Digital agriculture in Europe and in France: which organisations can boost adoption levels?

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ABSTRACT

This paper presents the way the digital transformation of the agricultural sector is implemented in Europe and in France. It describes main European and national strategies, the structuration of research and innovation initiatives, and the development of captivity building devoted to foster innovations and encourage adoption and use. More specifically the French research and innovation ecosystem on digital agriculture is described. The actors involved come from different organisations, such as research and higher educational institutes, government agencies, AgTech companies, farmer unions…, and work together by means of associations (e.g. Robagri), networks (e.g. RMT Naexus, DigiFermes, Fermes Leader), or living labs (e.g. Occitanum) on both digital technology assessment and co-design. Additionally, an important support is also devoted to capacity building (e.g. *Le Mas numérique*, Mobilab) and a better understanding of the drivers of adoption and use of digital technologies (e.g. FrOCDA). Among these various organisations, #DigitAg, the Digital Agriculture Convergence Lab, has been created to foster interdisciplinary research on digital agriculture. All these initiatives aim at creating digital technologies supporting the European Green Deal, Farm-to-Fork and Biodiversity strategies as well as the French orientation

towards more agroecological practices for safer and more sustainable food systems. Even though this ecosystem is developing fast, the objective of encouraging the coevolution of both digital and green transformations is not without challenges that still need to be overcome, either through new research and innovations initiatives or new collaborations between the actors involved.

Keywords: Digital agriculture, Innovation ecosystems, Green deal, Farm-to-Fork, Innovation adoption, Innovation use, Digitalization, #DigitAg

Introduction

The European Union (EU) is a world's leading agricultural power. Agriculture contributed to 1.3% to the EU-27's gross domestic product (GDP) in 2020. The member state (MS) contributing the most is France (18%), followed by Germany, Italy, Spain, the Netherlands, Poland, and Romania. Together, these seven Member States account for over three quarters of the total EU agricultural production value. More than a half (58.6%) of the total output value of the EU's agricultural industry came from the '*big four*,' namely France (€75.4 billion), Germany (€56.8 billion), Italy (€56.3 billion), and Spain (€52.9 billion). The EU agricultural annual income per worker has slightly fallen (-1.5%) in 2020 while remaining at an estimated rate of 27%, higher than the 2010 index level. About a half (52.8%) of the total output value of the EU's agricultural industry in 2020 came from crops (€217.5 billion), within which vegetables, horticultural plants, and cereals were the most valuable products. About two fifths (38.6 %) of this total output came from animals and animal products (€158.8 billion), the majority being provided by dairy products and pigs. Agricultural services (€20.2 billion) and related non-agricultural activities (€15.3 billion) contributed to the remaining 8.6 % (Eurostat Statistics Explained 2021).

However, the European agriculture is also facing challenges. On the one hand, it is subject to pressures induced by climate change and soil artificialization. Climate change requires crop adaptation and is the cause of extreme weather events that therefore requires in-depth risk management. Soil artificialization, i.e. the transformation of land into human habitats and infrastructures, is leading to a decrease in agricultural land areas in many EU regions. On the other hand, European consumers' expectations are shaping food markets, through health, animal welfare, climate change, and environmental concerns as well as convenience and affordability. For instance, in 2019, the EU consumers' most important factors influencing food purchases included cost, food safety, ethics, and beliefs (European Commission 2019a).

To face these various challenges, a real transformation of agriculture and, more globally, food systems is needed. This call for change is not only technical but also includes organizational, trade, and socio-economic transformations. The digital transformation, which can be seen throughout the food systems from 'farm to fork,' can clearly support a transformation towards safer and more sustainable food systems. In particular, it opens opportunities for digital agriculture to meet challenges such as: (i) The need to intensify production while productive land areas are decreasing and negative environmental impacts are reduced and positive environmental impacts generated; (ii) Demands for detailed and real-time monitoring of the environmental impacts of production systems; (iii) The need to deal with additional uncertainties involved by climate change at both a global and local level; (iv) New demands for a shrinking, aging and female workforce; and (v) The need to address consumer demands for local and ethical products, including animal welfare. Additionally, it becomes a high priority on political and scientific agendas to tackle these two transitions all together, i.e. the digitalization of agriculture and the transition towards safer and more sustainable food systems, in a systemic way while focusing on both their acceleration and monitoring.

The digitalization of agriculture stems from an exogenous dynamic. It uses information and communication technologies (ICT) and computational resources to capture, transmit and analyse data, in order to produce indicators, provide recommendations, or automate processes. This digital transformation started with precision agriculture and precision livestock around 1990, with the objective of specifically addressing plant and animal needs through the use of automatic observations. Nowadays, it has expanded to a much broader concept born around 2015, called '*digital agriculture*,' which embraces both several spatial scales, going beyond the management of the fields to encompass the exploitation, territory, value chain..., and temporal scales, from seasonal to long-term agricultural and food management. Therefore, digital agriculture tackles more complexity and changes the way decisions are made, work is carried out, and value chains are designed. More specifically, digital agriculture was made possible by the combined use of several new technical levers (Bellon-Maurel and Huyghe 2017):

- Abundant, low cost, and on-field/on-animal data, issued from new data sources, like satellite imageries or connected objects (*Internet of Things* or IoT);
- New capacities in artificial intelligence (AI), machine learning, and high performance computing, allowing new dimensional modelling;
- New capacities related to enhanced connectivity between actors, including social media; and
- Increased automation and robotization, including process controllers and autonomous robots.

The objective of this paper is to describe the development status of digital agriculture in Europe and in France through the implementation of new strategies and regulations and the creation of organizations aiming at supporting the transformation of agriculture by means of the adoption of digital technologies. Then, some perspectives are given on the potential of the ongoing new ecosystem to impulse a real change regarding the use of digital technologies in agriculture.

The R&I landscape of digital agriculture in Europe and France

Political agendas contributing to digital agriculture in Europe

The European digital agenda for the new decade (up to 2030) addresses the widespread, rapid, and extensive development of digital technologies and use. It focuses on creating secure digital spaces and services and regulating digital markets and large digital platforms, with the objective of strengthening Europe's digital sovereignty while, at the same time, contributing to the European goal of climate neutrality by 2050 (European Commission 2019b).

