

**Unclassified****English - Or. English****6 April 2022****TRADE AND AGRICULTURE DIRECTORATE  
COMMITTEE FOR AGRICULTURE****Working Party on Agricultural Policies and Markets****The digitalisation of agriculture: A literature review and emerging policy issues**Contact: Jesús ANTÓN ([jesus.anton@oecd.org](mailto:jesus.anton@oecd.org)).**JT03492966**

### **Note by the Secretariat**

This report provides an overview of the digitalisation of the agricultural sector based on the available literature, identifying relevant policy issues. The work is foreseen under Output Area 3.2.1.2.2 of the 2021-22 PWB of the Committee for Agriculture and a scoping paper was discussed at the May 2021 APM [TAD/CA/APM/WP(2021)14]. This literature review was prepared by the Secretariat drawing from background reports from Jonathan McFadden (University of Oklahoma) and Terry Griffin (Kansas State University) who contributed to this work as external consultants. Francesca Casalini, now in the Directorate for Science, Technology, and Innovation (STI) has been the main co-author from the OECD Secretariat.

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## Key messages

### What is the issue and why is it important?

- Agriculture in OECD countries faces mounting pressures from climate change, labour shortages, ecosystem degradation, demographic transitions, and evolving consumer tastes. Digitalisation offers the potential to help address these challenges.
- A thorough review of the current status of digital agriculture adoption helps identify where national governments can address bottlenecks in the development, and constraints to farmers' use, of digital tools. Reducing these barriers could help support the achievement of productivity, sustainability, and resilience goals in the agricultural sector.

### What did we learn?

- Precision technology use in *row crops* has been increasing since the early 2000s, although adoption varies by year, technology, and crop. Uptake is high – but not universal – in North America and Europe; data limitations pose challenges for estimating trends in many other countries.
- Digital technologies are starting to be used for *livestock production and specialty crops*, although many tools remain in the pre-commercialisation development stage.
- On-farm productivity, sustainability, and resilience benefits from digitalisation have been well documented for commercial row crop farms in several countries. Technologies for livestock and specialty crops have generally emphasised productivity increases, typically from reduced need for manual labour.
- Common barriers to adoption include costs (up-front investment and recurring maintenance expenses), relevance and limited use cases, user-friendliness, high operator skill requirements, mistrust of algorithms, and technological risk.

### Key recommendations

- Better information about the adoption, costs and benefits of different technologies is needed to support informed farmer and policymaker decision making. This information can be facilitated through large-sample surveys of farmers over time.
- Rather than promote specific technologies, policymakers should maintain appropriate incentives for digital innovations and seize new opportunities to be knowledge brokers and facilitators of data-sharing to spur inclusive, representative, and secure data ecosystems. This also underscores the importance of ensuring competition in technology input markets.
- Policymakers should also take account of intangible or difficult-to-measure aspects of technologies when considering their benefits (i.e. quality of life improvements or reduced family labour), including in terms of barriers to adoption (i.e. human capital requirements or mistrust in “black-box” technologies).

## Executive summary

The quantity and quality of digital technologies available to farmers have advanced considerably since the 1990s – when use of computer- and internet-based technologies for management of crop and livestock operations began to develop. Many factors – including increases in computational power, faster internet and greater connectivity, declining technology costs, and the rise of big data paired with advanced analytics – are driving the current wave of digitalisation that holds promise for helping to meet the sustainability, productivity, and resilience goals of commercial agriculture. The agricultural sector needs to adapt to a host of mounting challenges, including climate change and broad environmental degradation, farmworker shortages, rising population levels and dietary transitions. Digital technologies, including conventional precision agriculture technologies, are expected to be a major part of the solution to these challenges. To what extent are they being adopted? What are their impacts on productivity, sustainability and other goals? What can policymakers do to enhance adoption and impact?

A review of the academic and grey literatures highlights a number of major trends in the adoption and impacts of digital technologies. In row crops like corn, soybeans, wheat and cotton, evidence from national surveys in Australia, Canada, Colombia, Denmark, the United Kingdom, and the United States indicate broad use of digital tools, although uptake varies over time and by technology and crop. In farms specialising in livestock or specialty crops (e.g. fruits, vegetables and tree nuts), the evidence base is more limited, although certain national surveys and large-sample studies indicate considerable, but varied, use. Among the most widely used technologies are yield and soil maps and automated guidance in row crops; monitoring technologies (e.g. precision weighing, cameras, management apps) in livestock production; and precision pest management for specialty crops. Many tools involving algorithm-based decision-making and automation are being developed and piloted and will soon emerge.

Increasing productivity and profitability have been a priority for precision technologies in row crops production. However, evidence suggests small impacts to date on profitability and risk management, but points to potential increases in system-wide sustainability. Productivity improvements have been a central outcome of technologies for the other sectors, with specialised technologies like precision sensors to track animal behaviours in livestock production or precision canopy sprayers for orchards reducing labour needs while potentially bringing sustainability and resilience benefits. Major determinants of adoption in all sectors include farmers' age, human capital, perceptions of technology, and quality-of-life gains, in addition to farm scale. Major constraints to adoption continue to be technology costs, user-friendliness, relevance, clearly demonstrated net benefits, lack of high-speed internet connectivity, and mistrust in tools sometimes perceived as “black box” technologies.

Policymakers need to address the removal of specific barriers to farmers' adoption, while ensuring both enabling infrastructure and appropriate incentives upstream in markets for digital innovation. Governments have a particular role in ensuring robust competition in technology input markets; facilitating the provision of adequate telecommunications services; accelerating capacity building in good data governance; strengthening extension and other farmer outreach services; and promoting up-skilling or re-skilling of the agricultural labour force. More detailed country level representative information is needed about adoption and the costs and benefits of new technologies as directly experienced by farmers. This need is particularly acute for the livestock and specialty crop sectors, where evidence tends to be from small-sample studies. There is also a need for more data and analysis of the impacts of technology uptake on agricultural sustainability and resilience.

## 1. Introduction

1. Digitalisation is the defining technological transformation of this era, and, as in other sectors, it will have important impacts on agriculture. Digitalisation refers to the adoption of information communication technologies, including the Internet, mobile technologies and devices, as well as data analytics, to improve the generation, collection, exchange, aggregation, combination, analysis, access, searchability and presentation of digital content, including for the development of services and applications. The digitalisation process holds the potential to bring about a significant change in how agriculture functions, beyond discrete tools, technologies or practices, and to offer a path for innovation and new ways of organising production and supply chains. In particular, the agricultural sector is seeing a set of transformative trends due to digitalisation, such as a greater focus on precision agriculture, the internet of things (IoT) and the use of big data to drive production and business efficiencies.

2. Public and private actors in agro-food value chains and the wider agricultural innovation system (AIS) could benefit from the digital transformation of agriculture in multiple ways. For farmers, digital technologies and the insights that are generated from agricultural data could support better decision-making on farms, helping to boost innovation and improve agricultural productivity, sustainability and resilience. Digital technologies could also offer opportunities for new sources of efficiency and value creation upstream and downstream of farms, supporting research and innovation, the creation of new services for the sector, and improved traceability and more efficient transactions in value chains (Jouanjean, 2019<sup>[1]</sup>). In addition, policymakers could use digital technologies to improve how policies are designed, implemented and monitored, and design new, better policies for the agriculture sector (OECD, 2019<sup>[2]</sup>).

3. Over the past couple of decades, agricultural stakeholders have been increasingly leveraging digital tools to improve their operations (Bramley and Trengove, 2013<sup>[3]</sup>; Schimmelpfennig, 2016<sup>[4]</sup>; Lu, Reardon and Zilberman, 2016<sup>[5]</sup>), a trend that has been accelerated by the physical distancing measures imposed during the COVID-19 pandemic (SIANI, 2020<sup>[6]</sup>). Reflecting this, agro-food sectors increasingly consist of a mix of physical elements (for example, to produce, transport, process and deliver agro-food products to end-users) and digital elements (for example, electronic documentation and record-keeping software, decision-support tools, platforms and digital marketplaces), with increasing interaction between those physical and digital elements.

4. Nevertheless, the radical transformation foreshadowed from the digitalisation of the economy has not yet fully materialised for global agriculture systems (Khanna, 2021<sup>[7]</sup>; Birner, Daum and Pray, 2021<sup>[8]</sup>). Given the perceived benefits that such a transformation could bring, stakeholders are calling for greater efforts to promote the digitalisation of agriculture, and accelerating the use of digital technologies in the agricultural sector is seen as a priority in many OECD and non-OECD countries (European Commission, 2020<sup>[9]</sup>; CSIRO, 2019<sup>[10]</sup>; Governo Federal, 2019<sup>[11]</sup>).

5. In this context, this report provides a literature review of digitalisation in the agricultural sector with a view to addressing the following key questions for digital agricultural policy:

- What is the status of digitalisation in farmers' agricultural production?
- How is digitalisation contributing to productivity, sustainability and resilience policy goals?

- What are the key constraints to, and drivers for, digital adoption on farms and in the AIS?
- Which policy levers could the government use to strengthen the digitalisation of agriculture?

6. The first section of this report focuses on the actors involved in the digitalisation of the agricultural sector, and provides an initial assessment of how they are being impacted by the digital transformation.

7. The following three sections are organised according to the three main commodity types – row crops, livestock, and specialty crops. Each of the commodity-focused sections reviews available evidence with respect to trends in adoption, in particular for different types of digital technologies and applications.<sup>1</sup> It then brings together the evidence about the extent to which digitalisation is being leveraged or can be related to productivity, sustainability and resilience policy objectives in each commodity sector, taking into account that the outcomes with respect to these three purposes are not mutually exclusive and can often be linked. Finally, it highlights findings from the literature about the drivers and enablers of, and constraints to, adoption for each type of commodity production.

8. The final section summarises the policy insights emerging from the literature, and complements these with other policy considerations from the literature on agricultural digitalisation. It provides suggestions for policy-makers on how governments can contribute to further strengthening the digitalisation process for agriculture and identifies policy issues that require further consideration.

9. While extensive literature exists on the potential of digital tools for agriculture, often based on theoretical reasoning or limited field trials, this report emphasises the literature that presents robustly peer-reviewed studies and surveys in order to provide a representative snapshot of the status of agricultural digitalisation today.

10. This report also largely focuses on technologies that are more advanced than smartphones, tablets and other personal computing devices; Annex A provides a brief description of the more advanced digital agriculture technologies applications in this report. That said, these technologies are a necessary, but not sufficient, condition for the digital innovation ecosystem. This is based on the recognition that this type of equipment is almost ubiquitous in the agricultural sectors of developed nations, even if access to high-speed internet in rural areas is still an issue in a number of countries.<sup>2</sup> For example, one recent survey of more than 2 000 corn, soybean, specialty crop, and livestock farmers in the United States found that 9 in 10 operations used smartphones within the field or paddock (United Soybeans, 2019<sub>[12]</sub>). A similar study conducted by the Irish Farmers Association in 2019 found that 84% of the over 750 farmers surveyed used a smartphone (Skillnet Ireland,

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<sup>1</sup> While acknowledging the importance of emerging technologies, this report does not focus on them for three reasons. First, limited information is available on emerging technologies, in part because there is not a generally well-accepted definition of this concept, and existing information may not be reliable. Second, technological emergence (i.e. commercialisation) is not sufficient for technological success; many commercialised technologies are pulled from the marketplace after a short time if they remain unpopular with end users. Third, while emerging technologies often and rightfully merit substantial interest from regulatory policymakers, established technologies also typically have considerable policy relevance, especially if there are concerns related to market failures or anticompetitive behaviour.

<sup>2</sup> This literature review and accompanying policy insights are of most relevance to decision-makers in developed countries. However, this report incorporates evidence from developing countries to the extent that there is considerable overlap with technologies, their effects, and their constraints and enablers (Zheng, Wang and Wachenheim, 2018<sub>[197]</sub>; Pivoto et al., 2019<sub>[198]</sub>).

2019<sub>[13]</sub>). Based on a survey of 250 farmers in an agricultural region of central Italy, (Blasch et al., 2020<sub>[14]</sub>) found that 69-78% used smartphones and computers for their operations. Comparable adoption rates are found for farmers in Germany (Michels et al., 2020<sub>[15]</sub>) and many other countries.

11. While the focus of this report is on the process of agricultural digitalisation, the findings are relevant for broader discussions of innovation at the farm level and beyond the farm gate. Indeed, even if not all agricultural innovation relates to digital technologies, digital technologies can support the majority of other types of innovation. In this sense, this report hopes to contribute to better understanding the innovation landscape for agriculture and how relevant policies can best ensure sustainable productivity growth.

## 2. Key actors in the process of digitalisation of agriculture

12. This report explores the digitalisation of primary production actors. Three layers of actors are seen as being at the centre of the digitalisation of agriculture: farmers, technology providers, and ‘intermediaries’. End consumers of foodstuffs (e.g. supermarket shoppers, purchasing agents for cafeterias and other food service providers, restaurant diners) can also significantly, although indirectly, shape the course of technology development and farmer adoption (Khanna, 2021<sub>[7]</sub>). However, such demand-side aspects of agricultural digitalisation are beyond the scope of this review.<sup>3</sup> Similarly, although processors, wholesalers, and retailers of agro-food products are significant components of modern value chains, given the focus on primary agricultural production, they are not discussed here.<sup>4</sup>

13. **Farmers** are the crucial actors supplying processors and other direct purchasers with the commodities of interest. They also demand inputs, both in the form of physical factors of production and services, upstream from advisors and various firms.

14. Farmers vary widely with respect to their level of human capital – experience, education, and other relevant training (Huffman, 2001<sub>[16]</sub>). In this respect, one of the most robust findings from the literature is that adoption tends to increase with farmers’ human capital (Daberkow and McBride, 2003<sub>[17]</sub>; Schimmelpfennig and Ebel, 2011<sub>[18]</sub>; Tey and Brindal, 2012<sub>[19]</sub>; Lambert et al., 2014<sub>[20]</sub>; Schimmelpfennig, 2016<sub>[21]</sub>; Griffin, Shockley and Mark, 2018<sub>[22]</sub>; McFadden, Rosburg and Njuki, 2021<sub>[23]</sub>; Schimmelpfennig and Ebel, 2016<sub>[24]</sub>). In many cases, human capital differences account substantially for the digital divide that separates adopters from non-adopters. Therefore, baseline capacities of farmers, and the costs of building up human capital for farm workers, are an important element to consider—an important launching point—in assessing digitalisation of agriculture.

15. **Technology providers** are the developers of digital agricultural technologies. They provide a diverse array of differentiated products and services, usually in niche markets that afford them some degree of market power. With respect to technology providers, (Birner, Daum and Pray, 2021<sub>[8]</sub>) suggest the following taxonomy of developers: 1) large

<sup>3</sup> Digitalisation may also bring about changes to food labelling systems, such as through increased prominence of QR codes or other machine-readable labels or increased automation of certificate verification. These effects also fall outside this review’s scope.

<sup>4</sup> This report also does not consider the administrative burden placed on farmers who face official reporting requirements. Digitalisation holds promise here, too, for reducing such burdens (Poppe, Vrolijk and van Dijk, 2021<sub>[202]</sub>). Additionally, “smart” accounting systems that allow for automatic processing of invoices, as well as platforms to facilitate employment of seasonal farmworkers are digital innovations in farm financial management that can simplify accounting and human resources tasks on farm operations.

multinational agricultural input companies, 2) large multinational software and big-data companies, 3) non-agricultural hardware companies, and 4) start-up companies.

16. The role of multinational input companies in the provision of precision agriculture has been well studied (Fuglie et al., 2011<sup>[25]</sup>), although much less is known about the evolving influence of non-agricultural software and hardware companies (McFadden and Schimmelpfennig, 2019<sup>[26]</sup>). Figure 1 provides a visualisation of the overlap between software and hardware firms within the digital agriculture sector, with an emphasis on US firms. In addition to the entrance of new companies, Figure 1 illustrates that digital technologies have increased the complexity of the picture as they combine many elements of software and hardware.

17. Although recent increases in venture capital funding have spurred the creation of several new technology-focused start-ups (Graff, de Figueiredo Silva and Zilberman, 2020<sup>[27]</sup>), it is also the case that several of these have been acquired by traditional input companies (Birner, Daum and Pray, 2021<sup>[8]</sup>; McFadden and Schimmelpfennig, 2019<sup>[26]</sup>). For example, John Deere, a large American corporation that manufactures tractors and other agricultural equipment, acquired Blue River Technology, a start-up with heavy emphasis on robotics, in late 2017 for USD 305 million. More recently, Deere acquired Bear Flag Robotics, a start-up that develops autonomous tractors, for USD 250 million in August 2021 (White, 2021<sup>[28]</sup>).

