1

Towards Digital Agriculture?

This book examines the interactions between two trajectories in the agricultural sector: the development of digital technology and its ecologization. But what exactly do we mean when we talk about digital technology in agriculture? And what is the ecologization of agriculture? Why focus on the interactions between these two trajectories? And how can these two trajectories interact?

Agriculture refers to all human activities that, by acting on ecosystems and the biological cycles of species, allow the production of resources, particularly food, from living organisms (plants, animals, fungi and microorganisms). The agricultural sector thus encompasses all these activities, all the actors involved and the institutions that regulate them.

This chapter first aims to clarify the nature of the changes in the agricultural sector, namely, the ecologization of agriculture, on the one hand, and the development of digital technology, on the other hand. Section 1.1 sets out the historical context of the agricultural sector that has led to its necessary ecologization. Section 1.2 will explain what digital technology means in agriculture. Section 1.3 will demonstrate that, beyond technologies, digital technology implies the transformations of actors, public policies and practices within the agricultural sector. This overview will lead to a clarification of the controversies surrounding the links between digitalization and ecologization based on existing literature. Practices related to digitalization and ecologization are implemented at the farm level. However, these individual practices are interconnected with broader changes in the agricultural sector and are embedded in a wider socioeconomic system. This chapter is based entirely on a bibliographical study, carried out using scientific literature and gray literature: institutional documents, media sources and websites.

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1.1. Agricultural evolution: modernization and ecologization

In order to place the subject of this work in its historical and economic context, this section briefly describes major agricultural transformations from the second half of the 20th century to the present day.

1.1.1. *Agricultural modernization*

1.1.1.1. *In industrialized countries*

In the second half of the 20th century, agriculture in industrialized countries underwent a transformation known as "modernization". This modernization was enabled and supported by technological innovation in agriculture and throughout the entire value chain, particularly motorization, mechanization, the use of chemicals and genetic selection (Mazoyer and Roudart 2017). Genetics allowed for the development of varieties that incorporated the objectives of production intensification. These new varieties were combined with synthetic fertilizers and pesticides, technologies resulting from cross-sectoral dynamics with the chemical industry (Jas 2001). On farms, agricultural practices became mechanized with the arrival of the mechanical thresher and then the tractor, along with a range of other mechanical innovations (haymaking equipment, milking parlors, etc.). Research has notably played a role in ensuring the compatibility of these various innovations in genetics, mechanization and chemical production (Kirat 1991). Downstream transport and cooling technologies allow for the separation of production and consumption areas, thus enabling territorial specialization.

Upstream and downstream industries, then undergoing significant restructuring, strongly impacted the agricultural sector in its technical and spatial organization, notably contributing to the specialization of farms and territories. These developments have built what is now called "conventional farming" or "productivist farming," that is, capital-intensive, specialized, mechanized agriculture with simplified technical processes and significant reliance on external inputs (pesticides, fertilizers and animal feed) (Beus and Dunlap 1990).

This modernization is also the result of institutional and socioeconomic transformations: policies to support farmers, changes in trade rules, the concentration of upstream and downstream industries, credit regimes, research, subsidies to industries, etc. From the 1970s onwards, institutional transformations have accompanied globalization and the liberalization of agriculture, with increasing deregulation of international trade and the financialization of activities.

Thus, technological developments are impacted by, and in turn impact markets, agricultural policies, and organizations. All of these developments frame the development of a "techno-economic model for farm development" that integrates all these dimensions (Coulomb and Nallet 1980). Economic and sectoral developments are therefore reflected in agricultural practices, farm structures and the organization of the sector.

1.1.1.2. *In France*

In this work, we will focus particularly on the case of France for several reasons. First, it is a country where modernization has led to a productive, export-oriented (France is the world's sixth-largest exporter of agricultural and agri-food products) and technologically advanced agriculture. France has a strong national research and development capacity and is positioning itself at the forefront of digital development for agriculture. Second, it is a country where ecologization has taken shape in various ways: with the introduction of the environmental conditionality of subsidies from the European Union's common agricultural policy (CAP), with the inclusion of agroecological objectives in national policies[1], as well as with the strong development of quality and labeled agriculture, via indications of origin or organic farming (in France in 2022, 14% of French farms were engaged in organic farming and 27% engaged in productions with Protected Designation of Origin (PDO), Protected Geographical Indication (PGI) or *Label Rouge*[2]).

In France, in the aftermath of the Second World War, the State set itself a political project aimed at increasing agricultural production while freeing up labor, in a context of threatened food shortages and significant labor needs in the secondary sector (Servolin 1989; Flamant 2010). Added to this were objectives to stimulate growth, to free up purchasing power by reducing food costs or to strengthen France's trade balance through agri-food exports (Bartoli and Boulet 1989; Allaire and Boyer 1995).

In order to achieve these objectives, a variety of mechanisms and resources have been implemented, mobilizing the different dimensions of what can be conceptualized as an agricultural innovation system (research, experimentation, knowledge dissemination, but also regulations, institutions, technologies, etc.). Resources are mobilized to ensure the development and dissemination of knowledge necessary for agricultural modernization. The National Institute for Agricultural Research (INRA)[3] was created for this purpose in 1946. Technical institutes, agricultural colleges, agricultural high schools, chambers of agriculture, farmers' technical exchange groups (CETA)[4] and agricultural extension groups support the

1 Law of 13 October 2014 on the future of agriculture, food and forestry.

2 See: https://www.inao.gouv.fr/Nos-actualites/chiffres-cles-2022.

3 Institut national de recherche agronomique, in French.

4 *Centres d'études techniques agricoles*, in French.

dissemination and implementation of this knowledge (Gerbaux and Muller 1984). Political, legal and financial developments made it possible to reconcile the objective of competitiveness with the maintenance of family production structures through new rules governing access to credit, inheritance, land rights (the 1946 tenancy law) and control of the land market through land development and rural settlement companies (SAFER[5]) (Gueslin 1988; Boinon 2011). Modernization was also shaped by price support policies, up until the 1960s, which limited price volatility and secured investments. These policies relied on the construction and definition of so-called "professional" agriculture, delimited by thresholds in terms of size, labor or income to target a farming population that would benefit from agricultural policies (Laurent and Rémy 2000). They thus promoted a model of medium-sized family farms (Boinon 2011). These developments contribute to the movement of intensification and accumulation, which characterizes this agrarian period, itself inscribed in broader structural developments, linked to the development of the Fordist model of mass production and consumption, favored by an important role of the State and new institutions, but also the evolution of systems of thought and representations (Allaire 1988).

Increase in average farm size: from 19 ha in 1970 to 69 ha in 2020.

Decrease in the number of farms: 1,588,000 in 1970 compared to 389,000 in 2020.

Decline in the agricultural population: 2.8% of the French population today.

Simplification of crop rotations and reduction of intercropping.

Specialization of farms and territories.

Increased capital intensity of farms.

Increased yields: for example, from 4 to 7 t/ha for wheat.

Increase in input consumption: +60% in volume.

Increasing integration of farms into upstream and downstream structures.

Box 1.1. *The evolution of French agriculture with modernization*

5 *Sociétés d'aménagement foncier et d'établissement rural,* in French. SAFERs are organizations created in 1960 by the agricultural orientation law, which intervene in the land market through pre-emption and acquisition of land. The land is then resold to meet the objectives set by the law (establishment of farmers, expansion of small farms, etc.) (Boinon 2011).

The modernization of agriculture has therefore involved changes in technologies, knowledge, public policies, stakeholders, standards and institutions, and the farms themselves. These dimensions interact and evolve together and can be analyzed as a sectoral innovation system (Malerba 2002), contributing to the regulation and transformations of agriculture. Economic research has focused on studying these different dimensions to analyze the historical evolution of the agricultural sector (Allaire and Boyer 1995; Mazoyer and Roudart 2017) and its more recent transformations (Berriet-Solliec 1997; Labarthe 2006).

The so-called "productivist"[6] model entered a structural crisis in the 1980s and 1990s, characterized by frequent overproduction and growing criticism regarding health, food safety and the environment (Ansaloni and Smith 2021). This crisis led to reorientations of agricultural policies, changes in regulations and also in the organization of supply chains and production models (Touzard and Labarthe 2017). This change is sometimes defined as the implementation of an "economy of quality" in the agricultural sector (Allaire 2002). Quality encompasses several dimensions, including environmental quality. Environmental critiques of this productivist agricultural model were notably formulated by the agronomist René Dumont in France (Séjeau 2004). The environmental dimension will gradually gain importance in debates, societal expectations, research, policies and practices, in a process that we call the ecologization of agriculture.

1.1.2. *Integrating environmental concerns*

The environment, and more specifically the agroecosystem, is seen as a support for productive activities by theorists of agricultural modernization. The dominant epistemological paradigm upon which 20th-century agronomy developed reduces agroecosystems to "chemical systems whose inputs and outputs can be controlled" (Cohen 2017, p. 54). Living organisms are seen as a dimension to be controlled, mastered and standardized in order to implement homogeneous agriculture while remaining in control of circumstances (Bonneuil and Hochereau 2008). Agriculture is seen as one sector among many, which needs to be modernized in order to integrate into the global economy and markets (Bartoli and Boulet 1989). Modernization is associated with industrialization, which brings forms of

6 Productivist farming is thus characterized by "a set of technical processes, organizational arrangements and beliefs engaging actors around the requirement of increased and intensified production". It is part of a productivist mindset, defined as "the belief in the benefits of scientific and technical progress; the certainty that agriculture is a matter for professionals and specialists; and the belief that its primary mission is to feed the world's population while generating profits for actors in the sector" (Fouilleux and Goulet 2012, p. 32).

standardization and leads to adapting environments to crops rather than the other way around (Caplat 2014).

But the lack of consideration for the environment does not mean its disappearance. The publication of Rachel Carson's book *Silent Spring* (1962), which highlighted the effects of pesticides on biodiversity, brought the environmental dimension of agriculture to the forefront. The environment became a matter of societal concern and then a matter of national responsibility in the 1970s with the creation of the Ministry of the Environment in France, before becoming a subject of international negotiation following the 1992 Rio Conference (Larrère and Vermersch 2000). Agriculture is then often presented as contributing not only to the loss of biodiversity, but also to water, soil and air pollution, climate change and soil degradation. To address these challenges, there has been a growing debate on the ecologization of agriculture. This can be defined as the increasing integration of environmental issues into agricultural practices, knowledge and policies (Lamine 2011; Lucas 2021).

In French agricultural policy, this environmental shift began with the 1999 reform of the CAP[7] (Agenda 2000[8]). It took shape along in two dimensions. On the one hand, the principle of cross-compliance, strengthened during the 2006 and 2014 reforms, makes receiving subsidies from the first pillar of the CAP (income support) conditional upon compliance with minimum environmental standards (crop diversification, maintenance of ecological focus areas, etc.) (Avril et al. 2021). On the other hand, the second pillar aims to "address the specific needs and problems of rural areas", including resource management, ecosystem protection and combating climate change. Despite this shift, subsidies would be more favorable to farms with less environmentally sustainable practices, particularly due to the first pillar, which is insufficiently counterbalanced by the second (Kirsch et al. 2017). The CAP thus structures tensions between the productive and environmental challenges of agriculture. Ecologization public policies approaches are essentially based on a framework of ecological modernization, which articulates a neoliberal vision and environmental critique (Mormont 2013; Mesnel 2018).

At the level of agricultural practices, this environmental shift is multifaceted. Indeed, several agricultural models are proposed and implemented to address environmental challenges. Broadly speaking, two forms of agricultural ecologization

7 *Politique agricole commune* (PAC), in French.

