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Digital innovations for sustainable and resilient agricultural systems

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Abstract

Digitalisation is rapidly transforming the agri-food sector. This paper investigates emerging opportunities, challenges and policy options. We show that digital innovations can contribute to more sustainable and resilient agricultural systems. For example, digital innovations enable increased productivity, reduced environmental footprints and higher resilience of farms. However, these optimistic outcomes of increasing digitalisation of the agricultural sector will not emerge on their own, but this development comes with several challenges, costs and risks, e.g. in economic, social and ethical dimensions. We provide policy recommendations to explore opportunities and avoid risks. Moreover, we discuss implications for future research in agricultural economics.

Keywords: precision agriculture, smart farming, digitalization, big data, technology

JEL classification: O3, Q1, Q2, Q5

1. Introduction

There are many challenges currently facing the state of agriculture at global and local scales. The demand for food as well as for other ecosystem services provided by the agricultural sector is increasing (FAO, 2018; Gouel and Guimbard, 2019; Tilman *et al.*, 2011). At the same time, the underlying agricultural production potential is under strong pressure, for example, due to climate change and soil degradation (e.g. Borrelli *et al.*, 2020; Ortiz-Bobea *et al.*, 2021; Webber *et al.*, 2018; Wuepper, Borrelli and Finger, 2020). As a result, delivering both private and public goods is increasingly difficult and becomes more costly. Agriculture also faces accumulating economic, environmental and institutional shocks and challenges. Examples include extreme

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weather events, market shocks, pandemics and wars (e.g. Meuwissen *et al.*, 2021; Schmitt *et al.*, 2022). This reduces the resilience of the agricultural and food sectors (Meuwissen *et al.*, 2019). Moreover, the massive environmental footprints of the agri-food system need to be reduced (Foley *et al.*, 2011). To this end, resource overuse, environmental pollution (e.g. due to fertiliser and pesticide overuse), greenhouse gas emissions and biodiversity loss must be addressed (Chaudhary, Gustafson and Mathys, 2018; Kanter *et al.*, 2020; Pe'er *et al.*, 2014; Wuepper, Borrelli and Finger, 2020; Wuepper, Tang and Finger, 2023). Accordingly, recent policy goals such as within the Kunming-Montreal Global Biodiversity Framework and the Farm to Fork strategy of the European Union provide ambitious environmental targets that shall be met in short time frames (e.g. Candel, Pe'er and Finger, 2023; Schebesta and Candel, 2020).[1] Finally, social sustainability and animal welfare problems remain areas that need urgent action (e.g. Meemken *et al.*, 2021). To address these combined challenges, the agricultural sector needs to deliver more, with massively smaller footprints, despite reduced resources. In this way, various conflicts can emerge, e.g. between food production, profits and environmental protection (Wuepper *et al.*, 2020; Wuepper, Tang and Finger, 2023).

At the same time, digitalisation is rapidly transforming entire societies, including the agri-food sector, and agriculture is now undergoing its 'fourth revolution' (Walter *et al.*, 2017). This development can potentially contribute to addressing the big challenges of the agricultural sector, i.e. to increase productivity, reduce footprints and conserve natural resources, and thus can contribute to reaching the Sustainable Development Goals (Basso and Antle, 2020; FAO, 2022; Khanna *et al.*, 2022; Lajoie-O'Malley *et al.*, 2020). For example, the agricultural sector increasingly relies on new digital technologies such as precision farming, the internet of things, remote sensing, unmanned aerial vehicles, data-driven applications, artificial intelligence, digital twins, robotics and many more. Moreover, digital technologies transform food value chain interactions, governance systems and communication platforms (e.g. Ehlers *et al.*, 2022; Ehlers, Huber and Finger, 2021). This development has the potential to improve and transform production and management decisions and to reduce trade-offs, e.g. enable developments towards higher productivity, sustainability, resilience and animal welfare, all at the same time (e.g. Walter *et al.*, 2017; Wolfert *et al.*, 2017). Along these lines, digital innovations are expected to be 'key to developing sustainable agriculture' (Walter *et al.*, 2017).[2] However, optimistic outcomes will not emerge on their own, as the digitalisation of the agricultural sector also implies several challenges,

1 For example, the Farm to Fork strategy aims to reduce (i) nutrient losses, (ii) the use and risk of chemical pesticides and (iii) the sales of antimicrobials for agriculture and (iv) greenhouse gas emissions, all by 50 per cent by 2030 (see Schebesta and Candel, 2020). Other European countries like Switzerland have initiated similar plans, e.g. to reduce nutrient losses and pesticide use risk substantially, while maintaining food production levels (e.g. Finger, 2021).

2 Note, however, that this by no means implies that 'only' digitalisation can contribute to more sustainable and resilient agriculture. In contrast, a combination of various approaches, technologies, measures and behavioural changes is needed in the agricultural and up- and downstream industries (see, e.g. Möhring *et al.*, 2020).

costs and risks, e.g. in economic, social and ethical dimensions (e.g. Walter *et al.*, 2017). Thus, questions regarding how to untap potential opportunities while avoiding risks remain.

This paper aims to address these questions and to identify the potential of digital innovations to address production, sustainability and resilience challenges. More specifically, we investigate how digital innovations can be used to contribute to increasing productivity, lowering environmental footprints and adapting to increasing resilience challenges. To this end, we take a farmer-centred agricultural system perspective and provide an analysis through an agricultural economic and policy lens. We develop a systematic framework and an overview of digital technologies, their opportunities and challenges, as well as possible policy interventions to untap the potential of digitalisation to contribute to more sustainable and resilient agricultural systems. This paper focuses mainly on European agriculture and related agricultural policy goals.

The remainder of this paper is structured as follows: we first provide an overview of the existing and emerging digital technologies and applications in the agricultural sector. Next, we analyse how digital technologies and approaches can enable more sustainable and resilient agricultural systems and can reduce inherent trade-offs. Subsequently, we illustrate the limitations and risks caused by the increasing digitalisation of the agricultural sector. Based on this background, we discuss the role of policy in untapping the potential benefits of digitalisation while reducing its risks. We also outline how digitalisation may change future agricultural policymaking decisions. Finally, we draw policy conclusions and identify opportunities for agricultural economic research at the interface of digitalisation, sustainability and resilience.

2. Background on digitalisation of the agricultural sector

The use of digital technologies is growing exponentially in quantity and in scope, shaping the digital transformation of agricultural production and the agri-food sector at large (see, e.g. MacPherson *et al.*, 2022; Walter *et al.*, 2017; Wolfert *et al.*, 2017). Digital technologies have the potential to be widely used in all fields of agricultural production, e.g. ranging from arable systems and livestock production to horticultural production and greenhouses (e.g. Wolfert *et al.*, 2017).[4] Digital tools, technologies and approaches have become increasingly interconnected, often in real time. The combination of smart sensors, digital technologies and applications at the level of the field, stable, farm and value chains is often also referred to as 'smart farming' (e.g. Walter *et al.*, 2017; Wolfert *et al.*, 2017).

In this section, we aim to provide an overview of currently used and emerging digital technologies, tools and applications. To this end, we suggest a

For global reviews on digital agriculture, see e.g. Wolfert *et al.* (2017), Finger *et al.* (2019), Khanna *et al.* (2022), FAO (2022) and McFadden *et al.* (2022).

4 Note that *digitalisation* implies more than *digitisation*, i.e. more than replacing components from analogue to digital, but involves fundamentally new processes and approaches (e.g. Ehlers, Huber and Finger, 2021; Fielke, Taylor and Jakku, 2020).