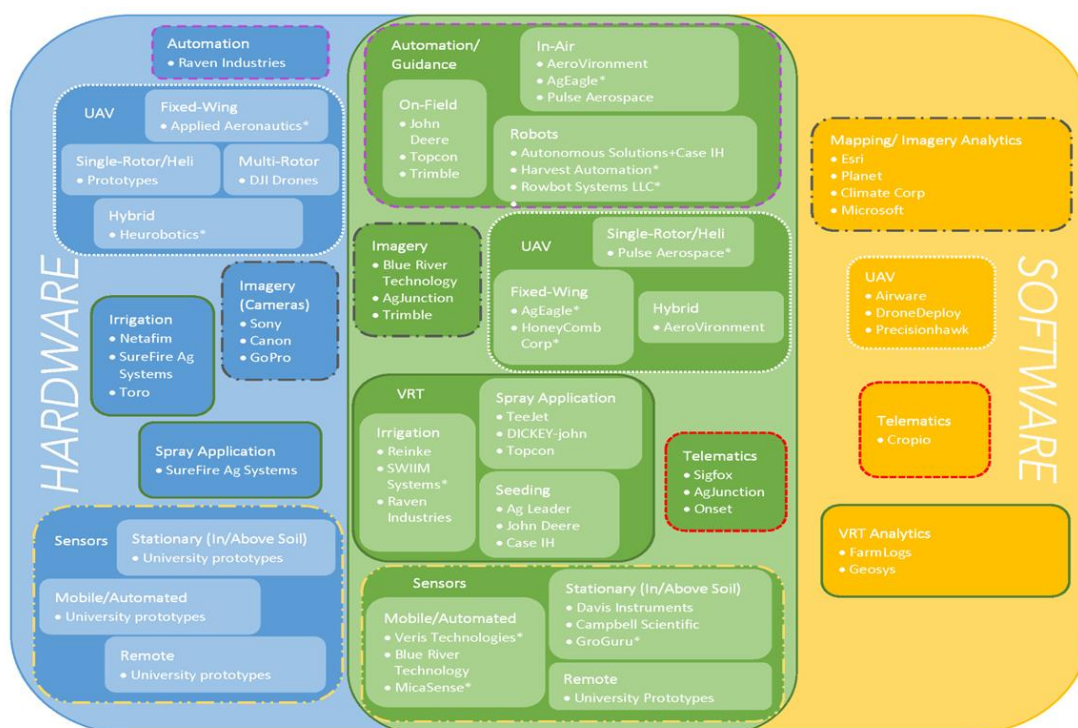
18. In view of the implications for competition, technology pricing, and costs to farmers, it should be noted that technology providers have, in recent years, been made up of newer and smaller firms (e.g. start-ups). As the above example illustrates, technologies brought into development by these firms are, in several instances, acquired by incumbent agricultural companies (McFadden and Schimmelpfennig, 2019<sup>[26]</sup>). This is consistent with a characterisation that a major part of the digital agriculture (technology provision) sector is transitioning from a nascence to growth stage (Klepper, 1996<sup>[29]</sup>), which is consistent with wider technology sector developments. Accompanying this development has been the entry of large technology firms that have not traditionally serviced agricultural markets, such as Microsoft, IBM, and Amazon, focusing mainly on applying predictive analytics to high-dimensional datasets in order to sell new insights.

19. A substantial continuum of **intermediaries** with increasing emphasis on digitalisation sit between farmers and technology providers, each having distinct purposes (for example, university extension and advisory services, independent crop consultants, farmers' co-operatives, input retailers).

20. Of these intermediaries, publicly funded university extension and government advisory agents, as science communicators and farm advisors, are increasingly required to develop expertise in digital technologies as a key instrument in modern farm entrepreneurial management if they are to remain responsive to farmers' needs. There is a similar focus with privately funded intermediaries, including crop consultants and retailers, although these actors are likely to also have the goal of boosting demand for certain products and services – as discussed in more detail in the companion issues note on the role of trust in digital agriculture [TAD/CA/APM/WP(2022)2/FINAL]. Nonetheless, both types increase awareness of digital technologies and, in some cases, could reduce transaction costs associated with adoption (e.g. by helping to flatten otherwise steep “learning curves”

for first-time users of certain disembodied technologies) (BenYishay and Mobarak, 2019<sub>[30]</sub>; Hörner et al., 2019<sub>[31]</sub>)).<sup>5</sup>

**Figure 1. Examples of technology providers and overlap of software and hardware components**



Note: The figure is meant to be illustrative of major providers and technology applications rather than comprehensive. The Climate Corporation, for example, offers services beyond mapping and imagery analytics, including VRT analytics and other decision support tools. Moreover, several unlisted firms exist solely and specifically to import, analyse, and re-sell data.

Source: Authors' elaboration.

### 3. Row crop farming

21. For the purpose of this report, the production of row crops (sometimes referred to as 'broadacre' crops) is the growing of annual grains and cereals, usually at a comparatively large scale, for commercial purposes, i.e. not subsistence production (OECD, 2021<sub>[32]</sub>). Common row crops include barley, corn, cotton, millet, oats, potato, rice, rye, soybeans, sugarcane, and wheat (both winter and spring varieties), among others.

#### 3.1. The status of row crop farming digitalisation

22. A wide range of evidence – of varying scope and quality – underpins current estimates of the scale of digital agriculture adoption in row crop production. Among this multitude of sources, surveys conducted by national governments provide the best evidence

<sup>5</sup> In this sense, digitalisation may be expected to reduce the 'distance' between farmers and input providers, while perhaps improving information transparency throughout the food supply chain. Although interesting, economic questions pertaining to the structure of input markets and distance to farmers are beyond the scope of this review.

because they are generally representative of one or more farming-related populations of interest and are thus generally free of biases that could result from very small or non-random samples. That said, only a few countries provide data that are representative at the national level.

### *Evidence from nationally-representative surveys*

23. Notwithstanding the fact that they provide the most reliable and internally consistent adoption estimates, very few countries carry out national surveys due to the sizeable costs and co-ordination efforts entailed in development and implementation.<sup>6</sup> As a result, robust evidence on digital adoption is only available for a small number of years and countries – generally high- to very-high income countries with relatively large agricultural sectors and advanced infrastructure for carrying out complex surveying tasks.

24. Even then, due to differences in survey design, estimates of adoption rates are reported differently, mostly as either a percentage of farms or as a percentage of arable land (Table 1). Since larger farms tend to adopt technologies at higher rates than smaller farms (MacDonald, Korb and Hoppe, 2013<sub>[33]</sub>; Khanna, 2021<sub>[7]</sub>), and because national agricultural production tends to be concentrated on larger farms in OECD countries, differences in reporting units can lead to significant differences between percentage-of-farm versus percentage-of-area estimates.

25. Against this background, key results emerging from existing national surveys are described below, noting that only partial benchmarking is possible due to differences in reporting units, reported technologies and time coverage (Table 2).<sup>7</sup> A broad overview of results from the academic literature follows for illustrative purposes.

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<sup>6</sup> For some countries, evidence on adoption from studies with small samples is scarce or non-existent. In Germany, for instance, a recent survey of 500 farmers there indicated that roughly 80% of those surveyed use various "smart farming" systems in crop production and/or animal husbandry. The large majority of farmers in that survey consider that digitalisation can substantially contribute to more sustainable agricultural production, including improved animal welfare (Bitkom Research, 2020<sub>[207]</sub>). Concerning developing countries, a review by (Nyaga et al., 2021<sub>[107]</sub>) found that no precision agriculture research had been performed in 21 sub-Saharan African (SSA) countries. Most of the existing SSA-located studies took place in South Africa, Nigeria, and Kenya, with an emphasis on soil and crop mapping and very little research on livestock systems.

<sup>7</sup> Given the survey-driven focus of this report, the digital technologies discussed and reviewed herein necessarily reflect those emphasized by national governments and studied largely by university researchers. As such, the development of a new typology or broader framework for classifying digital technologies is beyond the scope of this review. Nonetheless, regardless of sector (row crops, livestock, or specialty crops), the technologies can be categorized according to their primary function: data collection, decision support, precision equipment, or precision input adjustment. Such categories are neither mutually exclusive nor collectively exhaustive.

**Table 1. Existing national surveys of digital adoption in row crop farming**

Country	Year	Representation	Unit
Australia	2008, 2011, 2014, 2016	Large grain farms	Percent of area
Canada	2006	All farms	Percent of farms
Colombia	2017	Agricultural production units	Percent of units
Denmark	2017-2020	Cultivated crops farms	Percent of farms
United Kingdom (England)	2009, 2012, 2019	All farms, including cereals and other crop farms	Percent of holdings
United States	1996-2007, 2009-13, 2015-19	Various crops: corn, soybeans, wheat, oats, cotton, barley, sorghum, rice, peanuts, and others	Percent of area

Note: For the Australian surveys, to qualify for the 2011 survey, respondents needed to: 1) specialise in grains with a farm size of at least 500 hectares, or 2) specialise in grains and livestock with a farm size of at least 1 000 hectares. Survey eligibility criteria are not reported for 2015 and 2017. Regarding the US data, a small number of additional crops are surveyed in other years, particularly in early years, but estimates are not publicly available due to sample size concerns. Moreover, US adoption rate estimates are available for each of the listed row crops above.

Source: Authors' compilation.

**Table 2. Surveyed digital technologies for row crop farming in different countries**

	Yield Maps	Soil Maps	VRT	GPS and/or Automated Guidance	Telemetry	Controlled Traffic or Tramlines	Satellite or Drone Imagery	Crop Sensors
UK								
AUS								
COL								
DNK								
CAN								
US								

Note: A blue cell indicates the technology was surveyed at least for one year in that country.

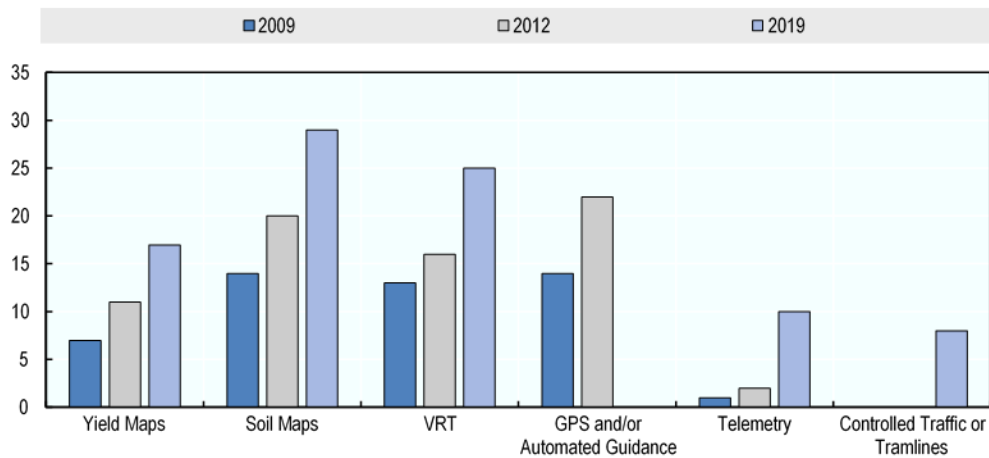
Source: Authors' own compilation.

26. In England, data is available from the Department for Environment, Food and Rural Affairs (DEFRA) (UK), for years 2009, 2012, and 2019 – reported as a percentage of all farms (holdings) (Figure 2 and Figure 3).<sup>8</sup> Across these three years, the proportion of farms relying on yield maps increased from 7% to 17%; use of soil maps increased from 14% to 29%; use of variable rate technologies (VRT) increased from 13% to 25%; and use of telemetry (remote sensing) increased from 1% to 10%. Between 2009 and 2012, use of global positioning systems (GPS) increased from 14% to 22% of farms, while controlled traffic farming stood at 8% in 2019 (DEFRA, 2013<sub>[34]</sub>; DEFRA, 2020<sub>[35]</sub>).<sup>9</sup> Across all farms and technology categories, adoption increased by 6-9 percentage points from 2012 to 2019. Substantial geographic differences also exist, with adoption being generally highest in the east of England region (DEFRA, 2013<sub>[34]</sub>; DEFRA, 2020<sub>[35]</sub>).

27. As the data in Figure 2 relate to all English farms, it is likely that it understates adoption for row crops specifically, since the literature tends to show lower rates of adoption for non-row crops. This hypothesis is reinforced by the relatively higher rates of adoption in cereals farm for which disaggregated data is available for 2019.

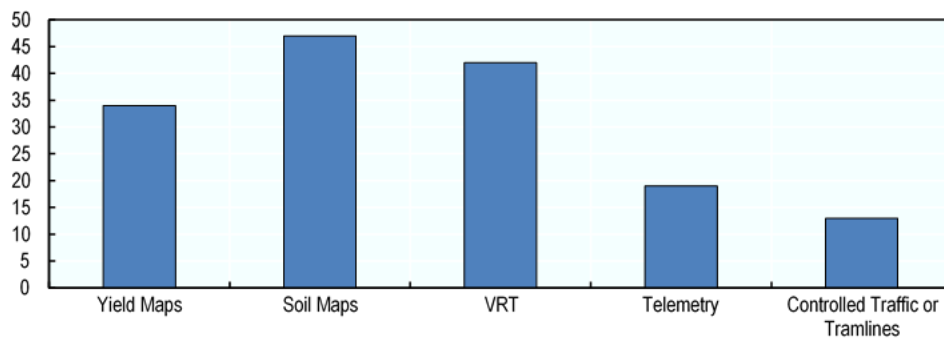
<sup>8</sup> In addition, note that data are only relevant for England, and did not include Scotland, Wales, and Northern Ireland.

<sup>9</sup> DEFRA did not survey farmers about GPS use in 2019 nor were farmers surveyed about controlled traffic farming in 2009 and 2012.

**Figure 2. Adoption of digital tools in England for all farms (% of holdings)**

Source: (DEFRA, 2013<sup>[34]</sup>); (DEFRA, 2020<sup>[35]</sup>); authors' own compilation.

28. Indeed, data are available for specific crops in 2019, and confirm that adoption in England has been highest on farms specialising in cereals and other crops, relative to those specialising in livestock or mixed systems, largely a reflection of the fact that digital tools are most established for row crop production – and with a greater variety of applications. Roughly 47%, 34%, and 42% of all cereal crop farms used soil maps, yield maps, and VRT in 2019, respectively, while the proportion of cereal farms using telemetry and controlled traffic farming was at 19% and 13% (Figure 3).

**Figure 3. Adoption of digital tools for cereal farms in England in 2019 (% of holdings)**

Note: No data are available for GPS and/or Automated Guidance.

Source: (DEFRA, 2020<sup>[35]</sup>), authors' own compilation.

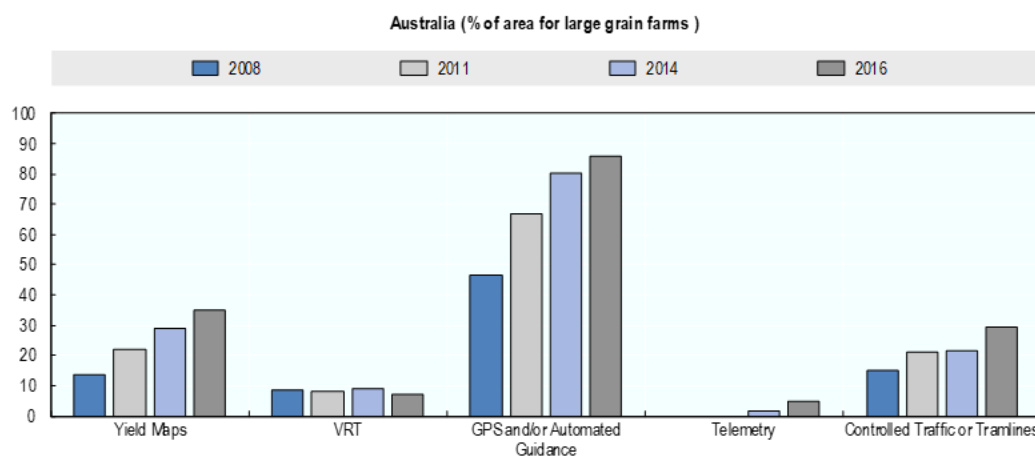
29. In **Australia**, the Grains Research and Development Corporation (GRDC)<sup>10</sup> conducted large-scale surveys of farms specialising in grains (wheat, coarse grains, pulses, and oilseeds) or mixed grain/livestock systems for years 2008, 2011, 2014, and 2016 (Figure 4) (GRDC, 2012<sup>[36]</sup>; GRDC, 2017<sup>[37]</sup>). Data overstate adoption because only large farms were surveyed.

30. GRDC surveys provide digital adoption estimates as a proportion of area and report that use of yield maps increased from 13.5% to 34.9% of surveyed farms between 2008

<sup>10</sup> The GRDC is a corporate Commonwealth entity that invests in research, development, and extension projects to benefit the Australian grains sector.

and 2016, and use of automated guidance (“autosteer”) increased from 46.7% to 86%. VRT usage was flat over this timeframe, at 7.0-8.7%, while usage of controlled traffic farming increased from 15.1% to 29.3%. Adoption of telemetry (remote sensing using the normalised difference vegetation index (NDVI) or electromagnetic sensing) has been low but increasing – from 1.8% in 2014 to 5.1% in 2016. Substantial regional heterogeneity in uptake was also observed.

**Figure 4. Adoption of digital technologies on Australian large grain farms (% of area)**



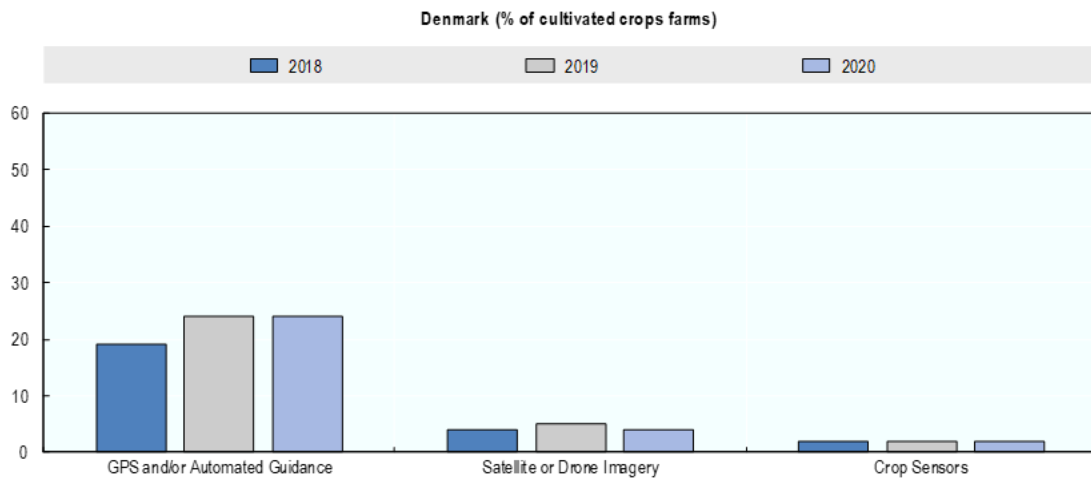
Note: Surveys of large farms will tend to overestimate actual rates of adoption. They include both grain and mixed grain/livestock farms.