The European strategy regarding digital agriculture is based on a multi-financial framework initiative, supporting research and innovation through the Horizon Europe programme together with a focus on the development and deployment of digital capacities in agriculture. Capacity development is implemented by means of different digital programmes, such as (i) the creation of a common European agricultural data space, facilitating the trustworthy sharing and pooling of agricultural data and aiming at increasing the economic and environmental performance of the agricultural sector; (ii) IA testing and experimentation facilities, to boost the uptake of trustworthy AI for the European agrifood sector; or (iii) Digital Innovation hubs, to provide technological expertise and experimentation facilities enabling the digital transformation of the agricultural sector.

In the European Strategy for Data, the European Commission also supports the research and development, and large-scale deployment, of next-generation cloud infrastructure and services across the EU. These new cloud and edge capacities should be highly secure and completely interoperable and should offer open, multi-vendor cloud platforms and services. The objective here is to enable European data spaces and foster innovative data-sharing ecosystems based on European cloud and edge solutions. Indeed, the European Strategy for Data, adopted in February 2020, aims to establish a single market for data, ensuring Europe's global competitiveness. This means enabling data sharing as well as practical, fair, and clear rules on data access and use. Besides, through the Data Governance Act of November 2020, the EU provides measures to increase trust in business-to-business data sharing and includes measures to facilitate the reuse of data. Moreover, digital innovation is also fostered by the European Digital Innovation Hubs (EDIH), a program covering all economic and institutional sectors, including agriculture. Between 2021 and 2027, €1.5 billion will be invested in the EDIH network, with a half coming from the '*Digital Europe Programme*' and the remaining from national and regional funds, to support approximately 200 digital innovation hubs. The objective is to fill the gap between research on digital technologies and their implementation and deployment and to bring research outcomes to the market in five specific areas: supercomputing, artificial intelligence, cybersecurity, advanced digital skills, and ensuring the use of digital technologies across the economy, especially agriculture. This initiative is completed by the Connecting Europe Facility (CEF-Digital), supporting public and private investments in digital connectivity infrastructure (e.g. 5G, backbone networks, digital connectivity in transport and energy projects) up to €2 billion until 2027. Otherwise, the EU has created the European Innovation Partnerships (EIPs) to promote participatory innovations at local scale by gathering together main stakeholders. The group dedicated to agriculture, called EIP-Agri, is particularly interested in digitalisation.

Regarding agriculture and rural areas, the political commitment of the European MS to join forces on digitalization is shaped by the '*Declaration of cooperation on smart and sustainable digital future for European agriculture and rural areas,'* signed in 2019. Moreover, one of the pillars of the EU Green Deal strategy is the Farm-to-Fork strategy, which sets the 2030 targets for sustainable food production and is really challenging and ambitious for the agricultural sector (European Commission 2020). Digital development and innovations are expected to play an important role in meeting those targets. Following these strategies, the Common Agricultural Policy (CAP) post-2020 is developed to foster a sustainable and competitive agricultural sector that can support the livelihoods of farmers and provide healthy and sustainable food for society, as well as vibrant rural areas. The New CAP aims to be a modernized policy, with a strong emphasis on results and performance and is structured around 9 specific objectives and a cross-cutting objective on digitization, knowledge, and innovation. The digital transformation of agriculture is a dedicated ambition of the CAP. The '*second pillar'* of the CAP, named the *European Agricultural Fund for Rural Development* (EAFRD), includes €8 billion for the Next Generation EU program to help rural areas make the structural changes necessary to achieve the goals of the European Green Deal and digital transformation, i.e. to build a greener, more digital, and more resilient Europe. For implementing these new strategies, MS will have access to a portfolio of CAP tools they can include in their National CAP Strategic Plans to boost digitalization in agriculture and rural areas, e.g. advisory services, knowledge exchange, or investment support.

Thus, the EU has and continues to dedicate massive funding to the development of digital technologies aiming at supporting the transition towards safer and more sustainable food systems, as stated in its Green Deal strategy. The strength of these investments is, first, to encourage numerous projects focusing on the coevolution of the digital and green transformations of agriculture, through the development of a European research-innovation-infrastructure continuum and the creation of synergies among all the funded EU projects and strong European networks of research and innovation actors.

Although research and development (R&I) structures dedicated to digital agriculture are still scare in Europe, the EU supports the development of precision agriculture and digital agriculture through the funding of specific research programmes. The most significant indicator of this strategy is the amount of grants allocated by the European Commission (EC) on collaborative projects. For instance, the Horizon 2020 research programme has dedicated €118 million to 16 European projects related to digital agriculture (see Table 1).

Insert TABLE 1 around HERE

European R&I initiatives in digital agriculture

To prepare rural areas and farmers to this ongoing and upcoming digital transformation, research initiatives on digital agriculture have been developed, mainly by research units already involved in precision agriculture or precision livestock. Most advanced initiatives structuring the digital agriculture ecosystems can be found in the Netherlands, the UK, and France.

In the Netherlands, the leadership in digital agriculture is insured by Wageningen University and Research (WUR), with a long-standing tradition on precision agriculture and social sciences dedicated to innovation. There are at least six academic chairs involved in digital agriculture development, focusing on Geo-information Science and Remote Sensing (GRS), Farm Technology (FTG), Mathematical and Statistical Methods (Biometris), Knowledge, Technology and Innovation (KTI), Information Technology (ITG), or Operations Research and Logistics (ORL). Following the creation of the Wageningen Data Competence Center (WDCC) in 2018, WUR made '*Data-driven and high-tech innovations*' one of the five research programmes of its 2019-2022 strategic plan. Moreover, in 2021, WUR became the host of the activities of the former CTA, Technical Centre for Agricultural and Rural Cooperation, a joint international institution of the African, Caribbean, and Pacific States supported by the European Union, for 20 years after the Cotonou Agreement. Digitalization has been a focus of CTA for more than 8 years, with a ICT Updates Newsletter launched in 2013.