8 This reform of the CAP comes in a context of crisis characterized by growing production surpluses, increasing budgetary costs, significant disparities between farms, as well as environmental impacts and health crises in food (Dehousse and Vincent 1998).

can be distinguished (Duru et al. 2015). On the one hand, an optimization model proposes improving the efficiency of the conventional production system in order to reduce its negative externalities on the environment. On the other hand, agroecology proposes applying ecological principles to agroecosystems to stimulate natural processes (Gliessman 1998). This implies a more comprehensive redesign of agricultural and agri-food systems to integrate the environment not merely as a context and support for agricultural production, but as an integral component. The first approach is the solution that seems to be favored by those involved in the paradigm of conventional farming. The second pathway is embodied in France, notably by organic farming. The latter is considered one of the prototypes of agroecology, which has become institutionalized (Bellon et al. 2011). Beyond these two pathways, a diversity of ecologization trajectories is being implemented. These different ecologization pathways are found not only at the level of individual practices on farms but also at the sector level. Indeed, organizations and institutions guide and frame these types of ecologization, whether in the production of knowledge, agricultural advice, political representation or the organization of supply chains and markets.

NOTE.– The ecologization of agriculture can be defined as the increasing integration of environmental issues into practices, knowledge and policies.

Several forms of ecologization exist, ranging from optimizing the conventional production system to reduce its negative environmental externalities to a more comprehensive redesign of agri-food systems via the application of ecological principles to agro-ecosystems.

The ecologization of agriculture is one of the challenges facing the agricultural sector, but it is far from being the only one. Agriculture also faces other economic and social challenges, such as those of remuneration and quality of work, farm succession, integration into peri-urban areas, and landscape maintenance, not to mention the major challenges of producing quality food for the entire population and contributing to climate change mitigation (Touzard 2018). Today, digital technology is revolutionizing the agricultural sector, both in terms of individual practices and collective organizations. At a time when agriculture is facing economic, social and environmental challenges, when numerous scientific studies affirm the need to change the agricultural production model, and when societal pressure is also driving this change, it seems important to examine this development of digital technology in light of the desired and ongoing changes in agriculture. What role can digital technologies play in contemporary transformations of the agricultural sector and how can we analyze their impact on different agricultural production models?

1.2. Digital technology in agriculture

This section aims to clarify the concept of digital technology and to specify it in relation to our field of study: agriculture. First, we will outline the multiple dimensions that underlie the concept of digital technology. Then, we will detail what digital technology empirically represents in the agricultural sector.

1.2.1. *Characteristics of digital technology*

While digital technology is omnipresent in discussions, it is rarely defined. This section aims to clarify the various dimensions encompassed by the concept of digital technology, from its technical aspects to its economic dimension.

The term *numérique* (digital) in French comes from the Latin *word numerus*, meaning number. It refers to a technique for encoding information, implying a discretization of information and contrasting with what is analog, that is, proportional and continuous. An analog phenomenon cannot therefore be perfectly copied digitally, as some of its properties cannot be digitized (Vadén 2004). This encoding, as a representation of information, offers possibilities for the production and reproduction, exchange, storage and processing of information, independently of the physical object. One of the main characteristics of digital objects is the ability to change the code without changing the physical object (Ceruzzi 2012; Dufva and Dufva 2018). Digital encoding thus allows the use of encoded information in a variety of tools. This information can then be managed and used remotely from the physical object.

Digital technology is therefore characterized by the codification of information. Promoting the circulation of information, this codification has given rise to another characteristic: the networking of information, particularly since the invention of the internet, the World Wide Web in the 1990s, and the Internet of Things (IoT), a field that has been growing since the 2010s (Srnicek 2018).

Digital technology exhibits significant physical and functional heterogeneity. Digital tools employ various techniques, often discussed in the field. Big data can be defined as a set of information characterized by such volume, velocity and diversity that it requires specific technologies and analytical methods to be transformed into value (Wolfert et al. 2017). The boundary is blurred, particularly with the notion of "big", which varies according to technological evolution (Carolan 2017b). The IoT refers to a network of interconnected objects based on standardized communication protocols (Verdouw 2016). The "cloud" refers to storage and computing services provided by remote computer servers. "Artificial intelligence" refers to algorithmic learning processes that enable the resolution of problems based on a given set of information. "Blockchain" is a method of storing and transferring data, without any intermediary being necessary to guarantee their authenticity and integrity (Acta 2018).

These different techniques are combined with each other and associated with hardware and knowledge to create digital technologies, which will be built, technically and socially, with the aim of fulfilling certain functions.

Digital technology is therefore first and foremost a technical system that takes shape in hardware devices. These devices have a terminal component, the one with which we interact directly, called the "terminal" or "interface": computers, phones, etc. These hardware devices also have a support component, which can be remote, particularly for the analysis, storage, or transfer of data: data centers, but also sensors, cables and antennas. The use of digital technology is sometimes described as dematerialization or virtualization. The use of these terms renders the hardware component invisible, especially the support component, which is nevertheless intrinsic to digital technology. But digital technology does indeed rely on hardware operation, and therefore uses energy and resources (Pitron 2017). On the other hand, the terminal hardware component is highly valued, as shown by the importance of design and fashion in these fields, or the development of luxury devices.

It is also important to add the human component, that is, the "human element that digital technologies contribute to putting to work" (Casilli 2019, p. 34). This human component intervenes at various stages, from design to final use, including the work of learning artificial intelligence, manufacturing and logistics. Academic research, starting in the 2000s, highlighted the emergence of new forms of work linked to digital technology, grouped under the concept of "digital labor" (Terranova 2000; Scholz 2012). This digital labor can be defined as the interactions with digital objects that are "forms of activity that can be considered work because they produce value, are subject to some kind of contractual framework and are subject to performance metrics" (Casilli 2019, p. 5).

In this book, we focus on the human element at the final stage, in other words, on uses. Use requires adopting the technology, but it also generally presupposes having appropriate infrastructure, inputs, peripherals, content, appropriable services, capacity for use, funding, learning and a governance structure (Warren 2007). Effective use can be defined as "the capacity and possibility of successfully integrating information and communication technologies (ICTs) in the achievement of objectives defined by users themselves or in collaboration" (Gurstein 2007, p. 9). The use of a technology is therefore associated with the construction of knowledge, adjustments and interactions with the context of use (Higgins et al. 2017). The use of a digital technology will thus change the nature, temporality and spatiality of the tasks performed.

“Digital labor” encompasses several categories of work. First, there is “on-demand” work, performed by platform workers. Second, there are “micro-tasks”, carried out by “clickworkers”, particularly tasks supposedly performed by algorithms, but which are more efficiently done by humans (e.g. facial recognition). The Amazon Mechanical Turk (MTurk) platform is the best known in this area, offering workers worldwide the opportunity to perform tasks such as answering surveys or identifying images in exchange for (micro)wages. In a different vein, “click farms” employ individuals to click on links, thereby falsifying connection numbers and thus increasing advertising or visibility revenue. Third, there is the unpaid and unconscious work performed by digital users. Indeed, the data produced by digital users are valued by the companies that analyze it. They feed into the learning of algorithms and databases. This type of work blurs the traditional boundaries between production and consumption, between work and leisure. Studies show the effort made to render this type of work invisible (Huws 1999; Gray and Suri 2019), as well as those of its workers (Gruszka and Böhm 2020). These phenomena of revised boundaries between work and consumption (Dujarier 2014), of increased flexibility and individualization of work (Srnicek 2018), and of the invisibility of workers (Daniels 1987) are not new, but the development of digital technology is changing their nature and scope. The question of the human element in digitalization is increasingly prominent in discussions: images of click farms have been published in the press, and social movements consisting of workers affected by what is called the “uberization of the economy” are emerging, with initial legal and legislative consequences. In France, for example, Deliveroo was fined €375,000 on April 19, 2022, for “undeclared work”. In California, despite a referendum that enshrined the independent contractor status of Uber drivers in 2020, debates about driver status remain heated.

Box 1.2. *“Digital labor”*

Beyond its technical and material components, the term “digital” also refers to a socioeconomic phenomenon. Its use has become widespread, encompassing not only all digital technologies but also the way they are integrated into a specific organizational and economic model. Definitions of big data illustrate this duality. One definition refers to the 3 V rule, highlighting its technical specificities that differentiate it from traditional data analysis:

– variety: the data comes from multiple sources and is heterogeneous;

– volume: the amount of data used is very large;

– velocity: data flows are in constant and rapid motion.

But a second definition integrates the organizational and economic model associated with the technical characteristics:

> The concept of Big Data refers to what can be done on a large scale, but not on a smaller scale, to extract new information or create new forms of value, thereby changing markets, organizations, the relationship between citizens and governments, and much more. (Mayer-Schönberger and Cukier 2013)

In discourse, the understanding of the concept of "digital" is therefore broadening and incorporating these components. Thus, businesses, as well as public actors, speak of the digital economy, the digital republic, digital ambition, digital inclusion and even digital agriculture. The digital economy refers to "businesses whose management models increasingly rely on information technologies, data, and the internet" (Srnicek 2018, p. 10). This definition demonstrates that digital technology is not merely a sectoral transformation, but affects all sectors and plays an increasingly important role.

The increasing use of digital technology in a field is called "digitalization" and can be defined as a process of datafication of reality. This process is also political and cultural. It can be analyzed as a stage in the history of capitalism and technological development (Srnicek 2018). It is part of a capitalist trajectory based on the pursuit of cost reduction and control over labor (Casilli 2019, p. 35) and on an economic vision that favors deregulation, property rights and flexibility (Durand 2020). It is rooted in a social trajectory of rationalization and quantification of social life (Huguet 2017). This digitalization process is gradual, and Lupton (2014) defines several stages:

1) arrival of computers and automation of repetitive tasks;

2) development of electronic identification systems and computerized management;

3) interactions, data exchanges between different institutions and systems.

Thus, the concept of digital refers not only to a technical definition, but also to the material devices, functions, uses and associated political and socioeconomic dimensions. Digital technologies can be seen as cultural and material artifacts that have political implications.

These different definitions refer to what constitutes a technology more broadly. A "technology" is not simply a set of tools, materials and equipment used for a human activity. To quote Deleuze, cited by Dockès (1990, p. 35), "machines are social before they are technical". According to Dosi (1982, pp. 151–152), a technology is also “a set of knowledge, know-how, methods, procedures, and experiences”. Technological change therefore implies a complex set of transformations that affect the organization of firms, production processes, institutional configurations, intersectoral dynamics, social relations and so on (Boyer 1989). Dobrov (1979) emphasizes that technology is a set of (1) physical components – hardware, (2) knowledge and skills – software, and (3) organizational equipment – orgware. He defines the latter as “the set of socioeconomic, organizational, and management measures designed to ensure the identification and effective use of a given technique and sociotechnical knowledge, as well as the potential capacity of the technological system to adapt, develop, and self-improve” (Djellal 1995). A digital technology is thus characterized by the techniques it implements, the tool, the function(s) it serves, the knowledge and skills required by the users of this technology, the organization it implies, the associated economic and organizational model, as well as the underlying social and cultural values (Dufva and Dufva 2018).

NOTE.– Effective digital use can be defined as “the ability and possibility of successfully integrating information and communication technologies (ICTs) into the achievement of objectives defined by the individual or in collaboration” (Gurstein 2007, p. 9). It is therefore associated with knowledge building, adjustments, and interactions with the context of use.