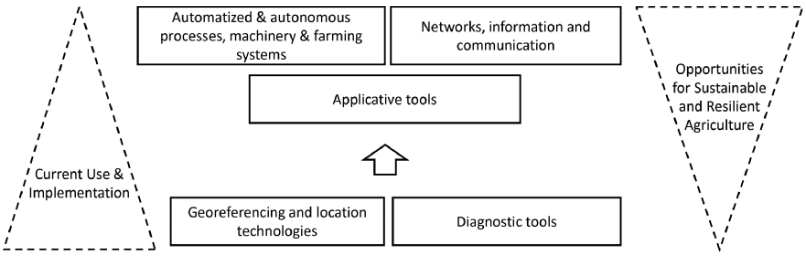

Fig. 1. Dimensions of digitalisation in agriculture.
Note: The combination of georeferencing and location technologies and diagnostic tools provides the basis for improved management (applicative tools) as well as further steps such as automatised and autonomous processes and new networks. Applicative tools, automatised and autonomous processes and new networks provide the largest sustainability and resilience opportunities but are currently used to the smallest extent.

framework combining five key dimensions of digital innovations: (i) georeferencing and location technologies; (ii) diagnostic tools; (iii) applicative tools; (iv) automatised and autonomous processes; machinery and farming systems and (v) networks, information and communication (Figure 1).

Georeferencing and location technologies, e.g. global navigation satellite systems and geographical information systems, are key elements for many digital developments and applications in the agricultural sector and are already widely used (e.g. Weersink *et al.*, 2018). Georeferencing and location technologies allow the use of guidance systems and controlled traffic farming, i.e. highly localised applications of operations (e.g. input application and harvesting). This enables some reductions in private costs and environmental externalities by avoiding redundant applications of inputs and implying fuel savings (e.g. Gasso *et al.*, 2013). Moreover, these technologies allow the exact execution of plans as designed beforehand (e.g. seeding maps) and documenting all steps of production, i.e. what was done, exactly how, where and when (Ehlers, Huber and Finger, 2021). Georeferencing technologies are also increasingly used in animal production systems, e.g. to locate animals and track movements both in- and outdoors (e.g. Dos Reis *et al.*, 2021; Hindermann *et al.*, 2020; Zhang *et al.*, 2021).

The development and use of digital *diagnostic tools* have grown rapidly and allow data to be gathered and monitoring systems to be used using sensing techniques along various temporal and spatial scales. The range of such sensors may go from handheld devices, sensors and scanners mounted on tractors to remote-sensing technologies, e.g. based on unmanned aerial vehicles such as drones and satellite imagery (see, e.g. Späti, Huber and Finger, 2021). Thus, information obtained with digital diagnostic tools can range from the level of a single leaf, a plant and parts of fields to entire landscapes (Mulla, 2013). Diagnostic tools provide a wide range of production-relevant data, for example, on vegetation, crop biomass, nitrogen nutrition status, soil moisture and weed occurrence (e.g. Anderegg *et al.*, 2023; Sa *et al.*, 2018; Walter, Liebisch and

Hund, 2015; Wang, Zhang and Wang, 2006). Diagnostic tools are also highly relevant in animal production systems. Sensors and devices allow us to track animal health, welfare and production aspects in real time (e.g. Dos Reis *et al.*, 2021; Lovarelli, Bacenetti and Guarino, 2020; Zhang *et al.*, 2021). Digital innovations also revolutionise agricultural performance measurement. Yield monitors, e.g. sensors at harvesters, allow highly localised performance measurement regarding the quantity and quality of harvest (Fulton *et al.*, 2018). Moreover, remote sensing increasingly allows the effective and efficient real-time and high-resolution quantification of yields, also in systems where this is difficult traditionally, such as grassland systems that are frequently grazed or mowed (Vroege, Vrieling and Finger, 2021b). In livestock production systems, for example, milking robots enable the documentation of animal-specific performance records (e.g. Martin *et al.*, 2022). In summary, there is a vast and increasing amount of diverse data and information collected at farms that can also be connected with each other and with other data sources, such as weather, pest occurrence and other environmental conditions (see, e.g. Dubuis *et al.*, 2019).

To untap the full potential of digital innovations, however, often requires that the collected data from georeferencing and diagnostic tools are combined with other components (Figure 1). A key element is *applicative tools* that allow decision-making to be adjusted based on collected information, increasingly even in real time and automatised (e.g. Wolfert *et al.*, 2017). For example, using precision farming, the distribution of fertiliser or pesticide use within a field as well as the timing of its application can be guided by data collected from various sources, e.g. sensors documenting vegetation health and yield monitors documenting yield potentials (e.g. Späti, Huber and Finger, 2021). Precision livestock farming is also of increasing relevance, allowing the adjustment of feeding and veterinary measures at the level of individual animals and even allowing preventive reactions to arising problems (Berckmans, 2017; Lovarelli, Bacenetti and Guarino, 2020; Zhang *et al.*, 2021). The application of inputs in precision farming is often based on new technologies, requiring costly investments, for example, fertiliser spreaders, seeders and pesticide sprayers that allow for variable rate application. However, conventional machinery and equipment can also be used to transform digital data into adjusted management decisions, for example, if the information is used to define larger 'management zones', a smaller number of regions within a field, in which intensities of seeds, fertilisers, pesticides, irrigation, etc., are adjusted (Finger *et al.*, 2019). Big Data technologies[5] and cloud-based and high-performance computing allow us to realise data-intensive applications increasingly more efficiently (e.g. Lokers *et al.*, 2016). Furthermore, artificial intelligence[6] increasingly becomes a vital element to link different sensors and data sources towards actual decision-making (e.g. Galaz *et al.*, 2021).

5 The term Big Data refers to the increasing Volume, Velocity, Variety and Veracity of agricultural data (Coble *et al.*, 2018; Lokers *et al.*, 2016).

6 This can include various technologies, e.g. machine learning or deep learning methods (e.g. Galaz *et al.*, 2021).

Along these lines, digital technologies also enable the switch to *automatised and autonomous processes, machinery and farming systems* (FAO, 2022). This comprises fully automated application of inputs, the detection and control of weeds within fields and feeding systems as well as the use of robots and other autonomous operating devices (Mogili and Deepak, 2018). While the use of fully autonomous operations and robots is already feasible from a technical and economic point of view for a wide range of production systems, regulatory issues still limit their application (e.g. Lowenberg-DeBoer *et al.*, 2022). Nevertheless, autonomous processes, machinery and robots are expected to be of large future relevance to carry out all kinds of activities on fields, in barns, in greenhouses and in vertical farms, without any human operator and decision-makers being directly involved (FAO, 2022). For example, the 'Hands Free Hectare' project in the UK shows how automated machines can grow, manage and harvest crops fully autonomously (see, e.g. Lowenberg-DeBoer *et al.*, 2021; Maritan *et al.*, 2023). In livestock production, autonomous technologies are increasingly relevant, e.g. in dairy production and especially for indoor production systems such as for pigs and poultry, so that manual labour and human decision-making are partly or even fully replaced, transforming farms into 'cyber-physical management systems' (van Hilten and Wolfert, 2022) (e.g. FAO, 2022; Fielke, Taylor and Jakku, 2020). Asseng and Asche (2019) even present showcases for entire 'farms without farmers'.

Finally, digital tools can revolutionise *networks, information and communication*. The interconnection of smart sensors not only allows for improving and automatising operations but also enables new connections among machines, operations and people and allows improved information exchange (van Hilten and Wolfert, 2022). While digital innovation in the past was focused on standalone applications at the level of individual farms (e.g. automating specific processes and procedures), this is now followed by an increasing focus on highly connected smart farming approaches (Wolfert *et al.*, 2023). Sensors, monitoring devices and machines are increasingly connected, e.g. involving the internet of things, computing and data sharing (Galaz *et al.*, 2021).[7] Along these lines, the use of digital twins (of machines, processes, fields, animals and entire farms and production chains) is emerging (e.g. Pylianidis, Osinga and Athanasiadis, 2021; Verdouw *et al.*, 2021). Digitalisation rapidly changes how individual persons (e.g. farmers and consumers), organisations (e.g. farmer associations) and networks operate and communicate (e.g. social media and online platforms) (Klerkx, 2021). This also affects agricultural knowledge, advice and extension systems (e.g. Fielke, Taylor and Jakku, 2020; Klerkx, 2021), as well as food value chain decisions, governance systems and even international trade (e.g. Bueno Rezende de Castro and Kornher, 2023, Ehlers *et al.*, 2022; Ehlers, Huber and Finger, 2021). However, digital systems spanning upstream industries to farmers, processors, consumers and policymakers are still only in their emerging phase (e.g. Wolfert

7 Galaz *et al.*, 2021), for example, estimate that in 2023, there are approximately 12 million 'internet-of-things' sensors installed and in use on farms globally.

et al., 2023). The increased use and connectivity of sensors will increase the transparency of agricultural production practices, for example, by enabling real-time records of all production steps from the seeding to the final product on the shelf. Many digital innovations and approaches rely on new network technologies, such as blockchain and new-generation communication technologies (e.g. 5G or 6G). These allow, for example, cost-efficient real-time combinations of many diagnostic and applicative tools and enable automatised and autonomous systems (van Hilten and Wolfert, 2022). Such technologies also allow data processing and analysis to be increasingly executed remotely on servers, e.g. based on cloud storage and analytics, offsite and not on individual machinery and farms. This may reduce costs and increase the resilience of new digital technologies and devices, e.g. because no processing capacity is needed on-site (e.g. on each piece of machinery or in each barn).