In the UK, two out of the four AgriTech Centers launched in 2016 by Innovate UK are related to digital agriculture: Agri-EPI (Engineering, Precision and Innovation) and Agrimetrics. These centres gather government, academia, and industry resources to deliver research, development, demonstration, and training activities on precision agriculture and engineering. Agrimetrics has created a marketplace dedicated to agrifood data, the world's largest sourcing, management and monetization infrastructure of pre-linked and analysis-ready agricultural and food data.

The French innovation ecosystem in digital agriculture

As often encountered worldwide, digital technologies suffer from a lack of adoption that may be due to: (i) technical issues, e.g. lack of relevance and suitability between the technologies developed and the real needs and/or constraints of users; (ii) lack of awareness and digital education; and (iii) lack of confidence, mainly due to broken promises about digital tool performances. The French ecosystem of innovation has been organized to tackle these issues through the development of specific organizations. These organizations are multi-partners and very often gather together research and higher education institutes, related to the Ministry of

Agriculture, like INRAE or L'Institut Agro, agricultural technical institutes, and AgTech companies. All these participants help strengthen the French ecosystem, showing complementarities, even with slightly different objectives, on testing digital technologies, demonstrating digital technologies, raising awareness and training farmers, fostering (open) innovation, but also through a better knowledge of the digital market by means of the mapping of main stakeholders or the diffusion of digital tools. Table 2 describes the most prominent organisations, their role, and the main targeted actors (farmers or AgTech companies).

Insert TABLE 2 around here

The organisation of the French ecosystem mainly focusses on three types of activities: (i) mapping the diffusion of digital agriculture in France; (ii) organizing and boosting the digital agriculture innovation ecosystem in France; and (iii), testing and demonstrating digital technologies in real conditions, at farm scale, to raise farmers and advisors' awareness.

Mapping the diffusion of digital technologies and services is really important. Indeed, reliable information about the adoption of Digital Agricultural Services (DAS) is essential for different stakeholders, such as: (i) service provider companies, by allowing an overview of the current uptake of digital tools and also helping design services that really correspond to current needs; (ii) academics and farmer's organisations, to define the most appropriate initial education and vocational training that can develop farmers and advisors' skills related to the use of digital tools; and (iii) regional or national institutions, helping them define strategies and regulations supporting the agricultural sector (Tey and Brindal 2012).

For organizing and boosting the uptake of digital innovation in France, there is a need for reliable statistics on DAS adoption and use. To meet this need, the French Observation Centre of Digital Agriculture Adoption (FrOCDA) was created in 2016 by L'Institut Agro Montpellier, with the financial support of the AgroTIC Corporate Chair and #DigitAg (described below). To gain knowledge on the adoption and use of digital technologies in agriculture in France, FrOCDA is led by an operational team embedded in a large teaching and research network interacting with students as part of their curriculum. Besides, a strong collaboration is set up with private partners who select the digital technologies to be studied and evaluate the outcomes of the studies before their diffusion. The approach implemented by FrOCDA is a progressive one, based on the assumption that the successive studies, each one targeting a specific digital technology, should consolidate statistics on the state-of-adoption of digital technologies in France. Thus, every three months, a study is carried out on a specific digital technology with the aim of answering the following questions: What is the level of use of this solution in France? What are the associated agronomic applications? What are their specificities, especially barriers or drivers of adoption? The methodology (see Figure 1) first provides a comprehensive inventory of the main stakeholders and main challenges for the digital technology under scrutiny and then interviews are conducted with main stakeholders, cross-checked by available data. It allows to collect and consolidate consistent and relevant information, while minimizing the time spent on data collection.

Insert FIGURE 1 around HERE

Between 2017 and 2021, 10 studies were carried out focusing on the adoption and use in agriculture of the following digital technologies: remote sensing, smartphone applications, farm management information systems (FMIS), geophysical measurements and soil mapping, robotics, variable rate application technologies (fertilization, seeding, etc.), global navigation satellite system (GNSS), yield monitoring, and weather stations.

Another prominent organisation that encourages innovation in digital agriculture is a French innovation hub dedicated to the agro-food sector in the South-West of France, called AgriSudOuest innovation or ASOI. ASOI has put digital agriculture innovations as a high priority for more than 10 years. This innovation hub, certified by the French Government and recognized by the European

Union, gathers together start-ups, private companies, research and higher education institutions, and public and private stakeholders supporting the economic development of the *Occitanie* and *New Aquitaine* regions. The ASOI's objective is to improve competitiveness through innovation, by fostering the encounter of all these actors and encouraging the creation of collaborative projects. It also informs its members about the latest available technologies and helps innovative ideas emerge. Lastly, ASOI was the partner of a European H2020 project called DIVA (see table 1), aiming at supporting the emergence and development of new industrial DigiTech value chains in the agro-food, forestry, and environment sectors.

