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ABSTRACT

Digitalisation is promoted by both private and public actors as a way of contributing to the ecologisation of agriculture. However, this idea remains controversial. The debate is all the more crucial, as different ecologisation models exist, and as agriculture is experiencing new levels of industrialisation. In the literature, use of digital technology in agriculture has mainly been approached from a linear perspective of adoption but is rarely linked to ecologisation. In this paper, we aim to define digital use profiles of farmers and explain how they relate to ecologisation models. We distinguish production and information technologies. Based on 98 interviews with crop farmers in Occitanie (France), we show that there is a diversity of digital profiles. Through a mixed-method, we relate these profiles to a set of variables representing ecological and economic transformation in agriculture. It highlights links between some digital profiles and the further industrialisation of agriculture intertwined with weak or symbolic ecologisation. However, some digital uses associate with new forms of ecologisation that are based on input substitution. Digital use does not appear to support stronger ecologisation of farming. This study highlights the risk of a single model of digitalisation that only promotes one type of ecologisation pathway.

1. Introduction

The objective of this paper is to investigate how the diversity of farmers' use profiles of digital technology can be tied or not to different models of ecologisation in agriculture. Ecologisation is defined as "the growing importance of environmental issues within agricultural policies and practices" (Lamine, 2011; Lucas, 2021). A diversity of farming models exists, each claiming to ecologise agriculture. Digital technology encompasses a wide range of technologies, including precision farming equipment, digital platforms, decision support systems for farmers and advisors, etc. (Prause et al., 2020). Different actors promote these technologies, including some representatives from the fields of science, farming and public policy. A series of high-level documents mention digitalisation as a way of improving farm productivity and reducing the adverse effects of agriculture on the environment (Lajoie-O'Malley et al., 2020). Public policies have participated in the rapid development of digital technology for farming, with increasing public and private investments, and a rising number of start-ups (Barrett and Rose, 2020).

However, the actual effects of digital technology on the ecologisation of farming practices is a matter of both scientific controversy and political debate (HLPE/FAO, 2019; Lioutas and Charatsari, 2020; Walter et al., 2017). One side of the debate concerns the compatibility of these technologies with the different models of agricultural ecologisation (Fleming et al., 2018; Klerkx and Rose, 2020; Knierim et al., 2019). Among the diversity of ecologisation models, some seek to reduce the impact of conventional or industrial farming by pursuing an optimisation of input use (fertilizers, pesticides). Others aim for a more radical reconception of farming systems. This later trend includes for instance organic or soil conservation farming models (Duru et al., 2015). Critical analyses suggest that digital technologies might reinforce the industrial model of agriculture, to the detriment of more alternative and ecologised models (Carolan, 2020; Lioutas and Charatsari, 2020; Rotz et al., 2019a; Wolf and Buttel, 1996). Other analyses are more positive on the impact of digital technology on ecologisation (Walter et al., 2017).

A paradox is that there is still a lack of social science research that links knowledge about farmers' actual uses of digital technologies on the one hand with knowledge about their practices and technological trajectories towards ecologisation on the other (Klerkx et al., 2019). The majority of research into the subject focuses on better understanding the adoption of precision farming technologies. They most often posit that these technologies have positive effects on the environment (Barnes et al., 2019) and go on to identify a series of obstacles and factors impacting the adoption of technologies, including variables of farm structure (farm size, specialisation), equipment, and farmer profiles (age, education, etc.). However, such research has not examined how digital technologies interact with the diversity of practices and

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organisations of farms. Other social science research has started to investigate this issue, particularly in sociology and the management sciences. However, most of these studies do not make the connection to broader debates about changes in farm economic models and trajectories (Eastwood et al., 2017; Lioutas et al., 2019; Moreiro, 2017). In total, even though digital technologies are promoted by public policy, very little is actually known about their use and effects on different categories of farms related to different agricultural models.

This leads us to the following question: does the development of digital technology benefit all models of ecologisation, or does it favour some models over others? To answer this question, it is firstly necessary to study the uses of digital technologies in all their diversity, and secondly, to associate these uses with different production and ecologisation models.

We have used a mixed methods research protocol (Fakis et al., 2014), based on 98 interviews with farmers from a region in South-West of France, which is engaged both with digital technologies and ecologisation. Our contribution is twofold: First, a quantitative analysis has allowed us to construct use profiles using a hierarchical cluster analysis (HCA) for two types of technologies - production digital technologies on the one hand, and information and communication technologies on the other. Moreover, it has allowed us to highlight the statistical differences between farmers with different use profiles of digital technologies. Second, the qualitative analysis has allowed us to understand the causal relationships and elements of the trajectory that are behind these differences. Combining the quantitative and qualitative analysis has contributed to an understanding of how these use profiles integrate into the different paths towards the ecologisation of farming, and more generally, of how they are tied to economic models.

Firstly, we will define and describe digital technology in farming for the purpose of studying those uses in more detail. We will then outline our methodology. Subsequently, we will present the use profiles and show how these profiles are tied to i) structural and economic characteristics, and ii) the ecologisation practices of farms. Finally, a qualitative analysis and discussion will return to these ties, with the aim of understanding how digitalisation and ecologisation are inter-connected.

2. Background to digital technology innovation and the ecologisation of farming

Our analytical framework is based upon innovation and institutional economics, with the aim to provide a systemic understanding of the relations between digitalisation and ecologisation. This perspective has led us to consider three steps: construction of farmers' use profiles for digital technologies and characterisation of agricultural models (2.1); grasping of digitalisation and ecologisation practices at farm level (2.2); interconnection between digitalisation and ecologisation (2.3).

