

1 What are the Priority Research Questions for Digital Agriculture?

2 1. Introduction

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

14
15 Such developments are framed by some as ‘the fourth agricultural revolution’ and the
16 accompanying narrative is one of improving agricultural efficiencies and productivity. Digital
17 technologies and big data in this context bring benefits to both food production and
18 ecosystems services (Weersink *et al.*, 2018; Rose and Chilvers, 2018) and set the foundations
19 for the future of sustainable agriculture (Saiz-Rubio and Rovira-Más, 2020; Garske *et al.*,
20 2021). Ongoing developments and big data advances (e.g., Walter *et al.*, 2017; Wolfert *et al.*,
21 2017) continue to make precision technologies more accurate, more widely applicable, and
22 more efficient (Weersink *et al.*, 2018), offering the prospect of a ‘step change’ in productivity
23 and profitability across the value chain.

24
25 However, this ‘agri-food tech solutionism’ has been critiqued as hype and over-confident by
26 a number of commentators (e.g., World Bank, 2016; Miles, 2019; Fairbairn and Guthman,
27 2020; Lajoie-O'Malley *et al.*, 2020). Evidence that digital agriculture can meet such
28 expectations is arguably limited to a few innovative firms (Zambon *et al.*, 2019), while big data
29 has yet to fulfil its promise (Huberty, 2015; Basso and Ante, 2020; Clapp and Ruder, 2020).
30 Others point to the relatively low uptake of precision technologies, particularly the more

31 complex applications (Barnes *et al.*, 2019; Lowenberg-DeBoer and Erickson, 2019; Carolan,
32 2020; Spati *et al.*, 2021). More fundamentally, the assumptions and “normative desirability
33 and expected benefits” (Fleming *et al.*, 2018, p19) of these technologies, articulated by
34 science and policy (Defra, 2021) and embedded in high level policy and international agency
35 discourse, are being questioned (Poppe *et al.*, 2015; Kuch *et al.*, 2020; Lajoie-O'Malley *et al.*,
36 2020; Schroeder *et al.*, 2021). Furthermore, it is increasingly understood that digital
37 agriculture is rooted in economic, political, social and ethical relations with a range of issues
38 being raised about data governance (Bronson and Knezevic, 2016; Carbonell, 2016; Capalbo
39 *et al.*, 2017; Rotz *et al.*, 2019) and the threat of reinforcing existing economic, spatial, and
40 social divides (Carolan, 2017a, 2020; FAO, 2019).

41

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

47

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

59

60 This need is particularly relevant to the UK where the evidence base is still relatively small
61 compared to more digitally advanced countries and regions (notably Australia, New Zealand

62 and North America). Building on the more mature precision technologies (Barnes *et al.*, 2019;
63 Houses of Parliament, 2015), digitalisation is now slowly permeating the UK's agri-food
64 system, as the industry is starting to adopt and adapt technology, software, sensor and
65 robotic innovations. Studies to date, however, have been disparate, from adoption of
66 precision farming (Barnes *et al.*, 2019), experiences with dairy robotics (Holloway *et al.*, 2014;
67 Bear and Holloway, 2019) and industry perceptions more generally (Barrett and Rose, 2020),
68 and crucially none have envisaged a future research trajectory or agenda to steer policy.

69

70 As such, a research prioritisation exercise was undertaken in the UK. Technological
71 innovations to boost productivity and enhance agri-businesses lie at the heart of the
72 government's discussions about a renewed agricultural sector and thus embody a
73 modernising technological discourse. This is illustrated by the positive language of UK policy
74 documents (Barrett and Rose, 2020) and the level and direction of investment from the
75 government's research funding body UK Research and Innovation through its Transforming
76 Food Production Challenge, which announced in 2018 funding of £90m (HM Government,
77 2018). This is core to the UK's Industrial Strategy Challenge Fund, which aims to address the
78 grand challenge of food system transformation. However, other perspectives are arguably
79 not being given due attention at this critical time of post-brexite policy development and
80 debate, as government and industry seek ways of achieving a sustainable agri-food system
81 (Defra, 2020).

82

83 The aim of the prioritisation exercise reported here was to identify priority research questions
84 concerning digital agriculture in the UK through consultation with a wide range of
85 stakeholders across a number of sectors and disciplines. Through this exercise, we
86 determined key questions by providing a space for both discussion between researchers and
87 stakeholders and finding a common understanding of knowledge needs in this important and
88 emerging area of research enquiry and policy interest. This paper aims to report these
89 outcomes and in turn opens up new perspectives that can guide agricultural research and
90 policy in this area in the future. These are immediately applicable to the UK but equally inform
91 research agendas in wider international contexts. With respect to the priority research
92 questions informing policy, there are two related aims: firstly, to identify and prioritise
93 existing and emerging issues that would benefit from a stronger evidence/research base and

94 that if addressed could increase the effectiveness of policies; and secondly, to influence the
95 way policy makers think, which is a necessary precursor to direct and longer-term policy
96 changes arising from research (Weiss 1997; Sutherland *et al.*, 2011). These aims are
97 commensurate with research published in this journal which has called both for a stronger
98 evidence base and for policy makers promoting digital agriculture to pay more attention to
99 different ‘agricultures’ and the contexts in which it is delivered (Vecchio *et al.*, 2020; Lioutas
100 and Charatsari, 2021).