Capacity building is another essential lever facilitating the diffusion of digitalization by increasing '*digital readiness*' (De Carolis *et al*. 2017) of the agricultural sector. Indeed, digital technologies are disruptive in agriculture, which means that specific capacities have to be built to support their development, encompassing the entire agricultural ecosystem, i.e. farmers and advisors as well as students who may become future managers of cooperatives, food supply chains, or machine and agricultural input providers. Thus, both long-term and sort-term capacity building is necessary. New capabilities and skills are needed in digital sciences, e.g. sensors, data science – data collection, analysis, and visualization –, information systems, interoperability, but also in humanities and social sciences (HSS), e.g. ergonomics, design, law on data usage and ownership, organizational management, and digital adoption and use. This means that higher-education needs to set up new interdisciplinary curricula with students developing double, even triple, competences, for instance, in agricultural sciences, digital sciences, and humanities. In France, a specific master curriculum, AgroTIC, has been running for almost 25 years by L'Institut Agro Montpellier and Bordeaux Sciences Agro, allowing students specialized in agronomy to get skills in digital and computer sciences. In the last four years, AgroTIC added new courses related to HSS into its curriculum, especially on data law and U-X design. Until now, in France, no 'mirror' process has been found elsewhere, i.e. computer-science students getting skills in agricultural/biological sciences in order to become digital agriculture specialists. Regarding short-term capacity building, vocational training has been developed. Besides, in 2017, l'Institut Agro Montpellier and Bordeaux Sciences Agro created the AgroTIC Corporate Chair. Thus corporate chair, funded by the two agricultural schools, 27 companies, three technical agricultural institutes, and a research institute, aims at of creating collective intelligence around issues related to education, collaborative research, and the adoption of digital technologies in agriculture. The advantages of this public-private organization are: (i) the commercial neutrality, which is ensured by the diversity of a large number of companies; (ii) the academic legitimacy, which is gained by the presence of academics; (iii) the warranty to focus on high-stake technologies, by involving technical agricultural institutes; and (iv) the access to important information on sales, innovation, and adoption, insured by the involvement of AgTech and digital advisory companies. The AgroTIC corporate chair has been at the origin of the creation of two original training infrastructure: (i) the MobiLab, a truck with up-to-date digital technologies to train farmers where they are and also to carry out with them co-innovation initiatives and (ii) the French Observation Centre of Digital Agriculture Adoption (FrOCDA), already described above. The creation of innovative training and innovation actions is really important for fostering the uptake of digital technologies in agriculture. The MobiLab's activities include demos and self-construction of low-cost digital solutions technologies (e.g. sensors, sensor networks, connected objects), which helps farmers understand what is 'behind' the digital technology. The Mobilab is funded by the AgroTIC corporate chair, showing that, far from being afraid by the potential self-construction of sensors/automated systems by farmers, AgTech companies consider it as a training activity aiming at increasing farmers' confidence in digital tools.

In 2020, the association of agricultural technical institutes (ACTA) launched the Naexus network, with the support of the French Ministry of Agriculture, to gather together a large number of French digital agriculture actors (54 in 2021), including research and higher education institutions, chambers of agriculture, technical agricultural centres, agro-machinery suppliers, farmer unions, AgTech companies, etc. The Naexus network provides to its members: (i) studies on new technologies; (ii) digital technology assessments; (iii) vocational training; and (iv) advisory services to support both digital and agroecological transformations.

Besides, the lack of confidence has also been identified as a cause of non–adoption of digital technologies. Creating technical and economic references on digital tools and services, testing them, and demonstrating their potential in real conditions are becoming more and more important to boost the uptake of digital technologies in agriculture.

In 2016, five French technical agricultural institutes (ITA) launched the '*Digifermes*' network in which digital tools are tested and demonstrated to farmers. The Digifermes network is a partner of the H2020 European project NEFERTITI (see Table 1), devoted to the implementation of regional hubs of '*demo-farmers*' dedicated to digital tools. Furthermore, the '*Fermes Leader*' network was launched in 2017, by the InVivo cooperative group. It aims at evaluating the technical and economic performances of digital technologies, by testing them on farms with farmers. The Fermes Leader network also carries out training and awareness raising sessions with farmers. In 2021, the network rallies 29 cooperatives and 400 farms. Academics, like INRAE, are partners of this initiative, but are not involved in the setting and the exploitation of experimentations.

In 2017, L'Institut Agro Montpellier has set up *le Mas Numérique* (the Digital Mediterranean Farm), supported by the AgroTIC Corporate Chair and #DigitAg (to be introduced below). In this unique educational and experimental farm, digital tools and solutions provided by 17 AgTech companies are used and tested by the technicians of L'Institut Agro Montpellier, not only to implement the farm's production activities but also to organise demonstrations and training, in both initial education and vocational training sessions.

To tackle the numerous challenges the agricultural sector is facing, e.g. agroecology, climate change, local food systems…, the Living Lab (LL), called Occitanum[1], was launched in 2020 (McPhee *et al.* 2021). Financially supported by the French '*Territories of Innovation*' programme, Occitanum gathers together academics, farmers, agricultural organizations, and technical agricultural

[1] https://occitanum.fr/eng/

institutes. Its objective is to build a set of references on the multi-performance of digital technologies, in real conditions, of seven production sectors, such as livestock, arable crops, fruits, vegetables, wine, etc. Occitanum aims at developing new indicators on the environmental or the social benefits brought by digital technologies. In the 13 experimental sites, located in the Occitanie Region, a local animation is organized to bring out farmers' bottlenecks and needs for innovation and to address them by either identifying an existing digital technology that can solve the problem and evaluating it or setting up a consortium to design a new digital solution. In 2022, Occitanum became partner in the CODECS Horizon Europe project[2].

To tackle adoption and use issues, it is essential to raise awareness of farmers mainly through demonstrations and training (e.g. *Le Mas Numérique;* the Mobilab). This topic is of interest anywhere worldwide. However, it is rather difficult to export digital technologies, since the success of its implementation is very dependent on local conditions and users. Building references on digital technologies is thus essential and is also at the top of the EU Horizon Europe agenda. Besides, it is also important to understand the real impact of the setting of living labs devoted to smallholders with regard to their digital transformation in such a multi-challenged context, e.g. climate change, agroecology, food quality…, especially when dealing with agricultural sustainability (Bronson *et al.* 2021).

#DigitAg, the digital agriculture convergence lab

The French research ecosystem on digital agriculture started to get structured in 2016, after the publication of the report entitled '*Agriculture innovation 2025*', made at the request of several French Ministries: Agriculture, Research and Innovation, and the Economy. Even though there exists a number of French research units involved in digital agriculture, the French research panorama on digital agriculture has been highly structured by #DigitAg (Figure 2).

[2] https://cordis.europa.eu/project/id/101060179

Insert FIGURE 2 around HERE

Main research teams, being part of the French ecosystem on digital agriculture, are most often, located within Agronomy Schools linked to the Ministry of Agriculture, covers numerous areas of expertise. For instance, ESA Angers has a research unit (LARESS) specialized in social and economic sciences, studying the impact of digital technologies on organizations and workforce in agriculture. In Dijon, the *Agroecologie* research unit has a team specialized in precision agriculture. The TSCF research unit in Clermont-Ferrand is at the heart of the robotics development for agriculture in France. It is where Robagri[3], the association dedicated to agricultural robotics, was created, in collaboration with AXEMA, the agricultural machinery union. Robagri now comprises more than 60 members, including manufacturers, start-ups, and research units.