2.1. Linking use profiles to agricultural models

The concept of use allows us to consider technologies in the light of their effective utilisation, and in interaction with farming contexts. This concept takes the technology beyond its purchase and prescribed use. It also considers its recurring integration into farming systems and practices (Badillo and Pélissier, 2015; DiMaggio and Hargittai, 2001). Effective use is defined as "the capacity and opportunity to integrate IT successfully into the achievement of objectives defined by the interested actors themselves, or in collaboration with others" (Gurstein, 2007, p. 9). The use of a technology is therefore associated with the construction of knowledge, and with adjustments and interactions between the different components of a farm (Higgins et al., 2017).

This concept of use makes it possible to consider the interdependencies between various digital technologies, but also between these technologies and farm production systems. So far, most economic research has studied digital technologies one by one, showing how individual, economic and technological variables affect their adoption (Barnes et al., 2019; Lowenberg-DeBoer and Erickson, 2019; Michels et al., 2020). However, digital technologies integrate and combine with each other, and with other technologies (Clapp and Ruder, 2020). These combinations of practices can be institutionalised over time. To facilitate accounting for these combinations, we decided to characterise farmers' use profiles of digital technologies. This profile-based approach has been applied in building typologies of digital uses in industrial sectors (Frank et al., 2019) or more general typologies about Internet uses (Brandtzaeg et al., 2011).

Farming models are used to characterise farming heterogeneity. Institutional economics differentiates between productive models by three means: productive organisation (methods and techniques, spatial organisation, resource mobilisation etc.), employment relationships, and product policy (target markets, volume, quality, etc.) (Boyer and Freyssenet, 2000). In agriculture, farming models are distinguished by their biotechnical types, their socio-economic contexts, or by both (Therond et al., 2017). They also differentiate by their values (Plumecocq et al., 2018), by the organisations and institutions that support them, and by their knowledge, their links to market, the state, the territory and the associated farming practices (Gasselin, 2019). They are also studied through the lens of "farming styles", which profiles farms depending on their mobilisation of various resources (Van der Ploeg, 1994). This diversity of models is explained by a diversity of sub processes that lead to complex and non-linear processes of differentiation (Van der Ploeg, 2018). In France, farming models are still largely based on familial structures. However, the number of familial structures is decreasing (39% reduction between 2000 and 2016) (Forget et al., 2019). Dominance of familial structure is questioned**,** with the existence of diverse farming models and differentiation mechanisms including the development of firm agriculture, the growing importance of outsourcing as well as the defence of more traditional (peasant) agricultural models (Gasselin et al., 2021; Nguyen et al., 2020).

Linking digital uses profiles to variables that characterise farming models allows us to go beyond adoption mechanisms and understand how digitalisation is tied or otherwise to different farming models, through reinforcement, lock-in and exclusion processes. Those processes can inform technological trajectories and possible path-dependency (Dosi, 1982).

2.2. Ecologisation and digitalisation trajectories

2.2.1. Digitalisation studied through two categories of technology

Digitalisation can be defined as the growing utilisation of Information and communication technologies in the economy, and in society (Lange et al., 2020). Several categories of digital technology can be defined, depending on the techniques employed, the functions performed and the impacts envisioned. For this study we differentiated two major technological areas with respect to their potential impact on the ecologisation of farming (Rotz et al., 2019b).

First, Digital Technology for Production (DTP) brings together technologies designed to modify the process of production directly. These include technologies for precision farming, which are categorised in the literature as recording, guidance and implementation or response technologies (Balafoutis et al., 2017; Schimmelpfennig, 2016). DTP is based on the use of satellite guidance technologies, parcel mapping and sensors. It can have a variety of impacts: on the management of inputs such as fertilizers, pesticides, and seeds; on outputs such as yield and production quality; on the implementation of certain practices such as tillage or crop rotation; on the nature, organisation and arduousness of work, and on productivity. DTP corresponds in part to the category of "embedded technologies" described by Birner et al. (2021).

Second, Digital Technology for information and Communication (DTC) brings together technologies used to access information and communicate with peers, advisers and customers, in order to exchange or co-create knowledge. It includes the use of specialised farming websites, social media networks such as YouTube or Facebook and other digital platforms or media. It can have an impact on the process of gaining knowledge and training (Burton and Riley, 2018; Leveau et al., 2019), or of getting information on markets, social movements or policies, which in turn, have an impact on the process of production.

Distinguishing between these two types of technology allowed us to capture the diversity of digitalisation. We also studied the ties between the two types of technology, which are often considered separately in academic literature.

2.2.2. Ecologisation: a new factor in the differentiation of farms

Ecologisation means the integration of environmental components into policies, knowledge and practices. The environmental challenge has brought new dimensions of differentiation between farming models, depending on their ecologisation strategy (Duru et al., 2015). We use the concept of ecologisation here, to integrate a diversity of objectives, means and temporality, towards a more environmentally friendly agriculture, as well as their political dimension. There are controversies on the effectiveness and environmental performance of those models, which create political confrontations between ecologisation models. There are two main approaches, sometimes referred to as "weak" and "strong" forms of ecologisation (Duru et al., 2015). One seeks to optimise the existing conventional model. The other, agroecology, seeks to reconceive production systems more systematically by relying on ecosystem services. This involves agronomic practices as well as methodological and socio-economic principles (Stassart et al., 2012). Organic farming in France is recognised as a form or prototype of agroecology which has been gradually institutionalised (Bellon and Penvern, 2014). However, the reality of these practices is more complex, with, on one hand, the process of a "silent agroecology", a "farmer-led movement for agricultural change […] that is largely unrecognized and poorly understood" (Lucas, 2021, p. 18); and on the other, a 'conventionalisation' of organic farming (Darnhofer et al., 2010). Introducing variables such as soil management, inputs and biodiversity management into agroecological practices helps to fine-tune the distinction between conventional and organic farming.

These approaches to ecologisation are intertwined with the structural and socio-economic characteristics of production systems. Certain forms of ecologisation might require specific organisations and knowledge systems (Stassart and Jamar, 2009), as well as adapted economic models, for instance market segmentation for organic farming (Van der Ploeg, 2018).