Digital tools and services have become increasingly essential elements of the business model of various industry players up- and downstream of the agricultural sector. For example, traditional input suppliers (e.g. currently specialised in selling seeds and pesticides) acknowledge that future profits are increasingly coming from 'selling positive social and environmental outcomes through the sale of big-data generated information' (Lajoie-O'Malley *et al.*, 2020: 2). The digitalisation of the agri-food sector also implies that in addition to large agricultural technology providers and agricultural transnational corporations (e.g. Bayer, John Deere or Syngenta), new actors, e.g. tech firms such as Alphabet (Google), Amazon or SAP, emerge as novel, relevant players (e.g. Fraser, 2022).

3. Potential of digital innovations to enable more sustainable and resilient agricultural systems

This section reviews and synthesises how digitalisation can contribute to rendering agricultural systems more sustainable and more resilient.

3.1. Digitalisation can contribute to more sustainable agricultural systems

To analyse how the digital innovations introduced in Section 2 can contribute to sustainability, we assess different technologies in the Efficiency, Substitution and Redesign framework (e.g. Hill and MacRae, 1996; Pretty, 2018; Pretty *et al.*, 2018) (Figure 2). In Table 1, we present examples in more detail.

Digital innovations can increase the *Efficiency* of farming systems. For example, guidance systems and controlled traffic farming allow the avoidance of overlapping operations and thus reduce input use and fuel consumption without affecting production levels (e.g. Gasso *et al.*, 2013). Moreover, variable rate technologies (i.e. applicative precision farming tools) enable a more targeted use of inputs (e.g. fertiliser and pesticide use), which reduce both private variable costs and external environmental costs (Finger *et al.*, 2019). Along these lines, adopting precision livestock farming (e.g. adjusted feeding and veterinary practices) can improve environmental and animal welfare

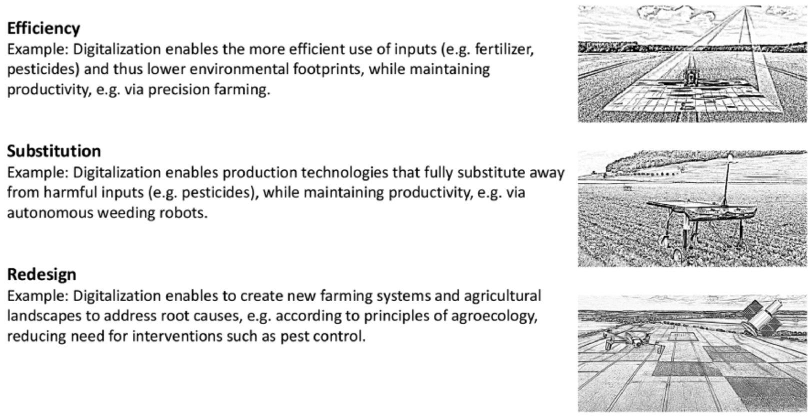

Fig. 2. Digitalisation can contribute to more sustainable agricultural systems via Efficiency, Substitution and Redesign.
Note: The upper image illustrates how automated systems, based on variations in soil conditions, crop development, nutrient status and pest presence, can help to tailor crop management temporally and spatially. *Source*: https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_focus_group_on_precision_farming_final_report_2015.pdf. The middle image shows an autonomous weeding robot by the Swiss company Ecorobotix, which can identify weeds in a field and control them also mechanically. *Source*: https://ecorobotix.com/en/. The bottom image shows the schematic framework of the patchCROP project, which is a living laboratory for digital tools used for more diversity in agricultural landscapes realised by the research institute ZALF in Germany. *Source*: https://comm.zalf.de/sites/patchcrop/SitePages/Homepage.aspx.

outcomes while maintaining productivity (Berckmans, 2014; Scholten *et al.*, 2013). Digitalisation can also enable farmers to *Substitute* environmentally harmful practices with less harmful approaches, e.g. substitute herbicides with mechanical approaches by weeding robots or by replacing hazardous work in the field or stable (Figure 2). By enabling Efficiency and Substitution, digital innovations can create environmental and animal welfare benefits as well as economic (e.g. cost savings) and social (e.g. avoiding hazardous working conditions) benefits without reducing food production or the provision of other ecosystem services (Table 1).

However, Efficiency and Substitution still focus ‘only’ on addressing the existing problems of current agricultural systems, while the causes of the problems remain. Digital innovations also allow us to go beyond these steps and to enable a transformative *Redesign* of agricultural systems.[8] More specifically, digitalisation can support farmers in establishing new farming systems that face fewer (or no) problems to be ‘cured’ (e.g. Finger, 2021; Pretty, 2018; Pretty *et al.*, 2018). For example, digital innovations can enable the efficient redesign of fields and even agricultural landscapes so that problems such as pest pressure and nutrient losses can be avoided or completely new production

8 Thus, Efficiency and Substitution are also referred to as ‘shallow sustainability’, while Redesign, in contrast, is referred to as ‘deep sustainability’ (Hill and MacRae, 1996).

Table 1. Examples of how digitalisation can create sustainable agricultural systems via Efficiency, Substitution and Redesign

Dimension	Underlying principle	Examples
Efficiency	Digital technologies allow increases in efficiency (i.e. cutting waste) that enable us to reduce footprints without reducing production levels.	Precision farming enables the more efficient use of inputs such as nitrogen, pesticides and irrigation within the field without reducing crop yields (e.g. Finger *et al.*, 2019). For example, Argento *et al.* (2021) show that nitrogen use in wheat production can be reduced by 5–40%. Balafoutis *et al.* (2017) show that reductions in herbicide use based on precision farming could be up to 90%. In orchards, sensors allow farmers to identify individual trees to be treated with pesticides, so that pesticide use can be reduced by up to 50% (Asaei, Jafari and Loghavi, 2019). Guidance systems and controlled traffic farming reduce traffic and inefficient operations (e.g. tillage, seeding and harvesting) and reduce greenhouse gas emissions and the use of inputs (this can reduce the use, for example, of fertilisers (1–26%), pesticides (1–26%) and fuels (23%) (Gasso *et al.*, 2013).
Substitution	Digital technologies allow to substitute inputs and procedures possibly harmful to the environment and human health with low-footprint approaches or to substitute away from costly resources such as labour, without reducing production levels.	Machine-vision-based weeding robots identify weeds and remove them mechanically, allowing to fully substitute herbicide use (e.g. Anderegg *et al.*, 2023, FAO, 2022, Li *et al.*, 2022). Digital innovations and automated processes can enable alternative pest control systems. In Switzerland, for example, a widespread switch to biological control of the European corn borer (*Ostrinia nubilalis*) with parasitoid wasps (*Trichogramma brassicae*) was enabled by an efficient application using automated drone-based positioning in maize fields (Erfurt, 2021). Insecticide used to control the European corn borer is fully avoided in this example. Hazardous work, e.g. exposing farm workers to pesticides, can be substituted using digital innovations. For example, using unmanned aerial vehicles and robots for pesticide application avoids adverse impacts on human health (e.g. Mogili and Deepak, 2018).