Within this panorama, #DigitAg, the Digital Agriculture Convergence Lab, led by INRAE, was launched at the end of 2016 for 8 years with a competitive grant of €9.9 million from the French Government programme called '*Investment for the Future*.' #DigitAg relies on a research-education-innovation continuum and aims at building interdisciplinary research on the responsible development of digital agriculture in France, Europe, and Southern countries. Additionally, #DigitAg also supports higher initial and vocational educational programmes and innovation facilities managed together with AgTech companies and farmers. Nowadays, #DigitAg gathers together 16 public and private partners, 30 research units, and around 700 affiliated people. The #DigitAg convergence lab is organized following a matrix crossing disciplinary axes, in which researchers of the same scientific disciplines can interact and evolve together, and interdisciplinary challenges, in which different scientific disciplines are needed to address research questions (See Figure 3).

Insert Figure 3 aroundHERE

[3] https://www.robagri.fr/en/

To support research, #DigitAg funded a large set of relatively small projects, carried out through PhD theses, 18-month postdocs, and master internships, with the aim of encouraging agility, interactions, and community building. Indeed, each PhD and postdoc student has two supervisors coming out from two different scientific disciplines, positioning the students at the cross-roads of interdisciplinarity. Sixty percent of the funds allocated to #DigitAg have been allocated to those interdisciplinary projects. The remaining 40% is mainly devoted the scientific animation of the Convergence Lab, which relies on both local and international actions selected by means of internal calls and covering the following areas: internal seminars and workshops, researcher summer schools, hackathons, invitation of foreign scientists, researcher mobility abroad, international conferences, common research and education actions with African universities or international organizations (e.g. CGIAR). After five years of existence, the strategy implemented by #DigitAg has led to two major changes: the development and strengthening of (i) interdisciplinarity in research projects and (ii) capacity building.

Interdisciplinarity is the foundation and the purpose of the creation of a Convergence lab. Within #DigitAg, three scientific communities are gathered together: (i) Science and Technology (ST); (ii) Life and Environmental Sciences (LES); and (iii) Humanities and Social Sciences (HSS). To encourage interdisciplinary networking, three processes have been created and implemented: (i) Interdisciplinary workshops, organized by the axis and challenge leaders, jointly with the direction of #DigitAg; (ii) The funding of PhD thesis and postdocs grants, co-supervised by researchers from two different disciplinary domains and located in two different #DigitAg research units; and (iii) The Executive Committee, an instance helping the #DigitAg direction in the design of its strategy and the selection of projects and their improvement through recommendations aiming at increasing interdisciplinary connections within the #DigitAg Convergence Lab. This committee is composed of 25 people from different disciplinary background and research units and comprises the leaders of the #DigitAg axes and challenges and the #DigitAg operating directors. The Executive Committee gathers four times a year, creating strong interrelationships among its members and acting as a powerful interdisciplinary driver. Consequently, interdisciplinarity in #DigitAg projects, around 56 PhD theses and 15 postdoctoral subjects, has grown all along the five years of #DigitAg existence.

To demonstrate it, 'simple' and 'extended' interdisciplinary indexes applied to co-supervised PhD theses has been created. A PhD thesis is considered as dealing with 'simple' interdisciplinarity when the two supervisors are from the same scientific community (namely, ST, LES or HSS) and 'extended' interdisciplinarity when the two supervisors are from two different scientific communities. Between the first and the fifth PhD campaigns, the 'extended' interdisciplinary index increased by 50%, from 60% to 90%. However, fostering interdisciplinarity has also created significant indirect impacts, beyond PhD students. Indeed, in 2020, an internal survey showed that 80% of the #DigitAg research units have created collaborations with another #DigitAg research unit they had never collaborated with before. Besides, #DigitAg researchers were involved in interdisciplinary groups (80% of the participants) aiming at setting new research agendas on digital agriculture (Bellon-Maurel *et al*. 2022a) and pushing forward new directions for research, especially on responsible digital agriculture (Bellon-Maurel *et al*. 2022b).

A snapshot on the deployment of digital tools in the French agriculture and the reconfiguration of food value chains in Europe

Adoption of digital technologies in the French agriculture.

Many studies worldwide have examined the current uptake of DSA and generally found that, except for GNSS guidance and related technologies (Lowenberg-Deboer and Erickson 2019), like sprayer boom control and seeder row shutoffs, adoption is generally low. Available studies, which provide reliable estimates of the implementation of digital agriculture by farmers, based on random sample methods, have mostly studied North-American and Australian farmers (Lewellyn and Ousman 2014;

Schimmelpfennig 2016). In Europe, uptake rates are less well studied and understood (DEFRA 2013; Paustian and Theuvsen 2017).

In France, the annual *Agrinautes* survey (carried out by *Web-Agri*, *Terre-net*, la *France Agricole*) gives a global overview of the digital involvement of web-connected farmers. In 2022, 46% of them were connected by obligation, 31%, by usefulness (i.e. to save time), and 23% were hyper-connected. Internet is available in 95% of the farms, but 5% of them only have a throughput lower than 512 kb/s. Smartphone penetration rate is now 80% within this category of web-connected farmers. In Table 3, the digital technologies, studied by FrOCDA, are ranked from the most to the least adopted ones. The outcomes are in accordance with studies on North America or other European countries. The most adopted digital technologies are those which provide an immediate perceived benefit (e.g. working comfort, ergonomics, etc.), that are easy to use and have a good interoperability with other equipment on farm. The use of GNSS for guidance or auto-steering is a perfect example of such a technology widely adopted, as well as smartphone applications and, to a lesser extent, weather data and weather stations. Other digital technologies are mainly adopted for regulatory purposes or to meet traceability requirements for marketing/business purposes. For instance, 75% of arable crop farms are predominantly equipped with farm management information system (FMIS) enforced by supply chain requirements or some remote sensing services are adopted to meet regulatory objectives related to the declaration of crop fertilisation plans. Otherwise, digital technologies that are more complex to implement or for which an immediate return is less perceptible are clearly less adopted. It includes solutions for implementing variable rate application, whether at the plot or at the intra-plot level. Indeed, the adoption of these technologies requires overcoming technical barriers related to the interoperability of the farm's digital equipment with, for instance, FMIS, data service providers, GNSS, and agricultural machinery (e.g. tractor, variable rate application tool, etc.). In order to be operational, these technologies must be simultaneously updated, and likewise for the skills of the farmers, operators and/or advisors.