101

102 **2. Research themes and priorities**

103 Questions about the future of digital transformation of agriculture have prompted a series of
104 reviews which identify technical and social research themes and agendas. With respect to
105 data, these cover: big data applications in smart farming (Wolfert *et al.*, 2017); big data
106 analysis (Kamilaris *et al.*, 2017; Lioutas *et al.*, 2019); and data and decision-making (Evans *et al.*,
107 2017). Collectively, these review-based exercises propose giving research precedence to
108 governance issues, which can enable equal exchange of value from big data and identify
109 suitable business models for data sharing in different supply chain scenarios. From a science
110 perspective, Shepherd *et al.* (2020) reported on priorities for scientists and institutions to
111 enable the potential benefit of digitalisation of science to be captured.

112

113 These reflect some emerging lines of social science enquiry clustered thematically by Klerkx
114 *et al.* (2019) (and updated here) in another literature review, which include: i. Adoption,
115 barriers, uses and adaptation of precision and digital technologies on farms (Pierpaoli *et al.*,
116 2013; Finger *et al.*, 2019; Knierim *et al.*, 2019; Balafoutis, *et al.*, 2020; da Silveira *et al.*,
117 2021); ii. Impacts on farm identity, farmer skills and farm work (Lioutas *et al.*, 2019); iii.
118 Power, ownership, privacy and ethical issues (farm and value chain) (Bronson and Knezevic,
119 2016; Jakku *et al.*, 2019; Wiseman *et al.*, 2019); iv. Implications for agricultural knowledge
120 and innovation systems (AKIS) (Eastwood *et al.*, 2019; Rijswijk *et al.*, 2019; Fielke *et al.*,
121 2020); and v. The economics, management of digitalised agricultural production systems
122 and value chains and impact on input industries (Phillips *et al.*, 2019; Birner *et al.*, 2021).

123

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

134

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

136 The method for identifying priority research questions for digital agriculture in the UK
137 followed an iterative process previously applied in agricultural, conservation, food systems
138 and related fields of research, often to deliberate societal grand challenges (see Pretty *et al.*,
139 2010; Sutherland *et al.*, 2013; Ingram *et al.*, 2013; Morris *et al.*, 2021). We applied the
140 principles and lessons on methods as set out by Sutherland *et al.* (2011). The method places
141 emphasis on making the process to identify the most important questions rigorous, inclusive
142 and democratic. The process involves identifying a large number of participants (50-100) and
143 eliciting an initial long list of research questions which is reduced and refined in subsequent
144 voting stages to select the top priorities by theme.

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

152

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

161

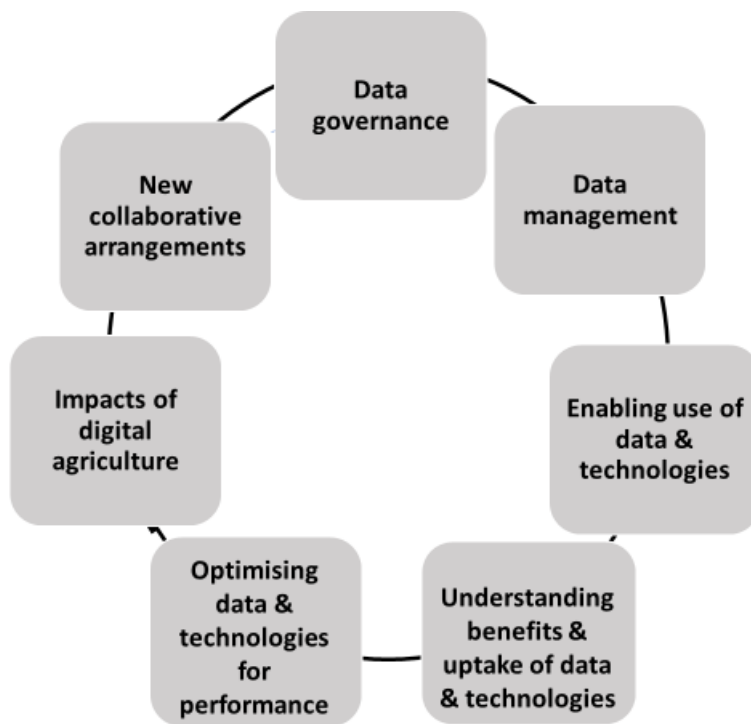
162 This first step generated 200 questions. After removal of some which were unclear or not
163 questions per se, the list was refined to 195. Preliminary analysis and clustering of the 195
164 questions was then undertaken. An inductive approach was employed since the analysis was
165 not guided by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

178

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

184 the questions according to their scores and identified the top 10 questions in each theme.
185 Questions remained unedited in Steps 1 and 2.