2.3. How digitalisation can link to ecologisation trajectories

We have examined the relationship between digitalisation and ecologisation in farming through a consideration of two types of digital technology, which have potentially different impacts on ecologisation pathways.

DTP aims to enhance the efficiency of agricultural production processes, and was designed for the optimisation of the industrial farming production system. Some authors argue it only has sense within such systems (Bronson, 2019). As a result, economic variables such as Utilised Agricultural Area (UAA), economic size and workforce are expected to have positive and significant effects on the adoption of DTP (Barnes et al., 2019). Further, the subcontracting of certain tasks to an agricultural outsourcing company, as well as membership of a cooperative, is playing a growing role in farming businesses and with their equipment (Nguyen et al., 2020; Wolf and Nowak, 1995). Moreover, DTP have been shown to foster industrial agriculture and to increase dependence on chemical inputs (Wolf and Buttel, 1996). As mentioned in 2.2, ecologisation trajectories are connected to economic models, and this leads us to our first proposition on the ties between the use of DTP and ecologisation:

- Proposition 1: the use of DTP is associated with weak forms of ecologisation that are intertwined with industrial economic models of farming.

DTC modifies the flow of information and knowledge exchanges and opens new possibilities for the co-creation and sharing of them. Through its technical, social and political dimensions, ecologisation requires changes in knowledge creation and circulation, especially concerning agroecological models (Duru et al., 2015). DTC can facilitate those knowledge transformations and promote a strong ecologisation (Bonny, 2017). This brings us to our second proposition:

- Proposition 2: The use of DTC is associated with stronger forms of ecologisation, which are based on a reconception of production systems.

However, this proposition is worth challenging empirically. In fact, digital technologies can lead to information and knowledge commodification, concentration and industrialisation (Rikap and Lundvall, 2020; Wolf and Wood, 1997). It could lead to de-skilling and path-dependencies that encourage the continuity of conventional agricultural systems. Furthermore, strong ecologisation requires learning that remains based on local and on-farm knowledge exchanges and experimentation (Van der Ploeg et al., 2019).

We could add social and institutional factors here, which may differ according to the farming model, and could play a role in the adoption of technology use. Regulations, funding, specifications and social norms have an impact on the use of these technologies (Fielke et al., 2020). In France in particular, environmental regulations, or the CAP (Common Agricultural Policy) are examples of institutions that can have an effect on farming equipment. Other research has shown that these environments are not neutral in the ecologisation trajectory that they support (Vanloqueren and Baret, 2009). At farm level, the micro socio-economic environment, such as relations with suppliers of advisory services or cooperatives, also influences the use of these technologies (Barnes et al., 2019; Wolf and Nowak, 1995).

3. Research method

In order to understand the diversity and complexity of farmers' uses of digital technology, we conducted 98 face-to-face interviews, using a mixed method that combined quantitative and qualitative approaches. It allowed us to integrate two types of data into the construction of our interpretation (Watkins and Gioia, 2015).

3.1. A mixed method for a better understanding of interrelations between digitalisation and ecologisation

In order to study farms with a systemic approach the questionnaire included closed-ended questions on structural, individual, socio-economic and agronomic dimensions of farms (as detailed in the Appendix A). The answers were then entered into a data base. Subsequently, each technology used was studied in more detail. More open–ended questions and moments of discussion gave substance to the collected material. They allowed us to i) adopt a systemic perspective on farming, ii) adjust the questions depending on the technology used, and iii) gain clarity about the uses and their impacts.

We used a hierarchical cluster analysis to categorize these uses while taking into account the connections between different digital technologies. Most of our variables being qualitative, we first completed a multiple-component factor analysis (MCFA). More specifically, we used the HCPC (Hierarchical Clustering on Principle Components) of the *FactoMineR* R software package (Lê et al., 2008). We selected technologies that are used by no less than 5% of the population for the two types of technology chosen, DTP and DTC.

For DTP, we selected 12 binary variables concerning the use of the following technologies: guidance, automatic guidance, section control, connected weather station, field mapping, variable-rate technology (VRT) for fertilizers, variable-rate technology (VRT) for seeding, connected tensiometer, yield map, decision support tool for crop protection, connected irrigation technology and farm management software. The percentage of inertia explained by the classification is 41%.

For DTC, we took the following seven variables for finding technical information: the frequency with which the internet is used, the use or otherwise of social networks, Facebook, YouTube, specialised agronomic websites, technical institute websites, and farming press websites. The percentage of inertia explained by the classification is 36%. During the interview, we asked farmers about their use of digital technologies to create or share knowledge. However, the majority of farmers were only using these technologies for consultation, so we did not include more participatory use in this profile construction.

The clusters obtained in this way can be considered as profiles of types of use. We linked them to the ecological practices and the socio-economic status of the farms.

The HCPC R function enabled the identification of specific individuals- i.e. the ideal type for each of the profiles. The transcriptions of these individuals were coded with MaxQDA and analysed. This qualitative analysis allowed us to 1) better understand the connections between variables to explore causality, 2) reveal other aspects which had not surfaced before, and 3) illustrate the analysis with quotes from the transcript.

3.2. *The Occitanie region as a field of study*

We chose to concentrate on field crops. This sector is emblematic of the history of modernisation of French agriculture. It is characterised by a substantial capacity for investment, and has been the focus of developing digital technologies for many years (Lowenberg-DeBoer and Erickson, 2019). The field interviews were conducted in the Occitanie region of France. This region is pioneer in both digital technologies for farming, and in ecologisation, while being in the average range of French farms in terms of size and production. Occitanie is the leading region in France for organic field crops, with 24.5% of France's organic farmland (Interbio Occitanie, 2018).