While these are major technical and human obstacles, direct benefits are sometimes difficult to evaluate, explaining why very few farmers currently adopt them.

Table 3 also highlights the difficulty of presenting the figures related to digital technology adoption in a homogeneous and synthetic manner. Indeed, for digital services which are accessed through annual subscription (e.g. remote sensing), adoption rates can be expressed as a percentage of subscribed area. When digital services are accessed through technologies purchased and implemented on farm and used for several years (e.g. GNSS, yield sensors, FMIS or weather stations), results are expressed as a percentage of farms currently equipped. In addition, some technologies require further details on the type of use, e.g. yield sensor, since it can be very different from one farm to another. For instance, FrOCDA revealed that even if the majority of new combines are equipped with yield sensors, only a few of equipped farmers use them to produce yield maps (~20%) and even fewer actually use them as a decision support system for variable rate applications (~5%). This shows that there is definitely a difference between adoption and use (Verdegem and De Marez 2011). Finally, the adoption is, of course, largely influenced by the characteristics of the farms, their digital maturity (De Carolis *et al.* 2017), and their links with upstream and downstream partners. FMIS is the best illustration of this. A majority of farms (~75%) with arable crops are equipped with traceability systems, due to the demand of their downstream partners for regulatory reasons, whereas practically none of the small farms involved in direct sales or short distribution circuits are equipped with such systems.

Insert TABLE 3 around HERE

Regarding the adoption and use of agricultural robots in France, results shows that they are mainly adopted, in 2018, by dairy farms with about 9,000 milking robots and 2,000 other robots (e.g. feeding, and stable cleaning robots), in nearly 10% of the French dairy farms. Those numbers have probably increased, since, in 2018, 70% of newly installed dairy farms chose to buy one or more milking robots. In breeding systems (bovine, caprine, or ovine dairy) about 2,000 robots are used to feed the livestock or clean buildings (scrapers and slurry vacuum cleaners). The adoption of robots in cropping systems, although a reality today, remains very limited with approximately 150 robots in 2018 (especially in vegetable cropping). These robots are mainly used for mechanical weeding with small autonomous weeders (e.g. Naio technologies). Numerous farms using these kinds of robots are vegetable organic farms (~100 robots). The study identified viticulture as the second robot adoption sector, just after dairy farms, with robots dedicated to mechanical weeding.

Digital technologies in the European Agri-food value chains

Digital innovations are also transforming agri-food value chains, by reshaping the way not only we produce, but also we supply, share and consume food. Benefits are expected in every aspect of our lives, ranging from more personalized and healthy diets to request for more transparency about the food we are offered, and more customized, local, and sustainable food productions. Data generated in value chains are important inputs for a better understanding of consumptions trends through the implementation of machine learning or data analytics. The way data are produced, shared, used, and re-used opens up to new challenges that need to be tackle in the coming years.

Indeed, changes are fast and profound. They are mainly due to AgTech start-ups, which offer digital services that can be operated on smartphones, tablets, laptops, and other computers, while others are embodied in specific equipment (Birner *et al.* 2021). However, digital technologies have not entered the various segments of agrifood value chains identically in Europe. For instance, in France, the production and retail/consumer segments are those where the larger number of start-ups are developing (Florez *et al*. 2022). In Germany, delivery services are where digital technologies are the most present. In the Netherland, start-ups are distributed all along the Agri-food Tech value chain due to a strong agrifood ecosystem, government incentives, and a network of universities, helping start-ups to look immediately for internationalization, as their local market is limited (DigitalFoodLab 2021).

In Europe, consumers are more and more concerned by the origin and quality of food and are looking to buy fresher, healthier, and more environment-friendly products. Digital technologies lay an important role in developing traceability of food and more transparency (El Hadad-Gauthier and Piot-Lepetit 2022). Start-ups developing blockchain-based applications promote food quality and create awareness on sustainable practices, in order to increase consumer trust and bring value to producers. Blockchain and e-certifications are also developed to facilitate international trade. Digitalization can become a driver of upgrading on global value chains and help develop more into higher value-added activities (López González and Jouanjean 2017). E-commerce platforms enable producers to get access to different inputs, price comparisons, allowing cost reductions, or to locally connect to their consumers, therefore empowering local markets associated with fast delivery. More and more digital technologies are also developed by start-ups with an objective of linking economic considerations with environmental or social ones. As pointed out by Liguori and Bendickson (2020), innovative start-ups are nowadays looking for value opportunities in connection to the sustainable development goals. For instance, in France, more and more digital services address the segment of waste reductions on various segments of the agri-food value chains, trying to support the development of more circularity in production (e.g., Organix[4], a brokerage platform for trading agricultural wastes and by-products) and consumption processes (e.g., Togoodtogo app[5]).

Discussion

Digital agriculture, as the use of digital technologies in agricultural production from farm to fork, goes far beyond precision agriculture or precision livestock. Although digitalization in agriculture is still limited in France, except in the dairy sector, France is in the world top 6 countries regarding investments in AgriTech (including digital tech and biotech), with around €1 billion invested in 2021.