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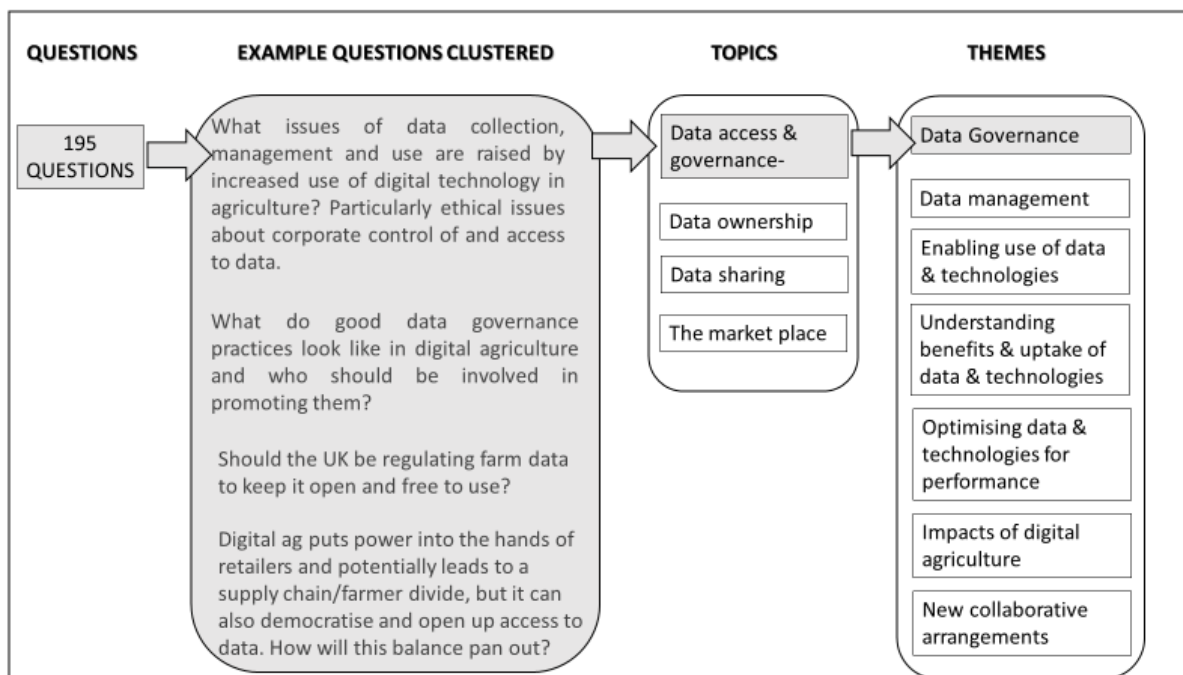
189 Figure 1. Key themes identified in the prioritisation exercise

190

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

203 discussed prior to the break out group activities to ensure all groups followed the same
 204 ranking process. A plenary session provided opportunity for discussions that cut across the
 205 themes.

206
 207



208

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

211

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

217

218 For this study, a wide range of perspectives were sought by inviting representatives selected
 219 from different stakeholder groups across UK agriculture. An initial list of relevant stakeholder
 220 groups was drawn up by the lead researchers using personal contacts, Google and Google
 221 Scholar searches to scope out participants' interests and expertise. The criteria for inclusion
 222 was firstly, stakeholder areas of operation, namely: academia, agricultural research institutes,

223 farmer representatives, agricultural suppliers, agri-tech businesses, NGOs, government
224 bodies and consultants (technical, business, legal), and secondly, relevant experience or
225 interest in digitalisation of agriculture. These criteria were used to reflect the technical, social,
226 legal and ethical dimensions of digital agriculture, shown in the literature to be significant,
227 and to capture a range of views, including conflicting or alternative views. Potential
228 participants (148 in total, see Table 1) were sent an invitation explaining the research and
229 were invited by email to propose questions. This was enhanced by a snowballing method in
230 which we asked those selected to suggest contacts or colleagues. In addition, a link to the
231 invitation was circulated via the host institution's Twitter account (2462 followers) and
232 website (2000 visit per month) which reaches a wider range of people in the agri-food and
233 agri-environment community. In total, 40 respondents sent in questions. Some of these
234 respondents (4) shared the task with colleagues (4-6) and agreed a set of questions together.
235 Table 1 shows the distribution of respondents compared to the original invitations.
236 Approximately half of respondents in Steps 1 and 2 were from the research community (this
237 included university departments and research institutes concerned with agriculture and
238 technologies, data analytics, agri-food systems and humanities) and research funders; and
239 half from a range of practitioner or commercial stakeholder groups. There was a good
240 representation across the range of targeted stakeholders. Although responses from
241 technology and data services were lower than hoped for, those who responded represented
242 some of the larger actors in this sector. No responses from agricultural suppliers suggest that
243 this sector does not consider this topic relevant. The aim was to include participants from
244 across the UK, and although the majority of respondents were from England, some
245 representation from Wales (4) and Scotland (2) was also achieved.