Source: (GRDC, 2017<sup>[37]</sup>). Authors’ own elaboration.

31. In **Denmark**, Statistics Denmark has carried out large surveys of precision agriculture use since 2017. Although data are not reported by type of farm, the available estimates generally pertain to row crop production (e.g. wheat, barley, rye, oats, and others) as these crops account for well over 50% of Denmark’s agricultural area (Statistics Denmark, 2019<sup>[38]</sup>).

32. Automated guidance using highly precise (real-time kinematics) GPS technologies was used on 16% of cultivated crop farms in 2017, rising to 19% in 2018 and to 24% in 2019 and 2020. Over this same time period, 3-5% of cultivated farms made use of photos from satellites or drones. During 2018 and 2019, 14% of farms used section control of injectors (i.e. automatic section control), which increased to 21% in 2020, while only 2% of farms made use of crop sensors on tractors or other machines (Statistics Denmark, 2020<sup>[39]</sup>) (Figure 5).

33. Reasons why crop sensor adoption is low may be gleaned from the **French** literature, which indicates a reluctance with this type of digital application related to the complexity of the technology (both for collection and transfer of data), reliability of sensor data, lack of direct relevance, and lack of visible profitability (Lachia et al., 2021<sup>[40]</sup>). All these factors may be caused by – or may further exacerbate – the digital divide.

**Figure 5. Adoption of digital technologies on Danish farms (% of farms)**

Source: (Statistics Denmark, 2018<sup>[41]</sup>; 2019<sup>[38]</sup>; 2020<sup>[39]</sup>). Author's own elaboration.

34. In **Canada**, a survey of nearly 14 000 farmers conducted by Agriculture and Agri-Food Canada in 2006 found that 23.2% of farms made use of GPS or related digital products in their operations (AAFC, 2006<sup>[42]</sup>). Of the farms making use of such technologies, nearly 78% indicated they used GPS for tracking or guidance systems to eliminate overlaps or to avoid other issues in field operations, while 32% of adopters used GPS to collect information for soil and crop management.

35. The longest running, nationally representative survey of farmers' digital agriculture use appears to be conducted by the **United States** Department of Agriculture (USDA) (Figure 6). Beginning in 1996, USDA's Agricultural Resource Management Survey has collected data on farmers' use of precision agriculture technologies on one randomly selected row crop field from the farmer's operation. Roughly 2 000-3 000 farmers are surveyed each year, although annual estimates are only available for 1-3 distinct row crops, which tend to be surveyed on a rotating basis every 4-5 years. There are 49 crop-year combinations of national estimates for years 1996-2019 (USDA-ERS, 2021<sup>[43]</sup>).

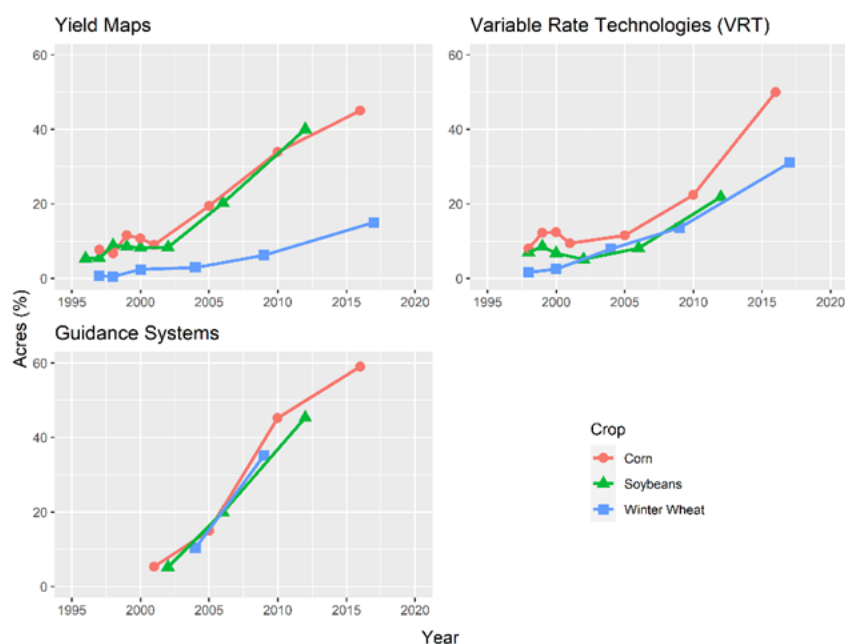
36. Broadly, the dynamics underlying US adoption estimates are similar to those of the other surveyed countries, although the US data very clearly show how magnitudes of adoption vary by technology and crop type (Figure 6). Adoption for each technology and all surveyed crops was generally below 25% of planted hectares prior to 2000, when many of these technologies were still relatively new. Subsequently, adoption has grown substantially for yield monitors across most row crops, largely because they have become "standard" components in new agricultural equipment for sale (Schimmelpfennig, 2016<sup>[4]</sup>).

37. The growth trend for yield maps and soil maps is similar, although less pronounced, while VRT use – as with nearly all other countries reviewed – remains sluggish. Automated guidance is becoming amongst the most widely used digital technology in US row crop production; at least 20% of planted hectares for each surveyed crop since 2006 (soybeans, cotton, wheat, corn, barley, sorghum, rice, and peanuts) have been managed with automated guidance (USDA-ERS, 2021<sup>[43]</sup>).

38. The most recent publicly available estimates suggest that yield monitors were used on 68% of corn hectares in 2016, while yield maps and soil maps were used on 45% and 22% of hectares, respectively. VRT use achieved a high of 50% in 2016, with automated guidance used on 59% of hectares. Although adoption of certain tools was lower for winter

wheat varieties in 2017 (yield maps: 15%, soil maps: 4%, VRT: 31%), automated guidance was similarly high at 61%. As with all other countries with reliable national estimates, telemetry use is low: 8% of corn hectares in 2016 and 1% of winter wheat hectares in 2017 (Lowenberg-DeBoer and Erickson, 2019<sup>[44]</sup>; Schimmelpfennig and Lowenberg-DeBoer, 2020<sup>[45]</sup>).

**Figure 6. Adoption rates of precision technologies for major row crops in the United States, 1996-2017 (% of area)**

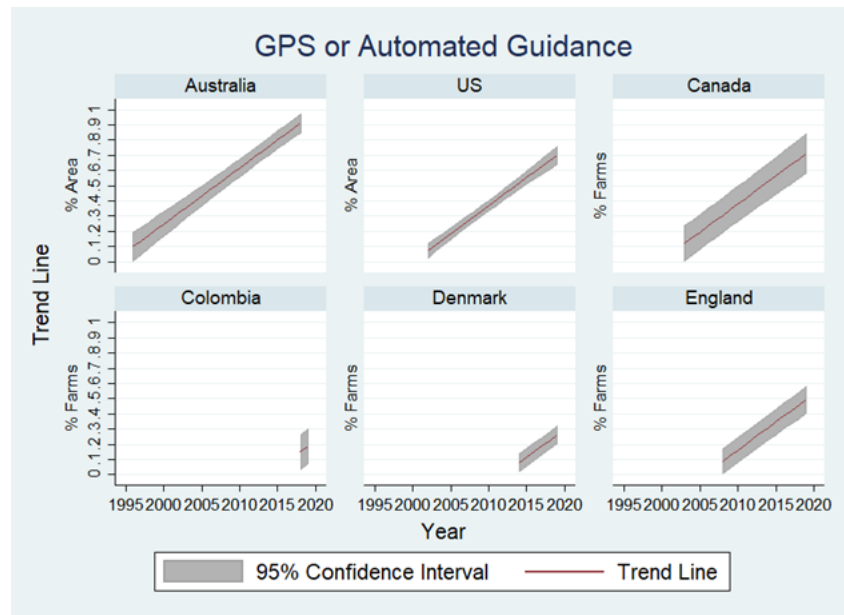


Note: The estimates for year 2016 are from (Lowenberg-DeBoer and Erickson, 2019<sup>[44]</sup>; Schimmelpfennig and Lowenberg-DeBoer, 2020<sup>[45]</sup>) using data from USDA-ERS. The estimates for year 2017 are from (Schimmelpfennig and Lowenberg-DeBoer, 2020<sup>[45]</sup>) which again uses data from USDA-ERS.

Source: (USDA-ERS, 2021<sup>[43]</sup>), “Tailored Reports: Crop Production Practices” database, (Lowenberg-DeBoer and Erickson, 2019<sup>[44]</sup>; Schimmelpfennig and Lowenberg-DeBoer, 2020<sup>[45]</sup>).

39. Finally, upward trends exist for the six countries considered here for which reliable data are available, but levels and rates of growth are not uniform – nor perfectly comparable. Nevertheless, although results are varied and difficult to compare or generalise, a key point that emerges from all types of literature is that even among large farms, which tend to have the greatest incentives to use these technologies (and hence adopt at the highest rates), adoption is far from universal. Even among row crops, differences remain in adoption rates, depending on a combination of specific commodity, technology and country context (Figure 7).

Figure 7. Multi-country trends in the adoption of GPS or Automated Guidance



Note: For the Australian surveys, to qualify for the 2011 survey, respondents needed to: 1) specialise in grains with a farm size of at least 500 hectares, or 2) specialise in grains and livestock with a farm size of at least 1 000 hectares. Survey eligibility criteria are not reported in (GRDC, 2012<sub>[36]</sub>; GRDC, 2017<sub>[37]</sub>). The “GPS and/or automated guidance” column refers only to automated steering. For 2008 and 2011, the survey refers to “controlled traffic or tramlines” as “controlled traffic/tramlines”, with no specific mention of “tramline” for the 2014 and 2016 surveys. VRT use in 2016 is an average of VR seeding and VR fertiliser. Telemetry refers only to use of EM38 or NDVI. For Canada, GPS use refers to use of GPS equipment or products. In the survey of Colombian farmers reported by (DNP, 2021<sub>[46]</sub>), the “GPS and/or automated guidance” column refers only to GPS, “Satellite or drone imagery” refers only to drones, and “Crop sensors” are reported as sensors. In the Danish survey, the “GPS and/or automated guidance” column refers only to high-precision steering with real time kinematic GPS. In the English survey, the “GPS and/or automated guidance” column refers only to GPS, and “controlled traffic or tramlines” are referenced only as “controlled traffic.”

Source: Authors’ own elaboration.

### *Evidence from the academic literature*

40. Alongside more robust national surveys, a large academic literature has sprung up since the 1990s examining determinants and adoption trends in precision farming technologies, as reviewed in (Griffin and Lowenberg-DeBoer, 2005<sub>[47]</sub>; Say et al., 2018<sub>[48]</sub>; Lowenberg-DeBoer and Erickson, 2019<sub>[44]</sub>).

41. In the academic literature, studies of adoption and related economic issues have been performed for the majority of OECD countries. In addition to the studies mentioned above, publications exist for France (Ayerdi Gotor et al., 2020<sub>[49]</sub>), Hungary (Ayerdi Gotor et al., 2020<sub>[49]</sub>), Germany (Reichardt et al., 2009<sub>[50]</sub>; Paustian and Theuvsen, 2017<sub>[51]</sub>), Greece (Kountios et al., 2018<sub>[52]</sub>) and Sweden (Lindblom et al., 2017<sub>[53]</sub>) – among others. However, this literature is not thoroughly examined in this report, given the small sample of farmers considered or other methodological issues encountered. Nevertheless, a few illustrative results are reported below.

42. For example, among some of the most recent studies of this type, (Motsch et al., 2021<sub>[54]</sub>) found from a sample of 1 000 **Austrian** farms in 2020 that one-third of respondents used automated steering, while only 15% used satellite-guided section control. In **Switzerland**, 16% of surveyed arable crop farmers in 2018 used automated steering systems, 5% used yield recording systems, and 3% used automatic data collection; use of

these same technologies was lower for fodder crop farmers (Groher et al., 2020<sup>[55]</sup>). In **France**, 2017 data from the Observatory of Digital Agriculture suggested that more than two-thirds of grain farms used remote sensing for fertilisation, seeding, or pesticide treatments, based mainly on satellite and drone imagery (Nguyen, Brailly and Purseigle, 2019<sup>[56]</sup>).

43. In a similar vein, a study of adoption determinants by (Michels et al., 2021<sup>[57]</sup>) relied on a sample of 167 **German** farmers in 2019, 22% of whom make use of drones in their operations. In contrast, a sample of 1 000 irrigated farms in the southern Murray-Darling Basin of **Australia** for the years 2015-16 revealed that only 4-8% made use of drones, although as many as one-third of respondents stated that they planned to use drones by 2020-21 (Zuo, Wheeler and Sun, 2021<sup>[58]</sup>). This is broadly consistent with data from the **United States**. Survey evidence from 809 farmers in 2018 in the state of Missouri indicated that only 8% had adopted drones (Skevas and Kalaitzandonakes, 2020<sup>[59]</sup>), which is consistent with findings that fewer than 3% of US cropland acres planted to corn in 2016 were managed with drones (Schimmelpfennig and Lowenberg-DeBoer, 2020<sup>[60]</sup>).

44. Along similar lines, **Colombia** has no national data on specific precision farming adoption, although the most recent national survey of 2017 indicates that 5.2% of agricultural production units applied innovation practices in their production, marketing, or administrative processes. More directly, based on a sample of primarily 2 400 farmers, it is estimated that a little over 11% of Colombian crop farmers used satellite services and GPS, while 1% or fewer used drones, sensors, or automated systems (DNP, 2021<sup>[46]</sup>).

45. Similarly, a survey of the sugar-ethanol industry for 2008 in the São Paulo state of **Brazil**, which produces 60% of Brazil's sugarcane, revealed high adoption rates for satellite images (76%), with lower adoption of VRT (29%) and automated steering (20%) (Silva, de Moraes and Molin, 2011<sup>[61]</sup>).

### 3.2. Digitalisation and productivity, sustainability, and resilience goals for row crop farming

46. In most countries, row crop production systems are facing pressures from increasing and aging populations, dietary transitions, environmental pressures and climate change, triggering considerable investigation into the role of technological improvements (Springmann et al., 2018<sup>[62]</sup>) – and particularly digital agriculture innovations (FAO, 2020<sup>[63]</sup>; Basso and Antle, 2020<sup>[64]</sup>) – as partial solutions.

47. The extent to which row crop agriculture will surmount these challenges will depend on the relative benefits and costs of the digital tools and other technologies and practices, as reflected in the adoption rates discussed in the previous subsection, and as influenced by enablers and constraints detailed below. In turn, the relative benefits of these technologies can be assessed by examining their efficacy for meeting productivity, sustainability, and resilience goals. In row crop production, contributions to these objectives vary by technology, although common lines of inquiry and themes emerge from the literature.

48. Disentangling the impact of the adoption of digital technologies from other factors and on-farm practices is a difficult task. Several indicators related to productivity, sustainability and resilience are reviewed in this section, such as profitability, yields, productivity of other inputs, input use efficiency, nitrogen fertiliser application and adoption of best management practices. In the literature, there are several estimates of the different level of these indicators among digital adopters compared to non-adopters. However, while useful, these estimates only depict a correlation – not a cause-and-effect

relationship – between digital agriculture and yield increases or other benefits since potentially confounding effects (e.g. farm size, human capital, farmers’ preferences for digital technologies, etc.) are not considered, nor corrected for.

### *Productivity*

49. **Profitability** has been amongst the most widely studied dimensions of digital agriculture for row crops (Swinton and Lowenberg-DeBoer, 1998<sub>[65]</sub>; Griffin, Lambert and Lowenberg-DeBoer, 2005<sub>[66]</sub>; Schimmelpfennig, 2016<sub>[4]</sub>; Bullock, Mieno and Hwang, 2020<sub>[67]</sub>; Schimmelpfennig and Ebel, 2016<sub>[24]</sub>).<sup>11</sup>

50. Several economic analyses of commercial grain farms show positive – but small and varying – effects of digital tools on profitability.<sup>12</sup> For example, in a study representative of US corn fields in 2010, (Schimmelpfennig, 2016<sub>[4]</sub>) found that GPS mapping had the largest effect on increasing operating profitability (by nearly 3%), while VRT had the smallest effect (1.1%). From these estimates, it is difficult to differentiate the effect of digital tools on revenues (e.g. productivity) from costs, but they provide at least partial, indirect evidence of productivity enhancements.