Our sampling was not representative but purposive to explore the diversity of profiles. To that end, we made contact with farmers through farming organisations (cooperatives) and via organic farming directories, and afterwards by snowball sampling (Atkinson and Flint, 2001). We aimed to have users and non-users of digital technology, as well as a range of agronomic practices (conventional and organic farming, conservation farming or other ecological practices). We could assess the selection bias of our farm sample through a comparison with data from the official census of the Ministry of Agriculture (using variables such as Utilised Agricultural Area, standard gross production and workforce).

4. Results of cluster analysis: relation between digital uses and Farms' characteristics

4.1. *Survey description*

Our sample brought together a diverse range of farms ($n = 98$), as can be seen on Table 1. The utilised agricultural area of farms ranged from 9.5 Ha to 570 Ha, with an average of 162 Ha, which is greater than the regional average of 59 Ha. This difference can partly be explained by the inclusion of farms run by multi-active farmers or retirees in the official census. We chose not to integrate these categories in our sample as they do not carry much economic weight. The standard gross production (SGP) and the workforce were consequently greater in our sample than the regional average, and with a high diversity. The interviewees were between 24 and 67 years old.

Table 2 shows the population distribution defined by some qualitative variables. 'Mixed' farms are those where only a proportion of the crops are farmed organically, with the other crops being not certified organic.[1] Interviewees had a range of levels of education.

Table 1
Descriptive statistics – quantitative variables.

Var	Obs	mean	sd	min	max	Regional mean[a]
Utilised Agricultural Area	98	162.1	113.0	9.5	570	59
Standard Gross Production	98	243,156	193,841	5559	1,053,895	58,123
Total workforce	98	1.9	1.1	1	6	0.9
Age	98	44.1	10.8	24	67	49.1 in France [b]

[a] Eurostat for farms specialising in grain or oil and protein crops - Midi-Pyrénées –2016 data – Eurostat.
[b] French statistics from MSA, 2018 - available at : https://statistiques.msa.fr

Table 2
Descriptive statistics – qualitative variables.

	Modality	Number	%
Crop certification	Organic	28	28.6%
	Conventional	58	59.2%
	Mixed	12	12.2%
	<Bac2	31	31.6%
	Bac + 2	42	42.9%
Education level[a]	>Bac2	25	25.5%
	Male	89	90.8%
Gender	Female	9	9.2%

[a] Bac + 2 is equivalent to a bachelor degree.

The clustering method resulted in three groups for DTP and three groups for DTC, as shown in Fig. 1.

Two profiles were constructed to characterise the two types of technologies: for production (DTP), and for information (DTC). By cross-referencing these profiles, (Table 3), we demonstrated that there is no significant overlap. The Pearson test allowed us to reject a dependence hypothesis between the types of digital use on farms.

4.2. *Use profiles for digital technologies for production (DTP)*

The three DTP use profiles are described below. We characterise the farms of those profiles. Table 4 recaps the variables that show the greatest differences between the three groups. A detailed description of the profiles and all their characterisations can be found in the Appendix B.

4.2.1. *No-DTP profile*

The first profile, that we called '*No-DTP*', makes up 39% of the sample. In this group, most of the farmers do not have digital technology for production. A little less than one third of them, however, do have farm management software (land and administrative management).

In this profile, farms that provide outsourcing services are under-represented, as are those which cultivate seeds, or which have contract farming. Organic farms, farms that sell directly to the customer, or that farm livestock, are, on the other hand, over-represented. The farms

[1] European Organic certification allows to have clearly separated units which are not all managed under organic production, only if units grow different varieties that can be easily differentiated and do not store organic and non-organic production (Council Regulation, 2007. No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation).

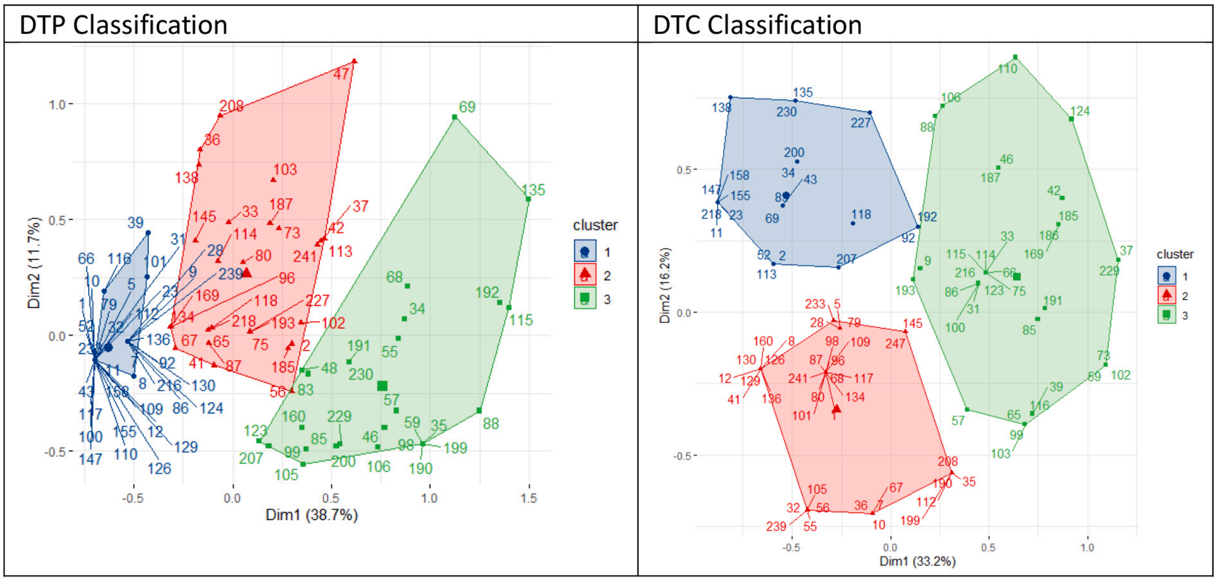

Fig. 1. R classification results.