246

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

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

248

249 **4. Results and discussion: Prioritised themes and research questions**

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

255

256 For each theme, the gold, silver and bronze questions as refined in the workshop, are
257 presented together with an analysis of the accompanying discussion. A brief list of the original

258 question topics (step 1) are provided, the refined top 5 questions per theme from the voting
259 (step 2) are available as supplementary material. In total 27 priority research questions were
260 identified: 15 gold, 7 silver and 5 bronze, across the 7 themes.

261 **4.1 Theme 1: Data governance**

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

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

276
277 Governing data ethically and responsibly was the priority issue for this theme in the
278 workshop. The two gold questions (Q1 and Q2) thus address respectively how to create
279 systems whereby people feel confident in entering and sharing data and in turn how to create
280 systems to govern the data for the benefit of all. These two questions are seen to be
281 interlinked, as “the way you make people trust and share the data, is to demonstrate that
282 you've got good governance”, as summed up by one workshop participant.

283 This strong focus on governance systems for sharing and managing data, and social and
284 ethical concerns about privacy and ownership, chimes with issues raised in the social science
285 literature. The need for transparent governance systems is not disputed (Stilgoe *et al.*, 2013;
286 Jakku *et al.*, 2019), because, as Hajer (2003) notes, emerging technologies often fall into an
287 ‘institutional void’. However, governance is often discussed as an abstract concept. Although
288 a range of governance mechanisms and models have been advocated with responsibilities

289 potentially distributed across private and public sectors (Linkov *et al.*, 2018; Rotz *et al.*, 2019),
290 our understanding of how these might be defined and operationalised is still limited, and
291 emerges here as a clear and important future research priority. In particular the coordinating
292 and monitoring activities (data processing, reporting, analysis and usage) and support that
293 enables the maintenance and operation of institutions, which is at the core of governance
294 arrangements (Bryson *et al.*, 2006), are only now receiving research attention in the digital
295 agriculture sphere (Newton *et al.*, 2020).

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

316

317 These discussions about data ownership and transparency resonate with Lioutas *et al.* (2019),
318 who argue that the focus on the rules of ownership, access and control of the *data itself*
319 should be shifted *to value* (see also Rotz *et al.*, 2019, Bronson and Knezevic, 2016), because

320 “what creates the power imbalance within a community is the uneven access not to big data
321 but to the value emerging from them” (Lioutas *et al.*, 2019 p 6). In line with other
322 commentators, they note that the distribution of value from big data is unequally allocated
323 across agri-food systems, with farmers enjoying only a limited share of it (Haire, 2014). In our
324 workshop deliberations it was deemed essential to shift the central question in the discussion
325 from ‘who owns the data?’ to ‘who owns or has the rights to extract the value underpinning
326 those data?’, as articulated by Stubb (2016).

327

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

335

336 **4.2 Theme 2: Data management**

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

343

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

351

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

367

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

374

375 For Themes 1 (Data governance) and 2 (Data management) the questions arise because of
376 the dominance of private corporations in creating platforms to aggregate data, enable data
377 exchange between systems and offer decision support (Finger *et al.*, 2019; Weersink *et al.*,
378 2018). High levels of investment in platforms and vertical integration by such firms (Birner *et al.*,
379 2021) not only raises issues of data ownership and power but also of so-called
380 ‘platformisation’, which risks closing down options for smallholders (Brooks, 2021; Chiles *et al.*,
381 2021). Different models are already in operation representing networks of competitors
382 and collaborators and the degrees of interoperability of their digital applications (Antle *et al.*,
383 2017; Kritikos 2017; Philips *et al.*, 2019; Rotz *et al.*, 2019; Finger *et al.*, 2019; Kenney *et al.*,

384 2020). How these are embedded institutionally will play a crucial role in determining the
385 outcome between closed, proprietary systems and open, collaborative systems (Wolfert *et*
386 *al.*, 2017; Carolan, 2017a/b). Prioritising research to understand how this unfolds is
387 emphasised in both Theme 1 and 2. An emerging area of research and policy interest is the
388 development of trust frameworks which offer new mechanisms to manage decentralised and
389 distributed collections of data, and enable secure information sharing for the benefit of all
390 stakeholders in the food system (Pearson *et al.*, 2021), although their deficiencies re
391 cognised (Van Der Burg *et al.* 2020). Interestingly, questions about technology ownership
392 and the proprietary nature of many commercial systems (Carolan, 2017b, 2020) were not
393 specifically raised.