51. More directly, (Schimmelpfennig and Ebel, 2011<sub>[18]</sub>) found evidence of a relationship between digital agriculture adoption and **yields** in US row crops. In 2001, adopters of yield monitors on corn farms had 10% higher yields than non-adopters, increasing to a 23% advantage in 2005. Similar corn yield advantages for adopters relative to non-adopters were found for GPS mapping and VRT (for fertiliser) over this timeframe, although the differential was smaller on soybean fields. This is consistent with US row crop farmers’ stated motivation for use of these technologies (Thompson et al., 2019<sub>[68]</sub>).<sup>13</sup>

52. Lio and Liu (2006<sub>[69]</sub>), using data averaged between 1995 and 2000 for 81 countries, also found a positive relationship between agricultural output (as measured by value-added in agriculture in USD) and an information and communication technology (ICT) index.<sup>14</sup> In particular, they estimated that a 10% increase in the ICT index boosts agricultural productivity by 2.1%, on average, with somewhat larger effects for high- and higher-middle income countries and smaller effects for low- and lower-middle income countries. The authors suggest their results are consistent with the notion that farmers benefit from ICT by: 1) gaining market information that improves their bargaining power,

<sup>11</sup> Likewise, profitability of digital tools has been a major focal point, if not the most frequently-researched issue, in the literature on precision livestock farming and digital technologies in specialty crops production, addressed below.

<sup>12</sup> Simulation methods, including mathematical programming models and partial budget approaches, have been used to evaluate the row crop profitability of VRT (Thrikawala et al., 1999<sub>[191]</sub>) or (Bullock, Mieno and Hwang, 2020<sub>[67]</sub>), automated guidance (Griffin, Lambert and Lowenberg-DeBoer, 2005<sub>[66]</sub>), controlled traffic farming (Jensen et al., 2012<sub>[192]</sub>), and autonomous equipment (Shockley, Dillon and Shearer, 2019<sub>[193]</sub>), to name very few. Other studies of profitability have relied on controlled agronomic field trials (Yost et al., 2019<sub>[206]</sub>). Qualitatively, findings from these studies generally agree with the results discussed above for commercial corn farms using survey data, although the exact estimates differ by study. Assessing the scope and causes of these differences is beyond the scope of this review, although it is expected that estimated profitability from simulation studies and controlled agronomic trials would be higher than estimates from studies using large-sample data from commercial farms as such farms do not typically experience ideal or tightly-controlled growing conditions.

<sup>13</sup> Along similar lines, 77% of English cereals farms that used precision farming tools in 2019 did so to increase their farm’s productivity or performance, with 81% stating their use was motivated by improving accuracy (DEFRA, 2020<sub>[35]</sub>).

<sup>14</sup> The ICT index incorporated data on internet, personal computer, cellular telephone, and landline/mainline telephone use.

and/or 2) leading to more specialised labour and intermediate goods. The smaller effects of ICT on agricultural productivity in lower-income countries could be due to lower levels of complementary inputs (e.g. infrastructure, human capital).

53. In related work, Fabregas, Kremer and Schilbach (2019<sup>[70]</sup>) found that uptake of agricultural information through mobile phones increased yields by 4% in India and sub-Saharan Africa and significantly increased the odds that farmers would adopt recommended agrochemical inputs.

54. For US peanut farms in 2013, Saavoss (2018<sup>[71]</sup>) estimated that automated guidance systems increase yields by 9% and that soil maps increase yields by 15%, whereas VRT had no significant effect on productivity. Saavoss hypothesised the yield effect of soil mapping could be driven by identification of field areas with problematic drainage or through changes to other inputs as a result of obtaining spatially varying soils information.

55. Similarly, McFadden, Rosburg and Njuki (2021<sup>[23]</sup>) documented that corn output per area on Midwestern US fields in 2010 and 2016 increased by 5.6% or 11.9%, depending on the model, from adoption of yield maps or soil maps. They also found that, on average, yield maps and soil maps increased efficiency (i.e. output per unit of input) by 8.5% and 7.2%, respectively.

56. While McFadden, Rosburg and Njuki (2021<sup>[23]</sup>) did not find evidence to support the claim that digital technologies like maps increase the **productivity of other inputs**, related work has demonstrated such a link. For example, Isik and Khanna (2002<sup>[72]</sup>) examined the impacts on yield per unit of nitrogen from soil testing and VRT nitrogen applications among Midwestern US grain farms. It was found that nitrogen productivity gains from adoption of both technologies was 33% on fields with below-average soil quality and 18% on fields with above-average soil quality, whereas soil testing alone improved nitrogen productivity by 6% to 7%. Similarly, wireless technologies may be improving irrigation water productivity in US agriculture (Sunding, Rogers and Bazelon, 2016<sup>[73]</sup>).

### *Sustainability*

57. There are multiple ways in which digital technologies are held to improve the environmental sustainability of row crop farming. Khanna and Zilberman (1997<sup>[74]</sup>) note greater **input use efficiency** as one such pathway. Lower rates – and more appropriate timing and location – of fertiliser and chemical applications per hectare can also reduce runoff and leaching, thus improving the quality of water for subsequent human, agricultural, or ecosystem purposes. In aggregate, substantial decreases in applications of agrochemicals could perhaps slow the onset of pesticide resistance (Bongiovanni and Lowenberg-Deboer, 2004<sup>[75]</sup>), and reduce greenhouse gas (GHG) emissions from the manufacturers upstream that produce agrochemicals. Employment of automated guidance or controlled traffic farming can also reduce on-farm fuel use – and thus GHG emissions – and lessen soil compaction and erosion. Moreover, mapping technologies can be used to locate field drainage issues, which when addressed, can prevent the potential for over-watering of row crops.

58. The nationally representative survey data that are available also suggest that farmers are using digital tools for **sustainability purposes**. In the United Kingdom, the proportion of adopting farmers that reported to use precision agriculture to improve soil conditions was 55% in 2009 and 48% in 2012, with 17% of adopters in 2012 motivated by reducing GHG emissions. Among English cereals farms in 2019, 66% of adopters used these technologies to improve soil conditions and 60% used them to reduce environmental impacts like soil loss and emissions (DEFRA, 2013<sup>[34]</sup>; 2020<sup>[35]</sup>).

59. Danish farmers of cultivated crops used photos from satellites or drones for environmental purposes during 2018-20. For example, 36% of adopters in 2018 used the information for variable rate fertiliser applications, while 30% of adopters were motivated by drainage planning. As a fraction of all Danish cultivated farms in 2018-20, roughly 1-2% used photos to inform variable rate applications of fertiliser, pesticides, or seed, and 1% used photos for drainage planning (Statistics Denmark, 2018<sub>[41]</sub>; 2020<sub>[39]</sub>).

60. In the United States, row crops for 2002-2005, monitoring crop moisture was the most prevalent reason for using yield monitors, although the share of adopters who used the technology for drainage purposes was on par with those of Denmark (Griffin, 2010<sub>[76]</sub>).

61. However, the evidence from commercial row crop farms on the links between **sustainability** and digital agriculture, although still limited to date, has been mixed (Finger et al., 2019<sub>[77]</sub>).<sup>15</sup> In principle, sustainability effects depend on the particular technology, effectiveness of the technology, and location-specific aspects (e.g. soil quality, soil moisture, topography, climate) of the farmer's field (Khanna, 2021<sub>[71]</sub>). More specifically, many of these tools can lead to decreased or even increased input use – and therefore pollution – depending on how the tools increase the efficacy of other inputs and the effect of altered input use on yields (Isik, Khanna and Winter-Nelson, 2001<sub>[78]</sub>).

62. Some impacts on sustainability can be inferred from **input costs**. Schimmelpfennig and Ebel (2016<sub>[24]</sub>) found significantly lower fuel costs on US corn and soybean farms for adopters of yield monitors relative to non-adopters in the early-to-mid 2000s. Although there were few significant differences in fertiliser costs, custom services costs were generally higher for adopters than non-adopters. There are similarly mixed results among cost categories for adopters and non-adopters of VRT fertilisation. For 2010 US corn farms, total costs of fertilisers, pesticides, seed, and fuel were generally lower for adopters than non-adopters across technologies, save for GPS, VRT, and combinations of yield monitors and GPS (Schimmelpfennig, 2016<sub>[41]</sub>). Similarly, (Saavoss, 2018<sub>[71]</sub>) found that use of automated guidance on US peanut farms significantly reduced fertiliser and fuel costs by 15% (each), although soil maps nor VRT had significant effects on fuel, chemical, or fertiliser costs.

63. Among mid-western US corn farms in 2010 and 2016, **nitrogen fertiliser application** rates were higher on fields with yields and soils that had been mapped using GPS technologies than on unmapped fields (McFadden, Rosburg and Njuki, 2021<sub>[23]</sub>). However, the relationship between information technologies and fertiliser application rates could depend on crop rotations. For US corn farms in 2001, 2005, and 2010, (Sung and Miranowski, 2016<sub>[79]</sub>) found that joint adopters of soil nitrate testing and crop rotations had significantly lower fertiliser application rates than those adopting only crop rotations, whereas such testing had no effect on application rates among farmers who grew corn each season.

64. Certain aggregate estimates of improved sustainability effects are large. For instance, (Basso and Antle, 2020<sub>[64]</sub>) reported that if nitrogen fertiliser applications were based on use of yield stability maps, total nitrogen use in the mid-western United States could decline by as much as 36%. Net energy savings and GHG emissions reductions from unused fertiliser were also found to be substantial. Another estimate suggested that even a

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<sup>15</sup> The majority of studies examining the relationships between digital agriculture and various aspects of sustainability in row crops has entailed simulation methods (Shockley, Dillon and Stombaugh, 2011<sub>[84]</sub>; Schieffer and Dillon, 2015<sub>[194]</sub>), despite calls from the international precision agriculture research community for greater public-private co-operation and data accessibility (Yost et al., 2018<sub>[203]</sub>). A detailed review of such studies is Balafoutis et al. (2017<sub>[195]</sub>). As above, emphasis is on evidence from large and/or nationally representative samples of commercial row crop farms.

10% increase in total US cropland acres managed with automated guidance could reduce annual fuel and herbicide use by many millions of litres (USDA-NRCS, 2006<sup>[80]</sup>).

65. In related work, (Schimmelpfennig, 2018<sup>[81]</sup>) uncovered significant correlations between adoption of various digital tools in US soybean production and five groups of sustainability-related “**best management practices**” (BMPs): soil care, nutrient control, field condition monitoring, inter-seasonal field operations planning, and written long-term planning. Although the framework considered how digital tools and sustainable BMPs jointly affected farms’ operating costs and profits, it is hypothesised that information from mapping, combined with the embodied precision technologies, could make it easier for farmers to adopt sustainability related BMPs. Similar results were also found for US rice farms (Schimmelpfennig, 2019<sup>[82]</sup>).

### *Resilience*

66. While a large body of work exists on productivity and environmental effects, much less is known about the risk management and resilience implications of digital technologies.<sup>16</sup> Khanna (2021<sup>[7]</sup>) noted that several technologies exist to reduce major sources of uncertainty, including variation in soil conditions and topography and weather risk. For instance, an early study focusing on corn in the state of Iowa in the United States found that use of late-spring soil nitrate testing – an information technology that reduces uncertainty about a crop’s nutrient needs – led to reductions in average fertiliser applications by as much as 38% (Babcock and Blackmer, 1992<sup>[83]</sup>). Non-adopters of this technology may find it profitable to reduce the chance of nutrient deficiencies later in the growing season, thus leading to great fertiliser application rates.

67. Likewise, McFadden, Rosburg and Njuki (2021<sup>[23]</sup>) found that variability in US corn yields due to inefficient production practices could be reduced through use of yield and/or soil maps. Average effects of these technologies on yield variability were on par with those found for human capital and crop insurance use. Moreover, use of traditional risk management tools, specifically crop insurance, was much higher on mapped fields than unmapped fields. Risk reductions have also been demonstrated for more complex, embodied technologies. For instance, automated guidance on US grain farms was found to be useful for managing production risk, although decreased risk was primarily due to adjustments in other production practices (Shockley, Dillon and Stombaugh, 2011<sup>[84]</sup>).

68. Underlying many digital tools, and especially decision support software (DSS), are massive amounts of agricultural production and environmental data that have been combined with other data, analysed – typically with machine learning methods – and then aggregated to generate actionable insights for farmers and farm managers (Coble et al., 2019<sup>[85]</sup>). Of unique relevance to farmers are weather and climate data to help limit production risk due to negative weather shocks (i.e. droughts, flooding, hail), seasonal or subseasonal forecasts for mitigating price risk, and “recombinant” data consisting of, for example, private farm structure information merged with public soil quality indicators (Coble et al., 2019<sup>[85]</sup>). More broadly, this data and its analysis is also likely to contribute to greater risk awareness and preparedness among farmers, which in turn can stimulate uptake of market-based risk management products and motivate mitigation and adaptation investments on- and off- farm. Consistent with the characterisation above, the impacts of digital technologies on risk management and resilience as a whole, are not fully understood,

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<sup>16</sup> Risk is defined to be the economically relevant implications of uncertainty (Moschini and Hennessy, 1999<sup>[196]</sup>). For purposes of this report, emphasis is placed on physical production risk resulting from uncertainty and variability in yields, rather than price uncertainty (Isik, Khanna and Winter-Nelson, 2001<sup>[78]</sup>) or farmers’ use of crop insurance to offset financial risk (McFadden and Hoppe, 2017<sup>[204]</sup>).

necessitating construction of more accurate and relevant agricultural data (Carletto, 2021<sup>[86]</sup>).

69. Digital technologies such as satellite and sensor data cannot only improve knowledge and reduce uncertainties, but also decrease information asymmetries that prevent insurance solutions to emerge due to moral hazard and adverse selection.

70. Digitalisation may also contribute to the development of new forms of index insurance – risk management tools that base indemnity payments on straightforward, area-wide indexes (e.g. rainfall, average yields). Technological advances in remote sensing and other means of geo-referencing are expected to increase the accuracy of the indices underlying these insurance products, reducing the basis risk and, thus, spurring greater uptake, primarily in developing countries.

### 3.3. Evidence on drivers, enablers and constraints to digitalisation of row crop farming

71. Although the empirical findings on enablers and constraints to digital adoption are not uniform across studies, there is substantial coincidence of results across the literature, and the results are consistent with economic principles. In particular, results suggest that farmers make technology adoption decisions based on decision-making criteria, technology characteristics, farm-level heterogeneity, behavioural preferences, and availability of complementary technologies (Khanna, 2021<sup>[7]</sup>). These elements can also explain the significant regional heterogeneity in uptake that has been observed in studies reported above.

72. Much of the economics literature on digital agriculture – and notably studies drawing on data from large samples of commercial farmers, such as many reviewed above – have pinpointed specific determinants of adoption, with much less formal analysis of large-scale constraints to adoption, such as those considered holistically, i.e. the digital divide.

73. As a result, there is relatively well-established evidence among high-income countries about the field, farm, and farmer characteristics that contribute to adoption, based on multiple large-scale studies. These consistently suggest that determined characteristics in sub-field variability in soil quality, topography, farm size, farm ownership structure, and the operator's age, human capital level (i.e. education, experience, digital literacy), risk preferences, and technology preferences are linked with digital adoption (Daberkow and McBride, 2003<sup>[17]</sup>; Schimmelpfennig and Ebel, 2011<sup>[18]</sup>; Tey and Brindal, 2012<sup>[19]</sup>; Schimmelpfennig, 2016<sup>[21]</sup>; Griffin, Shockley and Mark, 2018<sup>[22]</sup>; McFadden, Rosburg and Njuki, 2021<sup>[23]</sup>; Schimmelpfennig and Ebel, 2016<sup>[24]</sup>).

74. Among these, a strong relationship between **greater farm size** and adoption is observed because of high correlations between farm size and other relevant farm characteristics. In particular, larger farm areas tend to adopt digital technologies because greater size entails (MacDonald, Korb and Hoppe, 2013<sup>[33]</sup>; Khanna, 2021<sup>[7]</sup>): 1) reduced risk aversion, 2) lower per-unit costs of inputs (made possible by spreading out high fixed equipment costs over large areas, in conjunction with potential pecuniary externalities, such as quantity discounts for inputs, that can directly reduce variable costs), 3) greater soil variability by virtue of the fact that soil quality is generally more similar over smaller areas, 4) operations with greater access to credit that is needed to finance the purchase of sophisticated, expensive equipment, and 5) operations with a larger number of managers, permitting the kind of specialisation of managerial labour that could lead to greater awareness of (and expertise in using) digital technologies.

### *Barriers and constraints*

75. At the same time, nationally representative farm survey data has uncovered some notable barriers that constrain row crop farmers' adoption of digital technologies. Other information in this respect can also be indirectly derived from service providers' surveys, as described below.

76. In the United Kingdom, row crop farmers in 2019 identified a number of reasons for not using precision farming techniques, including that they are too expensive or not cost effective (63% of all cereals farms), not relevant for the operation (47%), too complicated to use (18%), or not accurate enough (5%) (DEFRA, 2020<sup>[35]</sup>). Responses from the 2012 survey of English farmers were similar, although 28% of all holdings noted that these technologies were not suitable or appropriate for the type or size of farm (DEFRA, 2013<sup>[34]</sup>).

77. In the 2018 and 2020 Danish surveys of cultivated farms, the largest barrier to adoption was expense: 50% of farms in 2018 and 55% of farms in 2020 cited large costs as a reason for not using precision technology. Other reasons included insufficient variability in conditions across the field (23% in 2018, 40% in 2020), missing competencies and knowledge (18% in 2018, 26% in 2020), and difficulty in getting the technology to work (34% in 2018, 13% in 2020) (Statistics Denmark, 2018<sup>[41]</sup>; Statistics Denmark, 2020<sup>[39]</sup>).

78. It must be noted that non-adopting farmers who indicated that the technologies were "too complicated to use" or that they were "missing competencies and knowledge" provides direct evidence on the digital divide. There are numerous reasons underlying the reality that some farmers will not stand to benefit from agricultural digitalisation, including a lack of broadband connectivity and access to credit financing of costly digitally enabled equipment, among other reasons. Such barriers point to the importance of eroding the digital divide through increases in farmers' human capital and access to technology.