Beyond a technical and material transformation, the development of digital technology also reflects a socioeconomic transformation. A digital technology can thus be characterized by the techniques it employs, the tool, the function(s) it serves, the knowledge and skills required by its users, the organization it entails, the associated economic and organizational model, as well as the underlying social and cultural values.

1.2.2. *Digital technology as an object of research in social sciences*

Digital technology, in its many dimensions, has gradually become an object of research in the social sciences, examined through various questions. A first set of questions relates to the context (technical, economic, social, political and cultural) of its design and construction: Why and how is digital technology developing? A second group of questions concerns the mechanisms of development, dissemination and use: What tools and what uses for which users? Here again, we find the different dimensions: technical, economic, social, political and cultural. A third dimension of inquiry focuses on the effects and consequences of digital technology in society, on the forms of meso- and macroeconomic regulation that accompany it, and more broadly on the links between digital technology and forms of capitalism: What does it change and what does it not? Some studies examine the effects on the economy, but also on social, political and cultural dimensions.

The first set of questions concerns the objectives embedded in digital technologies, the representations and imaginaries associated with them, as well as the intended uses and the power structures built into these objects. Technological development tends to be “naturalized” in discourse: it is presented as the result of a natural and inevitable evolution. This naturalization is crystallized in “laws” such as Moore’s law (the power and complexity of computing doubles every 18 months) and serves to generate legitimacy and credibility for technological projects. Digital technology is thus part of the “economy of technoscientific promises” (Joly 2015). However, the digitalization project is not a natural or necessary evolution, but rather a social, economic and political project. Analyses of digital technology design show that it was conceived within an ideology stemming from a hybrid of the American hippie counterculture and the free-market principles of Californian entrepreneurs (Durand 2020), but also, in the case of the internet, from the meritocratic spirit of the research world and the cooperative and reputational practices of computer scientists (Cardon 2010, p. 13). Despite an ideal centered on individual entrepreneurship, studies show that the development of digital technology has been largely funded by states (Mazzucato 2011).

This economic, political and cultural context thus led to the incorporation of characteristics of autonomy and networking in the design of early digital technologies, as well as the “deepening and radicalization of contemporary *individualism*” (Cardon 2010, p. 9): social innovation is linked to technological innovation. These characteristics are integrated into the technical architecture, for example, the internet and the microcomputer, and therefore perform and are reinforced through use (Flichy 2004). Indeed, representations of potential uses are incorporated into the sociotechnical development process of technologies. Thus, “the inventors of the internet materialized a set of values that exert a persistent effect on the form of the network, its organization, and its practices” (Cardon 2010, p. 14).

This question also arises with regard to “data”, which is a social construct and involves political and economic choices (What data do we collect? What data do we look at? How do we characterize these data?), and whose analysis is not neutral. Thus, questions and debates emerge around algorithms: What transparency is there, what governance of algorithms is there? Furthermore, other work in the social sciences focuses on the construction of digital technologies: the economic and political stakes of resource mobilization, labor and the integration of environmental concerns into the design of technologies.

The second category of questions focuses on the practices implemented. Indeed, the rhetoric of the technoscientific promises regime focuses on potentialities, on possible futures (Joly 2010). In contrast, the concrete modalities of technology adoption, the practices and uses associated with models of production, learning, change or even resistance, are much less well documented. This question is interested in concrete situations of use beyond discourse. Some studies examine the adoption and diffusion of digital technologies in society, but they sometimes tend to naturalize the social phenomenon, with technological evolution often simply being seen as the natural order of things (Bertini 2009). However, studies more specifically focused on adoption and use have highlighted individual factors, as well as economic, social and geographical factors influencing adoption. Research is examining the phenomena of the digital divide, digital skills, understanding and appropriation (Warren 2007; Brandtzaeg et al. 2011; Richardson and Bissell 2019). In order to understand the appropriation of digital technology, research also focuses on the effective use of digital technologies, that is, the integration of these technologies into practices and intended objectives (Gurstein 2007). Indeed, the use of a technology is the result of the interaction between the technology and the user: the user shapes the technical object by appropriating it (Williams and Edge 1996).

The third type of question relates to the economic functioning and the results and consequences of this technological implementation. These can occur at different scales, at different time intervals and for different dimensions. Analyzing these effects may lead us to focus on changes, but this should not, however, obscure what remains unchanged. Indeed, "technology stems from a force of conservation and perpetuation of the Same, at work in reality" (Bertini 2009, p. 19). The effects of digital development on society are a major societal issue, one that raises debates and controversies, and carries with it a multitude of hopes and fears. This question of the consequences of digital technology, and more broadly of technologies in general, is sometimes sidestepped in order to avoid the risk of technological determinism, but also the risk of slowing down technological progress and economic development by adopting a critical perspective or the precautionary principle (Bronner and Géhin 2010). However, technology and society interact and impact each other (Williams and Edge 1996).

The question of the impacts of digital technology is highly complex, as technological change always interacts with other societal developments. Some research on the consequences of digital technology examines its impacts on economic dynamics, or more broadly, on capitalism. The effects on productivity and growth are debated: the Solow paradox highlighted the fact that the development of digital technology in the 1970s had no effect on productivity. This lack of effect on productivity and growth is debated and could be linked to the measurement of productivity (Aghion and Antonin 2017). Regarding market structure, the development of the digital economy leads to monopolization and rent-seeking processes rather than investment (Durand 2020). It also reinforces trends toward increased outsourcing and just-in-time, personalized production (Srnicek 2018). On the other hand, digital technology is a source of commercial opportunities in many areas (Bai et al. 2020).

Several studies examine the consequences for work, highlighting the use of digital technology as a facilitating tool and a factor in improving working conditions and autonomy (Flichy 2004; Bai et al. 2020). On the other hand, digital technology can be used as a tool for control and subordination (Lupton 2014; Durand 2020), as a factor in the deskilling of certain tasks, job insecurity and the fragmentation of professional structures (Casilli 2019; Rotz et al. 2019b). The development of digital technology also has geographical impacts, with phenomena of spatial polarization of economic activities and socioeconomic divisions among populations (Warren 2007; Durand 2020). However, it is also seen as a factor in opening up and revitalizing rural areas, developing new services, disseminating knowledge and creating value in rural territories (Réseau Rural Français 2018). Digital technology is also changing the ways knowledge is constructed in science and business, leading to an epistemological shift in science and favoring certain rationalities over others (Kitchin 2014; Madsen et al. 2016). Data-driven scientific analysis, which “makes the data speak”, is thus of increasing importance. This would amplify path dependency phenomena, as digital technology relies heavily on the analysis of past data. Finally, the effects of digital technology on the environment are also the subject of research, whether in relation to the environmental impacts of its direct use, the impacts of the changes it brings about on production processes, or economic and societal dynamics. The controversies surrounding these impacts will be detailed in section 1.4.

These three questions are interdependent, as the consequences will result both from how the technologies were designed and how they are actually used. Similarly, the design and uses of technologies will be linked to the expected consequences. These questions can be explored and studied at different scales and across different territories. Indeed, the dynamics will not be the same from one country to another, as digital development will depend on infrastructure, markets, resources and so on. Digital technology can be studied at the scale of globalized capitalism in order to understand the overall economic dynamics associated with its development (Srnicek 2018; Durand 2020). On the other hand, some studies focus on the individual level of practices and perceptions (Brandtzaeg et al. 2011). Studies have been conducted to address these questions at the sectoral level, given that the functions and impacts of digital technology vary across sectors: for example, in the industrial sector (Frank et al. 2019), in the health sector (Lupton 2014), in urban planning (Marquet 2019) or even in the agricultural sector.

1.2.3. *Digital technology in agriculture*

Digital technology refers to both technical objects and economic dynamics. The development and integration of digital technologies will interact with and impact production models and practices, and will therefore vary depending on the sector. What about agriculture? This section will specify what digital technology empirically represents in the agricultural sector. This book focuses more specifically on the development of digital technology at the farm level. However, farming is interdependent with broader sectoral developments, hence the need for a multi-scale perspective.

1.2.3.1. *Digital technology on farms: a brief history*

In France, the arrival of digital technology on farms can be traced back to the 1980s and 1990s, first with the development of Minitel and then of the computer (Pillaud 2015). Minitel was the first digital platform for a range of applications, providing access to information on weather, agricultural prices and technical and legal advice. However, it was primarily for accounting and management, and later for administrative declarations, that the first digital technologies took off (Mazaud 2017). Farmers' access to and use of computers was not solely driven by individual adoption, but also, and perhaps more importantly, by the evolution of a professional community. Thus, the majority of farmers in the 1990s used computers through intermediaries such as management centers or via collective investment within groups of farmers (Bages 1992). The development of these uses is thus linked to the development of knowledge and skills, fostered by the forms of social interaction associated with them. These technologies contribute to the "professionalization" of agriculture and reinforce the divide within the farming community, targeting farms operating according to a business model. Gradually, the computerization of farm administration and financial management has become widespread. The regulation of agricultural activities is becoming more complex and increasingly linked to the use of ICTs (Weller 2006; Oui 2021b). For example, health declarations for livestock or customs declarations for wine production are computerized processes. The ecologization of agricultural regulations contributes to this dynamic, with, for example, the mandatory registration of plant health treatments. The CAP also plays a central role in the computerization of agricultural data, with the development of online CAP declarations and the digitization of the agricultural landscape (Mesnel 2017; Magnin 2019). Furthermore, the use of the internet and social media is becoming increasingly widespread in agriculture, as in the rest of society. The Agrinautes study estimates that in 2020, 86% of farmers used the internet daily and 68% consulted social media for professional purposes (Terre-Net 2021).

In the 1980s, in the United States, new technological opportunities were developing. In particular, the authorization for civilian use of certain military technologies, such as global navigation satellite systems (GNSS), better known by their American name, GPS (global positioning system), created new technological potential (Lowenberg-DeBoer and Erickson 2019). GNSS technology thus enables the design of yield monitors, which produce maps showing yield heterogeneity within plots, the first models of which were marketed as early as 1992. Machine guidance, which allows for easier, semi-automated, or fully automated operation of agricultural machinery, appeared a few years later, first in Australia and then in the United States. This was followed by section control technologies, a device that automatically closes certain sections of the sprayer, seeder or fertilizer spreader to prevent overlaps in input application.

With the development of diverse sensors and new data sources, data analysis and modeling have flourished. Observation and experimentation infrastructures have evolved towards the massive production of data, the analysis of which, since the 1990s, has centered around specialists in applied mathematics and computer science (Oui 2021b). Initially intended for the academic sphere, big data analysis has since been integrated into tools and consulting services established in partnership with companies and aimed at professionals in the agricultural sector. Thus, new decision support tools (DSTs) are used, which provide information or recommendations on agricultural practices. For example, variable rate application technologies combine guidance, sensors (via satellites or drones) and data analysis to create maps in order to adjust input application (fertilization, but also seeds or pesticides) according to the spatial characteristics of areas within fields.

These different technologies are often grouped under the term "precision agriculture". Precision agriculture, which originally involved taking into account intra-field heterogeneity, has existed since the 1920s. But precision agriculture, as it is defined today, integrates the use of digital technologies to account for this spatial and temporal heterogeneity (Sulecki 2018). It has been developing in France since the late 1990s (Oui 2021b). This development is notably the result of investments by companies in the space sector (Airbus, Geosys, etc.) that have partnered with organizations in the agricultural sector to develop new markets (Labarthe 2009). Today, GNSS guidance technology is reportedly used on half of French farms[9]. Approximately 30% of farmers in France are equipped with yield monitors, and 6% use them. Variable rate application is estimated to affect approximately 9% of arable land in France. Connected weather stations and irrigation technologies are also

9 The data on usage estimates in France indicated in this paragraph come from the observatory of digital agriculture uses (AgroTIC Observatory 2017).

widespread on farms. However, robots, while widely used in dairy farming, remain very rare in crop production.

