched area, despite the plethora of new tools now available. The questions intersect with those of Theme 1 (data governance), Theme 2 (data management) and Theme 5 (optimising data and technologies for performance) and accentuate the need for societal dialogue recognised as critical to innovations in food system transformation (Herrero et al. 2020). In particular, they resonate with conversations about democratising ownership and participation in digitalisation in the agri-food system. For example, scholars have pointed to harnessing new forms of citizen digital participation to potentially improve transparency, and to make institutions more accessible to ordinary people. This includes facilitating alternative organisations, like cooperatives and expanding how food system workers, small producers, citizen consumers, food justice activists, and scholars can participate in collective action and institutional decision-making (Chiles *et al.,* 2021; Carolan 2017a/b; Kenney *et al.,* 2020). In line with this, Chiles et al. (2021) argue for increased investments in research and education for the public interest and for government investments in publicly accessible digital infrastructures to facilitate a more just transition.

The impact of digital agriculture on the nature and experience of agricultural work and on farming identities were seen to be interconnected in Q3 (gold) and Q4 (silver). The unknown effect of applying sensor and precision techniques on farm workflows and labour requirements was discussed in terms of the repercussions for farmers' status, both on the farm and in the supply chain. In particular, whether their status might be raised by opportunities for enhancing digital skills or diminished in favour of 'off-farm' professionals taking a more prominent role was questioned. The participants noted that although questions about farmer identity featured in the top 10 questions in this theme from the voting exercise, they were missing from the top 5 despite being crucial to these discussions.

The change in the nature and experience of agricultural work is a topic echoed by researchers who envisage disruption to established farm labour structures and to the way benefits are distributed (Carolan, 2018; Fleming *et al.,* 2018; Rotz *et al.,* 2019). The displacement and devaluing of some farm jobs, as well as the benefits of removing the drudgery of others, have been considered but within quite specific contexts (Edwards *et al.*, 2020). Closely linked to this are questions of how digital agriculture challenges farmer identities, already explored by a number of researchers (Tsouvalis *et al.,* 2000; Bear and Holloway, 2019; Miles, 2019; Brooks, 2021). The concern is that values that characterise a 'good farmer' or 'smart farmer' may privilege larger scale and commodity crop farmers and disenfranchise the smaller farmer, or be incompatible with those active in short food supply chains (Lioutas and Charatsari, 2020). There was consensus that this is an area of socio-cultural research that not only needs expanding and strengthening, but also integrating into more technically-orientated research.

The question of how digitalisation will restructure relationships in agriculture between farmers, expert advisers, agri-tech companies, researchers and policy makers, and what are the implications for the power relationships in agricultural systems, was selected as a key point of enquiry of future analysis. Although it has been previously addressed with respect to advisory services (e.g. Fielke *et al.,* 2020), it has not been sufficiently researched in other contexts including the UK. It is particularly pertinent given the changing nature of farm and professional work in supporting organisations (Rijswijk *et al.,* 2019), changes in the structure of inputs industries, and the emergence of new non-traditional actors (Birner *et al.,* 2021).

4.7 Theme 7: New collaborative arrangements

Theme 7 clusters questions about farmer involvement in digital developments, collaboration and user-centred design, existing stakeholder models and new business models. The original questions (22) focused on: whose vision of agriculture? institutional changes to integrate users; governance and new models of working; and new markets and new contexts. These were filtered down in the voting process and prioritised in the workshop as follows:

1. Gold: What is the role of farmer-led innovation in the digitalisation of agriculture and how can it be improved to ensure farmer views are present in the design and trajectory of digitalisation?
2. Gold: How can different actors with vested interests, competing goals and hidden agendas work more collaboratively together on digital agriculture projects?
3. Silver: What action needs to be taken to ensure that digital divides do not deepen and to avoid a scenario where some farmers get 'left behind' (i.e. digital exclusion)?
4. Bronze: Can agriculture learn from the success stories of other industries (such as finance, healthcare) in the roll-out of digital tools to farmers?