79. Similar barriers also exist in developing countries, although infrastructure (both analog and digital) remain significant challenges. In Africa, many farmers are unwilling or unable to pay for tools such as advisory messages, thus necessitating reliance on donor-provided funding (CTA, 2021<sup>[87]</sup>) that may or may not be viable in the long term. In Indonesia, there are generally low digital literacy rates, limited access to technologies and integration across value chains, and low provision of agricultural services (FAO, CIAT and World Bank, 2021<sup>[88]</sup>). While infrastructure is not a constraint in Viet Nam, it must surmount inefficiency arising from gaps in information and communication, including lack of DSS for farmers (FAO, CIAT, and World Bank, 2021<sup>[89]</sup>). Meanwhile, agricultural production units in Colombia may have limited use of precision technologies because of obstacles to innovation arising from lack of resources, access to credit, and high investment costs (DNP, 2021<sup>[46]</sup>).

80. Moreover, some farmers who are willing and financially able to adopt digital tools may not be able to do so if their equipment and service providers do not offer them. In the 2017 survey of agricultural service providers in Ontario, Canada, over 60% of the 34 respondents agreed or strongly agreed with the statement that "the fees they could charge to farmers were not sufficiently high", and over 50% agreed or strongly agreed with the statement that "the necessary equipment changes too quickly" (Mitchell, Weersink and Erickson, 2018<sup>[90]</sup>). Similar surveys of agricultural service providers in Ontario, Canada were conducted in 2017 and 2019. Although the number of responses were low, they represented a relatively high proportion of the population (Mitchell, Weersink and Erickson, 2018<sup>[90]</sup>; Mitchell, Weersink and Bannon, 2021<sup>[91]</sup>). As in the United States, offerings and sales increased between these two years, with the most recent data suggesting

the highest sales rates for grid or zone soil sampling (87% of surveyed retailers), GIS field mapping (86%), VRT fertiliser applications (83%), and satellite/aerial imagery (80%). Technologies with low usage rates include VRT pesticide applications (33%), soil electrical conductivity mapping (30%), guidance equipment sales (21%), and telematic equipment sales (3%) (Mitchell, Weersink and Erickson, 2018<sup>[90]</sup>; Mitchell, Weersink and Bannon, 2021<sup>[91]</sup>).

81. In the corresponding 2019 survey, service providers were asked about their perceptions of their customers' (i.e. local farmers) barriers. They indicated that farm income, technology net benefits, confidence in site-specific agronomic recommendations, time-intensity of decision-making, data privacy, technology profitability due to soil type, and topography were concerns (Mitchell, Weersink and Erickson, 2018<sup>[90]</sup>). Very similar concerns emerged from a corresponding 2015 survey of US dealers, although with variation in the percentage of dealers who identified farmer-based versus dealer-based barriers to expansion of precision agriculture in their service areas (Erickson and Widmar, 2015<sup>[92]</sup>).

82. In principle, adoption of digital agriculture can also be constrained by agricultural equipment offerings at nearby retailers. In the United States, dealers of these technologies – primarily cooperatives and independent dealerships – have been surveyed by researchers at Purdue University about the technologies offered to farmers since 2000. Over this time, the breadth of precision technology offerings has increased, and technology purchases by retailers for sale to farmers has generally increased. For survey year 2020, the most highly offered services among the 169 surveyed dealers were grid or zone soil sampling (92%), GIS field mapping (86%), satellite or other aerial imagery (69%), and yield monitoring and other data analysis (64%). Among the least sold technologies were traceability tools (38%), soil electrical conductivity mapping (31%), and networks of wired or wireless sensors (19%) (Erickson and Lowenberg-DeBoer, 2020<sup>[93]</sup>). The data suggest that US farmer adoption is likely not highly limited by retail-specific supply chain constraints. However, these aggregate estimates could mask regional differences in the availability of certain technologies from certain retailers, although such differences – if any – are not currently tracked.

### *Drivers and enablers*

83. The literature reveals several attributes (i.e. technology features, farm or farmer characteristics, policy mechanisms) that can help facilitate or more directly promote uptake of the digital tools. In many instances, removal of barriers are among the most compelling ways in which adoption in row crops production can be enabled.

84. More specifically, in high-income countries, among the most significant non-financial barriers within row crop farming are data ownership, security, and privacy or confidentiality concerns, in addition to software compatibility and trust in “black box”, algorithm-based management practices (Coble et al., 2019<sup>[85]</sup>; Drewry et al., 2019<sup>[94]</sup>), (see also [TAD/CA/APM/WP(2022)2/FINAL]).

85. More broadly, qualitative interviews of scientists, research funders, and others within the agricultural sector reveal the need to develop co-ordination strategies throughout the agricultural knowledge and innovation system (Rijswijk, Klerkx and Turner, 2019<sup>[95]</sup>), including emphasis on increasing the user-friendliness of digital technologies (Regan, 2021<sup>[96]</sup>).

## 4. Livestock farming

86. For purposes of this report, livestock includes beef cattle, dairy, swine, and poultry, as well as crops for grazing as forage or pastures. With this in mind, precision livestock farming can be defined as the use of technology to automatically monitor livestock or adjust livestock-related inputs, their products and the farming environment in real time, in order to aid farm management, through supplying the farmer with relevant information on which to base management decisions, or by activating automated control systems.<sup>17</sup>

87. In comparison to row crops, much less is known about the adoption of digital tools in the farm-level production of livestock products. In fact, much of the digital agriculture literature has largely neglected this field of application. Moreover, among existing studies of digital adoption on livestock farms, the majority of these deal with cattle, either beef or dairy, and only few studies address poultry, swine, and sheep. Much of the digital livestock literature has focused on robotics, and less on farm management support and farm management information systems (Giua, Matera and Camanzi, 2020<sub>[97]</sub>). These have also been published for agricultural settings across Europe and Oceania while other regions have been represented with much less coverage (Rowe, Dawkins and Gebhardt-Henrich, 2019<sub>[98]</sub>).

88. However, the breadth of the literature does not necessarily reflect the amount of digital technology applications and farmers' uptake in these industries, as illustrated below. In this respect, the unbalanced use to publication ratio may have structural causes. For example, one salient feature of the livestock sector is the degree of vertical integration in the production process. In many countries, poultry and swine production are, to varying degrees, vertically integrated (i.e. the parent company provides capital and other materials to the farmers, who receive salaries based on their livestock-related performance), which has implications for farmers' technology use, as well as the number of studies that report adoption rates. For example, the largely integrated poultry sector in the United States uses vast amounts of digital technology but publishes relatively little on the extent of its use compared to that of the dairy sector, a relatively less vertically integrated industry.<sup>18</sup>

### 4.1. The status of livestock farming digitalisation

#### *Evidence from nationally representative surveys*

89. Although it is apparent that farmers are using digital technology for livestock production within the farm gate, specific rates of adoption are uncertain. Only from as recently as 2017 have national governments begun to survey livestock producers about their use and experiences with digital agriculture. At the same time, some agricultural groups – anticipating the need for greater information – have commissioned studies from market research firms in this area, alongside some academic interest in the topic.

90. As for row crops, this section focuses on national surveys first as sources for robust evidence on adoption trends (Table 3). It then provides an overview of some findings emerging from the academic literature. It must be reiterated that the evidence base from national surveys is exceedingly sparse, and the types of precision livestock technologies that farmers are inquired about (if at all) vary drastically across countries.

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<sup>17</sup> An increasing number of precision livestock applications, especially those making use of accelerometers, precision weighing, and tracking technologies are being developed with explicit recognition of animal health and welfare.

<sup>18</sup> Relatedly, a linkage between digital technology adoption and consolidation of livestock processing is likely to exist, though the literature has not fully explored such a relationship or its implications.

91. As Table 3 illustrates, evidence suggests that adoption for livestock or mixed crop and livestock remains in its infancy in several countries. In **Colombia**, usage rates of digital agriculture tools commercialised during the 1990s is similar between livestock and arable crop farmers. The same is true for **England**, although estimates also exist for farmers' use of automated heat detection, digital pasture management tools (e.g. plate meters, probes), and regular weight of livestock. At present, automated heat detection systems are adopted at rates two-to-three times as large as pasture management tools, although overall adoption remains quite low.

92. Comparably low adoption rates prevail on **German** beef and dairy farms for several technologies (e.g. automated feeding systems, milking robots, and stable/barn cameras). Based on a survey of 331 beef and dairy farms in Germany, only 2.6% of farms have autonomous robotic feeding systems, and only 4% plan to adopt them (Arnold, Raczowska and Kowarik, 2019<sup>[99]</sup>). According to the same survey, 18% of dairies use robotic milkers and another 18% plan to adopt. One exception is somewhat larger use of herd management computer programmes, with an adoption rate of 44%.

93. In **Ireland**, such programmes (computerised herd management systems) are adopted at similar rates (46%) among dairy farms, although their use is lower on beef farms (24%). The most used technologies in Ireland relate to digital record-keeping (e.g. calf registrations and recording of medical remedies), both of which have adoption rates in excess of 50% (of surveyed Irish dairies). Such high usage rates are not unexpected, given these technologies simplify farmers' management practices associated with regulatory compliance.

94. In the **United Kingdom**, 18% of swine and poultry farms used automated estrus detection (signalling the imminence of ovulation) systems in 2019 but data were suppressed for dairy and grazing livestock due to low sample size (DEFRA, 2020<sup>[35]</sup>). For dairy, 69% of farms used breeding indices/values while 32% of grazing livestock farms use the technology. Nearly 10% of grazing livestock farms utilised some sort of pasture measurement sensors.

95. Autonomous robotics for intensive livestock production has more rapidly advanced than in crop production, possibly due to more controlled production environments for livestock than for row crops (Lowenberg-DeBoer et al., 2019<sup>[100]</sup>). As these authors indicate, the structure and functioning of robots for intensive livestock production are different than those for crops; they can often be stationary and involve less decision-making because of their greater controllability.

96. National survey evidence of precision livestock farming does not exist for the **United States**, although representative surveys of cattle, hog, dairy, and broiler operations are conducted on a rotating basis via USDA's Agricultural Resource Management Survey. However, research initiatives are currently in place that would examine the status of precision farming adoption in US swine production in a multi-state region where swine production is common (Whitmore, 2021<sup>[101]</sup>).

**Table 3. The status of digitalisation of livestock or mixed crop/livestock production**

Country	Source	Year	Representation	Unit (%)	Yield Map	Soil Map	VRT	GPS and/or Automated Guidance	Telemetry	Controlled Traffic	Satellite or Drone Imagery	Crop Sensors	Regular Weighing of Livestock	Automated Heat Detection	Digital Pasture Management Tools
Colombia	(DNP, 2021 <sup>[46]</sup> )	2017	Ag. production units	units				13.4			1	0.7			
England	(DEFRA, 2020 <sup>[35]</sup> )	2019	Pigs & poultry	holdings									64	18	5
England	(DEFRA, 2020 <sup>[35]</sup> )	2019	Dairy	holdings	11	29	22		7	7					
England	(DEFRA, 2020 <sup>[35]</sup> )	2019	Grazing livestock LFA	holdings	3		11		2	3					8
England	(DEFRA, 2020 <sup>[35]</sup> )	2019	Grazing livestock lowland	holdings		14	12		4	5			50		9
England	(DEFRA, 2020 <sup>[35]</sup> )	2019	Mixed	holdings			25						49		
Country	Source	Year	Representation	Unit (%)	Stable Camera	Robot Column Pusher		Automated Feeding		Milking Robot	Herd Management Program		Body Condition Scoring Technologies		
Germany	(Arnold, Raczowska and Kowarik, 2019 <sup>[99]</sup> )	2018	Beef and dairy	farms	15.4	8.5		2.6		18	44		0.6		
Country	Source	Year	Representation	Unit (%)	Calf Registration	In-Barn Camera	GPS for Auto-steer	Health Monitoring	Remedy Recording	Satellite Imagery	Milking Robot	Weather Stations	Parcel Boundary Mapping	Herd Management Systems	
Ireland	(Skillnet Ireland, 2019 <sup>[13]</sup> )	2019	Beef	farms	56	30	7	6	27	6	1	12	5	24	
Ireland	(Skillnet Ireland, 2019 <sup>[13]</sup> )	2019	Dairy	farms	86	53	15	13	53	2	4	11	5	46	
Ireland	(Skillnet Ireland, 2019 <sup>[13]</sup> )	2019	Sheep	farms	26	18	7	7	16	9	1	12	11	17	

Note: In the survey of Colombian farmers provided by (DNP, 2021<sup>[47]</sup>), the “GPS and/or automated guidance” column refers only to GPS, “Satellite or drone imagery” refers only to drones, and “Crop sensors” are reported as sensors. In the English survey, the “GPS and/or automated guidance” column refers only to GPS, and “controlled traffic or tramlines” are referenced only as “controlled traffic”. In the German survey, 331 beef and dairy farmers were surveyed in 2018 by the Kleffmann Group on automation in housing and feeding technologies and digital tools for animal health and herd management. With support from the Irish Farmers’ Association, Farm Business Skillnet commissioned Amárach Research to survey Irish farmers, with a final sample size of 768 farmers. Adoption estimates reflect current or past use of the technology.

Source: Authors’ own compilation.

### *Evidence from the academic literature*

97. In terms of academic literature and market studies, some evidence exists that can help to complement the scattered information available from national surveys. As with the academic literature on adoption in row crops, studies on livestock typically involve case reports and surveys with small but perhaps statistically representative samples.

98. Rowe, Dawkins and Gebhardt-Henrich (2019<sub>[98]</sub>) conducted a systematic review of 264 peer-reviewed publications and conference proceedings on precision livestock farming applied to poultry. The highest category of country income grouping accounted for 89% (n=232) of the publications. Broilers accounted for 43% of bird types in the meta database, while precision poultry farming was not represented in the literature until the late 2000s.

99. By 2025, projections indicate that half of **northwest European** dairies will be robotically milked, up from one fourth in 2015 (Dairy Global, 2015<sub>[102]</sub>). For example, in 2015, roughly one-quarter of the dairy farms in **Denmark** and **the Netherlands** used robotic milking (Dairy Global, 2015<sub>[102]</sub>).

100. A small online survey of precision farming technology use among 109 dairy operations in nine countries was performed in 2013. Roughly 83% of survey respondents were dairy operators in the **United States**. Among the most commonly employed technologies were those used to measure milk yields (52%), cow activity (41%), and mastitis (26%). Among the least used were those technologies that measured methane emissions (1.8%), respiration rate (1.8%), and rumen pH (0.9%) (Borchers, 2015<sub>[103]</sub>).

101. Similarly, an online survey of 280 **German** dairy farmers indicated substantial use of precision technologies via smartphone. Approximately 93% of those surveyed use a smartphone, and 61% use a herd management app. Roughly 30% of the operators use such apps more than once each day (Michels, Bonke and Musshoff, 2019<sub>[104]</sub>). This is generally in agreement with an in-person survey of 310 farmers in 2017 from the Piedmont region of north-western **Italy**, an area for which livestock and mixed systems account for half of agricultural output. Of those surveyed, 66% use a personal computer, smartphone or tablet on a near daily basis (Caffaro and Cavallo, 2019<sub>[105]</sub>).

102. An online survey of 504 farming operations in **Brazil** undertaken in 2020, the majority of which were livestock producers or combined livestock-crop producers, produced somewhat incomparable estimates. While 70% of those surveyed have internet access, 22% use mobile applications, digital platforms, and management software, and only 7% use automated or robotic systems (Bolfe et al., 2020<sub>[106]</sub>).

103. In nations where manual labour is relatively less expensive or scale includes a large number of cows, e.g. over 1 000, such as **Australia, New Zealand, the People's Republic of China** (hereafter "China"), the **Russian Federation**, and the **United States**, robotic milking has not been as popular (Dairy Global, 2015<sub>[102]</sub>).

104. In line with these findings, livestock under precision management has been reported to be relatively low in **sub-Saharan Africa**. In Africa, many farmers are smallholders, with operations that may have scale or scope that are incompatible with the current suite of commercialised technologies. One analysis of 128 studies on precision agriculture in sub-Saharan Africa found that only roughly 3% of studies pertained to livestock (animal monitoring and protection), suggesting a major research gap (Nyaga et al., 2021<sub>[107]</sub>). Analysis of smallholders' use of automation technologies in other developing-world regions has been similar (Salimi, Pourdarbani and Nouri, 2020<sub>[108]</sub>).

## 4.2. Digitalisation and productivity, sustainability and resilience goals for livestock farming

105. Many digital technology applications for livestock production are associated with productivity benefits. However, there is very little literature estimating the impact of the adoption of digital technologies on productivity, sustainability and resilience in the livestock sector. In fact, most digital technology uses in the livestock sector seem to be driven by their labour saving and increased quality of life effects. Although labour saving and better quality of life may have impacts on productivity, sustainability and resilience in turn, these effects per se have received less attention in the literature, possibly also due to the difficulty of quantifying them in traditional productivity analyses.<sup>19</sup>

### *Productivity*

106. Detection of estrus, in cattle was one of the initial digital technologies applied to livestock especially for artificial insemination (AI) herd management (Neethirajan and Kemp, 2021<sub>[109]</sub>; Rosa, 2021<sub>[110]</sub>). (Diskin et al., 2000<sub>[111]</sub>) report commercialised technology that senses “mounts” via electronic pressure-sensors and transmit signals wirelessly over radio waves, e.g. HeatWatch for beef cattle (Walker, Nebel and McGilliard, 1996<sub>[112]</sub>) or DEC for dairy (Saumande, 2002<sub>[113]</sub>). More recently, (Reith and Hoy, 2018<sub>[114]</sub>) report a review of cattle estrus within fully automated production systems. Similar to utilisation in dairy, (Stock et al., 2017<sub>[115]</sub>) also report the utilisation of digital imagery for the selection of replacement gilts in swine production.