(continued)

Table 1. (Continued)

Dimension	Underlying principle	Examples
Redesign	Digital technologies enable us to create agricultural systems that face a lower need for interventions, without reducing production levels.	A combination of technologies allows the creation of new, more diverse farms and farming systems and more diverse landscapes that face lower pest pressure and lower need for external inputs (e.g. Donat *et al.*, 2022). Digital twins of agricultural systems and units (e.g. a field or an animal) forecast and predict potential problems (e.g. diseases) allowing early intervention to fully avoid the use of critical inputs such as pesticides or antibiotics (Pylianidis, Osinga and Athanasiadis, 2021). Automatised approaches in new production systems such as vertical farms allow us to avoid specific problems (e.g. pest pressure) and, for example, enable the reuse of most water and minimal use of pesticides and avoid all nutrient losses (Abbasi, Martinez and Ahmad, 2022, Asseng *et al.*, 2020).

systems that require minimal external inputs can be created (e.g. Donat *et al.*, 2022; Asseng *et al.*, 2020) (Figure 2, Table 1). Such Redesign and associated transformative changes in agricultural systems usually require going beyond specific technologies but require combinations of different digital innovations, e.g. using combinations of applicative tools, autonomous processes and new networks (Figure 1).

While the use of digital innovations towards more Efficiency and Substitution can often be implemented in short time frames (as the technologies are already on the market), focusing only on them alone would be insufficient. The major transformative opportunities of digital innovations to contribute to a deep transformation of agricultural systems also require a focus on Redesign (e.g. Ewert, Baatz and Finger, 2023). Using digital innovations for the Redesign of agricultural systems, however, often implies longer time frames (e.g. as changes in agricultural landscapes and crop rotations require multiple years) and are often more complex and more costly. Thus, digital innovations shall be used to exploit both short-term opportunities based on Efficiency and Substitution and long-term opportunities arising from Redesign.

However, digitalisation can contribute to reduced environmental footprints, improved animal welfare and higher economic and social performance of agricultural systems beyond Efficiency, Substitution and Redesign (see, e.g. FAO, 2022; Finger *et al.*, 2019; Walter *et al.*, 2017). Here, we list some additional dimensions that are potentially of large economic and policy relevance.

Precision conservation is a further area with great potential to increase the sustainability of agricultural systems that extends the ideas of Redesign (Basso, 2021). Precision conservation uses digital technology, data and algorithms to target conservation practices that maximise environmental benefits while reducing economic costs (e.g. Delgado and Berry, 2008). Digital tools are used to identify optimal areas for conservation (e.g. set-aside or high biodiversity areas) and enable the creation of mixes of agricultural production and high-ecological value patterns at the field or landscape level (e.g. Basso, 2021; Delgado and Berry, 2008; Mouratiadou *et al.*, 2023). Ecologically important measures, such as buffer and flower strips, fallow land and other elements to increase biodiversity (e.g. lapwing nesting sites within fields), can be established to maximise ecological impacts and minimise economic (opportunity) costs, e.g. if these elements are placed at points in fields where yield potential is low. Precision conservation can increase the efficiency of delivering a wide range of ecosystem services, such as regulation services (e.g. carbon sequestration), cultural ecosystem services (e.g. recreation) and supporting services (e.g. biodiversity provision) (Elmiger *et al.*, 2023; Huber and Finger, 2020). Such efficient provision of ecosystem services is of increasing economic relevance for European farmers, as incomes increasingly depend on public and private payment schemes that incentivise the realisation of various ecosystem services (e.g. Elmiger *et al.*, 2023; Möhring and Finger, 2022).

Digital innovations can affect supply chains so that more sustainable production at farms can be stimulated. For example, digital tools allow farmers to better connect more directly to consumers, e.g. by creating novel, bidirectional information opportunities (e.g. on production practices and consumer demands) and creating more direct market platforms (see, e.g. Fuentes, Cegrell and Vesterinen, 2021). Shorter supply chains can facilitate the adoption and diffusion of more sustainable agricultural practices (e.g. by better communicating details of production methods and enabling higher producer prices) (see, e.g. Finger, Zachmann and McCallum, 2023). Moreover, sensors, DNA barcoding, blockchain technologies and novel databases can enable real-time crop-, product- and traceability data in the entire food value chains locally and globally (van Hilten and Wolfert, 2022; Weersink *et al.*, 2018). Higher transparency may also enable farmers to compensate for more sustainable production. Product-specific environmental footprints can be calculated based on the actual input used in the field and can be communicated on final products in stores. This may also allow us to go beyond the dichotomy of labels (e.g. organic vs. nonorganic products) (Meemken and Qaim, 2018). Such a step may make sustainable farming practices more profitable for farmers. Moreover, higher traceability may reduce concerns about food fraud and mislabelling concerning environmental impacts and animal welfare (Weersink *et al.*, 2018). Digital opportunities can also contribute to avoiding food losses and waste along the entire food value chains, e.g. by adjusted logistics and cooling and by allowing real-time adjustments of farm-level management decisions to meet downstream demand for product quantity and quality (e.g. Defraeye *et al.*, 2019).

Increased transparency in digitalised agri-food systems may also enable more effective and efficient monitoring and enforcement of sustainability standards (Meemken *et al.*, 2023). This could increase incentives for more sustainable agricultural practices for all value actors of the agri-food sector. Governmental and private sustainability standards (e.g. for labels and agri-environmental schemes) and corporate due diligence regulations face key challenges in establishing effective, efficient, transparent and fair monitoring of compliance (Meemken *et al.*, 2023, e.g. Sellare *et al.*, 2022). Digital approaches, as presented in Section 2, have the potential to revolutionise such monitoring systems (Meemken *et al.*, 2023). For example, remote sensing increasingly allows for real-time tracking of land use and specific management practices as well as to identify deforestation, using both global (e.g. satellite imagery) and local scales (e.g. based on unmanned aerial vehicles) (e.g. Curtis *et al.*, 2018; Ehlers, Huber and Finger, 2021).[9]

Sustainability assessments of digital innovations comprise environmental, social and economic perspectives. Thus, a fundamental question is whether and which digital technologies pay off and how economic rents are distributed. This determines whether and which digital innovations are actually used, by whom, how and where. Many technologies described earlier provide economic opportunities to farms. Examples include cutting variable costs (e.g. by reducing fertiliser and pesticide use), increasing productivity, substituting costly inputs (e.g. labour) and enabling the efficient provision of ecosystem services and thus enabling more efficient access to government payment schemes (e.g. allowing to receive more payments for ecosystem services) and to specific marketing channels (e.g. allowing to sell for higher prices). However, adopting digital innovations on the farm often requires large investments (e.g. in machinery, software and knowledge). Such investments are only viable for some farms and technologies (e.g. Finger *et al.*, 2019). Thus, currently, only some farms and farming systems actually can benefit from the entire spectrum of digital technologies presented in Section 2, i.e. ranging from diagnostic to applicative tools and finally towards automated and autonomous processes. In general, more complex precision farming technologies (e.g. based on variable input use and automated processes) are currently adopted less frequently (Finger *et al.*, 2019; McFadden *et al.*, 2022). More sophisticated technologies are usually more capital intensive, implying that fewer farms can afford them. While georeferencing and diagnostic tools have become increasingly standard in agricultural machinery, translation into widespread uptake of applicative tools, automated and autonomous processes and new networks is still limited (e.g. Barnes *et al.*, 2019; Finger *et al.*, 2019; Groher *et al.*, 2020; Kamilaris, Kartakoullis and Prenafeta-Boldú, 2017). For example, the uptake of variable rate input application of fertiliser and pesticide use is currently still small in

9 However, Meemken *et al.* (2023) show that many open points remain, for example, technological uncertainties and the lack of efficient digital monitoring opportunities for social sustainability standards.