Digital technology has taken on a whole new dimension in agriculture in recent years, driven by a diversification of tools, leading some authors to predict a new agricultural revolution. The development of new technologies such as the IoT and artificial intelligence could even lead to data-driven agricultural systems. The terms digital agriculture, connected agriculture, smart agriculture, Agriculture 4.0, augmented agriculture and digital agriculture are then used to describe agricultural systems that make extensive use of digital technologies.

NOTE.– Digital technologies in agriculture are very diverse:

– computer tools for administrative, financial, regulatory, logistical management, etc.;

– digital technologies for information exchange;

– digital decision support tools;

– precision agriculture technologies;

– connected irrigation technologies;

– robotics, etc.

1.2.3.2. *Digitalization of agri-food systems*

Farming is also a component of the global agri-food system. Farm activities are interdependent with upstream and downstream activities within this system and are embedded in a broader socioeconomic context. This book will specifically highlight the role played by upstream and downstream activities, and the socioeconomic context of digital technology within agricultural operations themselves.

Digital developments in farming must therefore be understood within the broader context of the agri-food sector, where new technologies are emerging at every stage of the value chain. A concise overview of the digitalization of this sector was compiled by Prause (2020) based on an analysis of existing digital services. The article demonstrates the presence of digital services throughout the value chain, including sourcing (e.g. digital credit services), farming, marketing of primary products (digital marketplaces), processing, packaging (connected packaging), transportation (digital freight management), storage (automated warehouses), sales (e-commerce), consumption and value chain organization.

These food value chains are integrated into broader agri-food systems, which include:

– research and development: for example, digital technologies using satellite data, high-throughput phenotyping, the development of models based on data, or research based on data collected by civil society;

– education, including for example massive open online courses (MOOCs);

– regulatory modalities and public policies, which themselves also make use of digital technologies, for example, to carry out declarations, monitoring, farmer information or the instrumentation of measures for the ecologization of agricultural policies.

Digital technology in agriculture thus encompasses a diversity of technologies and activities at all stages of agri-food systems. These technologies can have different scales of application: a plant or an animal, a plot of land, a herd, a farm, or even a territory, a sector or a market.

In this research, we focus on digital technology at one of these scales: the farm. But this farm is embedded in an agri-food system, that is to say, a "socio-technical system that can be defined as encompassing farmers, advisors, research, upstream and downstream actors in the supply chains, public policies and regulatory bodies, consumers and civil society" (Lamine 2012, p. 139), and is more broadly integrated into a socioeconomic system. Therefore, agricultural operations must be considered within their socioeconomic environment, which itself is evolving with digitalization.

1.2.3.3. *Typologies of digital technologies*

The digital technologies used in agriculture are numerous and based on a variety of techniques. These can be distinguished as follows (Van Es and Woodard 2017):

– data collection techniques: geolocation, remote sensing, various sensors (fixed, onboard, on drone, by aerial system or satellite) which will capture data on the weather, the state of a crop (maturity, sap flow, etc.) or of an animal (heat, growth, etc.), on the soil, a resource or even a machine;

– data processing or data transmission techniques: decision support tools, radio-frequency identification, sensor networks and geographic information systems;

– action techniques: robots for livestock farming (milking, feeding, hygiene) or for crops (spraying, weeding, harvesting, etc.), drones, automated systems, automatic guidance, GPS section control, variable rate technology (which allows the application of seeds or other inputs to be adapted according to plot information), etc.;

– ICTs: on-board computers for agricultural machinery, websites (weather, markets, training, media, marketing, etc.), various software and applications (management, image recognition, etc.), as well as digital platforms.

Often, these techniques are combined to create a technology that fulfills a specific function. Thus, several types of technologies are proposed in the literature concerning digital technology in agriculture.

1.2.3.3.1. Existing typologies

A frequently cited typology relates to precision agriculture technologies. These are categorized as recording, guidance and execution or reaction technologies (Balafoutis et al. 2017). Recording technologies include those that collect information, such as sensors or satellite imagery used to create maps. Guidance technologies encompass all technologies that assist in guiding agricultural machinery. Reaction technologies use data from recording technologies to optimize input applications (water, fertilizers, pesticides and seeds). This classification clearly distinguishes the techniques that utilize digital technology in precision agriculture equipment. Originating from a mechanical engineering perspective, it does not consider how these techniques combine within technologies. Furthermore, it excludes other technologies as defined in the first section of this chapter.

In an economic analysis of the "digital revolution" in agriculture, Birner et al. (2021) distinguish between two types of technologies: embedded and non-embedded. Embedded technologies are those intrinsically linked to a specific physical object or machine. These correspond in particular to so-called precision agriculture technologies. Non-embedded technologies are software technologies that only require a generic terminal (smartphone, computer, tablet). These technologies correspond to mobile applications, management software and digital platforms. This distinction is relevant for a perspective that studies the supply of technologies. Indeed, the authors show that different actors are involved in the design of embedded and non-embedded technologies. However, this classification does not seem relevant for studying uses, which can combine both types of technologies. For example, variable rate application requires field maps (non-incorporated technology) and a fertilizer spreader adapted for variable rate application (incorporated technology). The designers of these two technological components may be different. However, the application results from the combination of these two components, and intermediaries in the agricultural sector (advisors, cooperatives, etc.) play a supporting role at the various stages of technology adoption, whether incorporated or not. Furthermore, whether incorporated or not, technologies can have very different functions.

1.2.3.3.2. Construction of a typology based on uses

Given the lack of a typology that takes into account the diversity of what digital technology encompasses in agriculture and the uses of these technologies, we propose a typology organized around the functions that these technologies fulfill. This typology distinguishes six categories, as shown in Table 1.1.

Category	Functions
Animal production	Animal feeding (automation, precision input), collection and dissemination of information on animals (health, heats, calving, etc.), milking, environmental management (bedding, buildings, silo), animal guidance, monitoring of practices and decision support.
Plant production	Soil analysis, analysis of plant condition (water, nitrogen, health), pest and disease identification, input management (phyto, water, fertilizer), soil preparation, treatment, weed control, grassland management, harvesting, transport of equipment or production, monitoring of practices, geolocation, task automation and decision support.
Management	Accounting, banking and financial services, economic analysis (calculating results/crop, etc.), inventory management, land management, environmental management, planning, official declarations, aid applications and equipment management.
Information	Information on weather, health conditions, markets, practices, legislation and online training.
Communication/collaboration	Collaborative platform: equipment rental, plot exchange, discussion networks, input purchase, service exchange, crowdfunding, equipment purchase/sale, product/co-product purchase/sale, connection with an agricultural contracting company[10] and connection with labor.
Valuation	Traceability, sale of production (financial markets, short circuits, etc.), sales management, marketing and exchanges with consumers.

Table 1.1. *Categories of digital technologies in agriculture based on their functional roles*

This typology of technologies based on functions allows us to consider digital technology in agriculture by including all dimensions of farms. These farms are the

10 *Entreprise de travail agricole* (ETA) in French. Farms that provide outsourcing services.

site of production processes, but also of economic management and decision-making processes that articulate a diversity of objectives, knowledge and constraints, in connection with the economic, institutional, social and informational systems in which they are embedded. Furthermore, this categorization is relevant for the study of uses, since it distinguishes between technologies according to the types of applications that can be made of them.

These tools and functions can be found at different scales: the plot, the operating system, the territory, the sector, etc. We therefore consider digital technology as a set of tools with a diversity of functions, and we do not consider digital agriculture as an agricultural model in itself (Leveau et al. 2019).

1.3. Transformation of the agricultural sector

The development of digital technology in the agricultural sector, which we will call the digitalization of agriculture, is leading to new uses and changes at the farm level. These transformations in farm practices depend on a number of factors: the individual characteristics of farmers (age, education, etc.) can play a role, but also the relationships they build with other actors, captured through the analysis of their ego-centered networks (Sutherland et al. 2018), or even broader sectoral developments (regulations, markets, incentives, subsidies, etc.). Thus, innovation is not here considered as a top-down process flowing from research to farmers, but as a complex process linked to a set of interactions between different types of actors, organizations, institutions and knowledge. Technological developments are therefore considered more endogenous to the sector and to the economy. Thus, even if we are interested in change at the farm level, this change is intimately linked to changes at a more global sector level. This section aims to describe the sectoral changes linked to the development of digital technology in agriculture.

1.3.1. *Changes at the actor level in the agricultural sector*

In the agricultural sector, digital technology can bring about changes in actors and in their ways of interacting. Indeed, the development of digital technology requires skills that were not present in the agricultural sector: new players are therefore being mobilized to provide these skills. This can be done through the expansion of activities of players in the digital or aerospace field (Orange or Airbus, for example), through the integration of digital skills into traditional organizations in the agricultural sector, or through the emergence of new organizations specific to “AgTech”, that is to say, specific to new technologies for agriculture.

1.3.1.1. *Actors involved*

1.3.1.1.1. New actors: startups and digital actors

The development of digital technology in agriculture is bringing new players into the sector, particularly startups offering digital technologies for agriculture (Chapus et al. 2023). Startups are highlighted as drivers and fosterers of innovation in this field. They are seen as central to the technical transformations, and even to potential socioecological transformations, of the sector (Pigford et al. 2018; Piot-Lepetit 2022). They are thus supported by governments, development organizations and institutions. International investors, as well as investment funds and large corporations (Sippel and Dolinga 2023; Klerkx and Villalobos 2024), are also key players. AgriTech startups have proliferated across the globe, with examples such as Climate Corporation in the United States, AgroMatch in Chile and Naïo Technologies in France. Some introduce new products or services, while others focus on renewing existing services, such as online sales of agricultural inputs. Global investment in agricultural and food technology startups has therefore experienced strong growth in recent years (AgFunder 2021). Startups are also central to innovation public policy: Entrepreneur/Start-Up Visa in Argentina, Start-Up Chile in Chile, Innovation and Skills Plan in Canada, etc. (Audretsch et al. 2020).

But startups are not the only new actors entering the agricultural sector. The development of digital technology in agriculture is also driven by companies with existing digital skills and expertise that are expanding into new sectors. These include digital giants like Alibaba, Adobe Inc., Google (e.g. with its Mineral robotics project), and Microsoft (with FarmBeats). In France, examples include Orange Business Services, a partner of AgDataHub and Suez, working to "develop solutions that accelerate the digital and environmental transition of the agricultural sector"[11] or SFR, which offers services for implementing IoT solutions, or even Airbus, which is working on remote sensing services for fields.

1.3.1.1.2. Actors traditionally present in the agricultural and food sector

However, the development of digital technology is not solely an external dynamic within the agricultural sector. It also results from the deployment of digital strategies within traditional organizations in the sector or those already present in the sector.

11 Description of AgDataHub dated April 27, 2021, see: https://agdatahub.eu/a-la-une/agdatahub-orange-business-services-et-suez-partenaires-au-service-de-la-transition-agro-environnementale/.

This includes actors from the upstream agrochemical industry – Syngenta, Dow DuPont, Bayer Crop Science, Yara International – but also from agricultural machinery companies like John Deere and Claas. These actors are notably involved in the development of precision agriculture technologies (Oui 2021b). For example, Yara is developing the N-Sensor nitrogen modulation tool, and John Deere offers hardware that enables variable-rate application of inputs. Bayer offers modulation boards via Climate FieldView, since its acquisition from The Climate Corporation. These companies also offer a variety of other decision-support tools: for example, Bayer's Movida tool for managing downy and powdery mildew in vineyards. These companies also offer management software including Myjohndeere by the eponymous company or AgriEdge by Syngenta.