The gold question (Q1) asks how to improve farmer-led innovation. As noted by the group rapporteur, "the one thing we did agree on was understanding the world of farmer-led innovation, and how to include farmer views and experience of tech and digitalisation". Another participant concurred: "about the farm involvement, I think that's absolutely critical. I think that really is the most important part of this, because I see so many things that have clearly been conceived without talking to a farmer. And then when they see them [….], they're instantly dismissed".

The need for farmer involvement and incorporating user-perspectives to address gaps between design and practice in digitalisation is acknowledged elsewhere (e.g., Fountas *et al.,* 2015; Van Es and Woodard, 2017). Involving users not only addresses underutilisation and low sustainability of innovations but also leads to valuable social learning and capacity building (Masiero, 2016; Steinke *et al.,* 2020). While user-centredness has been part of practice in digital advisory and decision support tools for some time (Eastwood et al., 2012), it is only now receiving attention in data platform and technology development through co-design and other collaborative activities (Newton *et al.,* 2021). This question, as in other themes, underscores the need for strengthening research that studies and enacts farmer-led innovation.

Gold question (Q2) acknowledges power relations in asking how can actors work more collaboratively together on digital agriculture projects when they have vested interests, competing goals and hidden agendas. Whilst the group agreed that the language in this question conveys certain assumptions about the power dynamics, they decided to retain it. Although collaborative arrangements with respect to new technologies and data have been examined in the literature (Jakku *et al.,* 2019) and already noted for Theme 1 (data governance) and Theme 2 (data management), the participants recognised a gap in research of networking and collaboration processes at the level of organisations and projects. Kendall and Dearden (2020) point out, collaboration is not a neutral process, and configuring a co-design project in ICT is inevitably a political act. Experience has shown the importance of building trust over time and engendering this trust through mechanisms which balance public and private interests and control (Newton *et al.,* 2021).

The silver (Q3) question identifies concerns about a deepening digital divide, in particular for: farming systems and sectors where the rate of technology development is relatively slow; and for those farmers lacking digital literacy capabilities to adapt to new technologies and/or the digital infrastructure. This echoes questions in Themes 3 (Enabling use of data and technologies and 4 (Optimising benefits). Although it was agreed that there is already a good understanding or sense of what is needed to prevent a digital divide (in terms of skills and infrastructure), researchers have not adequately explored why a divide might be amplified and why policies have not effectively addressed this (see Defra, 2018). The participants agreed that multiple aspects need to be considered in Q3 such as infrastructure (internet access, connectivity) and capital investment, also that there is a need for creation of sustainable business models that provide viable digital solutions for inclusion of small-scale farmers in the digital agriculture transformation process. Regarding Q4 (Bronze), about whether agriculture can learn from the success stories of other industries and sectors, participants did to elaborate but agreed that this opportunity has been under exploited to date, and presents a promising avenue for future research.

4.8 Nexus and methodologies for future digital agriculture research

In this final sub-section, we provide a cross-cutting analysis which explores the intersection between the themes and between the constituent questions which has been evident throughout the exercise. This highlights the need to make connections between the different dimensions of data-driven agricultural systems and associated research interests.

Regarding theme intersection, two nexus for future research emerge. The first coheres around the notion of value, which underscores questions across the themes. The significance of value to farmers was identified with respect to articulating value propositions, identifying benefits, building capabilities and investing in support, whilst understanding the institutional arrangements that govern value co-creation are an important precondition for managing fair use and distribution of value from big data. Reorienting research towards these dimensions of value will offer more coherence and understanding than a singular focus on, for example, adoption of technologies. The exercise also recognised that opportunities for digitalisation to enhance value to the environment and society need to be part of the research conversation.

The second nexus emerges from the number of the questions asking how social and institutional arrangements to support digitalisation in agriculture can be developed and enacted. These highlight the need for new governance and collaborative processes to foster ownership and participation in digitalisation and to include key governance actors. Researchers have a task ahead of understanding how the established and emerging agri-food actors and public action will come together to both manage the threats (such as market concentration, unaccountability) and exploit the opportunities (such as democratising knowledge) of digital agriculture. Here, transparency is an overarching concern, whether for data sharing, sustainability performance and accounting, or public accessibility, and needs to be the focus of future research exploring suitable governance instruments and processes. Models for governance and collaboration suggest that responsibilities are distributed across private, public and citizen sectors to different extents but how these can operate and what role policy support plays in this complex arena requires further investigation and new analytical tools and frameworks.