Table 3
Cross-referencing digital use profiles.

	No-DTC	Website DTC	Network DTC	DTC N/A	Total
No-DTP	8	19	10	0	37
Average DTP	6	11	13	1	31
Intensive DTP	8	8	11	1	28
DTP N/A	0	1	1	0	2
Total	22	39	35	2	98

in this group are smaller in terms of economic size[2] and agricultural area, have fewer annuities and a smaller workforce than the average. However, they do not have a lower Gross Operating Surplus (GOS). The costs for inputs per hectare and yields are significantly lower.

4.2.2. *Average DTP profile*

The second profile, named '*average DTP*', consists of 32% of the sample. It includes farmers who use some digital technology for production, but who do not have the full precision farming software package: nearly all use guidance technologies (97%) or automatic guidance (63%), and the great majority (87%) have land management software, but none of them use variable-rate technology for inputs. Furthermore, between 20 and 40% of them use section control technologies, decision making tools for their treatments, weather stations, and connected tensiometers and irrigation technologies.

Farms fitting this profile generally represent the sample average, but they also use more irrigation, have a higher salaried workforce, a greater expenditure on fertiliser per hectare, and do less direct marketing. The organic farms in this group ($N = 8$), have greater GOS, SGP, annuities, more irrigation, and do more trading within cooperatives.

4.2.3. *Intensive DTP profile*

The third profile, '*intensive DTP*', includes 29% of the sample, and is characterised by the intensive use of digital technologies for production. We found wide use of precision farming technologies: guidance (96%), variable rate fertiliser (92%), connected weather stations (65%), and yield monitoring (46%). 23% of the group use variable rate for seeding.

In this profile, farms practicing outsourcing, mixed farms, farms with seed cultivation and integrated pest management are over-represented. This group is higher than average with the variables Utilised Agricultural Area (UAA), SGP, total employed workforce and salaried workforce, GOS, costs of pesticides and fertiliser, and soft wheat yields. There are fewer certified organic or mixed crops.

4.3. *Use profiles of digital technology for information and communication (DTC)*

We will describe below the three DTC profiles,[3] and characterise farms belonging to those profiles. Table 5 recaps the variables that show the greatest differences between the three groups. A detailed description of the profiles and all their characterisations can be found in the Appendix B.

4.3.1. *No-DTC profile*

The first profile, '*No-DTC*', is defined by a limited use of the Internet to find information. Two thirds only use the internet to search for information from time to time, or use it rarely or never. Three quarters do not use social networks and do not consult specialist sites. Nearly none of them use YouTube, or the technical institute websites. However, 45% consult the online farming press.

This profile is characterised by a lower percentage of farmers with the French equivalent of a bachelor's degree or who belong to farmers' knowledge exchange groups (CETA). In this group, there is a higher percentage of farmers who get advice within cooperatives and have the lowest level of digital literacy. These farms have a higher expenditure on pesticides per hectare than average, have more ploughed land, and less no-tillage.

4.3.2. *Website DTC profile*

The second profile, '*Website DTC*', is defined by the use of the specialised sites to look for information. Although they do not use Facebook, YouTube, or the farming press online, all use specialised websites, in particular from technical institutes (36%).

The farmers in this profile cultivate less seeds, with more non-tillage or minimum tillage. On average, they grow a higher proportion of

[2] Economic size indicates a standard output criterion but is not a performance indicator.

[3] The constitution of DTC clusters was less obvious. Also, it seems that the use of DTC is more characterised by a continuation of practices, rather than distinct groups of uses.

Table 4
Synthesis of the ties between digital technology for production use profiles.

Variables	No-DTP	Average DTP	Intensive DTP
Structural			
Utilised Agricultural Area (UAA)	- ***		+ ***
Has outsourcing business	- ***		+ ***
Standard Gross Production (SGP)	- ***		+ ***
Total workforce	- *		+ **
Salaried workforce	- **	+ ***	+ **
Annuities	- ***	+ *	
Gross Operating Surplus (GOS)			+ **
Farms livestock	+ ***		- *
Individual			
Digital skills	3: + **	3: - *	
Socio-economic environment			
Gets advice from cooperative	- **		+ *
Sells wholesale	- **	+ **	
Sells seeds	- ***		+ **
Does contract farming	- ***		
Part of a CETA = Farmer's knowledge exchange group	- **		
Part of an Organic Farmers' Group	+ **		- *
Part of a CUMA = Farmers' machinery exchange group		+ *	
Attends agricultural shows	- ***		+ ***
Does direct marketing	+ ***	- **	
Agricultural practices			
Type of input management (1 conventional; 2 integrated; 3 organic)	1: - ** 2: - * 3: + ***		1 2: + ** 3: - ***
Cultivated biodiversity (1 meadow, 2 cereals 3 diverse 4 pulses)	1: + *** 2: - *	1: - **	
Main type of soil management (1 ploughed, 2 deep, 3 shallow, 4 no-till)	2: - * 3: + **		
Crop type	Organic+ *** Conv - **	Organic Mixed - * Conv + *	Organic - *** Mixed + *** Conv
Has associated crops	+ **		- ***
Cost of fertiliser per ha	- ***	+ ***	+ ***
Cost of pesticides per ha	- ***	+ *	+ ***
Soft wheat yield	- ***		+ ***
Hard wheat yield	- ***	+ ***	+ *
Irrigated land	- ***	+ ***	

+: positive effect on the probability for being in the group; −: negative effect; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

pulses, have lower costs of pesticides and higher yields of irrigated maize and hard wheat. The farmers are older on average, a higher proportion of them have an intermediate grasp of IT tools, and they are less likely to belong to a trade union.

4.3.3. Network DTC profile

The third group, '*Network DTC*', is made up of farmers who use social networks in a professional context (100%), in particular Facebook and YouTube. They either use the internet often or very often (91%), and they consult specialised websites (89%).