[4] https://www.organix.suez.fr/
[5] https://toogoodtogo.fr/fr/

In 2021 France counts 250 AgriTech start-ups. Investments in AgTech in Europe have followed the world's trend, representing 8% of total investments, half being dedicated to food delivery and e-business (La Ferme Digitale 2022). One can expect this trend to keep going. Indeed, the demand for food of higher quality and nutritional contents is growing, jointly with a consumer concern about food sustainability, food origin, and production processes. Farmers are also facing the climate change challenges, with increased temperatures, changes in rainfall patterns, more frequent extreme weather events and reductions in water availability. This situation calls for new levers to support producers. Digitalization can be one of these levers. In a recent report commissioned by the French Ministries of Agriculture and the Economy, a qualitative survey puts forward that five out of the nine most impacting levers to accelerate innovation in agriculture and food value chains are linked to digital technologies: data collection, robotization and automation, traceability, process digitalization, and artificial intelligence (La Ferme Digitale 2022). However, even if the digitalization of agriculture and the food value chain is underway in Europe and France, numerous challenges still need to be overcome.

A first challenge is 'not to miss the target' of innovation. As stated by Cook *et al.* (2021), the challenge is "more effective management processes enabled by digital agriculture, rather than the development of the technology itself." This means that technological development is not the most important part, and that the way digital technologies transforms processes has to be thoroughly studied. Furthermore, due to the pervasive character of data, digitalization not only transforms the specific part of the system where it is operating but also opens opportunities to trigger changes in other parts of it. Value can precisely be found in these indirect changes that could benefit farmers.

In Europe and in France, another conducive process, set high in the political agenda, is currently developing in agriculture, namely the agroecological transformation of agriculture. The deployment of these new production processes can be supported by the co-development of digital, green pathways, through the design of digital technologies specifically dedicated to the various forms of agroecology. To induce these transformative changes and this co-evolution, synergies need to be embedded in research and innovation programmes (Weber and Rohracher 2012), especially through new research directions as described in the INRIA-INRAE white book on 'Agriculture and digital technologies' (Bellon-Maurel *et al.* 2022a), based on the responsible research and innovation principles (Bellon-Maurel *et al.* 2022b).

The second challenge is to set up the institutional support needed for shaping this digital transformation of agriculture and food value chains (Cook *et al*. 2021). A first set of basic conditions can be considered as the minimum requirement for the use of digital technologies. It includes, for instance, technology availability, connectivity, affordability or ICT in education. The second set of incentives concerns enabling conditions, as factors facilitating the adoption of technologies and, among them, the development digital skills and an innovation culture (e.g. hackathons, incubators, accelerator programs). National digital strategies and regulations are another the driving forces behind digitalization as they create an enabling environment for competitive digital markets and e-services. For instance, the European Digital Strategy sets the objective of benefiting all (European citizens, business, etc.) and the environment, while at the same time improving data governance to mitigate negative side effects, to ensure that individuals, farmers and small businesses have the tools and means to decide what is done with their data. Besides, public interventions can also be necessary in some areas to develop a digital agriculture ecosystem conducive to innovation, allowing risk-taking, trust-based relationships between stakeholders, financial opportunities, professional services, and the emergence of appropriate skills. Especially, in France, this role has allocated to a large set of organizations, such as #DigitAg, Occitanum, RMT Naexus…, and initiatives, such as the French AgriTech launched by the Ministries of Agriculture and the Economy in 2021, with €215 million, or the 'Agroecology and Digital Technology' Priority Research and Equipment Program (PEPR) launched in 2022, with €65 million. The strength of this ecosystem is to be strongly connected and to cover all the steps of the research-training-innovation continuum.

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TABLES

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Table 2. The digital agriculture innovation ecosystem in France

Table 3. Adoption of Digital agriculture services (except of robotics) in France, ranked from the most to the least adopted.

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Fig. 2. The French research and capacity building ecosystem on digital agriculture

Fig. 3. #DigitAg, at the crossroads of disciplinary axes and interdisciplinary challenges

Table 1. Synthesis of the most important H2020 European projects dedicated to digital agriculture (from 2016 to 2020)

Acronym	Type	Project	Call	Obj.	Coordinator	EU support (k€)
agROBO-food	IA	Business-Oriented Support to the European Robotics and Agri-food Sector, towards a network of Digital Innovation Hubs in Robotics	2018	IL	Stichting Wageningen Research - NL	16,000
BigData-Grapes	RIA	Big Data to Enable Global Disruption of the Grapevine-powered Industries	2017	IL	Agroknow IKE, GR	4,442
DESIRA	RIA	Digitisation: Economic and Social Impacts in Rural Areas	2018	SC	Universitu of Pisa – IT	4,993
e-ROSA	CSA	Towards an e-infrastructure Roadmap for Open Science in Agriculture	2016	ES	INRAE – FR	399
FAIRshare	CSA	Farm Advisory digital Innovation tools Realised and Shared	2018	ES	Teagasc – IR	7,000
ICT Agri Food	ERA NET*	ERA-NET COFUND ICT-enabled agri-food systems	2019	SC	Bundesanstalt für Landwirt-schaft und Ernährung - GE	5,000
INNO-SETA	CSA	Accelerating Innovative practices for Spraying Equipment, Training and Advising in European agriculture through the mobilization of Agricultural Knowledge and Innovation Systems	2017	SC	Univ. Politecnica de Catalunya - SP	1,999

NEFERTITI	CSA	Networking European Farms to Enhance Cross Fertilisation and Innovation Uptake through Demonstration	2017	SC	ACTA (Association de Coordination Techni-que Agricole) –FR	7,000
RUST-WATCH	CSA	RustWatch: A European early-warning system for wheat rust diseases	2017	SC	Aarhus University – DK	5,000
SmaRT	CSA	Small Ruminant Technology - Precision Livestock Farming and Digital Technology for Small Ruminants	2020	SC	SRUC – UK	1,997
SmartAgriHub	IA	Connecting the dots to unleash the innovation potential for digital transformation of the European agri-food sector	2018	SC	Stichting Wageningen Research – NL	20,000
SmartCow	RIA	SmartCow: an integrated infrastructure for increased research capability and innovation in the European cattle sector	2017	ES	INRAE – FR	5,000
TRINITY	IA	Digital Technologies, Advanced Robotics and increased Cyber-security for Agile Production in Future European Manufacturing Ecosystems	2018	IL	Tampereen Korkea-koulusaatio SR - FI	15,997
WAZIUP	RIA	Open Innovation Platform for IoT-Big Data in Sub-Sahara Africa	2015	IL	Fondazione Bruno Kessler - IT	2,800
CYBELE	IA	Fostering precision agriculture and livestock farming through secure	2018	IL	Waterford Institute of technology - IR	12,408

		access to large-scale HPC-enabled virtual industrial experimentation environment empowering scalable big data analytics				
IOF2020	IA	Internet of food and Farm 2020	2016	LSP	Stichting Wageningen Research, NL	30,000
DIVA	IA	Boosting innovative Digitech Value chains for Agrofood, forestry and environment	2018	IL	AgriSudOuest Innovation - FR	4,029

Notes: IA: Innovation Action; RIA: Research and Innovation Action; CSA: Coordination Support action; ERA-NET: European Research; IL: Industrial Leadership; SC: Societal Change; ES: Excellent Science; LSC: Large Scale Pilot.