European agriculture[10] (Barnes *et al.*, 2019; Finger *et al.*, 2019; Groher *et al.*, 2020). As a result, the technologies that provide the greatest societal benefits are often adopted to the smallest extent (Figure 1). A key obstacle is that the value added specific precision farming technologies in terms of saved inputs in many cropping systems is often too small to justify investment by individual farms (Späti, Huber and Finger, 2021). For example, variable rate application of fertiliser may reduce nitrogen use by 10 per cent and more without reducing yield levels (e.g. Argento *et al.*, 2021; Finger *et al.*, 2019). However, a reduction of 10 per cent of nitrogen use in crop production may only represent savings of approximately EUR 10-20 per hectare and year. Thus, investments (in sensors, machinery, knowledge, etc.) in such new technologies may be not profitable for small-scale producers with only a few hectares of arable land (e.g. Späti, Huber and Finger, 2021). Pushing small-scale farms now into costly new technologies for such applications may even cause investment traps. However, digital innovations may become much more economically viable if they are shared across farms and are not only used for one specific purpose, such as improved fertiliser application, but also when digital sensors and platforms can be used for multiple purposes, e.g. to guide a wide range of on-farm decisions and to facilitate reporting to downstream actors and policy. Thus, once some digital innovations are used on farms, other applications may also become rapidly more viable (e.g. Finger *et al.*, 2019).

3.2. Digitalisation and more resilient agricultural systems

Digitalisation also provides opportunities to increase the resilience of agricultural systems and farms (e.g. FAO, 2022; McFadden *et al.*, 2022). Resilience is understood as the ability to cope with challenges, i.e. its capacity to ensure the provision of the intended services and functions (e.g. producing food and generating farm income) when facing shocks and stresses (e.g. economic, social and environmental) (Folke *et al.*, 2010; Meuwissen *et al.*, 2019). Here, we assess the resilience implications of digital innovations using a resilience framework that defines resilience capacity as more than short-term robustness (e.g. short-term yield stability) but also comprises adaptability and transformability (Meuwissen *et al.*, 2019) (Figure 3).

Digitalisation enables farms to increase their resilience in response to climatic risks and thus can support adaptation to climate change and extreme climatic events (Figure 3). Digital tools are being developed to support farmers in coping with the increasingly uncertain and risky nature of agricultural production (World Bank, 2016), for example, by improving forecast systems on the occurrence and potential impacts of extreme weather events (e.g. droughts and heat waves) and providing decision support tools (e.g. via farm management information systems) adapted to local conditions, e.g. accounting for location and crop specificity and using other locally sourced data. Digital tools provide farmers with information on the potential impacts of weather conditions events

10 The adoption in Europe is, for example, smaller than that in the USA (compare Griffin, Shockley and Mark, 2018; Lowenberg-DeBoer and Erickson, 2019 and McFadden, Njuki and Griffin, 2023).

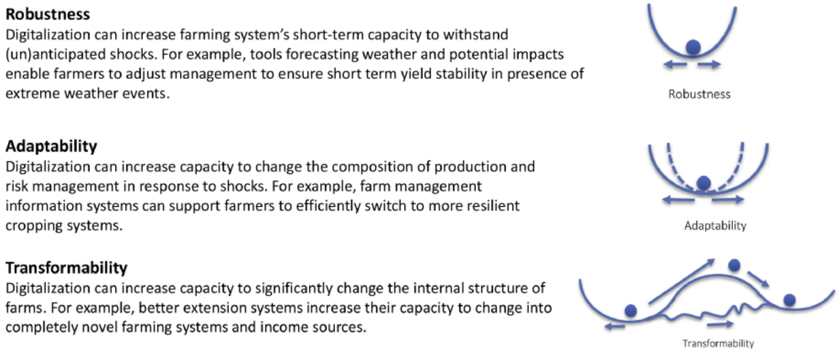

Fig. 3. Digitalisation and more resilient agricultural systems in the Robustness, Adaptability and Transformability Framework.
Note: The dimensions of the resilience framework are based on the study by Meuwissen *et al.* (2019).

as well as with information on optimal field-, farm- and household-level adaptation responses. This can guide farmers' decisions regarding what, when and how to plant, which soil management to use (e.g. regarding tillage systems), their crop management decisions (e.g. with respect to irrigation, fertilisation and pest management) and household resource allocation decisions (e.g. World Bank, 2016).

Digital technologies can enable the development of new and more efficient insurance solutions that allow farmers to offer better, cheaper and more widely applicable insurance solutions and thus increase the resilience of farms. For example, digitalisation allows the effective and efficient monitoring of changes in agricultural productivity over time and space, e.g. via remote sensing and sensors on machinery (e.g. Walter *et al.*, 2017). This allows the replacement of costly on-site loss adjustment and enables more cost-efficient insurance solutions. Moreover, remote sensing allows us to assess indices for index insurance, e.g. soil moisture and regional yields, more effectively and efficiently (Vroege *et al.*, 2021a; Vroege, Vrieling and Finger 2021b). This enables the design of new insurance solutions and provides new insurance opportunities to farmers, e.g. to develop insurance solutions for activities that are otherwise currently difficult to insure, such as yield insurance for meadows and pastures (Vroege *et al.*, 2021a). Thus, remote sensing allows the development of new index insurance schemes that provide farmers with better opportunities to insure systemic climatic risks such as droughts, for which insurance solutions are currently not available or are too expensive.[11] Vroege, Vrieling and Finger (2021b), for example, show that satellite-retrieved soil moisture index insurance can be a viable approach to cope with increasing drought risks.

11 For systemic weather risks like droughts, on-site loss adjustments (if at all possible) often involve logistic problems if many farms in a country or even continent are exposed to this extreme event at the same point in time (e.g. Vroege *et al.*, 2021a; Vroege, Vrieling and Finger 2021b).

Digitalisation stimulates the development of new networks, platforms and feedback mechanisms that can enable higher resilience. Digital tools offer new opportunities to enable efficient connectivity, online expert systems and benchmarking opportunities and thus improve agricultural knowledge, advice and extension systems (e.g. Fielke, Taylor and Jakku, 2020; Klerkx, 2021). This will be especially relevant for small farms that currently have limited resources to access targeted information, education and extension. New information and communication technologies can make it easier and cheaper to provide targeted information to these farms. Digital innovations also enable new learning and innovation spaces, including opportunities for gaming and augmentation, virtual realities, tools and services (Klerkx, 2021). Moreover, digital tools enable public and private institutions to obtain better insights into the actual needs of small and vulnerable farms, which allows improved strategic decision-making and thus increases the adaptability and transformability of farms (Ehlers *et al.*, 2022; Ehlers, Huber and Finger, 2021; Lajoie-O'Malley *et al.*, 2020). All this can support farms in adjusting production choices, activities and income sources more efficiently to become more resilient and better withstand environmental, economic and social shocks (Figure 3).

Along these lines, digital twins and artificial intelligence offer new opportunities for farmers to understand and identify failure sources and establish prediction systems and early warning mechanisms (e.g. on possible system failures or required maintenance) (Pylianidis, Osinga and Athanasiadis, 2021). For example, internet-of-things sensors in machinery allow to proactively prevent any malfunction due to real-time performance monitoring and early warning systems; the health status of crops and animals can be modelled and forecasted more efficiently, and digital twins allow to simulate the impacts of management interventions ex ante, i.e. before actually applying them to the physical system (Pylianidis, Osinga and Athanasiadis, 2021). This can decrease the probability and magnitude of how shocks impact the performance of agricultural systems along the entire resilience gradient (Figure 3).

4. Limitations, risks and challenges of the digitalisation of agricultural systems

While digital innovations are expected to have various potential benefits (e.g. Section 3), several challenges in economic, social and environmental dimensions emerge (see, e.g. Carmela Annosi *et al.*, 2020; Weersink *et al.*, 2018). For example, an increasing digitalisation of agri-food systems may increase energy intensity and related carbon footprint (see, e.g. García-Martín *et al.*, 2019). Moreover, we still face uncertainty regarding how and to what extent digitalisation can deliver all its promises (e.g. Klerkx and Rose, 2020). Technological risk and uncertainties remain: some novel technologies are still immature, and exact outcomes in terms of environmental performance, production and profits remain highly context specific and uncertain (Finger *et al.*, 2019; Jakku *et al.*, 2019; Stachowicz and Umstätter, 2021). Along these lines, some high-potential technologies (e.g. in the field of automatisation and autonomous processes) are still in the prototype stages (FAO, 2022). The remaining perceived lack of reliability of some digital technologies can be a major adoption hurdle for farmers (e.g. Späti *et al.*, 2022). Moreover, we lack detailed knowledge of what happens if technologies are widely adopted and what potential feedback and rebound mechanisms will occur, e.g. at markets and in farmers' decision-making. For example, an increasing productivity and profitability of farming activities due to digitalisation may counterbalance efforts to decrease the production intensity in ecologically relevant sites.