107. In parallel, automated or robotic milking has become a widely accepted labour-reducing technology that potentially increases milk output and quality (Tse et al., 2018<sub>[116]</sub>). Terentyev, Belokopytov and Lazko (2019<sub>[117]</sub>) reported how data collected from dairy farms could also be used in “big data” systems to improve breeding strategies. This is an issue that deserves further investigation since labour saving may be a key driver of adoption of some digital technologies, with corresponding implications for labour demand and skills.

108. Mobile device apps support precision agriculture systems including enabling the monitoring of livestock via sensors (Griffin, 2020<sub>[118]</sub>). Small inexpensive GNSS loggers support management decisions and monitor animal behaviour. Turner et al. (2000<sub>[119]</sub>) were one of the first studies to report cattle tracking with GNSS in Kentucky, United States.

109. These fully autonomous systems include pedometers to record the animal’s number of steps and accelerometers to measure changes in horizontal speed, as well as other biometrics such as body temperature (Reith and Hoy, 2018<sub>[114]</sub>). For example, in developed nations, swine are typically produced in close contact within houses, similar to poultry (Neethirajan and Kemp, 2021<sub>[109]</sub>). Biometric sensors and facial recognition methods replace and improve humans’ ability to sense the wellbeing of the animals and are adopted to avert behavioural issues, improving animal welfare on average and facilitating farms’ operations (Benjamin and Yik, 2019<sub>[120]</sub>; Neethirajan and Kemp, 2021<sub>[109]</sub>). Similarly, for dairy sheep, (Odintsov Vaintrub et al., 2021<sub>[121]</sub>) describe application of sensors and a wide range of biometric devices to monitor and manage herds in the Mediterranean, with labour

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<sup>19</sup> It should also be pointed out that, at the macroeconomic level, there may be tradeoffs between agricultural productivity and sustainability. For instance, land use change to promote the production of livestock feed has resulted in harms to ecosystems and biodiversity (Galaz et al., 2021<sub>[199]</sub>). However, such effects appear to be driven by global population increases, consumer dietary preferences, and local factor market conditions in developing countries rather than farmers’ uptake of digital tools.

saving effects. Bewley et al. (2008<sub>[122]</sub>) also report digital imagery for estimating body condition scores in dairy cattle in the United Kingdom.

110. The concept of rotational management intensive grazing (MIG) captures livestock behaviour to optimise rotation paddocks. In beef cattle production, georeferenced data can be used on existing paddock boundaries and water sources to subdivide paddocks into optimal units through GIS. The implementation of GIS in grazing studies has been applied to regional and landscape scales (Hill et al., 1996<sub>[123]</sub>; Kaufmann et al., 2013<sub>[124]</sub>; Schieltz et al., 2017<sub>[125]</sub>; Yool, Makaio and Watts, 1997<sub>[126]</sub>) but fewer studies have examined GIS for predictive use modelling (Brock and Owensby, 2000<sub>[127]</sub>) or for monitoring cattle movement within MIG paddocks (Turner et al., 2000<sub>[119]</sub>).

111. Precision livestock production often occurs in mixed systems with both crops and animals farmed on the same operation (Asare and Segarra, 2018<sub>[128]</sub>; Groher, Heitkämper and Umstätter, 2020<sub>[129]</sub>). One natural overlap of row crops and livestock is animals grazing in pastures. In this regard, the spatial analysis and understanding of natural variability of the pasture can be important in intensive grazing. As such, there have been many studies on the use of digital technologies to assess forage growth with the intent to support livestock production (Bernardi et al., 2016<sub>[130]</sub>; Moral et al., 2021<sub>[131]</sub>; Moral, Rebollo and Serrano, 2020<sub>[132]</sub>; Pullanagari et al., 2012<sub>[133]</sub>). This also includes the use of grass measurement technology for livestock grazing (Murphy, O'Brien and Murphy, 2020<sub>[134]</sub>) and digitally mapped silage on dairy farms (Cho et al., 2021<sub>[135]</sub>).

### *Sustainability*

112. Importantly, digital technologies can also help to improve the environmental performance and management of livestock productions. However, there is little evidence about these impacts from commercial livestock farms.

113. In one example, digital tools can help to track cattle near environmentally sensitive areas (Schieltz et al., 2017<sub>[125]</sub>; Kaufmann et al., 2013<sub>[124]</sub>). By tracking cattle, operators can better understand vegetation dynamics in response to livestock movements, with implications for the quantity and quality of available forage. This also allows better control of animal behaviour with respect to distance to water sources in order to understand how to manage various mechanisms regulating cattle.

114. One step further, “virtual fencing” allows restriction of livestock movement to specific areas of paddocks without physical constraints by using various electronic-based signals (Bishop-Hurley et al., 2007<sub>[136]</sub>; Umstätter, 2011<sub>[137]</sub>). In the more mature forms of this technology, there is a high potential to automatically protect environmentally sensitive areas from cattle at large scales (Campbell et al., 2020<sub>[138]</sub>).

115. In addition, sensors and GNSS trackers could be utilised to monitor urination locations and help to plan nitrogen extraction in a circular economy, which was demonstrated in a case study of dairy cows on a commercial dairy farm in New Zealand. A better understanding of the distribution of animal waste can result in the development of management plans that can more appropriately address nitrogen leaching, thus potentially improving water quality outcomes associated with livestock farming (Draganova et al., 2016<sub>[139]</sub>).

116. Digital technologies have also been applied to disposal of livestock manure as a soil amendment. Manure predates synthetic agrochemicals as the main source of fertiliser by millennia, but the same variable rate application technology, logging of as-applied data, and flow control meters are used for manure and synthetic fertilisers (Koelsch, 2019<sub>[140]</sub>). Precision manure management has positive social externalities including natural resource conservation effects (Kleinman et al., 2018<sub>[141]</sub>).

117. Overall, as opposed to crop production, nearly all of the digital technologies applied to livestock are “labour saving” such that their function is not just to simplify or support human labour, but to more directly substitute labour with sensors or automated systems. In fact, Odintsov Vaintrub et al. (2021<sub>[121]</sub>) discuss the relatively large portion of the enterprise budget for milking and sheep production associated with labour and how precision livestock farming technology can provide a ‘remedy’ for this.

118. The exceptions to this observation are the aggregations of technologies and digital data being collected from within the farm gate that may become useful for advanced analytics and traceability purposes (Neethirajan and Kemp, 2021<sub>[109]</sub>; Coble et al., 2019<sub>[85]</sub>; Birner, Daum and Pray, 2021<sub>[8]</sub>). Even so, these technologies may ultimately prove to result in lower demand for manual farm labour, even if such effects are indirect and possibly increase the demand for high-skill expertise in livestock operations (e.g. veterinarians, animal nutritionists).

119. On this latter point, to the extent that consumers (e.g. households, major purchasing agents, governments) become more interested in tracing livestock products throughout the entire food supply chain, farms that emphasise characteristics with high consumer demand (e.g. “sustainable”, “grass-fed”, “local”) may stand to receive relatively larger benefits. In this way, technologies that enable greater traceability could increase overall sustainability in livestock farming.

### *Resilience*

120. One of the greatest benefits attributed to digital tools in livestock farming relates to detection, control, and prevention of diseases (Neethirajan and Kemp, 2021<sub>[109]</sub>). In livestock production, it is crucial to control environmental factors including temperature and humidity so as to keep them within a narrow range. In this sense, real-time analysis from sensor technologies used in digital livestock production can provide important help to control these variables and manage risk.

## **4.3. Evidence on drivers, enablers and constraints to digitalisation of livestock farming**

121. Only few studies provide evidence about the drivers and constraints to digitalisation in livestock farming specifically, although several examine drivers and constraints common to both livestock and crop farming. Among the relevant factors found are: costs, lack of relevance for their farms, lack of human capital, asymmetry between those bearing costs (farmers) and those benefiting (downstream integrated companies) in vertically integrated chains, uncertain intellectual property rights and lack of broadband connectivity.<sup>20</sup>

122. One interesting fact from the DEFRA (2020<sub>[35]</sub>) survey of English farms is the proportions of farmers stating they do not adopt technologies because of expense are roughly equal between row crop farmers (63%) and livestock farmers (50% for pigs and poultry farmers; 58% for dairy farmers). However, livestock farmers are much more likely than row and specialty crop farmers to say that the reason they do not adopt is because the technology is not relevant to their farm. Between 60-80% of non-adopting English

<sup>20</sup> Regarding this latter constraint, some studies have placed increasing emphasis on the role of digital inclusion as it relates to farmers’ skill sets and labour needs. For instance, in Australia, a country where the value of production from (and acreage dedicated to) livestock exceeds that of row and specialty crops, farmers’ access to the internet and internet-based technologies lags behind rural Australia and the country more broadly (Nettle and Vera-Toscano, 2021<sub>[205]</sub>). This aspect of the digital divide reveals an important point that is overlooked in many literatures, i.e. some gaps exist in basic internet access in remote areas of developed country agriculture.

livestock farmers list irrelevance as a cause. Based on this, one likely major barrier to digital adoption in livestock farming is related to perceptions of relevance.

123. Specific to swine production, Hoek and Miller (2021<sub>[142]</sub>) argue for the importance of human capital investment in making use of technology. For US swine production, in particular, employment increased by an annual rate of 2.1% during 2001-15, consistent with a capital-intensive sector with increasing demand for full-time, skilled labour (Boessen, Artz and Schulz, 2018<sub>[143]</sub>)

124. In the United States, a few nearly completely vertically integrated companies (poultry integrators) control the production of layers (egg-laying chickens) and broilers (meat-producing chickens). A 2017 lawsuit alleged that the integrators colluded to collect and share data originating from farmers via a third party (Janzen, 2017<sub>[144]</sub>). This was likely the first example of farm data being involved in a lawsuit. The burden of adoption of data-intensive technologies, including sensors, is on the farmer to invest, and yet the benefits of aggregated data are perceived to go to entities controlling the flow of such data. This may inhibit incentives for adoption.

125. Similarly, uncertain intellectual property rights and unknown benefits of digital livestock farming has been a barrier to farm level adoption (Groher et al., 2020<sub>[55]</sub>). The unknown, or poorly understood, benefits from adoption are particularly salient in the livestock sector, where use cases have only recently been developed, and where smaller-scale, independent operations may have less of an advantage from uptake as larger, vertically-integrated livestock farms.

126. Use of mobile devices and other digital devices typically assumes the presence of adequate wireless broadband connectivity. The discussion about whether the public or private sector should develop communications infrastructure has been debated at every scale – from municipalities up to the national level. US legislation such as Iowa’s “Connect Every Acre” bill was signed into law in June 2015, demonstrating the recognition of this topic by policymakers (Swoboda, 2015<sub>[145]</sub>).

## 5. Specialty crops farming

127. For the purposes of this report, specialty crops include fruit, vegetables, and tree nuts. This characterisation does not include other commonly grown specialties, such as culinary herbs and spices, medicinal plants, and largely inedible crops produced in nurseries, floricultural systems, or horticultural systems. Although many of these excluded specialties have high output value, they tend to use far less agricultural land than row crop and livestock operations and are of less focus for commercial applications by manufacturers and other developers of digital tools.

128. Many specialty crops are perennials (such as in most fruit and nut orchards) requiring significantly greater – and more diverse – labour inputs (e.g. owners, managers, equipment operators, manual labourers, and other farm workers) as compared to row crops and livestock farming. In this respect, all these figures are likely to be distinct individuals with distinct roles in the farm business (Gallardo and Sauer, 2018<sub>[146]</sub>).

129. Much of the literature on the digitalisation of specialty crops has been: 1) conceptual and forward-looking overviews, with emphasis on large-scale potential, 2) qualitative case studies, or 3) demonstration of the engineering or economic viability of a particular technology. This includes an increasing number of forward-looking publications that identify pathways by which emerging technologies will affect fruits and vegetables, such as the impacts of blockchain-based technologies on US fresh produce

supply chains (Collart and Canales, 2021<sub>[147]</sub>). Therefore, there is less evidence for speciality crops farming systems.

130. The existing evidence base suggests many of the technologies developed to date for specialty crops relate to harvesting, a particularly more complex field operation for fruits, vegetables, and tree nuts than for row crops. Moreover, the literature points to the development of sophisticated technologies for pest monitoring, pest management, and irrigation.

### 5.1. The status of specialty crop farming digitalisation

131. The 2019 survey of **English** farmers reports that VRT was used on 42% of “other crop” farms, with lower proportions for telemetry (17%) and controlled traffic farming (12%) (DEFRA, 2020<sub>[35]</sub>). However, since much of the acreage of “other crops” was comprised of oilseeds and maize (DEFRA, 2020<sub>[148]</sub>), the true rate of use on fruits, vegetables, and tree nuts likely differs – perhaps substantially – from these estimates.

132. Comparable large-scale, nationally representative estimates of digital adoption for specialty-crops farming do not exist for the **United States** (Astill, Perez and Thornsbury, 2020<sub>[149]</sub>). Nonetheless, USDA routinely surveys fruit and vegetable growers in its annual Agricultural Chemical Use Survey about information and data use associated with pest management practices. In 2018, operators of 45% of US vegetable hectares had used field mapping to make pest management decisions, with 53% of total vegetable area receiving diagnostic laboratory services for pest detection. Pest scouting based on pest development models was done on 35% of total hectares, while the timing or need for pesticide use was based, in part, on weather data for 85% of treated vegetable hectares. Estimates on US fruit hectares in 2019 were similar, with use varying based on technology: field mapping for pest management decisions (47%), diagnostic laboratory services (51%), model-based pest scouting (43%), and use of weather data to inform the need or time of pesticide applications (82% of hectares on which pesticides had been applied) (USDA-NASS, 2021<sub>[150]</sub>).

133. With respect to mechanised harvesting – of paramount importance for reducing labour inputs – dichotomies largely exist between fruits and vegetables and between fresh and processing markets. In the United States, for example, Calvin and Martin (2010<sub>[151]</sub>) reported that roughly 75% of all US vegetable and melon area and 55% of US fruit hectares are mechanically harvested.<sup>21</sup> These percentages reflect the fact that most vegetables are annual crops that are planted in rows – for which it is easier to position machines, and with less concern for damage done to the plant. By contrast, most crops in vineyards and fruit and nut orchards are perennials, with location of fruit that can exhibit: 1) highly variable ripening, and 2) difficult-to-predict locations.

134. In the United States, large shares of tomatoes, cucumbers, carrots, peppers, oranges, plums, tart cherries, and wine grapes for processing markets are mechanically harvested. Fresh-market iceberg lettuce, melons, strawberries, and melons are harvested with mechanical aids that assist workers (Huffman, 2012<sub>[152]</sub>).

135. Several university-based surveys gauged the use of mechanical harvesters and/or digital tools in North American fruit production. For example, Gallardo

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<sup>21</sup> Although mechanical harvesting has been used in certain specialty crops for decades, digitalisation may improve the quality of certain harvesters or result in the development of new equipment for use in crops that have been typically harvested by hand. For instance, it is possible that digitalisation could cause the replacement of current harvest-assist technologies with fully automated harvesters, thus contributing to productivity increases while resolving current issues of team-based compensation in sectors where individual farmworkers have typically received piecemeal rates.

et al. (2018<sub>[153]</sub>) found that 33% of 228 surveyed blueberry producers from the **United States** and **Canada** in 2015-16 had used machine harvesting on their fruit destined for fresh markets. However, use of mechanical harvesters on blueberries for processing markets is routine (Gallardo et al., 2019<sub>[154]</sub>). In a 2002 survey of 161 US citrus growers in Florida, (Sevier and Lee, 2003<sub>[155]</sub>) reported significant variation in the percentage of farmers adopting digital agriculture by technology type: sensor based VRT (19%), remote sensing (4%), GPS receiver (17%), soil mapping (18%), water table monitoring (14%), harvesting logistics (11%), and yield monitoring (10%). Based on a state-wide survey of Florida fruit and vegetable growers, Wade (2020<sub>[156]</sub>) found that 23% of 52 surveyed citrus growers and 22% of 18 surveyed vegetable growers used precision agriculture.

136. University-affiliated studies exist on digital agriculture use for specialty crops in other regions, too. For example, in **France**, a 2017 survey of 127 wine technicians (i.e. advisors) suggested highly variable use by technology: laptop computers (virtually 100%), smartphones (80%), field- or soil-based sensors (roughly 75-80%), GPS (nearly 60%), and portable or on-board measurement systems (roughly 40%) (Observatoire des Usages de l'Agriculture Numérique, 2017<sub>[157]</sub>). Although yield mapping and soil mapping are common in **Australian** viticulture, adoption of digital tools among Australian vegetable growers has been negligible (Suarez et al., 2018<sub>[158]</sub>).

## 5.2. Digitalisation and productivity, sustainability, and resilience goals for specialty crops farming

137. Unlike the evidence for row crops and livestock farming, nearly all studies about the benefits of digital agriculture for specialty crops are from controlled experiments (e.g. field trials) that demonstrate a particular effect or simulations based on assumptions that could differ from those experienced in real-world production.<sup>22</sup> As with the row crops literature, the focus of the research on speciality crop digitalisation has been on profitability and costs.

138. For example, a simulation study of US blueberry production for fresh markets found that mechanical harvesting is not currently profitable, although large increases in labour costs (61%), large reductions in machine-induced yield losses (63%), or large decreases in quality losses (41%) would render it on par with – or more profitable than – hand harvest (Gallardo and Zilberman, 2016<sub>[159]</sub>).