Players located downstream of agricultural activities, such as Cargill, Nestlé and Carrefour, play an important role, particularly when focusing on marketing and traceability technologies. Players that gravitate around the agricultural sector, such as insurance companies, investment funds (Demeter, CapAgro) and foundations (the Bill and Melinda Gates Foundation, for example), are also investing in digital development.

Agricultural professional organizations also participate in digital development, including agricultural cooperatives, trading companies, chambers of agriculture, technical institutes and other advisory bodies. In France, for example, chambers of agriculture offer MesParcelles, a farm management software tool, while the National Federation of Farmers' Unions (FNSEA)[12] has designed and promotes the Data Agri charter. Other examples include InVivo, the French union of agricultural cooperatives, which acquired the startup Smag in 2012, and DigiFermes, supported by agricultural technical institutes, which offer farms dedicated to experimentation with digital technologies.

1.3.1.1.3. Public actors

The development of digital technology in the agricultural sector is not solely the result of private company initiatives. Public organizations and policies support the development of digital technology in agriculture (see section 1.3.2).

In France, the Agriculture-Innovation 2025 report thus includes digital technology as an element of agricultural public policy (Bournigal et al. 2015). The Digital and Data Delegation[13] created in April 2017 within the Ministry of Agriculture aims to "support the development of digital technology, whether in the

12 Fédération nationale des syndicats d'exploitants agricoles, in French.

13 La délégation au numérique et à la donnée, in French.

functioning and tools of the administration or in the public policies for which the Ministry is responsible" (Ministère de l'Agriculture 2021). Within research, teams have been dedicated to precision machinery (at the Cemagref, now the National Research Institute of Science and Technology for Environment and Agriculture [IRSTEA][14]) or to modeling (INRA) since the 1980s, with their work gaining new momentum in the 2010s (Oui 2021b). Little by little, the issue of digital technology is making its way into public research programs (e.g. DigitAg), or public–private programs (like PIA Occitanum), and into agricultural education.

1.3.1.2. *Networks*

We have discussed the evolution of actors in the agricultural sector linked to digitalization, but these actors do not act in isolation from one another. Digital technology in agriculture evolves via numerous partnership and network dynamics.

1.3.1.2.1. Partnerships

In order to combine skills in the digital and agronomic fields, many projects are being developed in partnership between actors specializing in each of these areas, particularly via public–private partnerships, which are seen as strategic in this new techno-scientific paradigm of precision agriculture and then of digital agriculture (Oui 2021b). A historical example is the Farmstar tool offered by the Arvalis technical institute for plants[15] (Labarthe 2010). Farmstar is a crop fertilization advisory service which is based on field observations through remote sensing. The images obtained are analyzed to determine the fertilizer doses to apply to a specific area of the plot, depending on the condition of the crops in that area and the desired outcome. This service was developed through a partnership between the Arvalis and Terres Inovia technical institutes and the company Airbus using academic research from INRAE. Other types of partnerships are being implemented, particularly to combine digital and agronomic expertise, such as Microsoft's partnership with InVivo.

These partnerships are developing not only for the design of digital technologies, but also for all the innovations associated with this technological development. These innovations can be standards, procedures or charters. For example, the Agro EDI Europe association brings together 280 members: "agro-supply industries, technology providers, agricultural technical institutes, professional agricultural organizations, as well as public stakeholders". Created in 1992, this association's objective is to establish data exchange standards between all these actors. Another

14 Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture, in French.

15 Arvalis is an agricultural technical institute that conducts applied research in the domain of field crops.

example is the Multipass project, a partnership between agricultural technical institutes, the Association for Agricultural Technical Coordination (ACTA)[16], INRAE, Orange and Smag, which manages the consent aspect of exchanging agricultural data and led to the creation of the company Agdatahub. The Data Agri charter, developed by the National Federation of Farmers' Unions (FNSEA[17]) in partnership with agricultural digital companies, sets out best practices for processing agricultural data. Beyond these formal alliances, meetings, exchanges and discussions are taking place among stakeholders, contributing to building a community of practice.

This interaction dynamic between actors also translates into mergers and acquisitions between companies. The most famous acquisition in this area is Monsanto's purchase of The Climate Corporation in 2013. Other examples include John Deere's acquisition of Blue River Technology and BASF's investment in ProAgrica. The Bayer and Monsanto merger is even thought to be linked to a strategy of positioning itself as a leader in the field of digital agriculture (Piot-Lepetit 2019). Agribusiness companies also directly support and finance the emergence of startups, through capital venture and incubators (Prause et al. 2020), such as Bayer Growth Ventures, Syngenta Group Ventures, Cargill Ventures or InVivo Digital Factory.

1.3.1.2.2. Building a community of practice

Beyond interactions around specific projects, identified via partnerships between stakeholders, these actors interact around the issue of digital agriculture and build networks on the subject. A number of professional events, informal exchanges and associations contribute to the creation of a shared cognitive framework (a repertoire of terms, routines, etc.), a common mission and a mutual commitment that aligns the practices of these actors regarding digital technology in agriculture, thus constituting a community of practice (Wenger 2010).

First, recent years have seen the emergence of a digital community at traditional events in the French agricultural sector, such as the International Agricultural Show (SIA)[18], the International Agricultural Machinery Show (SIMA)[19] and various agricultural fairs (Livestock Show, SITEVI [20], Innov'Agri, etc.). Digital and robotics

16 Association de coordination technique agricole, in French.

17 The National Federation of Farmers' Unions (FNSEA) is the majority professional union in the agricultural sector in France.

18 Salon international de l'agriculture, in French.

19 Salon international du machinisme agricole, in French.

20 International exhibition of equipment and know-how for the production of vines–wines, olives and fruits–vegetables.

companies gather and unite at these trade shows to gain visibility and present themselves as a community, a specific sector, for example, in the “Robotics Village” at Innov’Agri or in the “Startup Village” at SITEVI. In 2021, SIMA launched a day dedicated to digital services called “SIMA Tech Connect”.

Secondly, events specifically addressing the issue of digital technology in agriculture are being organized. Trade shows dedicated to this topic have emerged in recent years. The International Forum for Agricultural Robotics (FIRA) has existed since 2016. *La Ferme Digitale* (LFDay), first held in 2017, brings together startups and various stakeholders in the sector around the theme of AgTech. Educational and research institutions also organize events dedicated to digital technology: ESA Connect at the École supérieure des agricultures d’Angers, the DigitAg days and the AgroTIC seminars, for example. A number of seminars and webinars have developed around this theme, such as the webinars organized by DigitAg, Agreenium and ACTA.

Furthermore, this community is organized around associations. In France, La Ferme numérique and CoFarming are associations that bring together startups in the agricultural sector. Robagri is an international association that unites stakeholders in agricultural robotics: startups, but also companies in agricultural machinery and electronics, research laboratories, competitiveness clusters and agricultural actors. Similarly, WineTech brings together startups that develop digital technologies in the wine industry (storage, consumption, sales, etc.). On the academic side, networks are also being structured, notably the International Society of Precision Agriculture, which organizes an annual international conference on the subject and has its own scientific journal.

Gradually, this professional community acquires recognized expertise, legitimacy and has an impact on institutions and public policies, forming what can be called an epistemic community (Haas 1992; Cohendet et al. 2014).

1.3.2. *Public policies and digital development*

Public policies for the development of digital technology in agriculture encompass measures supporting research and training on the subject, infrastructure development, as well as supply-side policies – supporting innovation – and demand-side policies – subsidies for investment in new technologies. These public policies can be driven by economic and/or agricultural policies at regional, national or supranational levels.

1.3.2.1. *Research and education*

Digital research in agriculture has existed since the 1980s, though not necessarily under that name. With the advent of computing power and new data, research developed data analysis and modeling. These techniques were then integrated into decision-support tools for farmers, offered by researchers, developed through public–private partnerships, or directly by private companies. Subsequently, research expanded into precision machinery, initially in the United States, focusing on precision nitrogen fertilization technologies. Guidance technologies were commercialized in the early 1990s in Australia and then in the United States (Lowenberg-DeBoer and Erickson 2019). In France, public research in this field developed in the 1990s at Cemagref (which became IRSTEA, then INRAE) (Oui 2021b). Research has expanded to include a variety of sensors (Lowenberg- DeBoer and Erickson 2019) and robotics.

The social sciences were slower to take an interest in this issue, with the exception of the American work of Steven Wolf in the 1990s (Wolf and Nowak 1995; Wolf and Buttel 1996; Wolf and Wood 1997). In France, social sciences on digital technology in agriculture emerged with the work of Nathalie Hostiou on precision livestock farming (Hostiou et al. 2015), the work of Danielle Galliano on ICT and the agri-food industries (Galliano and Roux 2006), and the work of Pierre Labarthe on advice and knowledge (Labarthe 2010) and Philippe Jeanneaux on farmers' decision-making processes (Jeanneaux 2018).

It was in the 2010s that these various research projects came together under the concept of digital agriculture (Martin and Schnebelin 2024). This led to the development of a body of work on digital agriculture, focusing on its technological components as well as its social components. For example, the work of Fielke et al. (2020) highlights the emergence of organizations and structures for research on this topic, as shown in Figure 1.1.

In France, this growth is characterized by the establishment of the DigitAg convergence institute[21], which brings together sixteen public and private partners and 29 research units. Its objective is to "produce necessary scientific and educational foundations for the harmonious deployment of digital agriculture in France, Europe, and the Global South[22]". This institute has substantial resources

21 A convergence institute is an approach proposed by the National Research Agency (ANR), which aims to develop large-scale multidisciplinary scientific projects that structure research and make it visible in relation to major socioeconomic issues, while producing knowledge and offering training.

22 See: https://www.hdigitag.fr/fr/qui-sommes-nous-2/.

(€9.9 million) to develop research on the subject, notably via the funding of around 100 doctoral theses in computer science, geomatics, statistics, mathematics, optics, physics, agronomy, etc., as well as in the social sciences. Beyond being a source of funding in this field, the institute also provides a structure for French research on the subject, a network of the different French teams working on these themes and also a force for international communication.

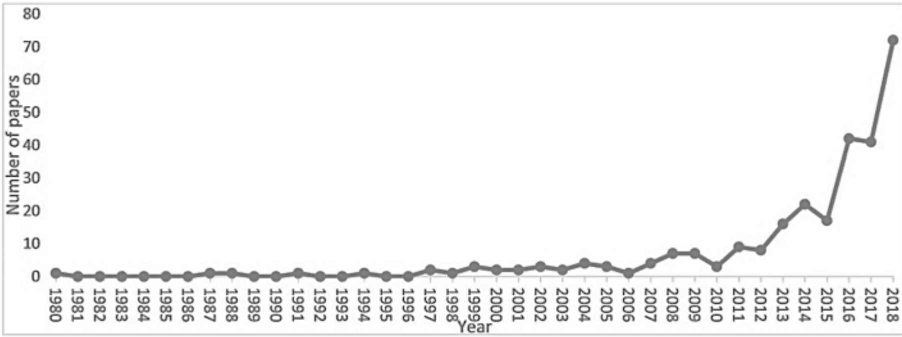

Figure 1.1. *Articles on Scopus that address digital agriculture and governance issues (from Fielke et al. (2020)). A search similar to that proposed in the article shows that this growth continues with 73 articles in 2019, 99 in 2020, 141 in 2021, 195 in 2022 and 166 in 2023 (search conducted on December 16, 2024)*

Education has also taken this technological development into account for several years. In France, for example, the AgroTIC specialization was created in the agricultural schools of Montpellier and Bordeaux to train engineers with dual expertise in agronomy and digital technology. In Australia, the master's program in Agriculture at Charles Sturt University offers a specialization in "Digital Agriculture", while the University of Western Australia offers a 3-year program called "Agricultural Technology" focused on digital skills for agriculture. In the United States, Cornell's *College of Agriculture and Life Sciences* also offers a "Digital Agriculture" option, and UC Davis offers a bachelor's degree in agricultural technology, including a "Digital Agriculture" option.