Moreover, various economic and social challenges remain. The potential benefits arising from digital innovations are often unequally distributed. Many cropping systems, regions and farmers cannot currently untap the potential benefits of digital innovations (see also Section 3). While the use of many digital technologies is growing, this growth mostly takes place in high-income countries (FAO, 2022). Limited financial resources and a lack of an enabling rural infrastructure (e.g. connectivity and regulatory frameworks) hinder more inclusive technology dissemination (FAO, 2022). Moreover, large farms tend to be more likely to be adopters and beneficiaries of digital innovations (e.g. Jakku *et al.*, 2019; Shang *et al.*, 2021). Additionally, gaps in education and knowledge limit the adoption of digital innovations (e.g. Pierpaoli *et al.*, 2013; Tey and Brindal, 2012). Furthermore, specific cropping systems (especially arable and high-value special crops) are currently more likely to benefit from digital innovations, while niche crops and more extensive farming systems profit less. As a result, the current adoption of digital technologies is largely restricted to specific farms and crops (e.g. Finger *et al.*, 2019; Griffin, Shockley and Mark, 2018). In the presence of such a digital divide, an increasing emphasis and reliance on digitalisation can imply larger inequality and concentration of power and may reinforce the lack of diversity in agriculture. More specifically, under such conditions, increasing digitalisation may lead to (i) decreases in the diversity of farmed crops and animals, (ii) reduced diversity of farming systems and (iii) accelerated structural change.

Along these lines, if private and public actors increasingly require the use of digital tools by farmers to increase the transparency of production processes (e.g. to deliver products in specific channels or to receive payments for ecosystem services), a digital divide may further increase inequalities among farms. While the use of digital technologies is already profitable for some, e.g. large farms, other farms may not be able to stem the required investments (e.g. in technology and knowledge) and are thus increasingly excluded from market opportunities (e.g. access to specific channels and labels) and policy opportunities (e.g. participation in specific voluntary agri-environmental programmes).

Digitalisation of the agricultural sector also involves new risks and resilience challenges. The use of big data, interconnected digital systems and automated, artificial intelligence–driven decision-making in the agricultural and food sectors can also create new systemic risks and thus reduce the resilience of the entire sector (Galaz *et al.*, 2021). For example, systemic risks emerge from algorithmic biases, network vulnerabilities and a growing concentration of actors. Furthermore, standardised automated processes (such as artificial intelligence–driven systems) imply the risk of inducing a simplification, i.e. reduction in diversity (e.g. at the field, farm and landscape levels) and a reduction in redundancy in systems. This in turn may imply a reduced resilience to shocks. Increasingly digitalised and automated systems are also increasingly vulnerable to cyberattacks (Galaz *et al.*, 2021). These risks and resilience challenges resulting from the increasing automatisation and use of artificial intelligence technologies are only poorly understood thus far (e.g. Galaz *et al.*, 2021) and need to be addressed by introducing appropriate standards, principles and policies.

Moreover, steps towards automated processes and farms create new challenges, for example, of responsibility and accountability. Who is responsible if an algorithm results in an automatised application of inputs such as pesticides that is inappropriate (reduces yields and increases costs) or even forbidden (e.g. using larger quantities than allowed): the farmer or the hard- or the software provider? Associated uncertainties currently limit the attractiveness of using such tools.

As data become a central element in the digital era of the agri-food sector, new challenges and risks emerge (MacPherson *et al.*, 2022). For example, the question, who owns the data increasingly collected, stored and processed? Who is in control of data also influences for what purposes it can be used. There is the risk that the concentration of a few dominant firms may result in problems of data grabbing and data monopolies (cp. Section 2). Such a situation would increase the risk that data are used to address the goals of selected firms and are not used to address larger societal goals (e.g. Fraser, 2022). New data and data-driven applications will make agricultural data more valuable to actors outside of the sector. For example, data from machines, farms, etc., are of increasing interest to traders and speculators, as it enables improved yield forecasts (Kamilaris, Kartakoullis and Prenafeta-Boldú, 2017). This reenforces concerns about data ownership, privacy and sovereignty (MacPherson *et al.*, 2022; Sykuta, 2016).

Along these lines, digital technologies and data-driven approaches could increase power concentrations, for example, if even fewer companies than today provide services and inputs to farmers (Clapp and Ruder, 2020; Sykuta, 2016). Increasing concentration in the hand of few could in the end limit the potential of digital technologies (Carbonell, 2016). Such a process can increase the risk that private actors take over extension and advise systems to farmers (e.g. Griffin *et al.*, 2010). More specifically, the increasing use of data-driven, even automatised, decision-making approaches may reduce the relevance of public, independent extension. However, such extension has been shown to be key to fostering the use of more sustainable farming practices (e.g. Wuepper, Roleff and Finger, 2021). Digitalisation may imply a loss of autonomy of management for farmers (MacPherson *et al.*, 2022). This raises fundamental questions, e.g. what actually defines ‘a farmer’ when up- and downstream actors (e.g. machinery providers and retailers) directly steer on-farm decisions by defining algorithms determining automatised decisions. However, the risks associated with the digitalisation of the agricultural sector differ largely across countries, scales and agricultural systems. For example, regulatory, institutional and cultural environments differ substantially (e.g. Ehlers *et al.*, 2022; MacPherson *et al.*, 2022).

Furthermore, the widespread use of digital tools and associated changes in production methods may also be associated with a possible loss of traditions and cultural heritage. Thus, digitalisation is sometimes critically discussed in production systems associated with traditional and artisanal production methods. For example, in Switzerland, different traditional cheese producer organisations (i.e. artisan raw milk cheese producers under Protected Designation of Origin) have banned milking robots from their production.[12]

Finally, there are concerns regarding the labour implications of widespread digitalisation of the agricultural sector. Many technologies outlined in Section 2 increase the quality of work for farm workers and imply lower health risks, for example, if inputs are applied more efficiently and/or are applied by unmanned aerial vehicles and not farm workers. However, automatisation can also imply that low-skilled jobs can be replaced, which can create social challenges (e.g. Carolan, 2020). However, in Europe, where labour scarcity is increasing and wages are rising, automation can benefit both employers and workers (FAO, 2022). However, an increasing reliance on digitalisation in the agricultural sector may also require additional high-skilled labour. This can create either bottlenecks for adoption if such skilled labour is not available or opportunities that skilled workers can enter into or return to the agricultural sector.

5. The role of agricultural policy in the era of digitalisation

There are two main ways in which the digitalisation of the agricultural sector and agricultural policy are interrelated. First, a key policy question is how to use and steer the digitalisation of the agricultural sector to ensure that policy goals are reached efficiently. More specifically, the agricultural policy may act proactively to ensure that the digital transformation of agriculture is used to reach the intended outcomes (e.g. production, sustainability and resilience) while enabling fairness and risk avoidance (Walter *et al.*, 2017). Second, the digitalisation of the agri-food sector will itself imply changes to agricultural policies. For example, new policy fields, such as the regulation of autonomous robots, emerge, and digitalisation allows fundamentally new policy designs to be created (Ehlers, Huber and Finger, 2021). In this section, we review these two dimensions to provide policy insights based on the above developed opportunities and risks associated with the digitalisation of the agri-food sector.

12 A central discussion point is the compliance with traditional habits and rules, e.g. to milk twice per day. Note that in the meantime important cheese organisations such as Gruyere AOP and Vacherin Fribourgeois AOP lifted this ban.

5.1. Policies to untap potentials of digitalisation and avoid risks

There are possibly large public benefits emerging from digitalisation (e.g. Figures 2 and 3), and digital innovations can be one contributing element to reaching ambitious policy goals, e.g. under the Farm to Fork strategy of the European Union.[13] Digital innovations can also enable farmers to better cope with shocks, e.g. due to extreme weather events, and thus contribute to climate change adaptation. However, often those digital applications with the highest potential societal benefits (e.g. those that can result in the largest reductions in input use and losses) may not be those that pay off first for farmers and are thus often least adopted.[14] This mismatch may rationalise policy intervention. For example, while the private benefits from adopting precision farming are often small, especially for small-scale farms, the resulting public benefits of reducing nutrient losses and pesticide use (e.g. with respect to benefits in climate, pollution and biodiversity) are often far higher (e.g. Prudhomme *et al.*, 2022; Späti, Huber and Finger, 2021).