These nexus emphasise the importance of interdisciplinarity and transdisciplinarity in research to support integrative solutions across the many interacting outcomes of digitalisation, and the need to build sufficient capacities within multi-partner research communities. Such approaches can offer insights into complex socio-technical systems, account for multiple perspectives, and better frame policy decisions. The question of scale also emerges for future research, by which we mean at what level (farm, supply chain, society) do researchers focus to disentangle multiple interactions in the system?

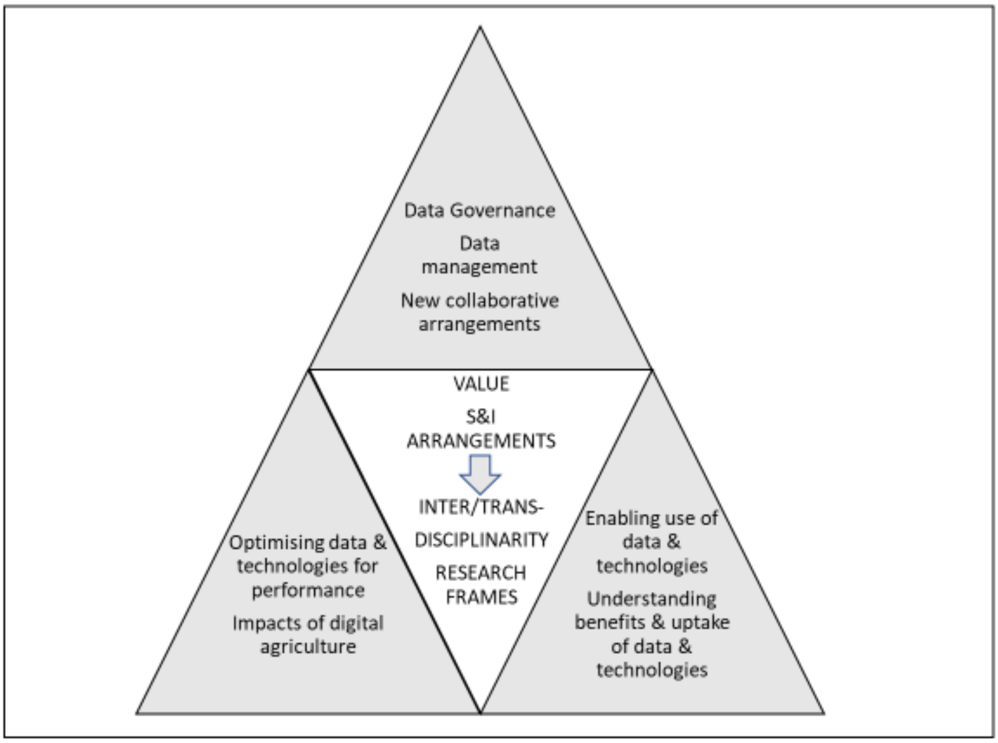

Figure 3. Multiple interactions between priority research themes and questions: nexus and methodologies (central triangle) to guide future digital agriculture research

In particular this exercise revealed that a future research agenda needs to tackle the binary nature of analytical frames. Rather than focus on the differences between process or data-driven approaches (often implied as distinct processes), or tacit or data-driven knowledge, the exercise suggested that research should be directed towards how these processes and knowledges can be integrated. In the same way, rather than assume that digital technologies have a single trajectory and will only advantage large-scale conventional farming systems, researchers should recognise and examine digital opportunities for smaller farms and for alternative agroecological systems building on the granularity of control and adaptability that digitalisation can offer to benefit agri-food systems overall.

Figure 3 depicts the interconnections between the themes, clustering Themes 1, 2 and 7 which focus on data governance and collaboration issues, Themes 3 and 4 which focus on implementation (enabling, benefits) and Themes 5 and 6 which focus on outcomes (performance and impact). These all cohere around the nexus of Value and Social and institutional (S&I) Arrangements, and require new methodologies and frames, as shown in the central triangle.

These insights are original to this research and highlight the need for research actions to inform policy, not only instrumentally by developing robust new frameworks, methodologies and empirical data to strengthen the evidence base, but also conceptually, to prompt new thinking and new directions commensurate with food systems challenges identified by policy and funders. This analysis applies equally to the UK and to other international research contexts.