1.3.2.2. *Innovation support policies*

Digital development within the agricultural sector mobilizes human resources, but also financial and political ones, at various levels. At the European level, research projects and digital development projects in agriculture are funded. The website of the European Innovation Partnership for Agriculture (EIP-Agri) lists research and operational projects supported by the European Commission. By entering the keywords[23] suggested by the website, which refer to digital technology in a broad sense, we thus obtain 163 projects. For example, the PigWise research project aims to develop digital tools to manage the production performance, growth and welfare of pigs, and is funded by European framework programs; the LoRa Experimental Digital Agriculture Platform project aims to create a communication platform between connected objects on an experimental farm and is funded with €130,000 by the 2014–2020 Rural Development Fund; The Smart Beekeeping Kept Simple project aims to develop good beekeeping practices based in particular on sensors, funded by Horizon 2020; as does the Internet of Food and Farm 2020 project, also funded by Horizon 2020, which aims to increase the productivity and sustainability of agri-food systems via the IoT. Thus, the European Commission reportedly invested €192 million[24] between 2014 and 2020 in research for and on the development of digital technology in agriculture. Public support for innovation is available at the various stages of technological maturity, from exploration – for example, with the SmartAgriFood program exploring the potential of digital technology in agri-food value chains and funded by the European Union – to deployment, with, for example, the IoF2020 project to develop the "Internet of Things" in the agricultural sector (Wolfert et al. 2023).

Around the world, networks, funding (often involving both public and private sectors) and infrastructure are developing to support the emergence of digital agricultural businesses (Klerkx and Villalobos 2024). Many countries fund incubators to support the growth of companies in this field, such as AgLaunch in the United States, French AgriTech in France and the Wageningen University and Research Start Hub in the Netherlands. In Chile, the "Transforma Alimentos" program aims to support innovative companies in the agri-food sector.

At the national level in France, general economic measures (support for innovation, startup funding and research tax credit) provide substantial support to companies offering digital technologies and services in the agricultural sector. *Le Grand plan d'investissement 2018–2022* supports "innovation and the structuring of agricultural sectors" (€500 million) and "the upgrading of downstream agricultural activities" (€1.6 billion). Furthermore, on August 30, 2021, the French government launched French AgriTech, a future investment plan that allocates €200 million to the development of agricultural startups over 5 years.

23 Blockchain, data management, data sharing, data innovation hub, digital learning, digitization, drone, decision support system (DSS), data-driven agriculture, ICT/software, ICT, information system and platform.

24 See: https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/factsheet-agri-digital-transformation_en.pdf.

1.3.2.3. *Policies supporting innovation in farms*

Agricultural policies can also drive the development of digital technologies. In Europe, the CAP also supports the digital development of agriculture through various means. First, the development of online CAP declarations, which became mandatory in 2016, along with various regulatory tools (online wine custom declarations, traceability of plant protection product use, etc.), constitutes a significant driver of digitalization (Mesnel 2017; Magnin 2019). Second, for the 2014–2020 CAP, the second pillar offers various digital financing tools[25]. Article 17 provides co-financing for equipment to modernize farms. This can facilitate investment in guidance or variable-rate application systems. The agri-environmental or climate measures proposed in Article 28 can be justified by the use of precision agriculture equipment. Article 35, which aims to promote cooperation, can finance the joint purchase of precision farming equipment. The measures on advisory services (Articles 14 and 15) can also be used to disseminate precision farming equipment. The role of digital technology will be strengthened in the future CAP, with Member States implementing strategies for their knowledge and innovation systems (Article 5) and explicitly focusing on digitalization as a key element of modernization, supported by the European Commission (Article 102) (Labarthe et al. 2021a). At the French level, the *Grand plan d'investissement 2018–2022* allocates over 1 billion euros to "supporting investments in agricultural businesses" (Agriculture 2021).

Various innovation support policies, targeting the private sector, the public sector or agricultural operations, converge, since innovation policy is based on relationships and partnerships between these types of actors.

1.3.3. *Digital technology uses in farms*

The development of digital technology in the agricultural sector translates into changes in terms of actors and public policies, but also into the development of new uses, that is to say, the effective use of digital technologies and their integration into agricultural operations.

Farmers' use of digital technology is relatively little known. Official agricultural statistics are beginning to include some figures on digital equipment on farms, but this information remains very imprecise and outdated.

In France, the 2010 agricultural census only provides a few variables related to digital technology: internet use, broadband internet use and the use of specialized

25 Information based on the European Parliament document, see: https://www.europarl.europa.eu/RegData/etudes/note/join/2014/529049/IPOL-AGRI_NT(2014)529049_EN.pdf.

accounting and technical management software (field monitoring, herd management, etc.). However, studies provide some information on digital technology use in French farms. *L'Observatoire des usages du numérique en agriculture* (the Observatory of Digital Uses in Agriculture), created by the Agrotic Chair and the DigitAg convergence institute, aims to demonstrate the current use of digital technology in France: the technologies used, the types of agriculture affected and the applications. Infographics are produced on the use of specific tools. Data are collected through literature reviews, interviews with companies providing these services and interviews with agricultural advisors and technicians. According to their studies, the commercialization of remote sensing services covered 905,000 ha in 2020 (compared to 1.1 million in 2016). This represents 10% of arable land and 1.2% of vineyards. Approximately 30% of farms use yield sensors. Tractor geolocation systems (guidance) are used by half of all farmers in France, with 30% using RTK correction. One in two farms has a connected weather station. In cattle farming, more than 10,000 robots were in use in 2018. In crop production, only a few hundred robots are used, mainly for weeding, with most still in the prototype stage. The smartphone is used for equipment adjustment applications (spreader, seeder, tires, etc.), surveying applications (plant sizing, etc.), for guidance (GPS), to access weather information or to enter field observations.

Since 2006, an annual survey on internet use by farmers in France, the Agrinautes survey, has been conducted for Terre-net média on a sample of nearly 1,000 farmers, whose responses are then weighted according to the region and the farm's technical and economic orientation (OTEX)[26]. These studies show that in 2020, 95% of farms had mobile network coverage, 70% of farmers owned a smartphone (45% in 2016) and 86% connected to the internet at least once a day. The study indicates that the most frequently accessed online content (i.e. by the largest number of farmers) was, in order, weather, banking services and classified ads. The results indicate that 68% of connected farmers consult social networks for professional purposes (42% in 2016), primarily Facebook (44.7%) and WhatsApp (40.9%), but also YouTube, Twitter, etc. The preferred sources of information remain printed agricultural press and distributor advisors. Furthermore, almost three-quarters of farmers make purchases online, mainly small consumables and spare parts. Regarding decision support tools, 44% use them (Ministère de l'Agriculture et de l'Alimentation 2016; Terre-Net 2021).

An Agrodistribution-ADquation survey on digital technology use in French agriculture was conducted in 2014. The data from these two surveys, although incomplete, are the primary source of information on digital technology use. It was notably used in the Renaissance numérique think tank's 2015 report, which describes farmers as "early adopters" and cites the following figures: 79% of

26 *Orientation technico-économique*, in French.

farmers use the internet and 76% check the weather online several times a week (Isaac and Pouyat 2015). This report appears to serve as a reference for the Ministry of Agriculture, which incorporates the data it contains into its infographic on digital technology in agriculture (agriculture.gouv 2016).

There are limited data on digital technology use in the scientific literature, particularly in France. Economic literature analyzes the factors influencing the adoption of digital technologies, but rarely examines the uses themselves. For precision agriculture technologies, this research highlights individual factors (age and education), economic factors (farm size, type of production, income and labor), socioeconomic factors (cooperative membership and consulting) and technological factors (ease of use, time required and available information on its effectiveness) (Barnes et al. 2019; Lowenberg-DeBoer and Erickson 2019). This research, which will be presented in more detail in Chapter 2, shows that these factors vary depending on the technologies involved.

Information on farmers' use of digital technologies is therefore still limited, with very little information on actual use, adoption and the consequences of these technologies on farms. National statistics currently provide little information on digital usage, and the scientific literature on the subject is also limited, both in France and internationally. The available data are incomplete, both in terms of representativeness and usage, since most data are concerned with the adoption of a technology or the use of a service in isolation. The consequences of these technologies mentioned in scientific and institutional documents are therefore essentially presuppositions and potentialities, since few studies examine the effects of these technologies in real-world conditions. The concrete changes brought about by these tools are poorly understood. Yet, digital technology is largely supported by public funds. This situation is even more paradoxical given that digitalization is the subject of controversy, particularly regarding its ability to address the environmental challenges of agriculture.

Digital technology can create knowledge or knowledge-creation tools, and it transforms knowledge transfer as well as knowledge itself. Indeed, the very nature of digital technology is the codification of information, which facilitates its transfer and storage: information, and therefore certain types of knowledge, can be easily disseminated, cataloged and so on. The codification process can change the nature of knowledge, for example, via the loss of tacit knowledge or its transformation into explicit knowledge.

Thus, the development of digital technology in agriculture encompasses a heterogeneity of technologies, but also of actors, institutions and socioeconomic transformations. "Digital agriculture" itself ultimately exists only through the technoscientific promise of this technological shift, which proposes digital technology as a solution to the environmental, but also socioeconomic, challenges facing contemporary agriculture (Martin and Schnebelin 2024). However, the development of digital technology is the subject of controversy regarding its capacity to resolve these challenges.

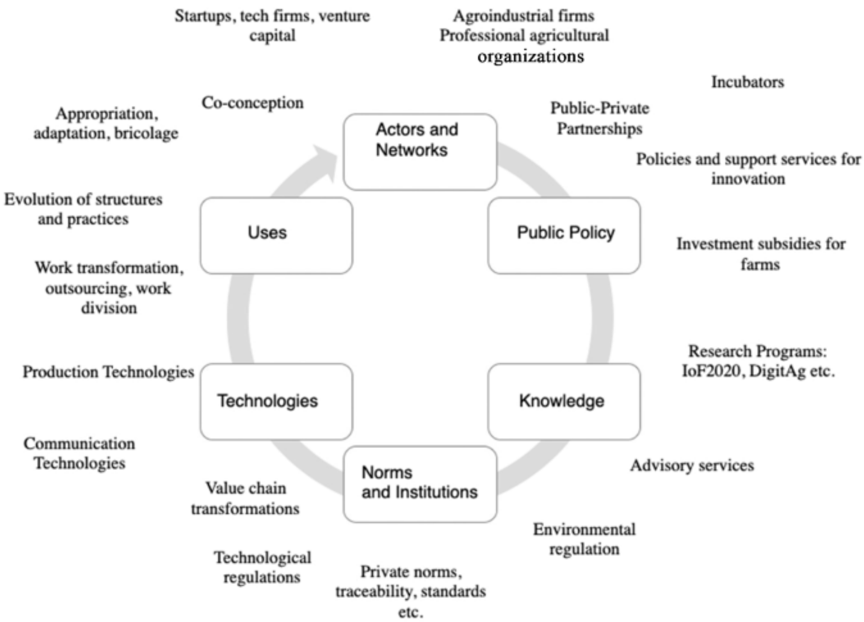

Figure 1.2. *A co-evolution of the dimensions of the agricultural innovation system with the development of digital technology*

1.4. Controversies surrounding digital technology and ecology in agriculture

The development of digital technology is being promoted by scientists, agricultural organizations and international bodies to both improve agricultural productivity and reduce its environmental impacts (Lajoie-O'Malley et al. 2020). Consequently, the deployment of digital technologies is supported and integrated into agricultural policies that aim for dual economic and environmental performance (Prause et al. 2020). However, this deployment is subject to controversy. In particular, the compatibility between the digitalization of agriculture and its transformation in order to integrate environmental issues is debated. First, the environmental impacts of digital technology are the subject of controversies not specific to the agricultural sector. Second, the impacts of digital technology are the subject of debates specific to the environmental question of agriculture, and particularly in relation to the agricultural model(s) that digital technology can support.