394

395 **4.3 Theme 3: Enabling use of data and technologies**

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

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

409

410 The first gold question (Q1) arose because, as one participant explained: “the ability to collect
411 data is [...] burgeoning, and it is understanding what data is actually useful to help make a
412 better decision that is important... the farmer has to be able to understand which bit of all
413 this morass of data is actually of a value to him or her”. The quality and accuracy of data and
414 availability at a high resolution was also seen to be important. The question reflects the fact

415 that, to date, the interpretation and use of data from smart technologies is not matching
416 expectations (Leonard *et al.*, 2017; Weersink *et al.*, 2018). It also underscores the fact that
417 understanding how data can be collated, combined and analysed to be useful and valuable
418 for farmers compared to current decision making has received relatively little research
419 attention (Sonka, 2015; Evans *et al.*, 2017; Ingram and Maye, 2020).

420

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

437

438 In comparing digital data with traditional knowledge for decision making (gold Q2), there was
439 agreement that: "you're basically moving from intuitive decision making, based on
440 experience, to database decision making", as one participant commented. When exploring
441 this further, there were a number of shared experiences between practitioner participants
442 demonstrating that data on its own does not necessarily provide the solution and in some
443 cases can be disruptive. This is commensurate with observations of disruption of 'hands-on'
444 and experience-driven management and embedded knowledge by digitalisation (Eastwood
445 *et al.*, 2012; Butler and Holloway, 2016; Carolan, 2020). The risk of accelerating agricultural

446 deskillling by transferring decision making authority to machines and algorithms has been
447 raised (Rotz *et al.*, 2019; Miles, 2019; Brooks, 2021), with the prospect of unskilled farmer
448 cyborgs who have lost all intuitive knowledge, as suggested by Brooks (2021).

449

450 However, participants suggested that research should understand how to achieve successful
451 data-driven agricultural systems through integrating all types of agricultural knowledge (e.g.
452 from farmers, agronomists and plant scientists) with remote digital data, rather than looking
453 at the tension between them. This view concurs with that of commentators who seek to
454 understand how data-driven decision making and processing in real-time interacts with highly
455 intuitive and experiential decision making to optimise the best of both worlds (Xin and
456 Zazueta, 2016; Shepherd *et al.*, 2018}. Without being able to integrate contextually specific
457 information, many farmers may struggle to trust or see value in the outputs from digital
458 analytical tools and it may also preclude certain agro-ecological trajectories based on
459 sustainable value creation as opposed to purely extracting economic value (Wittman *et al.*,
460 2020; Huang *et al.*, 2021). This question prioritisation and critical analysis on enabling and
461 optimising use of digital technologies and data emphasises an area of research which has
462 previously received limited attention, and highlights the need for interdisciplinary studies in
463 particular which can cross epistemological boundaries.

464

465 **4.4 Theme 4: Understanding benefits and uptake of data and technologies**

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

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

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

480 These questions recognise that ultimately the potential of digital agriculture technologies and
481 data can only be materialised when applied to derive improvements in management practices
482 (Finger *et al.*, 2019). Rather than a focus on how to encourage adoption of digital technologies
483 per se, the issue is reframed in this exercise by asking, what are the benefits and how can
484 (and which) farmers derive value? This acknowledges that farmers can have rational reasons
485 for not using digital technologies and can be wary of investing in an expensive set of
486 technologies of potentially questionable value (Defra, 2018; Lowenberg-DeBoer and Erickson,
487 2019). As well as asking what are the benefits, Q1 also asks for whom, but the participants
488 did not elaborate on this. Although benefits derived by those who support adoption have
489 been questioned (see Bryant and Higgins, 2021; Lioutas *et al.*, 2019), and disruption to their
490 professional practice and relations noted (Rijswijk *et al.*, 2019), further empirical data is
491 needed on this topic.

492
493 It was considered important to provide better evidence and to clearly demonstrate to farmers
494 the benefits of digital agriculture. On this point, participants' remarks included: "Farmers are
495 being told a lot at the moment that, you know, your data is valuable. But I think the question
496 that they will have is "Yeah, valuable to who at the moment?", it feels like it's probably more
497 valuable to suppliers, and maybe government agencies, than actually the farmer"; and "The
498 benefits seem to lie elsewhere". Such unclear or ambiguous value propositions explaining
499 why producers should change to digital agriculture are often noted as the main reason
500 farmers do not adopt digital technologies (Keogh *et al.*, 2016; Leonard *et al.*, 2017; Spati *et*
501 *al.*, 2021).