Farms in this profile have more irrigation. Farmers have started farming more recently than the average, and are younger. In this group, members generally have the best grasp of digital tools, as well as a more negative opinion of the economic health of their farm.

Table 5 summarises the effects of the variables that show the greatest differences between the three groups. Compared to production technology clusters, fewer variables are significantly different between one group and another.

5. Qualitative insights and discussion of results

The profiling of digital uses has allowed us to highlight how these technologies are interconnected within productive models (Clapp and Ruder, 2020). By these means, we have been able to identify some use profiles that correspond with reoccurring combinations of these technologies. We complement those profiles description with a qualitative analysis. This allows us to discuss the relationship between digitalisation and ecologisation trajectories.

5.1. Digital technologies for production, industrialisation and ecologisation

Our first proposition was that DTP use is tied to weak forms of ecologisation intertwined with the industrialisation of farming models. Our analysis confirms the link between the use of DTP and industrialisation, and fine-tunes its link towards ecologisation.

5.1.1. DTP uses support enlargement and industrialisation of farms

The importance of economic size stands out as one of the main factors driving the use of DTP, as demonstrated in previous research (Barnes et al., 2019; Konrad et al., 2019). Firstly, economic size influences the capacity to invest in this type of tool. This capacity may be attained by increasing farm size, by collective investment (relatively little-used in our sample) or by expansion through outsourcing. Nguyen et al. (2020) have demonstrated that outsourcing is a way of being able to access use of digital device without investing in it. We have completed this analysis by showing how having an outsourcing activity could be seen as a means of investing, as a way of expanding agricultural land and revenue, and consequently, expanding investment capacity.

Secondly, the results show that DTP are also a response to the specific

Table 5
Synthesis of the connections between DTC use profiles and variables.

Factor	No-DTC	Website DTC	Network DTC
Individual			
Age		+ **	- ***
Founding of the farm	- *		+ ***
Computer literacy	3: + **	1: - ** 2: + ***	1: + ** 2: - *
Background	> Bac + 2 - ***	> Bac + 2 + *	
Personal opinion on their farm economic performance			Negative+ **
Have children		+ **	
Socio-economic environment			
Advice from a cooperative	+ *		
Trading with seed companies	+ *	- ***	
Contracts		- *	
Part of a CETA = Farmers' knowledge exchange group	- **	+ *	
Belongs to a professional union		- **	+ *
Part of a farmers' knowledge exchange group on minimum/no tillage		+ *	
Agricultural practices			
Main type of soil management (1 ploughed, 2 deep, 3 shallow, 4 no-till)	1: + ** 4: - **		
No Till part	- **		
Pulse crops		+ **	
Costs of pesticides/ha	+ **	- **	
Hard wheat yield	- *	+ *	
Irrigated land		- **	+ *

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

needs of more industrial production models based on expansion, outsourcing activities, salaried employees, specialisation and intensification. DTP sometimes become an indispensable managing tool for organising man-power, knowing what has been done with what field of land, standardising, and managing logistics and traceability. Furthermore, these technologies facilitate expansion, as Baptiste explained[4]:

> *"I don't know if I have saved time in fact. Because in the time that you save, you have more other things to do. It's a cycle [...] my great grandfather had 16 ha. My grandfather had 200. My father 400-450. Now we work 8 or 900".* Baptiste (Intensive DTP)

Our results confirm a part of our first proposition: the link between DTP uses and industrialisation. Economic size influences the adoption of these technologies, which in turn facilitate the expansion trajectory of these models. This reinforces the hypothesis put forward in many social science research, that digital technologies, and more particularly those for precision farming, tend to favour and lock in the dominant industrial farming system (Bronson, 2019; Carbonell, 2016; Clapp and Ruder, 2020; Rotz et al., 2019a).

5.1.2. Value-chains organisations play a role in the use of DTP

Economic actors working for the industrialisation of farming can favour the use of DTP. As stated in 2.3, technological trajectories are tied to the socio-economic environment. We confirm the role of advisory services provided by cooperatives or groups of farmers in the adoption of DTP (Barnes et al., 2019). Our results show first and foremost, that seed cultivation and trading contracts, which are associated with a specific trading and advice model, favours, or even imposes, the use of DTP. Moreover, specific crops are high added value crops which also favour investment (Lowenberg-DeBoer and Erickson, 2019). Downstream businesses encourage or demand the use of these technologies through contracts in order to standardise and better control their supply.

5.1.3. DTP to optimise or to justify conventional models of agriculture

These technologies aim for an optimisation of inputs (mostly fertilizers and pesticides). This can limit their interest for others, such as organic farmers, who don't use the same inputs and have other strategies besides optimisation, as illustrated below:

> *"Other farmers who have GPS [...] they save money on diesel, seeds, fertiliser and weed killer. Because they only use what they need. So perhaps they can pay for things with what they save. But me, I am only going to save on diesel, and on time."* Thomas (No-DTP)

Moreover, a large percentage of organic farmers say that DTP is not adapted to their production systems, or is even counterproductive. Some farmers who have changed over to organic farming, have stopped using land management software or decision support tools which were no longer useful for them. In the *No-DTP* group, the Standard Gross Production is weaker but the Gross Operating Surplus is not. This could signal that farmers from the *No-DTP* profile implement different strategies to optimise and to increase profits, rather than those suggested by precision farming. It can be through transformation or direct marketing, or by optimising ecosystem services etc. DTP makes sense for farms that have a strategy based on increasing productivity, efficiency and maximum yield (Bronson, 2019), but less so for those whose strategy is more concerned with reducing external inputs by agronomic techniques, or with diversification rather than specialisation. Then, DTP could be linked with weak ecologisation trajectories focused on optimisation and efficiency.