1.4.1. *Digital technology and ecology*

Digital technology is presented as a solution to environmental problems in numerous institutional documents, scientific reports and think tank or corporate reports (ADEME et al. 2017; Bai et al. 2020; Babinet 2021; Ministère de la transition écologique et ministère de l'économie 2021; Potier 2021). Although rarely supported by evidence, the assumptions linking digital technology and the environment are based on several elements. The main element is the idea that data created by digital technologies allow for better process management, optimization and therefore a minimization of negative impacts. Thus, digital management is presented as "smart" management. The "smart city" based on sensors and automated systems to manage transportation networks, waste management, hospitals and so on would optimize flows and improve the management of urban energy consumption by modulating city lighting according to occupancy levels or optimizing building energy consumption (Marquet 2019; Potier 2021). The "smart factory" based on the near-complete automation of all company activities and flows would manage the quantity and quality of production and limit waste (Lezoche et al. 2020).

Businesses could better manage their waste. Digital technology would optimize the transport of goods and improve the synchronization of supply and demand through information sharing. These technologies could also promote the implementation of circular economy mechanisms by facilitating information exchange.

This positive perspective, which is reflected in these institutional and professional documents, contributes to a "soft" power, that is, the capacity to inspire, persuade and mobilize through ethical or intellectual arguments (Morgan et al. 2008, pp. 4–5). This contributes to the construction of a shared vision of a desirable future where digital technologies offer new ways to address society's environmental challenges. Digital innovation thus falls within the framework of the technoscientific promise economy, which helps to lend credibility to its promoters, legitimize their innovations and mobilize diverse resources (Joly 2015).

To avoid mechanistic and simplistic links between the use of digital technologies and the environment, Berkhout and Hertin (2004) describe the types of interaction and therefore the potential types of impacts of digital technology on the environment. This leads them to identify three types of impacts: direct impacts arising from the production and use of these technologies, indirect impacts resulting from the effects of using these technologies, and structural and behavioral impacts linked to long-term socioeconomic changes associated with these technologies (see Box 1.3).

The development of digital technology can have several types of impact on the environment:

– Direct impacts are the impacts directly resulting from the production and use of these technologies. Examples include the pollution generated during the design of technologies via metal extraction, or the energy consumption for the design and use of technologies, particularly for server operation. Estimates of the ICT sector's energy consumption vary widely and are subject to debate. Some estimates indicate that this sector used approximately 8% of global electricity in 2010 and could reach around 14% by 2030 (Lange et al. 2020). These direct impacts can also be linked to the use of non-renewable resources, waste production or recycling. The authors show that all these direct impacts have a negative environmental balance.

– Indirect impacts arise from the effects of using these technologies. For example, there are effects related to changes in production processes, such as the optimization of production processes via modeling or data-driven logistics and distribution management (Lange et al. 2020). Furthermore, digital technologies can enable the "dematerialization" of products, services or work: access to information, music, meetings and conferences, completion of certain tasks, etc. (Berkhout and Hertin 2004). These can replace existing goods and services, reducing environmental impacts, or add to them, creating new environmental pressures. According to the authors, these impacts are both positive (efficiency gains, virtualization and environmental management) and negative (proliferation and addition rather than substitution).

– Structural and behavioral impacts are broader and more difficult to assess because they interact with a range of other factors. These impacts are linked to structural changes in society, such as the sectoral restructuring of the economy, changes in lifestyles and consumption patterns, and evolving travel patterns. These structural changes can lead to what is known as a "rebound effect". Such an effect occurs when efficiency gains stimulate demand, the growth of which will counterbalance, or even exceed, the positive environmental effects associated with the efficiency gains. Indeed, an efficiency gain will potentially lead to lower costs, greater capacity and new demands. This has been observed with efficiency gains in computers and servers, as well as in the transportation and energy sectors (Berkhout and Hertin 2004). These changes can be positive or negative on the environment and can change over time and space.

Box 1.3. *Types of digital impacts*

The work of Lange et al. (2020) focuses solely on energy impacts. The authors also categorize the impacts into several categories: direct impacts, energy efficiency, economic growth and sectoral changes. Their work shows an overall negative effect of ICTs on global energy demand.

The key takeaway from these studies is that to analyze potential or actual effects, one must not limit oneself to the simplest effects on production processes, but rather consider the overall scope and temporality of these effects. However, hypotheses linking digital technology and the environment often only consider simple causal relationships, such as increased process efficiency. These hypotheses frequently neglect the intrinsic impacts of producing these technologies and broader impacts, such as the rebound effect. These impacts are difficult to assess because they are complex, interdependent, uncertain and dependent on the envisagedcontext and scale (Berkhout and Hertin 2004). They are also linked to social, economic and political effects that can interact with environmental issues.

1.4.2. *Controversies in the agricultural sector*

Technological innovations typically carry a dual perspective in society: on the one hand, they offer transformative potential and, on the other hand, they are a source of unexpected consequences and potential new problems, including environmental ones (Tenner 1997). Thus, technological development is in constant tension between these two facets (Clapp and Ruder 2020). The resulting debate on the links between digital technology and ecology is also found in the agricultural sector. On the one hand, digital technology is seen as a source of effective solutions to address the environmental challenges of agriculture while maintaining high productivity. On the other hand, digital technology is seen as a source of risks that could reinforce, or even extend, the negative impacts of agriculture on the environment and, more broadly, encourage the agro-industrial system. This debate is reflected in academic works, institutional documents, and a number of texts and political manifestos from economic, environmental and agricultural organizations, which have taken up the subject, either to promote or criticize it. The main arguments in this debate can be organized into several identified categories: agricultural practices and labor, knowledge, autonomy, material resources and the agricultural model.

1.4.2.1. *Effects of digital technology on the environment through the lens of agricultural practices and labor*

The most prevalent argument in discussions promoting digital technology as an environmental solution is its effect on process efficiency (Walter et al. 2017). This effect corresponds to “indirect impacts”, as explained in Box 1.3. In particular, many documents highlight the potential of digital technologies to optimize the use of inputs, whether it be fertilizers, pesticides or water (Bai et al. 2020; INRAE 2020; Microsoft 2021). This optimization is made possible by the ability to make data-driven, scientifically sound decisions. Digital technology is also said to promote higher yields and therefore require less land dedicated to production to “feed

10 billion people" (Microsoft 2021). It is also said to encourage non-tillage farming and thus carbon sequestration in soils (Clapp and Ruder 2020). Furthermore, the gains from process efficiency would help limit losses and waste, such as livestock effluents or nitrogen losses in the soil. Digital technology could also facilitate resource management at the territorial level, for example, by identifying material flows and facilitating collective decision-making (Bellon Maurel et al. 2022).

Digital technologies, by generating new data, offer potential for understanding and managing ecological processes, which could lead to better management of the complexity inherent in living systems and thus contribute to a more agroecological agriculture (Bellon Maurel and Huyghe 2017). They would provide the capacity to manage each agronomic decision on a case-by-case basis and to take into account the complexity of agronomic problems, for a "measured agriculture" (Grenier 2018, p. 30). At the value chain level, digital technology would enable better coordination between organizations and therefore greater efficiency (Sonka 2021). More broadly, digital technology would support the ecological, or even agroecological, transition of agriculture (Bournigal 2016).

Furthermore, these technologies would reduce labor requirements. This could facilitate the implementation of more agroecological, yet labor-intensive, tasks such as mechanical weeding (Bellon Maurel and Huyghe 2017; Lebrun et al. 2020). These arguments are echoed in the discourse of robotics companies, which propose to solve labor shortages, limit the use of precarious workers and reduce the arduousness of labor (Lenain et al. 2021).

Conversely, other scientific studies suggest that the gains from precision agriculture would be relatively small (some studies estimate them at around 10%) and could even be offset by a rebound effect that would limit the anticipated savings (Moschitz and Stolze 2018). For example, improved fertilization efficiency could encourage increased fertilization to maximize yields or the fertilization of more crops. These technologies would be designed by incorporating production-oriented objectives, integrating a vision of farming based on profit maximization and optimizing quantity at the expense of quality, thus reinforcing this mode of reasoning in farming, such as monoculture, simplified technical processes, etc. (Bronson and Knezevic 2016; Carolan 2020; Réseau Action Climat 2020).

Furthermore, if technologies are designed to optimize inputs, this does not incentivize the elimination of those inputs: it creates dependency effects between technologies and locks practices (Wolf and Buttel 1996). All of this would favor the continuation of the productivist trajectory based on increased productivity, but also on the specialization and concentration of production (Clapp and Ruder 2020; Lioutas and Charatsari 2020). Because these tools incorporate existing practices, their widespread use could lead to a homogenization of production systems (Wolf and Buttel 1996; Jakku et al. 2016). This could reduce the adaptation of agroecosystems to their local specificities, thus leading to a decrease in biodiversity. The development of digital technologies could also lead to a standardization of tasks and a deskilling of agricultural workers, contributing to their precarization (Rotz et al. 2019b).

1.4.2.2. *Effects of digital agriculture on the environment through a knowledge lens*

Agroecology requires extensive field and research knowledge, whether in relation to the functioning of agroecosystems, biodiversity or nutrition. Digital technologies could contribute to the creation of this knowledge and to new ways of knowing (Bonny 2017; Ingram and Maye 2020). Since agroecosystems are heterogeneous, the wealth of information would allow for better management of this spatial and temporal heterogeneity. This principle of managing heterogeneity is the basis of precision agriculture technologies, whose maxim is "The right dose, in the right place, at the right time" (Bordes 2017). Data from new sensors could be used for the precise understanding of ecological processes and thus for better use of ecosystem services or better integrated management of plant or animal health (Bellon Maurel and Huyghe 2017).

Digital technologies make it possible to reduce the cost of storing, disseminating and accessing information. This could promote knowledge exchange favoring the implementation of more ecological practices (Phillips et al. 2018; Leveau et al. 2019), as well as the redesign of production systems (Gkisakis and Damianakis 2020). It could promote the breaking down of silos in research (Damave 2017). Digital technology could be a tool in building commons around agroecological knowledge (Fraser 2020). The development of digital technology could also facilitate traceability, which could highlight and enable the economic valorization of products from agroecological production (Wittman et al. 2020).

Conversely, the use of digital technologies could lead to a loss of farmers' tacit and empirical knowledge, as this knowledge would be replaced by the use of technology (Barrett and Rose 2020; Clapp and Ruder 2020). This could result in a loss of agricultural know-how and sensory intelligence (Atelier paysan 2021). Furthermore, by integrating a new artifact between the producer and the environment, this could deteriorate the relationship with nature, and therefore the knowledge and consideration of the environment in decision-making (Rose et al. 2021). The quantification and standardization of practices through digital technology could rigidify practices, reduce farmers' field experimentation and thus limit the adaptation of practices to local specificities and freeze ecological knowledge (Burton and Riley 2018).