502
503 Workshop participants felt that this notion of value, and its distribution, in terms of economic
504 benefits, needed to be unpacked by researchers; furthermore, that all the dimensions and
505 dynamics of sustainable value (economic, environmental and social value) should be
506 considered, moving beyond the locus of the farm to shareholders, stakeholders in a supply
507 chain and society (Huang *et al.*, 2021). This emphasises the need to devise frameworks that

508 allow the value of information to be expressed not only by economic measures but also in
509 terms of environmental performance, animal welfare and health, and social well-being of the
510 decision maker (Rojo Gimeno *et al.*, 2019; Wittman *et al.*, 2020). With respect to how benefits
511 are evidenced, Relf-Eckstein *et al.* (2019) ask 'what evidence' is being used to advance smart
512 farming innovation in Canada arguing that industry survey data is not representative of the
513 population of farm operators, and that the industry lack the expertise, research skills, and
514 scale of resources to conduct rigorous scientific studies. They propose that governments need
515 to facilitate coordination among multiple groups of actors to gather valid evidence of benefits,
516 through experimentation.

517

518

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

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

538 language behind the questions, such as ‘benefits’ and ‘advantaged’ and ‘disadvantaged’,
539 which suggest a normative view that digital agriculture is universally beneficial and desirable.
540

541 Commentators argue that a range of technologies need to be available for a diverse set of
542 agricultural systems, across systems and across scales (Walter *et al.*, 2017), and need to be
543 scale-neutral so that they can be utilised by both small- and large-scale operations (Basso and
544 Antle, 2020). The potential for smart technologies to accelerate an agroecological transition
545 for smallholders, for example, has been explored (Wittman *et al.*, 2020; Cumulus Consultants,
546 2021) and their compatibility with short food supply chains assessed (Lioutas and Charatsari,
547 2020). Other forms of support such as opening up access across different scales, however,
548 can be problematic as inequalities persist. However, the ability to access something is not the
549 same as having the capabilities to do so in ways that generate benefits, and it is unclear how
550 disempowered farmers, who do not have the requisite skills and competencies, can exercise
551 their access rights so as to independently exploit the potential of big data (Mittelstadt and
552 Floridi, 2016; Carolan, 2017a; Finger *et al.*, 2019). This highlights a clear connection between
553 questions concerning benefits, capability and fairness and suggests that this intersection
554 deserves more focus in future research.

555
556 Questions about how technologies are experienced on a day-to-day basis, how farming
557 practices develop and change, and farmer experiences and impressions in terms of values and
558 benefits were also discussed and clarified in gold Q3. This was felt to be inextricably linked to
559 the other questions and important because there is a significant knowledge gap in terms of
560 what happens when farmers buy and start to use (or indeed stop using) data and new digital
561 technologies on their farms (Kerneck *et al.*, 2020), and adapt and experiment with it
562 (Carolan, 2018). This concurs with Phillips *et al.*'s (2019) critique of current research which,
563 they argue, tends to speculate about the future but lacks analysis of what is happening at
564 present in terms of changes or not to socio-material practices. This gold question emphasises
565 the importance of this hitherto neglected topic for future empirical study.

566
567 With respect to uptake of technologies (silver, Q4), the workshop participants acknowledged
568 that this question should be seen as integral to the other questions in this theme about
569 benefits and changing social practices. They agreed that, although demographic and farm

570 factors are influential determinants, there are many other critical factors, such as trust,
571 habits, skills and infrastructure, which deserve urgent research attention. These questions
572 intend to widen the scope of the existing evidence on farmers' uptake which tends to centre
573 on: determinants and drivers of adoption of precision farming (Pierpaoli *et al.*, 2013; Knierim
574 *et al.*, 2019; da Silveira *et al.*, 2021), context-related factors (Vecchio *et al.*, 2020), decision
575 making processes (Higgins *et al.*, 2017), and farmers' communication and co-operation
576 strategies (Kutter *et al.*, 2011). A more critical perspective on the enabling conditions in the
577 Agricultural Knowledge and Innovation System and the relations of the constituent actors was
578 also felt to be missing by some participants. This echoes studies showing the importance of
579 agricultural knowledge and advice network in increasing the utility of digital agricultural
580 technologies (e.g. Vecchio *et al.*, 2020; Fielke *et al.*, 2021; Newton *et al.*, 2021), and the need
581 to consider the role of so called meso-scale actors (Higgins and Bryant, 2021). The
582 requirement for a more networked and collaborative understanding of adoption is also
583 expressed in Theme 7 (New collaborative arrangements).

584

585 **4.5 Theme 5: Optimising data and technologies for performance**

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

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

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

617

618 The second gold question (Q2) collates questions asking how digitally enabled monitoring
619 impacts day-to-day treatment of animals and how this is perceived by different actors. This
620 reflects the specific interests of certain participants, the emerging literature on ethical
621 challenges and human-animal relationships of autonomous systems (Bear and Holloway,
622 2019, and the policy attention animal welfare receives in the UK.