4.9 Limitations of the method

The type and number of participants clearly determines the nature and scope of the questions in such an exercise, as Sutherland *et al.* (2011, p247) remarked, "[a]ny priority-setting exercise is the product of the people who participate". Given that the topic and practice of digital agriculture is relatively new in the UK, 40 respondents posing 195 (usable) questions was judged to be comprehensive; furthermore, the wide-ranging nature of the questions is indicative of a broad consultation. However, there are inevitably limitations to the initial elicitation step which relies on a purposive sampling. Whilst representatives were identified from organisations with an interest in technical, social, ethical issues and from conventional and alternative farming sectors, it was not always possible to ensure inclusiveness and equity in terms of ethnicity, age or gender because the characteristics of the stakeholders were largely unknown. There are also limitations associated with snowballing, which can favour pre-existing links or restrict access to the exercise to a bounded and connected community.

Representation from Wales (4), Scotland (2) and Northern Ireland (0) was low, however, participants from organisations in England had a good understanding and experience of agricultural communities across the breadth of the UK.

The effect of a self-selected cohort of interested and motivated stakeholders can also be amplified by the increasing concentration of participants from the research community as non-research community disengaged as the steps progressed (however 44% of non-academics continued to participate in Step 3). The commitment of researchers through the process is unsurprising given the nature of the study; however, they were not homogeneous, being represented by a large range of disciplines, views and experiences, and often working in close connection with practitioners. Furthermore, every effort was made in Step 3, the participatory workshop, to give equal voice to all participants in the group sessions, as revealed in the scope and nature of the debates in the discussions. Regarding potential bias or personal agendas, a diverse and moderately large group, clear criteria, and a democratic process all helped reduce the impact of any one individual. There are also criticisms that using themes as the unit of enquiry risks silo-ing questions, and tends to give them equal weight, however, we were confident that, with iterative voting and workshop dialogue, and the even spread of questions and voting patterns across each theme, this was avoided.

5. Conclusion

In total, 27 priority questions were identified (15 gold, 7 silver and 5 bronze) organised across seven research themes. This was achieved through iterative rounds of scoring and dialogue and involved a range of UK stakeholders. The questions reinforce previous clustering and agenda setting research using literature sources, but significantly enrich and extend these providing new perspectives and insights. Whilst we cannot claim that this list of questions is definitive, they highlight that uncertainties and gaps remain about the ramifications and opportunities of disruptive innovation in digitalisation and digital technologies. In this respect they offer a preliminary framework for a future research agenda in the UK, which can help to steer research investment and inform policy decisions.

Many of the questions and themes raised here have not been given due attention in the current research funding strategies and policies pertinent to transforming food production. Addressing them is not only critical for delivering a sustainable, equitable and accountable digitalisation of agricultural production, but more importantly for prompting debates about what future trajectories digitalisation can and should support. This is important in a time of agricultural transition where goals of improving productivity and environment, achieving net-zero and building resilient rural communities need to be reconciled.

Methods anticipating future research requirements in the digitalisation of agricultural systems have typically been review based, complemented by empirical studies and more recently scenario analysis. Prioritisation exercises offer a rigorous participatory methodology for capturing and ordering a wide range of views. The method is commensurate with calls for new forms of institutional, legal and scientific governance, as outlined in Responsible Research and Innovation (RRI) frameworks, where greater attention to questions of anticipation, inclusion, reflexivity and responsiveness are called for (Stillgoe et al., 2013). The method also offers a forum to explore the nuanced debates and discussions that lay behind the questions, which query the assumptions, implicit values and objectives of current and proposed research agendas and investments. Crucially, the method also allows participants, and particularly researchers, to pause and reflect on ideologies of knowledge production when conducting research in arenas such as digital agriculture. Insights from such reflection can inject fresh views and open up different policy discourse. The need for such exercises will likely become increasingly more important to steer future research and policy on key challenges in digital transformation of agricultural production systems, value chains and food systems both in the UK and beyond.

Declaration of Competing Interests

The authors declare that there are no conflicts of interest related to this paper.

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