139. A recent controlled experiment on fresh apples produced in Washington State compared a “smart orchard” – with irrigation, labour, and chemical decisions based on artificial intelligence algorithms using sensor and imagery data – to traditionally-managed apple orchards. Although there were no significant differences between the two systems regarding chemical expense, labour costs were substantially lower for the smart apple orchard (Amin, Badruddoza and Mantle, 2021<sub>[160]</sub>). One experimental study of fruit and vegetable production in India found that precision farming’s contribution to higher yields was 34% in tomato and 20% in eggplant (Maheswari, Ashok and Prahadeeswaran, 2008<sub>[161]</sub>).

140. At the production level, greater adoption of site-specific variable rate irrigation has large potential to improve water productivity, water and energy conservation, and the environment (Evans et al., 2013<sub>[162]</sub>; Lamm et al., 2017<sub>[163]</sub>).

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<sup>22</sup> Other factors beyond growing conditions can explain the divergence between expected profitability results (from the academic literature) and actual profitability on commercial farms, including pricing structures, data access, and farmers’ adjustment to potentially new and complex technologies (Khanna, 2021<sub>[7]</sub>; Shepherd et al., 2020<sub>[200]</sub>).

141. In somewhat related work, Bernard et al. (2017<sub>[164]</sub>) found that experimentally controlled access to weight and quality information substantially increased sales revenues to Senegalese onion farmers. Although the digital content of this information is low, the study points to the broader value that digitally enabled information can bring to farmers, both those operating at larger scales as well as smallholders in developing countries.

142. Regarding risk management and resilience, simulation evidence in (Gallardo et al., 2018<sub>[153]</sub>) that simultaneously models variability in yields, prices, quality damages, and costs for fresh US blueberries suggested that certain forms of mechanised harvest were the least risky – with manual harvest being the riskiest option.

143. Information and data use are also relevant for pest risk management (Roberts et al., 2009<sub>[165]</sub>). For example, mobile alerts and websites – updated in real time – with information about the locations and spread of weed and insect pests, in addition to crop diseases, are valuable tools allowing specialty crop farmers to take protective actions before biological infestations. To the extent that such tools provide guidance for minimising post-infestation losses, they also have potential for boosting farmers’ resilience.

144. A growing literature on precision pest management in specialty crops has identified promising new technologies with sustainability and resilience benefits. In particular, reflectance-based crop monitoring systems using remote sensing and precision pest control systems (e.g. natural enemy distribution and pesticide spray rigs) are more recent digital tools within farmers’ integrated pest management. Both systems can be implemented using drones, contributing to prevented pest outbreaks and thus potentially lower pesticide use (Filho et al., 2020<sub>[166]</sub>).

145. Likewise, there has been substantial technological progress in recent years in the market for precision canopy sprayers. Designed to increase spray accuracy while reducing spray volumes, a number of precision sprayers have been developed: 1) tower, 2) electrostatic, 3) tunnel, and 4) machine-vision controlled via infrared, ultrasonic, or laser sensors. Despite their substantial fixed costs relative to conventional technologies like radial air blast sprayers, precision systems are expected to improve profitability through more efficient chemical use and reduced labour demand (Warneke et al., 2021<sub>[167]</sub>).

146. Along similar lines, simulation results suggest that dynamic pricing and information disclosure based on use of sensor data can increase the sustainability of the fresh fruit and vegetable sectors by substantially lowering food waste at the retail level (Yang, Feng and Whinston, 2021<sub>[168]</sub>).

### 5.3. Evidence on drivers, enablers and constraints to digitalisation in specialty crops farming

147. A few studies provide evidence about the drivers and constraints to digitalisation in speciality crop farming. In particular, the 2019 survey of English farmers suggests that, among non-adopters of precision farming techniques, the percentage of farms for which the technologies are too expensive or not accurate enough are roughly equal among cereal and non-cereal other crops. In the former category, the estimates were 63% (cereal farms) versus 60% (other crops), and in the latter category, the proportions were 7% and 5%, respectively. However, a much smaller proportion of English other crop farms had operators who reported that the technologies were too complicated relative to cereals farms (8% vs. 18%) although a slightly higher proportion of other crop farms thought the technologies were not relevant (52% vs. 48%) (DEFRA, 2020<sub>[35]</sub>).

148. The results from England suggest that **operational suitability of the technology**, rather than technicality, may be more salient to specialty crop farmers, although costs

remain the single-largest impediment. It is also revealing that, relative to English cereals farms, a larger share of other crops farms stated their use of precision farming techniques was to increase productivity or performance (81% vs. 77%), while a lower proportion was motivated by reductions in environmental impact (53% vs. 60%) (DEFRA, 2020<sub>[35]</sub>).

149. Aside from the survey conducted in England, much of what is currently known about adoption enablers and constraints is derived from studies employing intensive, qualitative interviews with growers. In a study about the perceptions of precision technologies in the US fresh apple sector, Gallardo et al. (2019<sub>[169]</sub>) listed **inadequate field research** as a barrier to adoption, suggesting that more research and demonstration of applied research, in combination with extension programmes, could spur farmers' acceptance. Diffusion of information from **trusted sources**, such as precision service companies or crop consultants, were also reported to play an important role in advancing adoption (Gallardo et al., 2018<sub>[153]</sub>).

150. An early study of US citrus growers suggested that lack of adoption was motivated by too **little information** (23-38%, based on particular technology), **financial constraints** (29-36%), and **lack of profitability** from the technologies (9-14%). Although perhaps just as importantly, 44-60% indicated they were satisfied with their current technologies-practices (Sevier and Lee, 2003<sub>[155]</sub>). In a follow-on study using the same data, Sevier and Lee (2004<sub>[170]</sub>) found that older farmers were less likely to adopt precision agriculture, while those with perceptions of at least moderate within-grove variability were more likely to adopt.

151. Likewise, some studies conclude that farmers' **risk aversion** and **regulatory bottlenecks** dampen farmers' interest in adopting newer forms of precision spray technologies. However, as US wages to specialty crop farmworkers increase, in tandem with declining labour availability and greater consumer demand for more sustainably produced fruits and vegetables, farmers may have greater need for high-efficiency sprayers (Warneke et al., 2021<sub>[167]</sub>).

152. A similar case study of fruit tree growers in Pennsylvania and Washington States confirmed major obstacles to adoption of harvest-assist equipment included **cost, perceived risk, equipment complexity, and potential damage to fruit** (Caplan et al., 2014<sub>[171]</sub>). One insight from this study was that changes to incentive structures may be requisite to facilitate adoption. In the case of certain fruits whose harvest cannot be fully mechanised, changes from piecemeal to team-based remuneration for those operating a large harvest-assist machine may be too difficult for some farmer to implement, especially smaller operations that may have less sophisticated forms of labour monitoring. In some instances, production risk may increase as a result of mechanisation if harvesting equipment fails at critical times (Caplan et al., 2014<sub>[171]</sub>).

153. Indeed, objective advisory and extension services, in addition to private sector intermediaries (e.g. crop consultants, digital service providers), are likely to play an important facilitation, education, and science communication role in specialty crops production – as they are for row crops and livestock production (Tey and Brindal, 2021<sub>[172]</sub>). Owing to the relatively smaller land base for production, countries that have public advisory services that are roughly proportional to crop area (e.g. the United States) tend to have fewer advisors in the specialty crop sector – both in an absolute and relative sense. As such, public agricultural advisory specialists are responsible for a large portfolio of highly varied crops, with direct implications for the quantity of research and outreach effort that can be dedicated to a particular crop.

154. At the same time, as education and per capita income rise, the opportunity cost of agricultural work also increases. However, while the specialty crop industry as a whole has

made significant progress in mechanisation (Huffman, 2012<sup>[152]</sup>), many crops – across developed and developing countries – are still manually harvested. Rising opportunity costs of agricultural work – along with substantial agricultural productivity increases and an economic reorientation towards the provision of services, among other factors – has given rise to agricultural labour shortages on specialty crop farms in many OECD countries, either as an long-standing or temporary condition (Hertz and Zahniser, 2013<sup>[173]</sup>; Charlton and Taylor, 2016<sup>[174]</sup>).

155. In this respect, mechanisation of harvesting and increased automation in irrigation, fertilisation, and pest management could provide substantial labour-saving benefits to the sector, the promise of which has spurred entry by a number of non-traditional technology developers (McFadden and Schimmelpfennig, 2019<sup>[26]</sup>). Technology prototypes from private-sector firms and university agricultural engineers have been developed for harvesting, labour monitoring, pollination, yield forecasting and mapping, canopy volume estimation, pest detection, vegetation index calculations, and quality grading – to name only few (Fountas, 2013<sup>[175]</sup>).

156. However, while several of these technologies have been commercialised, many others have not, and adoption – although largely unknown for many specialty crops – may be lagging because of high equipment costs, physical obstructions to internet connectivity, farmers’ perceptions of profitability, and the need for costly re-configuration of orchards or vineyards that farmers cannot undertake in the short run (Caplan et al., 2014<sup>[171]</sup>; Gallardo et al., 2019<sup>[169]</sup>).

157. In fact, to the extent that specialty crops generally incur greater heterogeneity in growing conditions and heterogeneity across crop varieties, digital technologies may entail higher asset specificity that: 1) causes reluctance in farmers to adopt because of lower resale values, and/or 2) limits the ability of firms to manufacture equipment that is suitable across many markets. One or both of these factors may be contributing to the current landscape of many firms providing a small number of high-cost digital technologies. Without economies of scale or scope in development and/or manufacture, the cost of digital tools may continue to be high in the short run (McFadden and Schimmelpfennig, 2019<sup>[26]</sup>).

## 6. Policy insights

158. The agricultural policy community is increasingly interested in better understanding the digitalisation process of agriculture, and how policy can best support it. Mapping the existing knowledge about digital adoption rates, linkages with productivity, sustainability and resilience benefits, and adoption enablers and constraints, is a first key step in providing policymakers with the evidence they need to think through the issues that surround agricultural digitalisation.

159. This section summarises the key policy-relevant insights that have emerged from this literature review and complements it with other policy-specific literature that exists in this field. First, it considers the need for greater and better evidence to inform decisions on-farm and digital agricultural policy more broadly. In this sense, it signals how digitalisation may motivate some shifts in the role of the private versus the public sector to support agricultural innovation to achieve productivity, sustainability and resilience objectives. It then outlines other areas for policy to focus on, to enable well-functioning agricultural innovation systems by reference to specific, identified constraints and barriers that policies could directly address.

160. In formulating this section, preference has been given to lessons learned from the accumulated base of evidence in OECD countries as represented by the literature review.

Policy insights pertain to timely, relevant issues that, if suitably addressed, would be expected to improve the current status of agricultural digitalisation in developed countries.

### **6.1. There is a need for greater, better and more reliable evidence on agricultural digitalisation to support decisions at all levels**

161. Digital adoption in agriculture is commonly associated with potential improvements in societal objectives such as productivity, sustainability and resilience, contributing to the notion that digital technology adoption should be accelerated as a policy objective. The literature reviewed in this report shows that there are apparent linkages between digitalisation and productivity, environmental sustainability, and resilience in agriculture. There is some evidence for row crops that digital adoption can increase profitability (even if increases may not be large), and that it has effects on the environment and sectoral resilience, although these still need to be better explored. There is also evidence in the livestock sector that digital technologies can have significant labour saving effects and can lead to higher quality of life for farm workers, with potential implications for labour and skills.

162. To some extent, it is conceivable that adoption of digital agriculture can have “knock-on” effects that extend beyond productivity, sustainability, and resilience benefits, in addition to reduced labour supply and quality of life gains.<sup>23</sup> For example, reduced operator fatigue due to automated guidance could bring substantial gains in on-farm safety, and quality of life gains could cause improvements in mental health in rural settings. These potential secondary effects, while intriguing, have not been well studied, in part because it may be difficult or impossible to attribute causation to the technologies themselves.

163. However, the literature review also shows that these linkages can depend on the technology and on the specific circumstances of the farm, the commodity type, or location where digital adoption is deployed. In this sense, digital technologies and achievement of policy objectives cannot be disentangled from other best management practices on farm and could play an enabler role.

164. Currently, a key challenge pertains to the lack of relevant data in many countries, which makes it difficult to establish evidence of linkages between different elements relating to digital adoption and the achievement of agricultural objectives. Better information about the costs and benefits of different technology options is needed for stakeholders to be able to make informed investments and decisions. For farmers in particular, it is crucial to be able to access reliable evidence-based knowledge about the effects of digital adoption, and the extent to which different tools respond to their different needs.

165. In light of this evidence, policies should not focus on the promotion of specific digital applications but they should strive to keep in place the appropriate incentives for innovation to enable farmers to choose, among a range of technologies, including digital ones, those that are most appropriate for them. In particular, to enable potential societal gains from agricultural digitalisation, there is a crucial need for the creation and sharing of

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<sup>23</sup> It is well known that farmers’ adoption of certain technologies oftentimes leads to adoption of complementary technologies—bundled, in some cases. In the context of precision agriculture, one classic example is the linkage between yield monitors, georeferenced field maps, and variable rate fertiliser applications (Schimmelpfennig and Ebel, 2016<sub>[24]</sub>). Within the context of this report, these bundles are considered to be instances of sequential adoption rather than productivity-related “knock-on” effects.

knowledge on digital technologies and their impacts, while enabling the development of, and the access to, those technologies for all stakeholders.

166. In this respect, governments may consider shifting their role in agricultural policies and allow more space for the private sector where previous market failures can now be overcome thanks to digital tools, for example in insurance markets. Instead, they could focus on a role as ‘brokers’ of the knowledge (both data and evidence) needed for digital and digitally-enabled innovations to be developed, diffused, and adopted across the sector.<sup>24</sup> This new function could imply a range of public investments and policies aimed at gathering data and at facilitating data sharing, ensuring usability and relevance of digital tools, but also at bolstering trust in digital products and services for farmers, for example, through independent verification and certification programmes, advisory services, or governance actions such as development of safety standards for broad technological diffusion (Rose et al., 2021<sub>[176]</sub>).<sup>25</sup>

167. Indeed, global navigation satellite systems (GNSS), agronomic data and information used in apps (such as large-scale soil surveys), knowledge about the quality and impacts of different digital applications and some parts of the general farm extension and advisory services are public goods (Birner, Daum and Pray, 2021<sub>[8]</sub>). As the private sector tends to provide inefficiently low levels of public goods, such instances of market failure rationalise and necessitate government intervention – a largely uncontroversial, fundamental principle of public economics.

168. For example, an issue that has emerged in the literature as constraining farmers’ adoption of digital technologies, relates to the need of farmers for tools that are useful to them, in terms of being tailored to the specific conditions that they experience. Even if digital technologies provide new opportunities for customisation, this is sometimes in conflict with the business tendency to look for solutions that are more easily scalable and thus more profitable. In this sense, policymakers may have a role in ensuring an inclusive and representative data regulatory environment, to spur the development of more tailored and specific services for all farm operations, and in so doing, may help to erode the perceived digital divide between adopters and non-adopters.

169. At the same time, for the cost of digital tools to reflect the potential of digital technologies for agriculture in the long-term, it is crucial that the system lead to innovation outcomes and advisory services that are operationally suitable for farm operations, which is reported to be a challenge with digital tools developed for agriculture in some cases. In this respect, policymakers may need to ensure that public funds for agriculture knowledge and innovation systems go towards farmer-centric programmes and initiatives. This implies a solid understanding of different farmers’ needs and constraints to enable the development of relevant and viable solutions for existing primary production challenges.

170. Similarly, since farmers often turn to their neighbours and independent advisors for farming-related information, governments should consider ways to strengthen networking and information-sharing, including among actors closest to the different production types (Blasch et al., 2020<sub>[14]</sub>), and to foster two-way communication between farmers and service providers. In that vein, access to extension and advisory services that are perceived as

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<sup>24</sup> Readers are referred to (Ehlers, Huber and Finger, 2021<sub>[201]</sub>) for a detailed, qualitative overview of ways in which agricultural digitalisation can influence the design of general agricultural policies.

<sup>25</sup> Additional benefits of standardisation include a competition-inducing effect (Birner, Daum and Pray, 2021<sub>[8]</sub>), and a reduction in farmers’ technology switching costs, both of which would be expected to lower barriers to adoption.

neutral is crucial for building trust in digital technologies and decreasing the learning cost barrier (Khanna, 2021<sup>[7]</sup>; OECD/FAO, 2021<sup>[177]</sup>).

171. Furthermore, to assess the extent to which positive externalities exist that would justify policy interventions aiming to generate greater digital adoption, beyond levels determined by cost-benefit decision-making at the farm level, a greater understanding of the relationship between adoption of specific technologies for specific types of production, and agricultural sustainability and resilience performance remains necessary. In this sense, governments must continue to seek ways to gather nationally representative data to support policymaking (Isik, Khanna and Winter-Nelson, 2001<sup>[78]</sup>).

172. Although perhaps less costly, use of farmers' data from agricultural machinery and digital equipment will not generally be a viable alternative to traditional sources of production data (e.g. carefully designed government surveys, or more sophisticated ways of data aggregation or observation that could be developed in the future) because of potential sample biases arising from private-sector customer bases and attrition due to opt-out mechanisms.