However, it is evident from the interviews that this link between the use of DTP and a better efficiency is a matter of debate. The reasons given for using DTP are essentially ergonomics, comfort, time-saving and productivity. However, their effects are disputed by some users, in particular in the case of variable rate technology. Some farmers state that the variable rate does not save money, so they may stop using it. Farmers question some effects on yield and input consumption. This is in line with the critical assessment that finds DTP to be a tool for a "symbolic ecologisation" based on quantification and justification, rather than on real optimisation (Wolf and Wood, 1997).

5.1.4. DTP uses for input substitution strategies

The results show that the choice of agronomic practices and the choice of tools have an effect on each other, and that the use of DTP seems to encourage optimisation over redesign. This needs to be qualified, however, as we have also observed links between more radical changes of practice and the use of DTP. The implementation of

[4] Our indication in brackets signals that the interviewee is a specific individual within this profile. Interviewees' names have been changed.

sustainable soil management has led farmers to use DTP, in particular, precision auto guidance (RTK) as explained by Louis:

> *"We have come to RTK because we have changed agronomic practices. As a lot of our work is with cover crop, [...] when we sow maize among beans, which are a bit taller, it is good to have guidance."* Louis (Average DTP)

Some farmers have used DTP as a means of introducing organic farming, as explained by Baptiste:

> *"If I had not had guidance for organic crops, perhaps I would not have done it, plain and simple. Because we have the capacity, we have the size, and so we have big tools. Where we are organic, we can use 8.2 m tools with guidance, it's great."* Baptiste (Intensive DTP)

In Louis' case, a change in practice brought about the use of DTP. Conversely, for Baptiste, the use of DTP led to the installation of new agronomic practices.

The results show an over-representation of mixed farmers in the *Intensive DTP* profile. We could propose the hypothesis that digital technology allows some conventional farmers to move towards organic farming, while retaining a somewhat similar way of working: organic fertiliser rather than chemical, pesticides authorised in organic rather than in conventional farming, mechanical weeding with precision hoeing rather than chemical weed-killer. Thus DTP could be consistent not only with efficiency strategies, but also with substitution strategies (Hill and MacRae, 1996). This over-representation of mixed farmers should be contextualised by the fact that these farmers have a larger area of land and often have outsourcing activities. They belong to a more 'industrial' model of organic farming.

Digital technology seems to favour another form of ecologisation: the development of organic farming in big farms. This echoes a political and academic debate about the 'conventionalisation' of the organic farming (Darnhofer et al., 2010; Stassart and Jamar, 2009). Digital technology could be an accelerant in this conventionalisation, to the detriment of more radical organic farming, and smaller farms.

5.2. Digital technologies for information and communication, knowledge and ecologisation

Our second proposition was that the use of DTC is tied to stronger forms of ecologisation than DTP is. DTC profiles characterisation highlights that DTC profiles relate to completely different variables than DTP. Consistently with Konrad et al. (2019), factors leading to adoption and use depend on the digital technology studied. However, the links between DTC and ecologisation models needs to be refined.

5.2.1. The use of DTC is linked to a socio-economic environment, but above all, to individual characteristics

Individual characteristics of farmers: education, age and skills, as well as individual preferences are key variables to distinguish between DTC profiles. However, economic factors are not significant, contrary to the results of Michels et al. (2020), although that research was only onto the adoption of smartphones.

Socio-economic environment plays a role, for good or ill, in the use of DTC. Both being a member of a cooperative and benefiting from advice by seed companies are tied negatively with the use of DTC. This could be a result of the formalisation and standardisation of production processes integrated within contracts with downstream industry, which limits possible changes for farmers, making them less inclined to look for information and knowledge. It could also be explained by the fact that production contracts and membership of a cooperative already include knowledge exchanges (Cholez et al., 2020). Membership of a trade union is tied positively with the use of social networks. Membership of a Farmers' knowledge exchange group or to other forms of farmers groups, is also tied positively. Belonging to this kind of group could signal an interest in agronomic and technical innovation information. Moreover, the internet is a source of information that appears to be complementary to local knowledge sources. It allows insight into what is being done elsewhere as opposed to what is being done locally, or having a lot of information as opposed to having precise information that is adapted to local conditions.

5.2.2. The internet facilitates access to new information on new and more radical practices, but with limitations

It came out during the interviews that the internet seemed to be source of information for what to do in atypical situations, or for getting knowledge that is not available in local networks. It equally acts as a source of inspiration to try out new practices, and a means of monitoring agronomic practices. These range from the adjustment of practices (what to do when faced with the new conditions caused by climate change, for example), to the search for information on more radical changes in practice, in particular, because information is not available on the usual information networks, as Baptiste explains:

> *"The cooperative was a bit behind in this, so I went to see what they are doing there quite a lot. Also plant species mixes. I bought and made my own little mixes."* Baptiste (Network DTC)

We should add to this the idea of exchange, participation, and being themselves a source of information. However, interviewees often mentioned problems with the reliability or the relevance of information, in terms of local soil and weather conditions, as seen below:

> *"Well, people have different experiences, but something that works for one person, does not necessarily work here".* Corentin

Our second proposition also needs some qualifications. First, it seems that the links between the use of DTC and agronomic practices could go one of two ways: as both a cause and a consequence. Using the internet means discovering new practices, and the desire to establish new practices encourages the use of the internet to search for information. Second, the internet is not necessarily a privileged form of access to knowledge, but it makes it possible to fill the gap in agro-ecological information from traditional networks (advisors, neighbours, family) (Lucas, 2021). For instance, the internet appears to be a major source of information for cover crops and conservation agriculture. Knowledge gained from the internet does not seem to be able to completely replace knowledge acquired orally, in particular in the case of ecological, localised and adaptive know-how (Burton and Riley, 2018). Moreover, in our sample, there is no widespread use of DTC in order to co-create knowledge and redesign knowledge systems.

DTC uses allow for a combination of information sources, rather than replacing direct exchanges. It is therefore often the farmers who are involved in local knowledge exchange groups that make the most use of technical information on the internet.