However, the support of digital innovations is not a policy purpose on its own. In contrast, policy shall aim to achieve overarching policy goals (e.g. reducing environmental externalities, increasing resilience and improving animal welfare) in the most cost-efficient ways. To prioritise policy intervention, the effectiveness and costs of digital innovations to achieve these goals shall be quantified and compared to the effectiveness of other approaches. While there is evidence that digital technologies can contribute to more sustainable and resilient agriculture (see, e.g. Section 3), the specific effects are often very context specific (i.e. not the same technology is most appropriate at every farm) and uncertain (see, e.g. Section 4). Moreover, the development and adoption of digital innovations take place in highly dynamic environments, with innovations being rapidly developed and released to the market. As Pearce (2018) describes it for precision farming, 'In the world of precision agriculture, each new growing season seems to bring a fresh batch of brand-new technologies'. The most efficient technology may change rapidly. Thus, the focus of policy interventions shall not be on specific digital technologies and approaches. In contrast, policymakers can create an enabling environment and establish incentive schemes that incentivise and allow the development and application of the most cost-efficient strategies to achieve these goals, either using digital innovations or using other approaches.

To ensure effective and cost-efficient policies, we thus suggest that policy interventions shall be based on a combination of the following principles: (i)

13 A key question is whether the required environmental benefits from digital innovations are large enough to warrant large public investments and how to meet ambitious policy goals (e.g. within Farm to Fork) in the most efficient way, i.e. with low costs while avoiding trade-offs (e.g. with food production). Such analysis shall consider both digital innovations and other approaches (e.g. Ewert, Baatz and Finger, 2023).

14 For example, georeferencing and location technologies have smaller effects on input savings and losses on a per-hectare basis (Table 1) but are widely used (and cheap to implement). Thus, their aggregated environmental impact is large. However, other technologies (e.g. applicative tools) have the potential to decrease input use and losses to even larger extents. However, these technologies are currently not widely used (and more expensive).

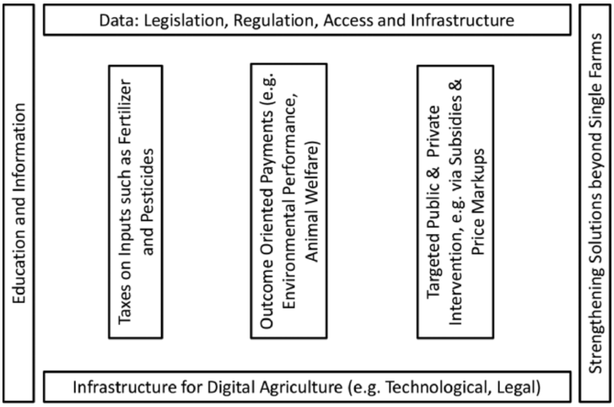

Fig. 4. Elements of possible policy interventions to support digitalisation to enable more sustainable and resilient agriculture.
Note: Creating infrastructure and foundations (e.g. legal and education) for digital agriculture and data use as well as strengthening solutions beyond single farms is the starting point for more targeted policy actions.

providing a sufficient digital agriculture infrastructure, (ii) enabling frameworks for data use and exchange, (iii) fostering education and information, (iv) strengthening support policies that go beyond individual farms (e.g. supporting collaboration and sharing) as well as economic instruments such as (v) taxes on inputs such as fertilisers and pesticides, (vi) a stronger focus on outcomes, e.g. via result-based payment schemes and (vii) targeted subsidies and direct payments (Figure 4).

A core element of public support for digitalisation is the creation of an enabling environment by providing a wide gradient from technological infrastructure and legal frameworks to education and information (Finger *et al.*, 2019). Such infrastructural support can comprise supporting connectivity by realising telecommunication infrastructure, e.g. for high-speed internet access and new network technologies (FAO, 2022). Moreover, governments can support farmers and up- and downstream actors by providing support for and access to satellite imagery and data, e.g. useful for adjustment of input use decisions or for high-precision georeferencing applications as well as for insurance purposes (e.g. Riecken and Kurtenbach, 2017; Vroege, Vrieling and Finger, 2021b). Currently, the use of some digital innovations with large potential for sustainability and resilience is restricted due to a lack of sufficient legal and regulatory frameworks (e.g. Lowenberg-DeBoer *et al.*, 2022). Thus, providing proactive frameworks to enable the efficient use of digital technologies, e.g. with respect to data handling and use, autonomous machinery, unmanned aerial vehicles, etc., can provide cost-efficient policy action points.

A further area of policy focus is to address inherent data-related issues, e.g. realising common semantics and ontologies as well as open and interoperable standards for data exchange and management (e.g. Bahlo *et al.*, 2019; Kamilaris, Kartakoullis and Prenafeta-Boldú, 2017; Lokers *et al.*, 2016).

The European Union, for example, formulated 'A European Strategy for Data' and a 'Coordinated Plan on Artificial Intelligence'.[15] Public authorities may also provide farmers and other stakeholders with specific data (e.g. on forecast systems and satellite imagery). This can allow farms to increase their sustainability and resilience by using these data in combination with other digital tools (e.g. Lacoste *et al.*, 2022). In the longer run, the role of government may even change towards becoming a broker of digital information (Ehlers *et al.*, 2022; Ehlers, Huber and Finger, 2021). Along these lines, governmental efforts may also contribute to data-sharing platforms that facilitate the abovementioned standards and allow safe and fair data exchange (see, e.g. Finger *et al.*, 2019; Forney and Dwiartama, 2023).

Education, information and extension is another policy dimension with potential large leverage to support the sustainable use of digital innovations. The lack of education and information often limits the adoption of new digital technologies (Pierpaoli *et al.*, 2013; Tey and Brindal, 2012). Sometimes, basic education elements are missing, even in European countries. For example, Ammann, Walter and El Benni (2022) show that in Swiss farm management vocational education, 43 per cent of surveyed young farmers learned nothing about digital technologies during their basic agricultural training. Thus, simple fixes in educational programmes as well as targeted information and extension may have large effects on the use of digital innovations. Education and information can also contribute to reducing the digital divide by making digital innovations more inclusive for a wide range of farms and farmers, as well as those often marginalised (FAO, 2022). Along these lines, farmer networks can be exploited and strengthened. For example, social networks among farmers have been identified as essential for the uptake of digital technologies in agriculture (e.g. Blasch *et al.*, 2022). Thus, policies to promote networking and knowledge sharing among farmers can be vital.

Investment in digital innovations is often not profitable for individuals, especially small farms. Thus, developing cheap(er) technologies can promote the widespread benefits of digital innovations. Moreover, approaches that go beyond individual farms shall be strengthened to facilitate the widespread adoption. For example, joint investment, farmer networks and cooperation as well as machinery rings and contractors will be of increasing importance to foster the use of digital agriculture in Europe (e.g. Kutter *et al.*, 2011). The policy shall support this development, e.g. by supporting multifarm solutions. In this way, policies can also avoid creating investment traps, especially for small-scale farms. Such a focus beyond individual farms, however, may affect the efficacy and efficiency of policy measures. For example, Wang, Huber and Finger (2022) show that in markets where contractors provide digital approaches

15 See e.g. https://digital-strategy.ec.europa.eu/en/policies/strategy-data and https://digital-strategy.ec.europa.eu/en/policies/plan-ai#:~:text = The%20key%20aims%20of%20the,AI%20policy%20to%20avoid%20fragmentation.&text = The%20Coordinated%20Plan%20on%20Artificial%20Intelligence%202,021 per cent20Review%20is%20the,global%20leadership%20in%20trustworthy%20AI.

(e.g. variable rate input use) to farms, subsidies may render ineffective and inefficient, especially if contractor markets are highly concentrated.