1.4.2.3. *The question of autonomy at the heart of the relationship between ecology and the digitalization of agriculture*

Autonomy is a recurring theme in debates surrounding digital technology and, more broadly, technology in agriculture (Clapp and Ruder 2020). Rarely defined, the concept of autonomy can encompass a variety of interpretations, some more individualistic and others that view it more as a form of collective capacity building (Atelier paysan 2021; Stone 2022). This diversity of interpretation leads to a heterogeneous use of the concept of autonomy, ranging from advocating for farmers' independence from external labor to the autonomy of professional communities to repair their own equipment, and including autonomy in marketing their produce or decision-making autonomy.

In debates on the environment, and particularly on agroecology, autonomy is seen as essential. On the one hand, reduced dependence on external inputs would allow farms to be more resilient to economic and ecological risks, and would promote more economical use of resources (Van der Ploeg et al. 2019). On the other hand, farm autonomy is also seen as having a certain independence from the industrial agri-food system, and would therefore allow for a broader range of actions, by integrating other objectives and values, more in line with the environment (Wolf and Nowak 1995; Atelier Paysan 2021). Autonomy would thus be the expression of a form of power for farmers vis-à-vis other economic actors (Carbonell 2016).

Digital platforms and websites could redefine how farmers communicate and market their products. Digital technology is thus highlighted as a way to access marketing channels that are independent of traditional actors (Carolan 2017a). It would offer new opportunities for cooperation among farmers, thereby strengthening their capacities (CoFarming 2017). In another area, digital technology would facilitate the implementation of new, more participatory research methods and could allow farmers to be directly involved in research projects that concern them (Bellon Maurel et al. 2022). Digital technology would be a tool for asking new questions, while leaving decision-making power with the farmer (Grenier 2018). Farmers would have greater autonomy thanks to a more comprehensive view of their activities (Damave 2017).

Finally, digital technology would facilitate direct exchanges between farmers: whether for selling, renting, or buying produce, equipment, farmland, services, etc. This would promote their own autonomy. Agricultural robotics companies also emphasize this notion of autonomy, which would be amplified through the use of robots, freeing farmers from dependence on labor, work, herbicides, etc. (Lenain et al. 2021).

On the other hand, some point out that digital technology creates technological and economic dependencies, potentially leading to forms of lock-in (Lioutas and Charatsari 2020). The use of technologies for inputs would increase dependence on those inputs (Wolf and Buttel 1996). Since a number of digital technologies originate from the GAFAM companies[27], new forms of dependence on these companies would develop, thus fostering the concentration of power. Digital technology would contribute to a privatization of the commons and an increased dependence on digital technology actors (Confédération Paysanne 2021). The high investments involved in purchasing digital technologies for a farm can lead to a loss of autonomy, by, for example, creating dependencies on sources of financing or loans, the need to make the investment profitable, and therefore the need to continue using the production methods managed by the purchased technology (Gkisakis and Damianakis 2020). These phenomena could lead to the exclusion of some farms (Bellon Maurel et al. 2022).

Information and advisory technologies also challenge farmers' decision-making autonomy (Jeanneaux 2018). Furthermore, based on a highly individualized view of advice, digital technology, as offered by companies, is incompatible with the social and collective dimension of farmer autonomy, which is based on social relationships of work and information (Stone 2022). Overall, digital technology leads to increased dependence on the agro-industrial system (Atelier Paysan 2021). Discussions surrounding autonomy encompass different approaches, both individualistic and collective. For example, American farmers obtained an exception law that allows individual modifications to the programming of their agricultural machinery, but prevents the development of epistemic communities on this topic (Carolan 2017a). The author contrasts this with the development of open-source platforms that foster user communities and collective autonomy.

1.4.2.4. *Material dimension*

Another aspect of the debate concerns the most direct impacts linked to digital hardware devices. This broadly corresponds to the direct impacts of these technologies.

These technologies can enable the "dematerialization" of certain tasks and reduce their environmental impact: for example, by limiting the use of certain resources or reducing travel. However, the design, use, and operation of these technologies require energy and resources, particularly rare metals (Atelier Paysan 2021; Confédération Paysanne 2021). The extraction of these resources is known for its negative consequences on the environment and on the populations working in this

27 GAFAM is an acronym used to refer to the dominant firms in the digital market: Google, Apple, Facebook, Amazon and Microsoft.

extraction or living near mines (Pitron 2017). The potentially widespread use of digital technologies in agriculture also raises the issue of obsolescence and waste management for these technologies.

1.4.3. *Controversies surrounding digital technology and pathways to ecologization*

The agricultural sector is characterized by debates on the ecologization pathways to follow. Indeed, as mentioned in section 1.1, there are different ways to consider the transformations of agriculture so that it limits its environmental impacts. One of the proposed paths is the optimization of the conventional model through incremental innovations and in particular technological innovations. Another proposed path is the more profound redesign of agri-food systems based, in particular, on the use of ecosystem services (Duru et al. 2015). Organic farming is among the models that offer a more comprehensive redesign, or at least a prototype of such a model (Bellon and Penvern 2014), even though there are debates about the potential conventionalization of organic farming (Darnhofer et al. 2010). Several agricultural models therefore coexist within the sector. Their coexistence depends on the power dynamics that structure the sector.

Consequently, the controversy surrounding digital technology is reflected in the debate on forms of ecologization. Part of this debate, therefore, raises the question of which agricultural model is favored by digital technology. Does digital technology create a new agricultural model, as some claim (Bournigal 2016)? What more structural transformation does it accompany? Does it apply generically to all forms of agriculture and therefore all forms of ecologization, or does it favor some over others? These questions relate more broadly to the structural impacts of digital development in the sector. However, this aspect of the debate is rarely addressed in the literature.

The often-used concept of digital agriculture might lead one to believe that there is a new, digital agricultural model, as opposed to a non-digital one. In the characterization of digital technology in agriculture presented in this chapter, digital technology encompasses a multitude of technologies, but also a multitude of functions and actors. This raises the question of the boundaries beyond which agriculture could be considered digital. The unity of digital agriculture in discourse seems to stem from an umbrella term that contributes to the construction of a technoscientific promise, but does not correspond to a homogeneous agricultural model (Martin and Schnebelin 2024). In the work presented here, digital technology is not considered as a carrier of a new agricultural model, but rather as a set of heterogeneous technologies.

Digital technology in agriculture therefore does not appear to be a new agricultural model: it is being integrated into existing agricultural models. But is it being integrated homogeneously into all models? Is it better suited to one model than another?

One aspect of this debate concerns the compatibility of these technologies with agroecological models. ICTs and precision agriculture are indeed among the main controversies related to agroecology (Migliorini et al. 2020). Other questions, very present in debates on agroecology, are concerned with the role of agrochemicals and biotechnologies, farm size, short supply chains, social justice and gender issues.

Contradictions	Synergies
Process production: agricultural practices, labor	
Homogenization of production systems, no adaptation to local specificities Rebound effect, locking in practices Productivist objectives – specialization	Input optimization, multi-criteria decision-making Managing complexity Facilitation of normally labor-intensive tasks
Knowledge	
Tacit and empirical knowledge loss Deteriorates relationship with nature Reduced experimentation, rigidity	More information, more knowledge: improves understanding, differentiated management Reduced cost of access to information
Autonomy	
Dependence on large agricultural supply companies, on GAFA Loss of decision-making autonomy	Better communication with consumers Participatory research Sharing, cooperation
Paradigm, agricultural model	
Promotes industrial model, reinforcement effect Elimination of alternatives	Generic technologies, for all types of models, also meet the needs of agroecology
Material setup	
Impacts of digital technology construction, energy cost	Dematerialization
References	
(Wolf and Buttel 1996; Carolan 2017b; Bronson 2018; Rotz et al. 2019a)	(Pillaud 2015; Bellon-Maurel et al. 2017; Van Es and Woodar 2017; Walter et al. 2017)

Table 1.2. *Main arguments in the controversy on the links between digital technology and ecological agriculture*

Innovations of all kinds, including technological innovations, have played a significant role in the past evolution of agricultural production systems and continue to play an important role in the trajectory of agricultural models. It is therefore necessary to examine which technologies are acceptable and beneficial for different agricultural models. This involves economic, social, environmental, organizational, cultural and political questions regarding these innovations. Here, we develop an economic approach that questions their compatibility with production models.

Agroecology definitions do not in themselves exclude the use of digital technologies. This depends on the type of technology and its effects. There are few studies to date on digital technology and agroecology. Various effects can be discussed: the impacts of these tools on production, social impacts, costs and benefits, and mechanisms of economic dependence. Technologies could promote productivity, input efficiency, concentration and specialization (Wolf and Buttel 1996; Carolan 2020). Thus, these technologies would not promote agroecological models, but rather the continuation of the conventional agricultural model (Bronson and Knezevic 2016; Lioutas and Charatsari 2020). On the other hand, technologies could provide localized solutions for optimization and consideration of heterogeneity and the mechanisms of living organisms, which could help the implementation of agro-ecological practices. Thus, the question of future agricultural practices favored by digital development remains open.

1.5. Conclusion

This chapter has highlighted the fact that the introduction of digital technology into our economies, far from being a simple technical change impacting the efficiency of production processes, implies systemic changes across sectors: modifications to the system of actors, public policies, knowledge and so on. Consequently, digital technology raises various questions about the development of technologies, their uses and their consequences. In agriculture, digital technology offers hope for its ability to address the multiple challenges of contemporary agriculture. It is therefore promoted in the discourse of various organizations, both public and private, national and international, agricultural and non-agricultural. Beyond being promoted in discourse, digital technology in agriculture mobilizes resources, whether for research, for funding startups in the field, for financing public-private projects or for encouraging investment in farms. However, the development of digital technology in agriculture is subject to controversy. These issues raise questions about the economic, social and political effects of digital technology, but also challenge its ability to address the environmental challenges facing agriculture. Reflecting on these controversies leads to two observations regarding the state of knowledge in this field. First, the information available on the uses of digital technology in agriculture, and even more specifically in French agriculture, is very limited. While some studies on the adoption of digital technologies exist, a systemic perspective is lacking, one that integrates digital uses into the socioeconomic environment of farmers and their production systems. Studies often view the development of digital technology in agriculture as a linear and uniform process, paying little attention to the heterogeneities and diversity of trajectories. Secondly, little knowledge is available on the interactions between the digitalization and ecologization of agriculture. The impacts of digital uses in real-world contexts are poorly documented, and there is very little literature that examines the structural impacts of digital uses on farms. This paradox, between a significant promotion of digital technology, on the one hand, and controversies that the current state of knowledge does not allow us to answer to, on the other hand, leads us to our empirical problem.

How does the development of digital technology in the agricultural sector impact and integrate into different ecologization trajectories? Does it favor some more than others?

The general overview presented in this chapter raises two major implications for addressing this problem. To compensate for the lack of knowledge regarding the development of digital technologies in agriculture, their uses and their implications, it appears necessary to conduct significant empirical research on this issue, integrating the microeconomic scale of these uses into a broader study of transformations within the agricultural sector. To integrate the various dimensions of digital technology development in agriculture and the controversies surrounding their effects on the sector‘s ecologization, a systemic and institutional perspective seems essential. To address these implications, we develop an analytical framework suited to a systemic, multilevel, heterogeneous and dynamic view of innovation by proposing a political economy of the agricultural innovation system.