623

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

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

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

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

653 **4.6 Theme 6: Impacts of digital agriculture**

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

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

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

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

673 The gold questions (Q1 and Q2) ask what role digital data and tools might play in creating a
674 more democratic food system. The possibilities for using digital data for establishing better
675 relationships between farmers and publics (referring here to food consumers and citizens)
676 was recognised as an under-researched area, despite the plethora of new tools now available.
677 The questions intersect with those of Theme 1 (data governance), Theme 2 (data
678 management) and Theme 5 (optimising data and technologies for performance) and
679 accentuate the need for societal dialogue recognised as critical to innovations in food system
680 transformation (Herrero et al. 2020). In particular, they resonate with conversations about
681 democratising ownership and participation in digitalisation in the agri-food system. For
682 example, scholars have pointed to harnessing new forms of citizen digital participation to
683 potentially improve transparency, and to make institutions more accessible to ordinary
684 people. This includes facilitating alternative organisations, like cooperatives and expanding
685 how food system workers, small producers, citizen consumers, food justice activists, and
686 scholars can participate in collective action and institutional decision-making (Chiles *et al.*,
687 2021; Carolan 2017a/b; Kenney *et al.*, 2020). In line with this, Chiles et al. (2021) argue for
688 increased investments in research and education for the public interest and for government
689 investments in publicly accessible digital infrastructures to facilitate a more just transition.

690

691 The impact of digital agriculture on the nature and experience of agricultural work and on
692 farming identities were seen to be interconnected in Q3 (gold) and Q4 (silver). The unknown

693 effect of applying sensor and precision techniques on farm workflows and labour
694 requirements was discussed in terms of the repercussions for farmers' status, both on the
695 farm and in the supply chain. In particular, whether their status might be raised by
696 opportunities for enhancing digital skills or diminished in favour of 'off-farm' professionals
697 taking a more prominent role was questioned. The participants noted that although questions
698 about farmer identity featured in the top 10 questions in this theme from the voting exercise,
699 they were missing from the top 5 despite being crucial to these discussions.

700 The change in the nature and experience of agricultural work is a topic echoed by researchers
701 who envisage disruption to established farm labour structures and to the way benefits are
702 distributed (Carolan, 2018; Fleming *et al.*, 2018; Rotz *et al.*, 2019). The displacement and
703 devaluing of some farm jobs, as well as the benefits of removing the drudgery of others, have
704 been considered but within quite specific contexts (Edwards *et al.*, 2020). Closely linked to
705 this are questions of how digital agriculture challenges farmer identities, already explored by
706 a number of researchers (Tsouvalis *et al.*, 2000; Bear and Holloway, 2019; Miles, 2019; Brooks,
707 2021). The concern is that values that characterise a 'good farmer' or 'smart farmer' may
708 privilege larger scale and commodity crop farmers and disenfranchise the smaller farmer, or
709 be incompatible with those active in short food supply chains (Lioutas and Charatsari, 2020).
710 There was consensus that this is an area of socio-cultural research that not only needs
711 expanding and strengthening, but also integrating into more technically-orientated research.

712

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

721 **4.7 Theme 7: New collaborative arrangements**

722 Theme 7 clusters questions about farmer involvement in digital developments, collaboration
723 and user-centred design, existing stakeholder models and new business models. The original

724 questions (22) focused on: whose vision of agriculture? institutional changes to integrate
725 users; governance and new models of working; and new markets and new contexts. These
726 were filtered down in the voting process and prioritised in the workshop as follows:

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

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

743 The need for farmer involvement and incorporating user-perspectives to address gaps
744 between design and practice in digitalisation is acknowledged elsewhere (e.g., Fountas *et al.*,
745 2015; Van Es and Woodard, 2017). Involving users not only addresses underutilisation and
746 low sustainability of innovations but also leads to valuable social learning and capacity
747 building (Masiero, 2016; Steinke *et al.*, 2020). While user-centredness has been part of
748 practice in digital advisory and decision support tools for some time (Eastwood *et al.*, 2012),
749 it is only now receiving attention in data platform and technology development through co-
750 design and other collaborative activities (Newton *et al.*, 2021). This question, as in other
751 themes, underscores the need for strengthening research that studies and enacts farmer-led
752 innovation.