173. Indeed, advancements in digital technologies may offer governments new and better ways to collect and share a range of data at a disaggregate scale, capturing sector-specific elements of technologies, production environments, farm households, and rural economies, that are relevant to the achievement of other policy objectives. For example, digital technologies hold promise for better management of agriculturally induced air and water pollution, including GHG emissions. However, development of targeted policies to handle runoff of nitrogen fertilisers has been constrained by limited information (Parris, 2011<sup>[178]</sup>). This is because such emissions are nonpoint sources of pollution, i.e. they are sources of pollution for which it is generally not possible to trace back to the individual polluter. Digital tools can facilitate the conversion of agricultural sources of nonpoint pollution into more manageable point pollution, and sustainability of farming could be drastically improved, potentially bringing about additional environmental quality co-benefits (Khanna, 2021<sup>[7]</sup>). In such cases, supporting digital adoption as a means to achieve better sustainability could be a possible policy pathway.

174. At the same time, an observation arising from this literature review is that a majority of digital livestock technologies are of a **labour saving** nature, and such benefits are also reported for specialty crops, especially as they relate to automated harvesting and precision pest monitoring and control, and can be assumed to exist for row crops (although this feature may not be the most important driver of adoption for row crops). This may suggest a need in digital agriculture policy to explore further characteristics commonly omitted from traditional cost-benefit analyses, such as quality-of-life gains from adoption of digital technologies on farms and implications for labour and skills in the sector. In particular, this raises the question of the main reasons that drive technology adoption and the extent to which this is driven by quality of life incentives rather than productivity and sustainability drivers, which may be an equally important variable for agriculture policy-makers to consider.

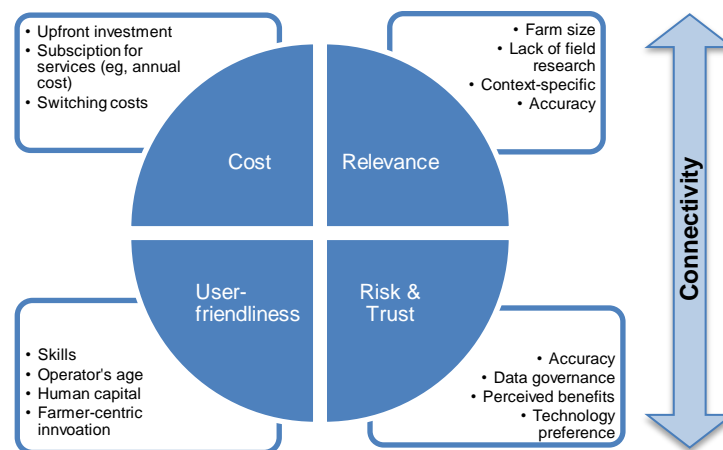
## **6.2. A range of other enabling factors should also be considered by governments to strengthen digital agriculture innovation systems**

175. The role for government in promoting an enabling environment for innovation and the adoption and diffusion of innovations throughout the agricultural sector and in supporting a **well-functioning agriculture innovation system** is well recognised (OECD, 2013<sup>[179]</sup>). In this respect, potential issues, such as the nature of any constraints to the generation, adoption and diffusion of digital innovations, need to be considered to

determine if the manner in which governments traditionally deliver agricultural innovation policy remains fit for purpose in light of the widespread digitalisation of the economy. This implies identifying whether there are weaknesses in the enabling environment for reaping the benefits of digitalisation in agriculture – and if so, whether there are areas for policy intervention that matter more, or less, and what other issues policymakers need to be thinking about.

176. Although the underlying data and methods used in the studies considered in this literature review vary substantially across countries, a few commonly identified enablers, barriers and constraints to adoption directly implicate possible policy responses. In particular, agriculture policymakers should focus on issues relating to infrastructure and connectivity, cost, relevance, user-friendliness and skills, and risk and trust-building to enable digitalisation to take place (Figure 8).

**Figure 8. Identified constraints to digital adoption on-farm**



Note: This is a synthesis figure of the authors' reading of the literature. The size of the wedges is not necessarily proportional to the importance of the factors, which will vary across farmers and operations.

177. Cost is reported as possibly the major perceived barrier to digital adoption, and this is likely to be especially the case for small farms. While equilibrium cost for digital technologies will be determined by markets, **ensuring competition** in the sector is likely to represent a first key step to help lower farmers' costs of digital technologies adoption and, ultimately, production costs of food and agricultural commodities. In recent years, US antitrust enforcement agencies have been more likely to cite innovation-related and lock-in on specific technologies concerns in legal challenges to mergers among agricultural firms. For example, the US Department of Justice in 2016 challenged John Deere's intended purchase of Precision Planting, LLC, alleging that a merger would decrease innovation in high-speed planters (USDOJ, 2016<sub>[180]</sub>). Decision-makers must ensure that rising concentration in input markets, should it continue, will not reduce the quality or quantity of digital innovations or pose risks to the physical viability of agricultural supply chains (Kenney, Serhan and Trystram, 2020<sub>[181]</sub>). Similarly, international trade policy must be considered – the extent to which trade in sensors, chips, and other necessary equipment and tools are subject to tariffs, and the degree of openness to trade in services will all matter in lowering costs, widening farmers' choices, and enabling digitalisation to take place (López González and Ferencz, 2018<sub>[182]</sub>; López González and Jouanjean, 2017<sub>[183]</sub>).

178. In a similar vein, the wide use of mobile phones and smartphones, and the reliance of many digital technologies on digital **connectivity** for optimal utility, all also point to the fundamental role of reliable and widely accessible high-speed internet for realising digital

gains in farming (Mark, Griffin and Whitacre, 2016<sup>[184]</sup>; LoPiccalo, 2021<sup>[185]</sup>). Provision of telecommunication services, however, involves high fixed costs and network externalities, generally resulting in natural monopolies. Through suitable regulation and investments, governments can boost the provision of telecommunication services relative to what would occur in a monopoly market in agricultural areas, thus improving digital infrastructure and reducing the potential for this pathway to be a limiting constraint (Birner, Daum and Pray, 2021<sup>[81]</sup>), also leveraging synergies with rural development objectives where appropriate.

179. In addition, private firms developing digital technologies for agriculture will often rely on large-scale collection of data on private farms, which can create a tension between perceived fairness in value capture in the data value chain. To address data-related issues, governments may need to consider enacting or strengthening capacity building in terms of **data governance** among farmers, and ensure farmers have contractual agency and legal guarantees in case of data misuse or data breaches to strike a balance between the interests of private firms and farmers (Jouanjean et al., 2020<sup>[186]</sup>).

180. At the same time, a lack of basic knowledge about digital offerings was also a common theme reported by studies as potentially hindering greater digitalisation. This suggests that to strengthen **extension services** to provide education to farm decision-makers may be warranted, particularly on digital and entrepreneurial skills, especially when social externalities such as environmental stewardship are impacted.

181. Nevertheless, **skills** and **human capital** are also inextricably linked to best farm management practice and effective integration of digital adoption in turn. The literature also pointed to the difficulty of using more sophisticated digital tools as a self-reported challenge for farmers, underscoring the persistence – and urgency of reducing – the digital divide. Indeed, while agricultural policy should certainly support up-skilling and re-skilling of the agricultural labour force, to build capacities and a more productive, sustainable and resilience sector, any study of digital agriculture must consider how changes in generational attitudes and behaviour, as well as structural changes, will affect interactions with technology. In particular, the utility derived from digital adoption may vary across farms and contexts in multiple ways, and across time. For example, average utility from adoption is likely to increase with increasing consolidation – as farm owners acquire new land that they know less well and for which they are looking to fine-tune processes, there are potentially higher returns to adoption of decision-support tools than for older farmers with smaller fields, who have acquired extensive knowledge of those fields over time.<sup>26</sup> Utility of adoption is also likely to be strongly associated with age. Younger farmers, who are increasingly digital natives, will tend to be endowed with basic digital literacy such that adoption may have higher returns as result of lower costs of investments in re-education. Inertia is another important behavioural constraint to be considered. For all these reasons, any policy aimed at digital agriculture should account for such dynamics in its underlying analysis.

182. Finally, while these policy insights can help to start thinking through some of these policy issues that matter for digital agriculture, it holds true that more information about drivers, enablers, constraints or actual barriers to adoption would be highly beneficial. These would allow farmers to overcome some barriers, and it would allow policymakers to determine whether and which policy interventions may be appropriate to target existing inefficiencies and constraints.

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<sup>26</sup> This is consistent with the observed strong relationship between greater farm size and adoption.

## Annex A. Description of Select Digital Agriculture Tools

### Description of Select Digital Agriculture Tools

183. Digitalisation refers to the adoption of ICTs (information communication technologies), including the Internet, mobile technologies and devices, as well as data analytics used to improve the generation, collection, exchange, aggregation, combination, analysis, access, searchability and presentation of digital content, including for the development of services and applications. There are, however, specific applications for the agricultural sector. This annex enumerates the set of major digital technologies currently being surveyed and considered in the literature for the production of row crops, livestock, fruit, vegetables, or tree nuts.

184. For ease of reference, this annex lists and describes technologies in alphabetical order. Within this enumeration, however, the technologies can be straightforwardly classified as belonging to one or more of three categories: 1) data/data collection, 2) decision support software/tools (DSS), 3) precision equipment or input adjustment.<sup>27</sup> These are indicated behind the name of each technology, in parentheses. For reasons identified above, the development of a new typology or more general framework for categorizing digital technologies is beyond the scope of this review.

185. The following is provided for contextual purposes. Given the large number of digital tools that have been developed recently or currently commercialised in OECD countries, it is not possible to construct an exhaustive list and set of descriptions. For a high-level overview of digital tools, especially as they are applied to crop production, readers are referred to (OECD, 2019<sup>[2]</sup>). For a detailed review of precision livestock farming in pasture-based systems, see (Aquilani et al., 2022<sup>[187]</sup>).

#### *Accelerometers (data collection)*

186. At the broadest level, accelerometers are electromagnetic devices that measure accelerating forces. In combination with digital systems, accelerometers generate data that are processed by algorithms to interpret livestock movement that signal behavioural patterns. These animal behaviours include feeding, drinking, walking, standing, sitting, and lying – among others. Commercialised technologies to date have focused on animal health and welfare, with applications for cattle, sheep, goats, swine, and horses.

#### *Automated Guidance/GPS/GNSS (precision equipment)*

187. There are different levels of automation for steering an agricultural vehicle. Relatively inexpensive navigation aids, known as visual parallel tracking devices for manual steering or, more commonly, lightbars, are being used by operators to visualise their position with respect to previous passes and to recognise the need to make steering adjustments if a measured geographic position deviates from the desired track. More advanced auto-guidance options include similar capabilities with the additional option of

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<sup>27</sup> This simplistic categorisation suggests a logical “sequence” of technology adoption starting with data collection tools and progressing to precision equipment. Such sequential adoption based on technology function can occur regardless of sector (row crops, livestock, and specialty crops), though tools can be adopted in isolation or “out of sequence.” For example, some precision equipment can be operated without data collected from the operator’s specific fields; similarly, certain decision support tools (like yield maps) can be used independently of other digital technologies.

automatically steering the vehicle using either an integrated electrohydraulic control system or a mechanical steering device installed inside the cab.

***Automated Heat Detection (data collection)***

188. Heat detection is a key driver of reproductive performance in the dairy herd. Automated heat detection can be used for identifying pre-mating heats, cows that need to be submitted for artificial insemination in the mating period, and those that aborted and resumed cycling later. There are two main types of automated heat detection systems: monitors of individual cow activity or camera inspection of heat patches.

***Controlled Traffic (precision input adjustment)***

189. Controlled traffic farming is a system that confines all machinery loads to the least possible area of permanent traffic lanes. It is used to reduce heavy or repeated agricultural machinery passes on the land.

***Crop Sensors (data collection)***

190. Crops sensors help farmers to improve crop conditions by measuring plant water potential, yield quality, stage of development (ripeness), nutrient levels, pest and disease infections, and various morphology factors such as biomass, leaf area, and distribution of plants and organs. Sensors may be attached to or embedded in mobile farm equipment, or they may remain stationary. A large number of sensors remain under development, and the many that are currently commercialised have experienced quality improvements over time.

***Digital Pasture Management Tools (data collection, precision equipment)***

191. Precision pasture management is a compilation of various tools, although they commonly include pressure sensors, plate meters, and probes, the latter commonly used to measure temperature and other attributes of animal health. Rising plate meters are tools that consist of a weighted plate and shaft that are used to measure pasture productivity (i.e. quantity of pasture cover) and pasture growth rates. Pressure sensors are various tools for measuring pressure and weight, with a wide range of application, including jaw movement in cattle, egg weights, and gaits in goats. Satellite and drone imagery are also sometimes considered to be digital pasture management tools.

***Distributed Ledger Technologies (decision support tool)***

192. These technologies are digital ledgers (basic transactional recording technologies central to commerce) shared by multiple entities operating on a distributed network. They are part of a larger architecture that can ensure recorded information represents reality (e.g. state of a physical commodity). Among the most common examples of these tools are blockchain technologies (lists of records, i.e. blocks, linked together through cryptography) that underlie cryptocurrencies. In agriculture, DLTs can be used for food export certification, tracking inputs and transparency of food chains, and warehousing and tracing output with quality assurances (Commandré, Macombe and Mignon, 2021<sup>[188]</sup>; Griffin et al., 2021<sup>[189]</sup>).

***Milking Robot (precision equipment)***

193. Automated milking systems are a form of ‘voluntary’ milking systems in which dairy cows are not manually milked (conventionally twice per day). These systems involve the use of a chamber with RFID detection that determines if the cow needs to be milked based on the time of previous milking and other information. If so, a robotic arm system

with sensors is activated, which locates individual teats of the cow's udder and automatically applies milking cups. Upon completion, a gate opens, the cow is permitted to leave, and a self-cleaning system is activated prior to the arrival of another cow.

#### ***Precision Weighing Scales (data collection)***

194. Scales have been used for centuries to determine the weight of livestock raised for meat. Recently, automated platform weighing scales have been used for broiler and turkey flocks, with the possibility for installation directly into the perching systems of enriched colony houses. RFID sensors have been used in tandem with weighing scales to quantify the movement, feeding, and nesting behaviours of individual birds within group housing (Xin and Liu, 2017<sup>[190]</sup>).

#### ***Satellite/ Drone Imagery (data collection)***

195. Remotely sensed imagery from satellites, aerial, and small unmanned aerial systems (UAS or drones) have been available in different resolutions and wavelengths. The availability of imagery predates many digital technologies by decades, e.g. Landsat. Similar to other data intensive technology, imagery requires interpretation before actionable decisions can be made. Although substantial research effort has focused on automating farm recommendation from imagery, commercialisation of these processes have not been widespread. Substantial human capital is required to make use of imagery with little to no quality-of-life improvements for the farm operator. Differences between platforms are negligible and usually segregate by resolution and time to access the data after imagery collected; therefore imagery from satellites, aircraft, and drones are considered near-perfect substitute.

#### ***Soil Maps (decision support tool)***

196. Digital soil mapping (DSM, also known as predictive mapping) aims at the quantitative creation of geographically-referenced soil databases and maps at various scales. It uses a wide range of tools to acquire, combine, and process information on soil nutrients and composition, and the environment, including relief parameters, vegetation indices, proximal and remote sensing data. Soil maps help to create, calibrate and validate spatial prediction models, produce maps and georeferenced databases of soil properties tailored to user demands, and assess the accuracy of predicted data.

#### ***Telemetry (precision equipment)***

197. The use of telemetry systems consists in the implementation of an information system to provide data on irrigation parameters throughout a year, also taking into consideration other meteorological parameters. The need for a telemetry system for irrigation is emphasised by the market's interest in having access to fully automated monitoring and automation solutions for energy efficient and cost-effective agricultural crops.

#### ***Tracking of Livestock (decision support tool)***

198. Grazing livestock are geographically tracked using technologies such as wirelessly connected GNSS-enabled collars and other sensors. Radio-Frequency Technology (RFID) tags are used in dairy and feedlots to track individual animal consumption of feed or output of products, e.g. milk. RFID tracking systems use a unique identifying transponder (tag) and an antenna such that when the tag is in proximity to the antenna, the tag's identity, time stamp, and location (of the antenna) are sent to a central repository. By contrast, GNSS-

based tags have less variable expense, although they cannot be used indoors, and their development has been lagging for swine and poultry.

#### ***Variable Rate Technology (precision input adjustment)***

199. Variable-rate technology (VRT) allows seed, fertiliser, chemicals, lime, gypsum, irrigation water and potentially other farm inputs to be applied at different rates across a field, without manually changing rate settings on equipment or having to make multiple passes over an area. These technologies are contrasted with uniform rate (UR) applicators that only permit constant rates of input application within or across fields. These technologies usually rely on GNSS-enabled controllers that have been mounted on the equipment. Map-based VRT relies on pre-processed “prescriptions” from georeferenced data, while on-the-go VRT makes use of real-time sensor data processed via algorithms.

#### ***Virtual Fencing (data collection)***

200. Digital fencing systems replace the traditional physical barrier with an acoustic stimulus. In close proximity to the virtual fence, the animal receives an audible signal to stop its approach; if this audible clue is ignored, the animal receives an electric shock. The system includes delineation of the grazing area (by the farmer), collars with GPS trackers for the livestock, and a battery-powered appliance that administers the shock.

#### ***Yield maps (decision support tool)***

201. Visualisations of georeferenced crop yields and yield variability continuously over space (across fields) are made using data from sensors and other tools associated with geospatial coordinates. Farmers use yield maps to assess spatial patterns in yields that could indicate the need for variable input adjustments or other customised area-based management.

#### ***Yield monitors (data collection)***

202. Sensors are mounted on combine harvesters and cotton pickers/strippers that measure in real-time the amount of grain that passes through the combine when the crop is being harvested. Yield monitors have been available since the early 1990s and have been key in the development of precision agriculture because they were one of the first means to define, quantify, and characterise the within-field variability in crop production.

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