To untap the full potential of digital technologies, their adoption needs to be economically viable for a large share of farms (Finger *et al.*, 2019). To increase profitability and reduce risks of adoption, targeted economic incentives can be used. For example, taxes on inputs such as fertilisers and pesticides internalise their external costs and stimulate the attractivity of input-saving digital technologies such as precision farming (e.g. Späti, Huber and Finger, 2021). Tax revenues may be used to further support these technologies (e.g. infrastructure and education), creating leverage effects (e.g. Finger *et al.*, 2017). Moreover, digital innovations become more attractive if a higher sustainability performance pays off for farmers (e.g. via payments for ecosystem services and result-based payment schemes). Private companies may also stimulate the uptake of digital farming practices (e.g. via price premiums) that are more environmentally friendly and increase animal welfare and can document these achievements more effectively and efficiently. Further side benefits of digital innovation, such as the increase in transparency and traceability in production processes, can justify further support from up- and downstream industries.

Finally, as a 'last resort' of governmental interventions, public support may also use targeted subsidies to stimulate technology uptake, e.g. via investment support for input-saving precision farming equipment and direct payments for specific practices, for example, to address urgent environmental problems.[16] However, such policy measures are often inefficient, as they usually need to be tight to specific technologies (and thus lack flexibility) and induce deadweight losses. However, which technology is best suited to address sustainability issues is highly context dependent (e.g. Basso and Antle, 2020). Moreover, digital agriculture faces rapid developments and technological progress over time. Thus, policies shall not target specific technologies but rather use result-oriented policies and create enabling environments to use digital innovations to achieve these results (Figure 4).

An important question is also where public policy intervention is needed. While technological developments will be mainly realised by the private sector itself, public policy can ensure that these developments are used to reach sustainability and resilience goals. Moreover, more than national and European policies will be needed. Digitalisation does not stop at country or continental borders, and the increasing digitalisation of agricultural systems globally has implications for European agriculture and its policies. For example, this concerns the sustainability of food imported to and exported from Europe, as well as standards used in global food value chains. Thus, policy efforts, e.g. on creating standards and enabling environments, also need coordination at global levels.

16 Such incentive schemes are already tested, for example, in Switzerland where precision farming is subsidised specifically to address problems of pesticide use (Wang, Huber and Finger, 2022).

5.2. Digitalisation of the agricultural system implies changes in agricultural policies

The ongoing digitalisation of the agri-food sector also implies inherent changes to agricultural policies. For example, agricultural and related policies must address the regulation of new technologies and tools, such as the regulation of autonomous robots and unmanned aerial vehicles (Lowenberg-DeBoer *et al.*, 2022). Digitalisation can also make the existing policy instruments more effective and more efficient (e.g. Ehlers, Huber and Finger, 2021; OECD, 2019). For example, digital administration and digitalised monitoring and control of policy measures (e.g. based on remote sensing, sensors on machinery and access to farm-data platforms) can reduce their transaction costs, as it reduces paperwork, incentives to cheat and the need for on-farm controls. New technologies can enable more direct exchange opportunities between farmers and administrators, enabling more effective and efficient bidirectional communication (Ehlers, Huber and Finger, 2021; Wolfert *et al.*, 2023). The associated transition into e-government services to handle data exchange electronically and to fulfil their information obligations comes with benefits but also implies costs, challenges and acceptance hurdles (e.g. Reissig, Stoinescu and Mack, 2022).

Digital innovations allow fundamentally new policy designs and approaches to be created (Ehlers, Huber and Finger, 2021). Using digital tools may allow improved spatial targeting of policies. For example, policy intervention may be restricted only to sites where environmental problems have been detected (e.g. a large erosion potential or pollution of water bodies). Such spatial targeting implies reduced costs for both farmers and the government (Ehlers, Huber and Finger, 2021). Moreover, a wide range of sensors may facilitate the wide use of result-based payment schemes, i.e. compensating farmers to reach tangible outcomes, e.g. regarding biodiversity or animal welfare. For example, digital technologies, such as smartphone apps, unmanned aerial vehicles and satellites, may enable better monitoring of biodiversity and thus offer opportunities for new policy instruments (Elmiger *et al.*, 2023; Mäder *et al.*, 2021).

More generally, benefits can be enhanced further when digitalisation helps target actual outcomes and not just proxies of the desired results of policy measures. Moreover, the intertwining of precision farming and precision conservation will increasingly allow farmers to receive direct feedback on the potential ecological, environmental and animal welfare implications of a specific action before it is actually implemented. This information provision can change farmers' behaviour as a 'green nudge' (e.g. Peth and Mußhoff, 2020). This combination of precision farming and precision conservation also facilitates conservation beyond the level of individual farms that are important to realise the ecological and economic benefits of spatial coordination and landscape approaches (e.g. Banerjee *et al.*, 2017; Sayer *et al.*, 2013).

6. Conclusion

Digital innovations such as precision farming, the internet of things, remote sensing, data-driven applications, artificial intelligence, digital twins and robotics have the potential to contribute to more sustainable and resilient agriculture. These innovations can increase productivity, reduce environmental footprints and improve animal welfare. We show that to untap this potential, digital innovations shall be used to increase efficiency and substitution as well as to fundamentally redesign agricultural systems. Digitalisation also allows agricultural systems to become more resilient, e.g. adapting to increasing climatic risks. Furthermore, digital innovations can revolutionise farming and conservation, enable more effective and efficient agricultural policies and contribute to increasing transparency in food value chains. However, currently, digital applications with the highest potential public benefits are the least profitable and least widely adopted. Moreover, we show that an increasing digitalisation of the agricultural sector comes with several challenges, costs and risks, e.g. in economic, social and ethical dimensions. For example, the potential benefits of digitalisation are currently unequally distributed and many cropping systems, regions and farmers cannot profit from digitalisation. In the presence of such a digital divide, an increasing emphasis and reliance on digitalisation can imply even larger inequality and concentration of power.

Our analysis allows us to draw policy implications. We observe a mismatch between the societal benefits of some digital technologies and how widely they are currently used in European agriculture. This rationalises policy intervention to untap unexploited potential public benefits where it is cost-efficient. We develop a set of possible policy interventions to support the use of digitalisation to enable more sustainable and resilient agriculture (Section 5). Policy measures should be prioritised to increase possible public benefits arising from digital innovations while minimising costs, for example, by creating an enabling environment, e.g. by strengthening digital infrastructure, legal frameworks and education. Policies to support digital agriculture should be embedded in larger policy pictures. This means that the support of digital innovations shall not be a stand-alone policy purpose but shall contribute to higher-level policy goals. Moreover, investments and other policy actions to promote digital innovations should be based on context-specific conditions (e.g. type of farms, existing infrastructure and knowledge). Digitalisation also implies changes to agricultural policies, e.g. by creating new policy fields such as the regulation of autonomous robots. Moreover, digital technologies allow fundamentally new policy designs and approaches, e.g. new policy measures based on result-based payment schemes and nudging. These opportunities shall be exploited by proactively developing agricultural policies suited for the era of digitalisation.

There are also implications for future agricultural economic research. Agricultural economists can contribute to assessing sustainability and resilience implications if digital tools and approaches are adopted at larger scales, regionally and globally. Farmer behaviour towards digitalisation and related decisions by other agri-food sector actors remain areas of research need. To guide and prioritise policymaking, better insights into the public and private costs and benefits of digital innovations must also be provided. Our profession can contribute to quantifying the implications of feedback and rebound mechanisms arising from the widespread use of digital technologies and assessing the potential role of policies. Moreover, agricultural economists shall strive to be more relevant to support other disciplines, e.g. by identifying in which field digital innovations may be most fruitful in terms of economic opportunities and policy needs. Finally, the digitalisation of the agri-food sector will change the way agricultural economic research is conducted. For example, while we currently often face a lack of data (e.g. on outputs, costs and input use), we transition into a phase of massive data availability (e.g. Woodard *et al.*, 2018). Data collected by billions of digital devices and platforms ranging from the levels of plants, animals, fields and farms to the entire food value chain will become available. This development offers ample opportunities and risks (e.g. more refined data may increase issues of anonymity) and will require our profession to make use of new tools, knowledge and approaches.

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