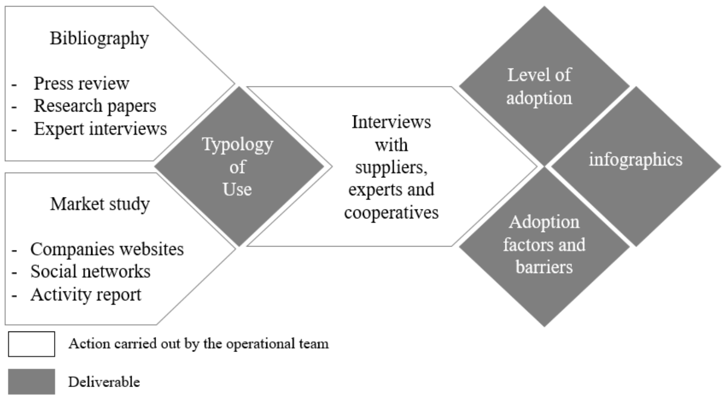
Table2. The digital agriculture innovation ecosystem in in France

		Led by	Test	Demo	Innovation	Awareness raising	Mapping	Targ.
Digifermes	2016	5 ATI	**	***		*		F
Fermes Leader	2017	InVivo	***	**	**	**		F
Mas Numérique	2017	L'IA	*	***		***		F
FrOCDA	2016	L'IA				**	***	A
ASOI		ASOI			***			A
Occitanum	2020	INRAE	***	**	***	**		A/F
Naexus network	2020	ACTA	*			***	**	F
French AgriTech	2021	SGPI			***	**	***	A/F

Notes: ATI: Agricultural Technical Institutes, members of ACTA; L'IA: L'Institut Agro - Montpellier SupAgro; FrOCDA: French Observation Center of Digital Agriculture Adoption; ASOI: AgriSud-Ouest Innovation; SGPI: General Secretariat for Invetsment (governmental office attached to the Prime minister); Targ. (Target): A: AgTech companies; F: farmers.

Table 3. Adoption of Digital agriculture services (except of robotics) in France, ranked from the most to the least adopted.

Type of technology	% of farmers equipped and using the technology
GNSS (Egnos, RTK)	~50% of French farmers
Smartphone application for professional use	~50 % of farmers have more than 3 applications in agriculture; weather, GNSS and equipment set up are most common apps.
Weather data and station	~50 % of farmers (owned stations or data from providers)
Farm management Information System	~25 % of farmers (but ~75 % of arable crop farms)
Yield monitoring	~ 22 % of arable crop farms
Remote sensing (UAV, satellite…)	~10 % of arable crop area ~1 % of viticulture area
Variable rate application	~10 % of arable crop farms
Soil maps (conductivity or resistivity)	Less than 1 % of farmland (~130 000 ha cumulated over the last 10 years)



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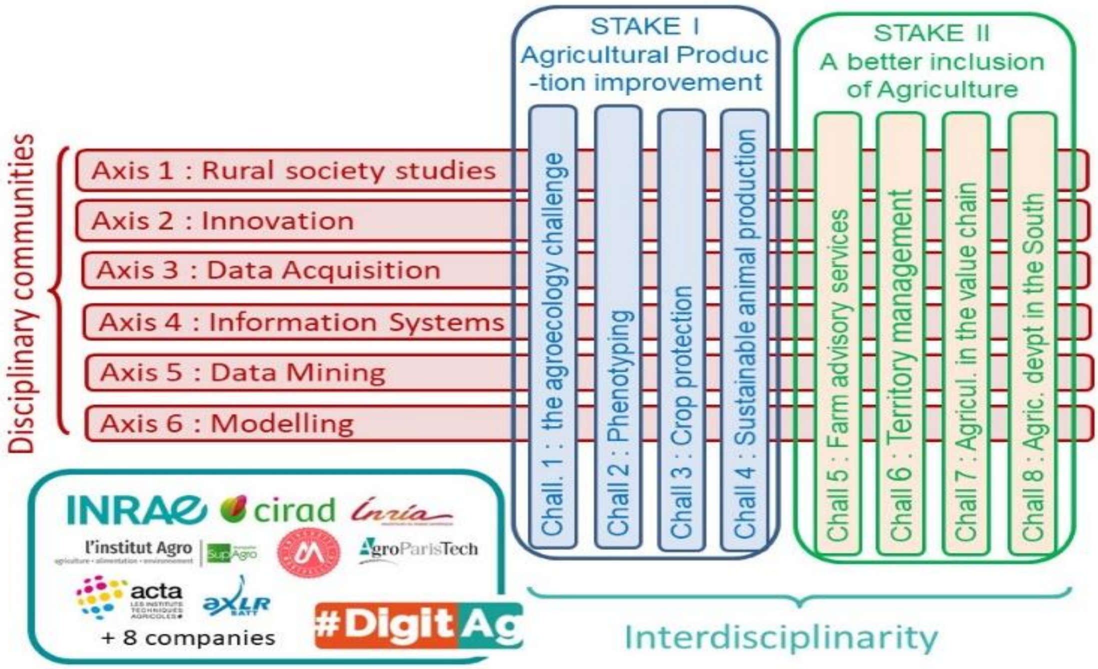

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