5.3. Understanding use profiles highlights trajectory mechanisms

Qualitative insights complement the quantitative description of the profiles. They made it possible to demonstrate trajectory mechanisms, and in particular non-linearity processes. First, we have shown the non-linearity of the process of digitalisation at the level of individual farmers' decisions. We note phenomena of farmers trying out the technologies, but then abandoning them. Second, farmers are not on a unique 'S curve' of adoption (Rogers, 2010). Categorisation as "pioneers" or "laggards" does not seem relevant here. Not adopting a technology does not necessarily signal a resistance to change, or a slower adoption process that "laggard" farmers would follow. It can be a coherent choice that matches their practices and objectives, towards a different technological trajectory (Eastwood et al., 2017; Rogers, 2010; Van der Ploeg, 2018). The adoption and use of a technology may not be so much the result of individual 'pioneer' behaviour, but the result of a production model interacting with a socio-economic system that encourages, or even imposes, these technologies.

Moreover, we have observed reinforcement mechanisms: the use of digital technologies for production (DTP) facilitates further industrialisation trajectory and expansion of farms, which in turn favours the use of DTP. This leads to mechanisms of path dependency and reinforces the dominant farming production systems as suggested by Bronson (2019) or Vanloqueren and Baret (2009). However, our analysis is only one snapshot in time, and it would be interesting to complete it with a long-term longitudinal analysis. It would make it possible to go more deeply into the processes tied to the trajectories. This would involve on-farm and long-term research, but also underlines the importance of having access to public databases on farms structures, practices and uses of technology.

Our research also confirms the major role of intermediaries, such as advisory services, but also training organisations and value-chain actors, such as agricultural cooperatives, in digital uses and trajectories (Eastwood et al., 2017; Fielke et al., 2020). Moreover, regulation, agricultural policies and private norms play a role in digital uses and participate in farming trajectories and path dependency mechanisms. There is a need to provide institutional analysis of the roles of intermediary actors on rules and practices that impact the relation between digitalisation and ecologisation trajectories. It also implies that digitalisation policies must be considered alongside public policies on knowledge development and extension services as well as with economic incentives and social and environmental regulations.

Technologies and practices are interconnected within technological systems (Clapp and Ruder, 2020). Only focusing on one form of digitalisation would mean supporting only one form of ecologisation of agriculture. We can put forward a range of propositions to enable digitalisation to embrace more agroecological and diverse models, including the following. The basis unit of digital technologies could move from one crop to one complex system. Participatory conception could be promoted (Jakku and Thorburn, 2010). Digitalisation objectives could integrate a diversity of expectations, such as promoting on-farm experimentation, systemic analysis and knowledge exchanges rather than optimising inputs and increasing traceability (Lacoste et al., 2021; Schnebelin et al., 2021). There is also a need to renew the economic and political models of technologies, such as open or collective technology as data commodification is tied with industrialisation (Carolan, 2017; Wolf and Wood, 1997).

More broadly, to avoid a monolithic orientation of digitalisation, there is a need to question who and what drive innovation trajectories. Innovation trajectories depend on the complex interplay between economic forces, institutional and political factors (Dosi, 1982). Authors argue that digital agriculture is mostly driven by private industries, notably agri-business and digital firms, supported by national policy (Birner et al., 2021; Prause et al., 2020). There is a risk that this configuration reinforces the lock-in of ecological innovation (Vanloqueren and Baret, 2009), especially as AgTech firms do not perceive the ecologisation heterogeneity and its implication for digitalisation as previously shown in Schnebelin et al. (2021). National policies such as research funding and orientation, can play a role to escape such a lock-in effect (Cowan and Hultén, 1996). These policies could acknowledge the heterogeneity of innovation system to better include actors outside the dominant paradigm (Klerkx and Rose, 2020). They could also re-balance power and invest in alternative digitalisation pathways. There is also a need to study digital technologies conditions of use and to provide evidence on their real effects (Ingram et al., 2022). Digitalisation policies are not neutral and there is a need to engage a reflection on changes in governance and orientation of innovation systems (Klerkx and Rose, 2020; Pigford et al., 2018).

6. Conclusion

Based on a large number of interviews with crop farmers in France about their use of digital technology, our research identifies a diversity of digital use profiles rather than a single digitalisation. These profiles relate to farming models. Intensive uses of Digital Technologies for Production are tied to, and reinforce, the industrialisation of farming that is characterised by expansion, outsourcing activities and a salaried workforce. The use of DTP facilitates the industrialisation trajectory, which favours the use of DTP in return. This leads to mechanisms of path dependency, and reinforces the dominant farming production systems. Uses of DTP can be linked to weak ecologisation or "symbolic ecologisation" strategies. It can also support some substitution strategies such as the development of industrial organic farming. The use of Digital Technologies for Information and Communication appears to complement and to add new possibilities for knowledge exchanges while, thus far, not challenging farmers' knowledge and production systems. This analysis invites a consideration of the adoption and use of technology as the result of production models interacting with socio-economic systems, rather than the choice of an independent individual. This cross-sectional analysis allows us a glimpse of the technological trajectory that is being promoted by the current development of digital tools in farms. At a time when French farm structures are being challenged and are undergoing a more profound differentiation, current digital use is mostly encouraging the development of industrialisation, rather than the agroecological farming system. This work calls for other research, to better understand technological trajectories. There is a need for multidisciplinary research, to evaluate changes and environmental performances through a longitudinal analysis of digital use by farmers, and to develop tools, digital or not, that support agroecological farming systems. The policies of digitalisation are not neutral, as the technologies promoted are used more by certain models than by others. Limiting focus to one technological model means promoting a specific farming trajectory. To promote a diversity of ecologisation pathways, other forms of digitalisation development should be considered alongside knowledge, economic and social policies, that imply changes in policy and in orientation of innovation systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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