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

765
766 The silver (Q3) question identifies concerns about a deepening digital divide, in particular for:
767 farming systems and sectors where the rate of technology development is relatively slow; and
768 for those farmers lacking digital literacy capabilities to adapt to new technologies and/or the
769 digital infrastructure. This echoes questions in Themes 3 (Enabling use of data and
770 technologies and 4 (Optimising benefits). Although it was agreed that there is already a good
771 understanding or sense of what is needed to prevent a digital divide (in terms of skills and
772 infrastructure), researchers have not adequately explored why a divide might be amplified
773 and why policies have not effectively addressed this (see Defra, 2018). The participants
774 agreed that multiple aspects need to be considered in Q3 such as infrastructure (internet
775 access, connectivity) and capital investment, also that there is a need for creation of
776 sustainable business models that provide viable digital solutions for inclusion of small-scale
777 farmers in the digital agriculture transformation process. Regarding Q4 (Bronze), about
778 whether agriculture can learn from the success stories of other industries and sectors,
779 participants did to elaborate but agreed that this opportunity has been under exploited to
780 date, and presents a promising avenue for future research.

781

782

783 **4.8 Nexus and methodologies for future digital agriculture research**

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

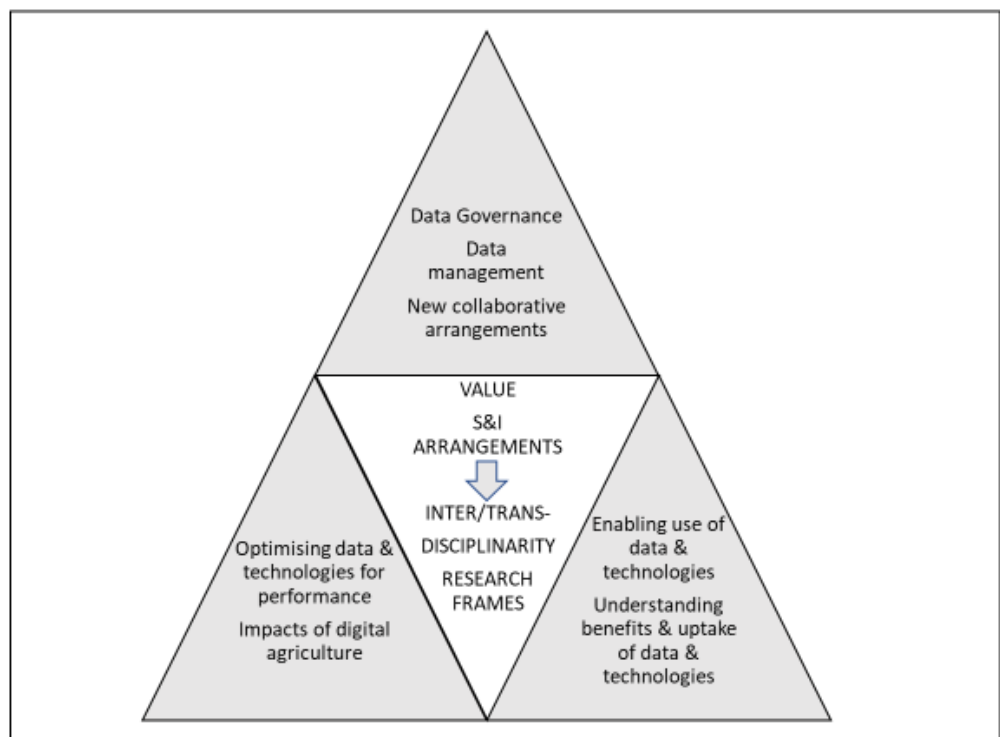
788

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

798

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

813 These nexus emphasise the importance of interdisciplinarity and transdisciplinarity in
 814 research to support integrative solutions across the many interacting outcomes of
 815 digitalisation, and the need to build sufficient capacities within multi-partner research
 816 communities. Such approaches can offer insights into complex socio-technical systems,
 817 account for multiple perspectives, and better frame policy decisions. The question of scale
 818 also emerges for future research, by which we mean at what level (farm, supply chain, society)
 819 do researchers focus to disentangle multiple interactions in the system?
 820



821
 822
 823
 824 Figure 3. Multiple interactions between priority research themes and questions: nexus and
 825 methodologies (central triangle) to guide future digital agriculture research

826
 827 In particular this exercise revealed that a future research agenda needs to tackle the binary
 828 nature of analytical frames. Rather than focus on the differences between process or data-
 829 driven approaches (often implied as distinct processes), or tacit or data-driven knowledge,
 830 the exercise suggested that research should be directed towards how these processes and
 831 knowledges can be integrated. In the same way, rather than assume that digital technologies

832 have a single trajectory and will only advantage large-scale conventional farming systems,
833 researchers should recognise and examine digital opportunities for smaller farms and for
834 alternative agroecological systems building on the granularity of control and adaptability that
835 digitalisation can offer to benefit agri-food systems overall.

836

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

843

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

850

851 **4.9 Limitations of the method**

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

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

867

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

882

883

884 **5. Conclusion**

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

894

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

902

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

919

920 **Declaration of Competing Interests**

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

922

923

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